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Folded MEMS 3-D Structures for Inertial Measurement Applications

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Folded MEMS 3-D Structures for Inertial Measurement Applications

DISSEETATION

submitted in partial satisfaction of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

in Mechanical Engineering

by

Montgomery Chittenden Rivers

Dissertation Committee:
Professor Andrei M. Shkel, Chair
Professor J. Michael McCarthy
Professor William C. Tang

2015
DEDICATION

This work is dedicated to my wonderful parents Randall and Julia, my dear sister Rachel, and my always supportive Lisa.
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ABSTRACT OF THE DISSERTATION

Folded MEMS 3-D Structures for Inertial Measurement Applications

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An innovative approach for creating miniature Inertial Measurement Units (IMU’s) has been developed using folded MEMS fabrication. This enables a path toward a high-performance IMU with a chip-scale footprint of <1 cm². The explored method of manufacturing chip-scale IMUs utilizes folded MEMS structures rather than chip-stacking or single-die implementations. Inertial measurement units have previously been developed to detect translational and rotational motion, and miniaturization of such technology is desired for many applications. A fabrication process is developed in this work for creating chip-level IMU’s utilizing a 3-D SOI backbone which is suitable for high-performance single-axis sensors with an overall package volume of 1 cm³ or less.

Inertial sensor test structures are designed and implemented on prototype IMU structures. Conventional packaging methods are used such as wirebonding and flip-chip die attachment to connect the sensor bond pads to the overall package. Results indicate that the scale factors are found to be 0.43 mV/°s for the gyroscopes and 3.7 Hz/g for the accelerometers. Methods for providing reinforcement of the folded MEMS devices are explored including epoxy bonding, eutectic soldering, and silicon welding. Folded structures reinforced with silicon welding resulted in survival of up to 260 g of acceleration and experienced its first modes of resonance above 10 kHz.
Performance estimation of the capabilities of the folded MEMS IMU devices is simulated with a mathematical error model. A coordinate transformation is defined to translate the inertial sensor vector axes to navigational frame coordinates. Transformations from the IMU body frame to the navigational frame are created for pyramidal and cubic folded IMU structures. The resulting calculated CEP rate values indicate that the device is capable of moderate navigational performance compared to current technology. This type of IMU shows an overall performance advantage compared to existing chip-scale IMU devices, and is capable of producing a moderate-performance chip-scale device that exceeds the currently available technology.
Chapter 1

Introduction

Position, trajectory, and orientation monitoring has been used for many centuries among a wide variety of applications. Several traditional devices have been utilized for this purpose including maps of the night sky, position of the sun, sextants, compasses, and other apparatuses. More recently, inertial sensors such as gyroscopes and accelerometers are implemented in place of, or in parallel with these classical devices. The miniaturized sensors are generally designed and arranged in a manner to detect three axes of rotation rate as well as three axes of linear acceleration, much like that of classical inertial detection systems. When combined, this allows for inertial detection along a total of six sense axes. With this type of configuration, the overall system is able to fully measure position and orientation of a moving object and is also completely self-contained. Such a device is dubbed as an Inertial Measurement Unit (IMU) with six degrees of freedom (DOF) of inertial detection.
1.1 Background

The ability to monitor the location and attitude of an object or piece of equipment has significant advantages in many industries including defense, aerospace, robotics, exploration, navigation, and consumer applications. For this reason, inertial sensors have been created that utilize various physical phenomena to detect motion. Examples of detection elements include spring-mass-damper systems, vibrating masses, light waves, and even the nuclear spin of atoms. In general, performance of each type of inertial sensor directly depends on the overall size of the sensing element. For instance, a large, heavy proof mass in a spring-mass-damper accelerometer responds with a larger detectable force due to an applied acceleration. When using a smaller, lighter proof mass, the induced inertial force on the proof mass is lower, and thus is more challenging to detect as size further decreases. However, as applications for IMUs and inertial sensors are evermore increasing, desire for further miniaturization is rising. With the existence of cell phones, laptops, Global Positioning System (GPS) devices, and other products, it is now desired to put an IMU into nearly everything. Therefore, exploration has been conducted over the past few decades to develop miniaturized IMUs with performance equivalent or better than that of larger devices.

In prior years, utilization of IMUs were generally limited to navigational applications such as aerospace, defense, and space exploration [1, 2]. Another application is to detect motion of human functions for the purpose of rehabilitation [3]. As technology has progressed, miniaturization of IMUs has stimulated demand from a growing amount of purposes. In most circumstances, GPS devices deliver results that satisfy navigational requirements. However, when the GPS signal is not available due to interference, the data cannot be delivered. In such situations, an IMU can detect motion internally. Common situations in which this occurs is underground or underwater exploration, guidance in space, or when the signal is intentionally jammed by an outside party.
Tracking objects is also utilized for a wide variety of applications. Location information from a GPS can be easily compromised, at which point a self-contained IMU can assume functionality to provide location information without GPS data. Also, for global positioning, a high-performance IMU can be used to detect the Earth’s rotation and centripetal acceleration to acquire latitude measurements and calculate true north. Additionally, IMUs are lately being desired in consumer devices such as cellular phones and video game controllers for entertainment purposes. Due to the rising amount of applications requiring miniaturization, it is necessary to develop a new path for creating a chip-scale IMU while still maintaining high-performance of traditional devices.

1.2 Research Objectives

The purpose of the work presented in this dissertation is to develop a novel path for creating miniature IMUs while also combining the advantages of existing approaches and also minimizing their limitations. The method explored in this thesis uses foldable MEMS structures to create chip-scale 3-D form factor systems with inertial sensors embedded in the sidewalls. Silicon-on-insulator (SOI) substrates are used to allow fabrication of high-aspect-ratio single-axis sensors. Bulk micromachining is utilized to create three in-plane accelerometers and three z-axis gyroscopes fabricated with an in-house process optimized for the single-axis SOI sensors [4, 5]. In parallel, a foldable structure is fabricated on the same substrate. The entire structure consists of a sensor on each sidewall, flexible hinges, electrical interconnects, and mechanical latches [6, 7]. Once fabrication is complete, the device is assembled into a 3-D structure to provide the spatial orientation required for six axes of inertial measurement with single-axis sensors. Volume of the entire package utilizes less than 1 cm$^3$ and has a footprint of less than 1 cm$^2$. Sensor packaging is performed by attaching glass lids with patterned metal traces that connect the sensor bond pads to the folded structure interconnects. A
conceptual image of a folded MEMS IMU with packaged sensors is depicted in Figure 1.1. A performance simulation of the overall devices is also done to consider the overall capabilities of the packaged IMU structures using various reinforcement techniques and geometries.

Figure 1.1: Concept of a folded MEMS structure with interconnect lids included for sensors packaging.

Compared to the current techniques for creating miniature IMUs, the presented approach has distinct features and advantages. With a footprint area of less than 1 cm$^2$, the IMU in its entirety is a chip-scale device due to the fact that the footprint area is comparable to a single sensor die. Scaling of the device can also be done to reduce size and form factor to fit applications that require smaller area, or increase size to allow for higher performance. Fabrication of the sensors and the underlying foldable structure is completed in one process flow, which minimizes post-fabrication assembly steps. A major advantage of this approach compared to other chip-scale IMUs is that it provides a large ratio of sensor surface area versus footprint size, which allows for utilization of larger sensors. This directly improves the performance capability of each sensor, resulting in an IMU with higher performance compared to those integrated with smaller sensors to minimize size. Additionally, the internal volume of the folded structure can be co-integrated with CMOS signal detection electronics, a GPS receiver, or a wireless data transmitter. The folded MEMS approach is also modular,
allowing for integration with single-axis sensors, multi-axis sensors, or any other type of device compatible with the fabrication process. Examples of other devices that can be included are pressure sensors, energy scavengers, optical detection sensors, and other SOI devices.

In addition to the advantages of the proposed process, several challenges were faced with creating a folded MEMS IMU device. Development of the fabrication process required multiple iterations to achieve process maturity suitable for creating an IMU with in-situ SOI sensors. For this reason, the work on developing the folded MEMS IMU fabrication process will be discussed in different phases. A brief description of each phase is given below and more details are to follow in Chapter 2.

- Phase 0: Initial work done to explore the possibility of manufacturing folded MEMS structures with electrical interconnects. This work was primarily discussed previously.

- Phase 1: Inclusion of SOI sensors fabricated in-situ with the folded MEMS structures.

- Phase 2: Increased resolution of sensor features and incorporation of more complex sensor designs, as well as a second protective layer of polyimide.

Because the entire device is created in the same process flow, many fabrication steps are required for manufacturing. Each individual process therefore must be compatible with all prior and successive processes, and fabrication must be done on both the front and back side of the substrate. Cleanliness of the wafer throughout the entire process is critical to successfully manufacture an operational IMU, which was difficult to maintain due to the number of fabrication steps and combination of materials.

Another challenge involved with the folded MEMS process is developing the mechanical design of the overall IMU. In parallel with exploration of the fabrication process, the design
of the foldable structure required iterative cycles throughout all phases of development. Modifications to both the design and fabrication process were necessary to create a suitable folded MEMS platform for operational inertial sensors. The design must also allow for conventional device packaging after fabrication is complete. Each sensor requires individual packaging, and the overall IMU needs to be additionally packaged to allow interfacing the entire device with external signal detection electronics.

Rigidity and durability of the structure are also concerns because deflections experienced by the IMU structure results in signal errors due to sensor misalignments. For instance, high-performance sensors installed onto a structure with low rigidity leads to an IMU with limited performance. This is because the sensors detect the imperfections of the structure in addition to the motion of the underlying skeletal structure. Therefore, the overall performance of the IMU not only depends on the sensors themselves, but also the underlying rigidity of the platform. Since the foldable MEMS structures are comprised of silicon, rigidity of individual sidewalls is very high. However the integrity of the assembled structure significantly depends on the method used to adhere the sidewalls together. For this reason, several methods for structural reinforcement are explored to maximize the rigidity of the structures, thus improving the performance capabilities possible with the folded MEMS IMU approach.

Materials such as epoxy or eutectic solder can be used to reinforce the assembly, although it is desirable to maximize structural rigidity by performing silicon welding at the latching areas. By doing so, the entire skeletal platform of the IMU is formed from silicon panels. Not only does this provide optimal rigidity, it also minimizes thermal mismatch of materials which would cause misalignments of the sensors due to temperature variations. Exploration of silicon welding is therefore explored to create a folded MEMS IMU with extremely high structural rigidity along with minimizing mismatch of thermal material properties.

Evaluation of the performance of the overall IMU is done by simulating the Circular Error Probable (CEP) rate error over a predefined trajectory. Pyramidal and cubic structures
are considered as well as the difference between epoxy and solder reinforcement. Sensor characteristics are based on values experimentally obtained from other sensors potentially compatible with the folded MEMS IMU fabrication process. Given these characteristics, the CEP rate error provides information regarding the capabilities of an Inertial Navigation System (INS) integrated with a folded IMU device. Errors considered in the model include bias, scale factor, and estimated temperature misalignment. Results from the simulated study indicate that the cubic configuration is optimal when experiencing minimal fluctuations. However the pyramidal geometry is more robust to large changes in temperature.

In summary, the primary goal of this research is to create a path toward a chip-scale IMU using a folded MEMS approach that provides miniaturization without compromising overall performance. A cubic structure has been designed to allow for three accelerometers and three gyroscopes, each of which are single-axis devices, to be mounted orthogonally with respect to each other. Other form factors were also considered, such as a pyramidal structure, and are discussed in this dissertation. Structural reinforcement optimization is explored with various techniques, including epoxy, eutectic solder, and silicon welding. Laser and resistive welding methods are investigated to perform fusion of bulk silicon on the IMU structures. Each type of welding is experimentally conducted to enable a path toward maximum rigidity, and also to provide minimal variations of thermal properties of the folded MEMS IMU devices.

1.3 Review of Existing Technology

Many methods have been previously explored to decrease the overall size of IMUs, and generally fall into three scopes of design. One technique for creating a small IMU is accomplished by using Commercial Off-The-Shelf (COTS) inertial sensors combined with electronic signal detection architecture on small Printed Circuit Boards (PCBs). By assembling the circuit boards into a 3-D structure, or by using multi-axis sensors, inertial motion can be detected
along six independent axes [9][12]. Another approach is to combine all inertial sensors on a single die integrated with CMOS circuitry [13]. With this method it is common to utilize multi-axis sensors to minimize the footprint area of the IMU chip. More recent approaches use chip-stacking of inertial sensors and CMOS electronics to reduce the footprint area to the size of a single die [14]. Although this method is in its infancy of development, it is currently being explored as an alternative to the former techniques for miniature IMU designs. Because of the large number of miniature IMUs being explored, an abbreviated collection of examples of the technology representing current status quo is explained in this section regarding multi-DOF IMUs of small form factors.

1.3.1 Commercial IMU Products

Several IMUs of various size and performance specifications are commercially available for a wide range of applications. Because the goal of this research is devoted to developing a chip-scale IMU, the focus is narrowed to discussing IMUs of very small form factors. Since inertial sensors generally have better performance when made larger [15], there is an obvious trade-off when scaling down the size of the overall IMU. However, it is ultimately desired to create high-performance IMUs of miniature size to allow for integration into a broader range of applications.

One commercial IMU by XSense™ is dubbed the MTw™ and contains a three-axis gyroscope, three-axis accelerometer, three-axis magnetometer, as well as a pressure sensor. This allows for a total of 10 degrees of freedom (DOF) for measurement and is thus defined as a 10-DOF IMU. The gyroscope has a bias stability of 20°/hr and the accelerometer has a noise floor of 0.003 m/s²/√Hz. Package size of this IMU is 34.5 x 57.8 x 14.5 mm, which is 28.9 cm³ in volume [16]. While this is quite small compared to navigational grade IMUs, it does not offer simple integration with applications requiring minimal size and weight.
Analog Devices, Inc. offers a variety of compact IMUs using MEMS sensors, all of which are in the iSensor® family of products. Available models contain anywhere from 4-DOF to 10-DOF of sensing and are approximately 1-2 in³ in package volume. The most advanced IMU currently available for purchase is the iSensor® ADIS16480 which contains triaxial models of a gyroscope, accelerometer, and magnetometer. A pressure sensor is also included to create a 10-DOF IMU. Bias stability of the three-axis gyroscope is 6.25 °/hr and 0.1 mg for the three-axis accelerometer [17]. Size of the overall packaged device is 47 x 44 x 14 mm which results in a volume of 29 cm³ and thus is essentially the same size as the XSense™ MTw™ with identical sensing degrees of freedom. Based on these parameters, this IMU is appropriate for use in most civilian consumer applications. Although the sensor specifications show that the ADIS16480 is a device with higher performance, it still suffers from a large size when attempting to integrate it into complete miniature IMU systems.

A chip-stacked IMU, the MPU-9150 by InvenSense®, has recently been developed and commercialized which is much smaller than the others described above. Size of the overall package is 4 x 4 x 1 mm, making it a volume of 0.016 cm³ and therefore is a chip-scale IMU. Similar to the others, this unit also contains a combination of a three-axis gyroscope and a three-axis accelerometer, as well as a three-axis magnetometer. Because the device is in the latter stages of commercialization, performance evaluation is not yet complete and may change prior to release [18]. However an initial specification given by InvenSense® declares a zero-rate output of the gyroscope of 20 °/s and a zero-g output of 150 mg for the accelerometer. These figures indicate that the device is not necessarily a high-performance IMU, however it is capable of integration into a much wider range of applications.

MicroStrain® also provides a selection of COTS IMUs, such as the 3DM-GX3® series. Model 3DM-GX3®-45 is equipped with MEMS inertial sensors combined with a GPS receiver to create a complete INS [19]. The purpose for integrating an IMU with a GPS unit is to allow for inertial navigation while GPS information is unavailable or satellite signals are
weak. Combining the two is a common method for creating a reliable INS, in which the GPS data is used to recalculate position when the satellite signals are available. Specifically, the 3DM-GX3\textsuperscript{®}-45 device delivers a bias stability of 0.04 \textit{mg} and 18 °/hr for the accelerometer and gyroscope, respectively. Size of the device is 44 x 24 x 14 mm, which is larger than other devices and not able to be integrated on the chip-level for compact applications.

1.3.2 Academic IMU Research

In addition to the products available on the commercial market, chip-level IMUs are also being explored by academic institutions. Research conducted involves determining optimal methods for miniaturizing IMUs with new technologies that are not necessarily mature enough for mass production. One example consists of a rectangular structural housing comprised of silicon with COTS sensors, a battery, and electronics mounted internally. Each inner surface functions as a PCB created on a silicon substrate rather than the traditional FR-4 material which is commonly used for PCB manufacturing. A three-axis accelerometer and a three-axis gyroscope are then attached to the inner bottom surface in addition to signal detection electronics. Overall size of the device is 12 x 12 x 25 mm, or 3.6 cm\textsuperscript{3} in volume \cite{20}. The silicon skeletal structure is fabricated on the wafer level to allow for smaller size compared to navigational-grade IMUs, however has a footprint much larger than that of a single chip. Further miniaturization of this device is possible, but is limited by the size of COTS sensors, electronic components, as well as the external silicon housing.

Miniature IMUs have also been explored by fabricating all sensors on a single die. For example, a single-chip IMU containing two single-axis accelerometers, one seismic accelerometer for z-axis sensing, and two magnetometers was developed on a die with a footprint area of 4 x 4 mm. By utilizing a system-on-chip method for fabrication, the IMU is also integrated with CMOS electronics for signal detection \cite{21}. However, this IMU does not contain any
gyroscopes and thus rotation rates cannot be directly measured. A much larger die would be required to include the gyroscopes needed to create a complete IMU that directly measures rotation rates along with multi-axis acceleration.

Other IMU devices have been created using a single-die approach \[22, 23\]. The main advantage of this method is that it allows for the footprint of the system to be small enough for chip-level packaging. Also, since fabrication is done at the wafer level, sensors are aligned using photolithography, which reduces the difficulty of post-fabrication calibration. Despite these advantages, there are significant drawbacks to the single-die IMU architecture. Inevitably, sensors for in-plane and out-of-plane detection must be fabricated on the same substrate. But each type of sensor has certain design parameters required for optimal performance. In the case of out-of-plane (z-axis) sensors, in-plane stiffness of the proof mass must be large to suppress x-axis and y-axis responses. However, for out-of-plane sensors, the z-axis stiffness must be low to maximize detection capabilities. Conversely, in-plane sensors require high out-of-plane stiffness and low in-plane stiffness for the same reason. For both to co-exist on the same substrate, a compromise in fabrication and performance must be made to accommodate multiple sensing axes on the same substrate. Inherently, this approach results in conflicting performance for in-plane and out-of-plane sensors, which creates non-symmetric IMU signal detection.

Another emerging method for creating micro IMUs involves chip-stacking \[24\]. With this technique, each sensor is fabricated independently and then known-good dies are stacked together onto a single chip. In comparison to the PCB and common substrate approaches, the overall footprint of the IMU is reduced to that of a single sensor. Also, because each die is fabricated independently, signal detection electronics can be included within the stack to create a self-contained chip-scale IMU system. However, there are drawbacks to this approach as well. For instance, both in-plane and out-of-plane sensors are inevitably included because of the chip-stack geometry. Because these sensors must be created with different processes,
they are not identical in design and suffer from mismatched sensitivities between the in-plane and out-of-plane inertial sensing capabilities. Another challenge with this method is minimizing electrical cross talk. Due to the large number of interconnects that are required to pass through the chips at the bottom of the stack, significant parasitic capacitance exists which induces noise and degrades overall IMU performance.

### 1.3.3 Miniature 3-D Assembled Systems

In addition to inertial sensors, other types of sensors have been configured into compact 3-D packages to accomplish multi-directional detection capabilities. Assembly of multiple sensors is useful in many applications such as wireless systems, biosensors, and electromagnetic relays, to name a few [25, 26]. Since the folded MEMS approach allows for significant modularity of integrated sensors, prior art is reviewed for all types of compact systems with 3-D architectures containing multiple devices. Therefore the technology is inherently related to the research objective and an exploration of current approaches is necessary, even if not related to inertial navigation.

Some designs involve several dies stacked together that each contain different components, similar to the stacked die IMU approach. Each die contains sensors or circuitry that can be fabricated separately, then packaged and connected to each other to create a system-in-package (SIP). One example of this has been developed using package-on-package assembly to create a wireless biosensor system [27]. This particular device includes a wireless transceiver, antenna, 12-bit microcontroller, analog to digital converter, and custom CMOS circuitry in a 14 x 14 x 12 mm package.

Another device for biological and environmental sensing purposes was developed using the same chip-stacking technique [28]. Packaged in a volume of 0.15 cm$^3$ is a set of capacitive sensors for detecting pressure, temperature, and humidity. This device also includes memory,
a microcontroller, sensing elements, and a custom Application Specific Integrated Circuit (ASIC) within the chip stack. Overall, the device consists of three layers. The top layer includes the sensors and the ASIC, and the second layer provides the microcontroller along with Through-Wafer Vias (TWVs) to allow for electrical interconnections between all three layers. Memory and the sealing cap are fabricated on the third layer to complete the system, resulting in a compact device capable of measuring multiple physical phenomena in a 3-D package.

Solid-state memory with very high density has also been developed by ISC8, Inc. using the chip stacking technique. The system-on-chip memory modules are created from a stack of wafers and after being bonded together, and the sides are lapped and polished. Electrical traces are then deposited onto the sidewalls to provide connections to each layer within the stack [29]. Using this method, high density memory storage is enabled that surpasses the density of the memory modules widely used in current technology. External packaging of the memory units done with a Ball Grid Array (BGA) package, allowing for simple integration with PCB assembly technology. Using a similar process, SOI substrates with inertial sensors can be manufactured to create an IMU with an array of stacked chips rather than a memory module.

Another device utilizing stacked dies is the Wireless Integrated MicroSystems (WIMS) cube, which consists of individual dies stacked inside a cubic silicon skeleton. Connections to each layer in the stack are provided by flexible hinges on the inner sidewalls. The individual dies are fabricated separately, then assembled within the cubic structure. Ribbon cables consisting of polyimide, metal traces, and fluidic channels are created on each chip in the stack. The structure itself is also equipped with electrical and fluidic connections to allow interfacing between each die, as well as to provide external inputs and outputs. Connection of the ribbon cables to the inner sidewalls of the structure can be performed mechanically or with thermal actuation [30–32]. Although this approach is similar to the research objective,
the main advantage of the folded MEMS IMU approach is that the devices and ribbon cables are created in-situ with the supporting structure to minimize handling operations during assembly which can cause errors and thus reduce yield of operational units.

Each described 3-D sensor fabrication technique provides large package density with minimal volume. A wide variety of applications benefit from miniature sensor systems such as navigation, biosensors, environmental detection, and robotics. Assembled miniature sensor systems offer a large degree of modularity, making them useful for a broad array of uses. Although current technology provides capability of small-scale IMU systems, none are pursuing wafer level integration of sensors and the underlying support structure. Using the folded 3-D MEMS approach, sensors are created in parallel with the external skeleton, minimizing handling operations and alignment errors after the system is fabricated. Although this approach focuses on creating an IMU, modularity of this method allows for a wide variety of applications and is not limited solely to inertial navigation.

1.4 Trade-offs of Current Approaches

Based on existing technology for creating compact systems, it is observed that three primary methods, or combinations thereof, are being utilized. Conceptual examples of each general approach are shown in Figure 1.2. The first method utilizes COTS single-axis sensors mounted on PCBs with signal detection electronics, then assembled with a 3-D spatial configuration, conceptually depicted in Figure 1.2(a). With this method, sensor performance is optimized due to the maturity and performance capabilities of single-axis COTS inertial sensors and PCB fabrication. Currently, this approach is commonly used to create compact IMU devices that are commercially available. However, drawbacks do exist. First, significant post-assembly of individual PCB-compatible components is necessary. For this reason, the device is inherently less compact than what is achievable with other approaches. While units
developed with this process are quite small (on the order of 1-2 in\(^3\)), further size reduction to a chip-scale device is extremely difficult.

(a) Approach 1: Use COTS sensors, assemble into a 3-D configuration. (b) Approach 2: Fabricate all sensors on one large die. (c) Approach 3: Stack individual sensors and CMOS components onto one base die.

Figure 1.2: Fabrication approaches used for status quo IMUs of miniature size.

The second approach consists of single-axis or multi-axis sensors fabricated on the same die, Figure 1.2(b) This approach is advantageous due to its compact design, lithographic alignment, and minimal post-fabrication assembly procedures. Because the sensors are all created on one die, the footprint of the system is small enough for packaging in a large chip cavity. Lithographic alignment also reduces the difficulty of post-fabrication calibration because the x-, y-, and z-axis sensors are orthogonally patterned with light waves. However, there are drawbacks to this type of design as well. First, creating sensors for in-plane and out-of-plane detection generally require different design parameters as discussed in Section 1.3.2. Additionally, this type of design requires a footprint area the size of several dies, which requires a large package. The alternative is to scale down the sensor size to reduce the overall footprint to that of a single die, but the obvious trade-off is reduced sensor performance.

A more recent approach to creating a chip-level IMU involves chip stacking, Figure 1.2(c) as discussed in Section 1.3.3 for other systems. With this technique, each inertial sensor can be manufactured as a single-axis or multi-axis device, depending on how many chips are included. Additionally, CMOS signal detection electronics can easily be included on a separate chip within the stack. One drawback to this design is that temperature stability
largely relies upon heat dissipation throughout the entire system. Because there is potentially several dies in the stack, thermal conductivity from the top die to the bottom will be quite poor and will result in thermal variances in each die. Another concern is electrical cross-talk between signals due to the large density of interconnects at the bottom portion of the system. Additionally, a challenge is involved with integration of out-of-plane sensors and in-plane sensors, which can result in mechanical cross-talk causing cross-axis sensitivity and thus reduced IMU performance. Similar to the approach using a single die with multiple devices, each type of sensor will be created using different fabrication techniques, resulting in variances in sensor performance. Due to these challenges and trade-offs for each method currently used for fabricated compact sensor systems, it is advantageous to determine an alternative approach for fabricating a chip-level IMU.

### 1.5 Organization of Dissertation

Current techniques for creating chip-level IMUs contain inherent trade-offs, and thus a new path for manufacturing a miniature IMU is largely desired. Initially, research and exploration of creating folded silicon structures on Single-Crystal Silicon (SCS) substrates without sensors was performed [8]. In parallel, sensors were created independently for experimental purposes, and later integrated into the folded MEMS structure design. Further development explained in this dissertation utilizes SOI substrates to enable in-situ sensor fabrication on each sidewall. Although the design is modular, allowing for inclusion of any type of SOI device, inertial sensors are implemented to create a 6-DOF IMU. Single-axis sensors are used rather than multi-axis sensors to avoid compromising performance for additional degrees of freedom. Using a cubic structure with three accelerometers and three gyroscopes, and with one sensor on each sidewall, a device created using this approach is capable of measuring three independent axes of rotation rate and acceleration.
In Chapter 2, details of the overall folded MEMS IMU approach are described. Although several iterations of development were required to create a suitable fabrication process, only the final two are provided. Each of which involves integrating SOI sensors into the folded structures. The processes are similar in many respects, however the differences have advantages and tradeoffs for both. For instance, the first process requires fewer steps to complete fabrication, and provides a minimum sensor feature resolution of 8 µm. The second process is capable of 5 µm sensor resolution, although it contains additional processing and thus needs more time for completion. Details of IMU fabrication are given in Chapter 3 further explaining each process step. This includes process recipes, photographs, microscopic images, and modifications for improving the individual processes.

Packaging and electrical characterization of the IMU structures is described in Chapter 4. Following fabrication, each individual sensor must be packaged, followed by the entire IMU structure. Interconnect plates and lids are attached to each sidewall for this purpose, explained in Section 4.1. Characterization of the sensors is also discussed, beginning with accelerometers fabricated independent of the overall IMU, Section 4.2. Sensors fabricated in-situ with the folded MEMS IMU fabrication process were also characterized, with details given in Section 4.3. Electrical characterization of a fully packaged IMU is presented in Section 4.4 and results indicate feasibility of the folded MEMS IMU approach.

Rigidity enhancement of folded MEMS IMUs using silicon welding is described in Chapter 5. Other types of reinforcement are also discussed, including epoxy bonding and eutectic soldering. Trade-offs of each reinforcement method are discussed in Section 5.1. Overall, the desired method for structural reinforcement is silicon welding because of the minimal mismatch in thermal properties. Therefore an exploration of bulk silicon welding has been conducted. For general welding methods, two techniques are used: joule heating and laser heating. Both methods are explored for welding bulk silicon areas on the folded IMUs, demonstrating the capability to fuse larger pieces together than previously performed.
Resistive welding is described in Section 5.3, beginning with computational modeling in Section 5.3.1. Results indicate that a large amount of power is required to conduct welding, and thus a robust power supply is required to provide single pulses of high-current with variable voltage, pulse time, and current output. Because such a power supply does not yet exist commercially, design and construction of such a power supply has been done, described in Section 5.3.2. Experimental work is shown in Section 5.3.3 with results indicating successful welding of bulk silicon using the manufactured power supply. Laser welding is also explored in a similar manner in Section 5.4, beginning with modeling shown in Section 5.4.1. Experimental research is discussed in Section 5.4.2 and has shown laser welding to be successful for bulk silicon. Qualitative analysis of the results is then conducted by breaking the welds and examining the areas with a scanning electron microscope. Folded IMU structures were successfully welded together along the latching seams to provide the desired reinforcement. Structural characterization was also performed on the structures to compare the results with other methods of reinforcement. Characterization results are given in Section 5.5 for laser welded pyramidal IMU structures. This includes environmental testing such as vibration, mechanical shock, constant acceleration, and exposure to temperature. Conclusions indicate that silicon welding provides much higher rigidity compared to other methods and thus is preferred for creating a high-performance chip-scale IMU.

Inertial navigation mathematics is presented in Chapter 6, providing an algorithm for transforming the folded MEMS IMU sensor signals into useful navigational information. Notation and rotation matrices are presented in Appendix B specifically for the IMU designs. Accommodation for fabrication misalignments of sensors is then explained in Appendix B.1 using the defined notations. Once the misalignments are accounted for, each sensor vector is translated to the ideal IMU body coordinate frame. These calculations are described in Section 6.2 for both cubic and pyramidal IMU form factors. The algorithm provided also applies to any IMU form factor as long as there is an appropriate definition of sensors on each sidewall. Vibration effects on alignment are also discussed in Section 6.3.
Exploration of other error sources common for inertial navigation systems are presented in Chapter 7. Both sensor- and system-level errors are described. Sensor-level error discussion includes bias, dynamic misalignment, scale factor errors, noise, and anisoelasticity. Other errors exist in addition to these, but are generally compensated for during calibration. At the system-level, both tilt misalignment and system error due to gyroscope bias are described. All errors are translated to inertial units such as rotation rate or acceleration, and are transformed to the coordinate system of the chip using the transformations defined in Chapter 6. Performance of the IMU devices is determined by simulated CEP radius and CEP rate error calculations, Section 7.4.4. The folded MEMS IMU approach is compared to existing technology for each error described, however the simulations only consider bias error, scale factor error, and misalignment due to temperature. This is largely due to the fact that most current manufacturers of IMUs do not publish several of the errors discussed in Chapter 7. In most circumstances, the proposed folded IMU approach proves to exceed the theoretical capabilities of the currently available chip-scale IMU devices of similar size.
Chapter 2

Folded MEMS IMU Development

A technique for fabricating 3-D MEMS structures on a wafer level has been developed which stems from the WIMS cube process [32]. This process combines the advantages of the current manufacturing approaches while additionally mitigating some of the inherent challenges as discussed in Section 1.4. This approach involves creating high aspect ratio single-axis sensors on a single substrate using a parallel fabrication process for all devices. Bulk micromachining is done to create a system of in-plane accelerometers and z-axis gyroscopes on a common platform. Each sensor is fabricated using a previously developed process optimized for single-axis inertial sensors. In parallel, a foldable structure is fabricated on the same substrate and then the entire system is assembled into a 3-D system providing the spatial orientation required for inertial measurement along multiple independent axes, Figure 2.1.

The folded structure consists of an SOI substrate containing a sensor on each sidewall, as well as flexible hinges and electrical interconnects [6]. Once assembled, the entire package utilizes less than 1 cm³ of volume and a footprint area less than 1 cm², and thus can fit onto a single chip. Although the proposed approach has its advantages, several challenges must be considered including creation of a fabrication process, structural rigidity of the folded
Design and development of the folded MEMS IMU fabrication process required multiple iterations. The major iterations are referred in this work as phases of development. The following is a description of the milestones accomplished for each phase:

- **Phase 0**
  Fabrication of a foldable MEMS structure with flexible hinges and interdigitated latches, but absent of inertial sensors, [8].

- **Phase I**
  Implementation of polyimide hinges, metal interconnects, as well as accelerometer and gyroscope test structures.

- **Phase II**
  Improvement of the fabrication process to include two layers of polyimide, encapsulated metal interconnects, and high-performance inertial sensors.
Details of each Phase I and Phase II are discussed in this chapter. Previous work is considered to be Phase 0 of development \[8\].

## 2.1 Phase I: Folded MEMS IMU Design

Several functional items are addressed to create a suitable design of the folded MEMS structures. Sidewalls must be able to easily fold into place without damaging the hinges or other components of the device. Once assembled, structural rigidity must be maintained to minimize misalignment of the sensors. Any alignment errors that occur will induce bias into the output signals yielding undesired information to be detected. Electrical interconnects must also be provided on each sidewall to allow for communication with the sensors. Forethought must be used when designing the traces to minimize impedance, parasitic capacitance and electrical cross-talk between neighboring signals. An example of a possible cubic IMU design from the Phase 0 work is shown in Figure 2.2 showing the design components necessary for fabrication. In parallel with cubic IMU development, a pyramidal form factor was also explored. Details of the individual design elements are further discussed below.

In Phase I of development inertial sensors were included with the folded MEMS structure. This IMU cube design requires a total of four masks for fabrication. The masks required were used for the following process steps:

(I) Polyimide

(II) Metal Traces

(III) Sensor Etch

(IV) Backside Etch
2.1.1 Mechanical Design Features

Structurally, the backbone is comprised of a number of silicon panels, each containing one or more inertial sensors. Due to its high rigidity and long-term mechanical performance \cite{33}, silicon is a suitable material for an inertial sensor platform. The ratio of the Young’s modulus to the material density is much larger than that of most materials. This property allows for a lightweight IMU with high rigidity, which minimizes the forces induced on the sidewalls from environmental loading such as shock, constant acceleration, and vibration. Additionally, multiple fabrication techniques exist for etching silicon and are readily available in most foundries, making it an optimal choice for the IMU structural material.

Latches explored in Phase 0 of this work \cite{8}, are provided on the edge of each sidewall to hold the structure together after assembly. By using an interdigitated design, the strength and number of latches along each edge is maximized to provide high rigidity of the overall structure. Several types of designs have been explored, varying in shape and size. The example shown in Figure \ref{fig:2.2} is designed to minimized initial interference and aid in alignment.
of the sidewalls during assembly. Once assembled, the latches help to maintain the alignment of each sensor, minimizing potential bias errors. However, the latches alone do not provide the rigidity needed for a high-performance IMU. For this reason, the structure must be further reinforced after initial assembly. Structural reinforcement methods are discussed in Chapter 5.

Compliant hinges need to be provided to allow for folding of the sidewalls into place. These hinges need to comply with large-angle bending of 90° or greater with a small radius of 500 µm or less. Additionally, the hinges must be able to withstand dynamic environments, and therefore the material needs to be resilient to vibration as well as environmental exposure. It also is required to be a good electrical insulator capable of transmitting active signals through metal traces with minimal crosstalk. In general, metal deposition on polyimide benefits from a smooth surface using spin-coating techniques. Polyimide is a good candidate for a material that meets the requirements of the folded MEMS IMU, and is largely used in the electronics industry for creating ribbon cables in compact devices. Another benefit of polyimide is its resistance to a wide variety of chemicals including solvents and several acids [34–36].

2.1.2 Electrical Interconnects

In addition to mechanical design, electrical properties must also be considered for the folded MEMS IMU devices. It is desired to have low impedance of each individual metal trace to minimize electrical resistance as well as potential influence of outside electromagnetic interference. For the design shown in Figure 2.2, which is from the Phase 0 work, all traces are 60 µm in width except for the ground trace, which is 100 µm wide to allow for more current flow. Compared to existing techniques, these dimensions are quite large, and result in resistances of 15-20 Ω for the longest traces. In most areas, the pitch is equal
to or greater than the width of the traces which maximizes spacing and reduces electrical cross-talk. Also, the bond pads on each sidewall are located near each sensor anchor to simplify packaging after fabrication. This reduces the length of each wire-bonded sensor connection. Packaging of the entire IMU device was done using a flip-chip method since all interconnects are designed to terminate on the bottom of the structure to enable connection to outside electronics. Mounting of the IMU device is then implemented by connection to an interconnect adapter plate designed for a larger DIP package. Alternatively, the IMU structure can be directly integrated onto a printed circuit board (PCB) to allow for easy implementation into hand-held electronics.

2.1.3 Inertial Test Structures

Components of an SOI transducer generally consist of a proof mass, suspension beams, actuators and detectors. Several methods are used for creating each type of element contained within SOI devices. Common methods for actuation include electrostatic forcing, piezoelectric response, and thermal response [8, 37]. Figure 2.3 shows two typical design elements capable of electrostatic actuation: comb drives and parallel plates. By applying a voltage difference between the proof mass and the capacitive structures, electrostatic forces cause attractive displacement of the proof mass. These structures can also be utilized as sensing structures by monitoring the capacitance. Changes in capacitance can be precisely measured with electronic signal detection methods. In general, comb drives are commonly used for actuation, whereas parallel plates are often used for capacitive sensing. Other techniques can also be used such as piezoresistive and optical detection for inertial measurement [38, 39], however in this work, both sensing and actuation is done capacitively.

Double-sided detection and actuation is generally implemented to improve inertial sensor performance. By placing sense electrodes on both sides of the proof mass, the nominal
capacitance is doubled, making it possible to detect small proof mass displacements. This directly improves performance of the sensor by reducing the lowest level of detection. Nearly all devices such as gyroscopes, accelerometers, pressure sensors, and temperature sensors greatly benefit from differential detection. Additionally, the double-sided design improves actuation in the same manner. Electrostatic methods of actuation are capable of inducing force in only one direction (attractive). Providing actuators on both sides of the device allows for constant amplitude control over the full range of motion of the proof mass \[40\]. Specifically for resonators, gyroscopes, and other active sensors, this significantly improves performance. Therefore all inertial sensors integrated onto the folded MEMS IMU cubic structure are designed to have the ability for both differential sensing and differential drive control.
2.1.4 Phase I Fabrication Process

A cross-sectioned process flow of the fabrication process explored during Phase I development of the folded MEMS IMU, shown in Figure 2.4, which utilizes an SOI substrate. This process is capable of manufacturing sensors with a minimum feature size of 8 $\mu$m for the sensors.

![Fabrication process flow](image)

Figure 2.4: Fabrication process for folded IMU structures capable of 8 $\mu$m sensor feature resolution.

Phase I implementation of this process requires multiple masks, which must be aligned to one another during manufacturing. Alignment marks are provided in the mask designs to allow for precise alignment of all process masks on a single SOI wafer. This includes the through-etch process, which requires backside alignment to features on the opposite side of the substrate. A total of four masks are required, including both front-side and backside fabrication are needed for the following processes:

(I) Deposit and pattern polyimide (front-side).

(II) Pattern metal interconnects (front-side).

(III) Pattern and etch inertial sensors (front-side).

(IV) Etch through the wafer (backside).
Photodefinable polyimide is first deposited by spin-coating the substrate then photolithographically defining the pattern, Figure 2.4a. Inevitably, the polyimide will function as flexible hinges between the folded IMU sidewalls. The type of polyimide used is HD-4110, available from HD MicroSystems™. After curing, the result is a 20 µm layer of polyimide that is flexible, durable, resistant to most chemicals, and is also a good electrical insulator. Next, a 0.5 µm layer of gold is deposited on top of a 500 Å chromium adhesion layer to create the electrical interconnects, Figure 2.4b. Final patterning of the metal is done using lift-off processing, however the details are not discussed because it is a common industrial procedure.

After defining the metal traces, the remaining front-side process is to create the sensors. This is done by first depositing a layer of AZ P4620 photoresist on top of the existing features. Using the third mask, the photoresist is lithographically defined to create the sensor features on each IMU sidewall, Figure 2.4c. In the fourth step, Figure 2.4d, the SOI sensors are etched using DRIE to penetrate through the entire device layer while using the photoresist as an etch mask.

Once front-side processing is complete, the features need to be protected during backside etching. Additionally, because the entire thickness of the wafer will be etched, the sample must be mounted to a carrier wafer for support. A thick, 30 µm, layer of photoresist was used for initial protection of the sensors and other front-side features such as polyimide and metal. For increased protection, a layer of dicing tape is applied on top of the photoresist. A carrier wafer is then attached using thermal grease as an adhesive which also provides a thermal conductive path to the fabrication wafer to keep it cool while etching.

Because of the thickness of the wafer is combined with the buried oxide layer, a very long etch is required to penetrate completely through the wafer, hence why a thick 30 µ layer is utilized. Backside etching begins using DRIE to etch through the 500 µm carrier layer of the SOI wafer, Figure 2.4b. Wet etching of the 5 µm buried oxide layer is performed using
BOE at a 6:1 ratio of HF to ammonia. This maintains the photoresist mask much better than direct HF solution. The process isotropically etches the oxide at \( \approx 0.1 \, \mu\text{m per minute} \) [41], requiring about 50 minutes to complete, shown in Figure 2.4f. Etching of the remaining 50 \( \mu\text{m} \) device layer is then performed again using DRIE, thus completing the through-wafer etch, Figure 2.4h.

### 2.2 Phase II: Implementation of Inertial Sensors

From the Phase I development, considerations discovered in Section 2.1.4 were accounted for in Phase II of the folded MEMS IMU development process. Due to experience with the fabrication process and system assembly, the design has been modified to include several improvements. In the Phase I design for the cubic structures, a total of four IMUs were included on a single wafer, along with other test structures. Also, only five sensors were included on each structure, which is not adequate for a 6-DOF IMU. It was also noticed that the backside etch design could be improved to reduce differences in etch rate of certain features. Specifically, the gaps in the hinge fingers and width between sidewalls required a significantly greater etch time compared to the rest of the wafer. The latches were also noticed to be easily broken, needing refinement to increase robustness. An additional issue was observed showing that the electrical interconnects are fragile and can easily be compromised during the backside etch process or during cleaning and assembly of the IMU. In Phase II of the design process, modifications have been provided to accommodate these challenges. The Phase II changes made to the cubic IMU design include, but are not limited to the following:

(I) Integrated a sixth sensor on the bottom of the cube.

   Enables complete 6-DOF inertial measurement.

(II) Increased minimum trench width size from 50 \( \mu\text{m} \) to 150 \( \mu\text{m} \) for the backside etch
mask.

Allows for better penetration of hydrofluoric acid (HF) while etching the buried oxide.

(III) Increased size of individual latches from 50 µm to 300 µm.

Prevents breaking of latches during assembly and creates higher structural rigidity.

(IV) Increased number of electrical traces.

Gyroscopes require additional signals for higher performance, not provided in the previous design.

(V) Added a second layer of polyimide on top of the metal traces.

This encapsulates the metal traces, except for the bond pads, to provide protection of the fragile sections of each interconnect.

(VI) Customized positions of the bond pads on polyimide.

Moved bond pads nearer to the sensor anchors to simplify packaging.

(VII) Increased number of structures per wafer from four to six.

Additional cubes per wafer offer potential for higher yield.

(VIII) Added a total of six smaller IMUs.

Half-size versions of the cube are included for exploration of further miniaturization.

Designs of full- and half-sized folded MEMS IMU cubes are shown in Figure 2.5 with all masks overlain on top of one another. The latch design has been modified from that of Phase I for ease of assembly, maximized sidewall alignment, as well as for potential welding purposes. Curved latches are used along sidewall edges that will be in place while another sidewall slides into place. By creating the bottom edge of each latch with a curve, interference is nearly
eliminated and thus prevents excess stress on the latches during assembly. As mentioned above, a second polyimide layer was included that covers all metal traces except for the bond pads. The traces themselves have also been completely redesigned such that the location of the bond pads can be very near to the sensor anchors. To increase yield, the overall masks includes more devices. A total of 12 structures are now included on each wafer, with six being 10 mm IMU cubes as before, and the other six are 5 mm IMU cubes (Figure 2.6). Overall, the design includes several modifications which will alleviate past challenges with fabrication and assembly, as well as to explore the possibility of reducing the overall IMU size.

In the Phase II design, additional masks are required. However many of the masks for the past set are again needed for the modified design. One new mask is needed for the additional layer of polyimide used for protection of metal traces when exposed to solvents, developer, and acids. Also, another mask is required to open the sensor areas for Deep Reactive Ion Etching (DRIE) etching after the other layers have been processed. The purpose of etching the sensors after applying the other layers is to improve the minimum resolution from 8 μm to 5 μm, which will be further explained in Section 2.3.2. A total of six masks are necessary for fabrication of the Phase II design as listed below. Reduction in the size of minimum
features will inevitably result in sensors that can perform better and be smaller in size. Both of these reasons provide motivation to decrease the minimum feature size for the inertial sensors.

(I) Sensors

(II) Polyimide Layer 1

(III) Metal

(IV) Polyimide Layer 2

(V) Sensor Open (for SOI etch)

(VI) Backside Etch

Similar issues were experienced during fabrication and assembly of both types of devices, and therefore a new mask design has been created for Phase II of the folded MEMS IMU.
development process. Modifications of the structures were very similar for each IMU form factor. One main difference, however, is that the second layer of polyimide was not included on the pyramidal structures. This was done because the traces on the pyramidal structures are generally shorter than those on the cubic IMU structures. Therefore the pyramidal IMU devices tend to not experience the same fragility issues with the metal traces. Additionally, rather than moving the sensor etch process to a later fabrication step, the minimum feature size in the sensor designs remains at 8 µm.

Phase II of the IMU pyramid designs require additional fabrication masks, just as for the modified IMU cube designs. However, since the second layer of polyimide is not used, a total of five masks are needed for processing. The fabrication process will be nearly identical to the Phase I samples, but with the added modifications should allow for higher performance and fabrication yield. The overall mask set for one wafer, overlain on one another, is shown in Figure 2.7. Also included in the figure is the previous design for comparison.

The Phase II set of masks includes a total of 14 pyramidal IMU structures, eight of which are the original size and the other six are half-size structures which are intended
for exploration of further miniaturization. Smaller accelerometers and gyroscopes have also been designed for the smaller versions of the structures with a width and length of 1.75 mm. Figure 2.8 shows a model of the original (large) pyramid alongside the smaller one which has a 75% reduction in volume, much like the miniature IMU cube designs.

![Figure 2.8: Model of the original design compared to the miniaturized design.](image)

### 2.3 Folded MEMS Fabrication Process

The folded MEMS IMU design approach requires a fabrication process that accommodates parallel manufacturing of inertial sensors, flexible hinges, electrical interconnects, and a foldable silicon backbone. This necessitates integration of different types of materials, and each successive step must be compatible each of the previous fabrication process. Additionally, care must be taken when processing the backside of the samples so that the front-side features are not damaged. After multiple iterations of development, suitable processes have been developed. SOI substrates are used to allow for simple integration of in-house inertial sensors, which are fabricated on the same substrate as the rest of the IMU structure.

#### 2.3.1 SOI Sensors

To release the mobile portions of the devices, the underlying silicon dioxide layer is etched using HF. Alternatively, solutions of HF mixed with ammonia, industrially dubbed as Buffered Oxide Etch (BOE), also can be used. However, due to the high surface tension of these types
of solutions, it may be necessary to add a surfactant, such as Novec™ 4200, to allow for penetration into high aspect ratio trenches. Since all of the underlying oxide is being etched at once, the anchors must be large enough to survive the exposure time required by the released components, hence why they are created at a minimum of 200 x 200 µm in footprint area. For large features that are required to be released, such as the sensor proof masses, etch holes are used to allow uniform penetration of the HF or BOE into all areas of the structure. This is a common method for reducing the overall etch time to prevent the anchors from being released. Once completed, the desired movable portions are released and free to move, leaving the anchors attached to produce an operational SOI device 5.

2.3.2 Phase II Fabrication Process

With the Phase I fabrication process in Figure 2.4, the photoresist for sensor definition is applied by spin-coating the entire wafer, covering the existing metal and polyimide features. Because of the polyimide height, the exposure mask cannot directly contact the photoresist for sensor patterning on the wafer surface. During the photolithography exposure procedure, light is thus able to penetrate into areas larger than what is defined on the photomask. This results in a minimum sensor resolution of \( \approx 8 \) µm, which is capable of creating operational inertial sensors, but is not suitable for high-performance designs. Therefore it is desired to change the Phase I fabrication process to accommodate better resolution of sensor features.

In general, the Phase II process is very similar, with a few differences in the sequence of fabrication steps and materials used. The basic fabrication flow of the Phase II process is given below:

(I) Pattern and etch oxide sensor (front-side).

(II) Deposit and pattern polyimide (front-side).
Conduct half-cure process.

(III) Pattern metal interconnects (front-side).

(IV) Deposit and pattern second layer of polyimide (front-side).

Conduct full-cure process of both polyimide layers.

(V) Pattern and etch inertial sensors (front-side).

(VI) Etch through the wafer (backside).

The sensor patterning process is done first, using an oxide mask, to eliminate the problem of existing polyimide features that cause errors in photolithography. This allows for improved sensor resolution compared to the Phase I fabrication process. Also, a second layer of polyimide is added to provide protection of the metal traces during the backside etch process. Cross-sections of the Phase II process is shown in Figure 2.9. This process is capable of <5 µm resolution for the SOI sensor features and thus increases the performance capabilities of a resulting IMU device.

Different from the Phase I process, fabrication begins by depositing a thin film of silicon dioxide on the device layer of the SOI substrate. Once patterned and etched, Figure 2.9a, this layer will act as a hard etch mask for the sensors, compared to a photoresist soft mask utilized in the previous process. Polyimide is then deposited and patterned around the areas occupied by the sensors, Figure 2.9b. Once the polyimide is applied, deposition and patterning of the metal traces, similar to before, is done either with a lift-off process, Figure 2.9c. For this process, a 500 Å layer of chromium is used as the seed layer underneath 5000 Å of gold. This composition is chosen due to its compatibility with conventional wedge and ball wirebonding techniques. Other materials can be used, such as copper, but as explained in Section 3.3, this is not an optimal choice due to corrosion at low temperatures. Moreover, since most metals are inevitably oxidized in air, gold is determined as the optimal solution. Following the
patterning of metal traces, a second layer of polyimide is applied using the same process as for the first layer, Figure 2.9d. This encapsulates the majority of the metal, leaving openings only at the bond pad locations.

After the polyimide and metal processes are completed, photoresist is patterned to surround the sensor areas for protection during DRIE etching of the sensors, as depicted in Figure 2.9e. Next, the sensors are etched using DRIE to provide nearly vertical sidewalls, Figure 2.9f, which is optimal for capacitive actuation and detection. Silicon dioxide is used as an etch mask defined in the first step of the fabrication process. Front-side fabrication is then finalized by removing the photoresist around the sensors using solvents and oxygen plasma as described in Appendices A.1.1 and A.1.2.

The remainder of the wafer-level process involves etching through the backside to release
the foldable structures from the fabrication wafer. Because the wafer will be entirely etched through, a double layer of AZ P4620 photoresist is patterned following the recipe given in Appendix A.2.3. A carrier wafer is first attached to the front-side prior to patterning and etching to provide rigid platform compatible with photoresist spinners and etch tool chucks. Etching is done similar to that of the Phase I process to penetrate the handle layer and oxide layers of the SOI wafer. The structures can then be released from the wafer by dissolving the front-side protection materials and removing the carrier wafer, along with the individual foldable IMU structures.

Removal of the buried oxide layer underneath the movable portions of the sensors must be completed to make the sensors operational. As described in Section 2.1.4, this is performed using an HF solution. During this process, the oxide hard mask used to etch the sensors is removed in parallel, as depicted in Figure 2.9. This completes the fabrication process, and the foldable MEMS structures can be assembled and packaged to create an IMU with a 3-D form factor.

2.4 Conclusion

A design approach for creating chip-scale IMU cubes has been proposed considering several required key elements. Features such as flexible hinges, electrical interconnects, inertial sensors, and the overall structural skeleton have been defined. Basic SOI sensor operation has been discussed including interdigitated combs and sense plates, both of which can be used for electrostatic actuation or capacitive sensing. Additionally, a pyrmidic IMU form factor has also been explored with similar design parameters. Due to experience in fabrication of both types of devices, modifications were made to provide higher yield, as well as increased sensor performance. Mask sets for cubic and pyrmidic IMU structures have been created with such modifications, allowing improvements in fabrication and yield of operational devices.
Fabrication of an oxide sensor mask resulted in an achievable minimum sensor feature size of \( \approx 5 \mu m \), which is an improvement over the 8 \( \mu m \) feature size achievable in Phase I. This allows for sensor designs with higher performance capabilities. Additionally, during the lift-off photolithography process for defining metal traces, the areas of importance are all on top of the polyimide features. Therefore the existence of oxide patterns do not affect the results of photolithography processing because no critical features are present in these areas. Overall, by moving the sensor feature patterning process to the very beginning of the fabrication process, the potential performance capabilities of the resulting IMU devices are significantly increased.

Another major change in the modified fabrication process is the addition of a second layer of polyimide. Adhesion of metal directly to silicon or silicon dioxide is generally quite high [15], however for deposition on polyimide, the adhesion strength is much lower. This resulted in delamination of long metal traces while undergoing the final fabrication steps, such as backside etching. A second layer of polyimide protects the metal by encapsulating the long traces, leaving open only the bond pad areas. Overall with the second layer of polyimide added to the process, the yield of intact electrical interconnects is increased, and thus minimizes defects on folded MEMS IMU devices after assembly and packaging. Therefore robustness of the electrical interconnects is greatly improved with this process. Modifications of both the sensor mask patterning process and inclusion of a second layer of polyimide in Phase II of this work produced higher quality IMU devices, and at the same time improved the fabrication yield.
Chapter 3

Fabrication Details

In Chapter 2, fabrication processes for each phase of research were briefly described. Although explanations were given for each fabrication step in both phases of research, very few details were provided. In order to give a comprehensive narration for manufacturing folded MEMS IMUs, a discussion of additional technicalities are required. Since each individual process for the Phase II fabrication process are similar to that of the Phase I fabrication process, only Phase II work is described within this chapter. Each individual process is further explained, providing details for the procedures utilized within this work.

3.1 Oxide Sensor Mask

Because patterning the sensors is the most delicate part of the overall process, this is done before all other steps. The minimum feature size in the sensor designs is 5 µm, and any flaws can cause a reduction in performance, or for the sensor to be non-operational. For this reason, much care must be taken during the photolithography process. A 1.5 µm layer of oxide is first deposited onto the wafers, either done by the manufacturer, or on blank wafers
using CVD or PVD techniques. Prior to processing the samples, the surface is first treated with solvents and oxygen plasma using the recipe given in Appendix A.1.6. This maximizes adhesion of photoresist to the fabrication wafer.

![Photoresist sensor mask patterned on a 1.5 µm layer of silicon dioxide on a fabrication wafer.](image)

Photoresist (AZ P4620) is deposited and patterned onto the wafer shortly after the surface treatment. Figure 3.1 shows a photograph of a wafer with sensor patterns defined after photolithography is complete. This sample, along with others, were processed using the recipe in Appendix A.2.1. Results of this process indicate that nearly all sensors have been properly defined. To determine the quality of lithography, the smallest features and gaps are examined through a microscope. Figure 3.2 shows the drive electrodes and a proof mass mechanical stop of an accelerometer. As designed, the drive electrodes are 8 µm in width and the same gap size between them, whereas the mechanical stop gap is 5 µm. Both sets of features resolved well on nearly all sensor patterns on each wafer fabricated, leaving no bridged gaps or broken features.

Examination of the gyroscopes was also performed in the same manner. Unlike the accelerometers, the gyroscopes contain many more 5 µm features. For this reason, they are more challenging to fabricate, and therefore the yield of operational gyroscopes is inherently lower than that of accelerometers. Interdigitated 5 µm comb fingers are designed along each outer edge of the gyroscope to act as drive electrodes, or for frequency tuning in the future.
Utilizing the patterning process defined in Appendix A.2.1, nearly all gyroscope patterns contain no imperfections. Shown in Figure 3.3 are gyroscope sense comb fingers and sense plate gaps successfully patterned.

After patterning the sensors using a photoresist soft mask, the pattern must be transferred to the oxide layer underneath to define the hard mask. This is done by dry etching using a combination of RIE and inductively coupled plasma (ICP) with an STS Advanced Oxide Etcher. Silicon dioxide is etched at a measured rate of 4000 Å per minute with this tool, requiring a total of 4.5 minutes to complete the etch. Although the etch rate of oxide significantly depends on feature size, etch time was successfully completed in all areas as shown in a picture of a wafer in Figure 3.4. Photoresist still remains on the patterned areas, however it can be observed that the oxide has been fully removed.

A closer inspection must be performed to determine if the small sensor features have
Figure 3.4: Oxide etched using a photoresist mask to define the oxide sensor hard masks.

(a) Gyroscope drive combs  (b) Gyroscope sense plates

Figure 3.5: Silicon dioxide sensor mask patterned on wafers showing microscopic images of the proof masses, sense plates, and drive combs.

been successfully defined. Microscopic images of one wafer are shown in Figure 3.5 with all excess oxide completely removed and the photoresist mask remaining. Figure 3.5(a) and Figure 3.5(b) indicate that no oxide exists in the trenches between gyroscope drive combs and sense plates, respectively. These areas are the most intricate among the sensor designs with 5 µm features sizes. Results show that the sensor masks provided the desired sensor resolution results and therefore are ready for DRIE etching, which will happen later in the fabrication process.

Following the sensor hard mask patterning, the remaining photoresist must be removed to allow further sample processing. Cleansing was then performed using the process in Appendix A.1.1, then exposure to oxygen plasma at 1200 W for five minutes using a downstream plasma system. Further cleansing followed by soaking in a solution of ‘piranha’ etchant, consisting of a 3:1 solution of hydrogen peroxide and sulfuric acid. The mixture was heated to
a temperature of 100 °C to initiate the reaction and begin cleansing of organic materials, such as photoresist or any other remaining residue left over from the etch process. Because silicon and silicon dioxide both cannot be etched with piranha solution, there is no limit to exposure time. However after 10 minutes, the photoresist is completely removed, which was confirmed with microscopic observation.

3.2 First Polyimide Layer

After definition of the sensor hard mask is complete, the next step in the fabrication process is to deposit and pattern the first layer of polyimide. Due to delamination issues noticed in Phase 0 and Phase I fabrication runs, an adhesion promoter (HD MicroSystems VM-652) is used prior to applying the polyimide emulsion.

Immediately after applying the adhesion promoter, HD-4110 photodefinable polyimide is spun onto the wafer. Much like processing photoresist, the samples are baked, exposed and developed to define the desired pattern. The detailed recipe for this procedure is given in Appendix A.4.1. Wafer-level results of this process are shown in a photograph on one sample in Figure 3.6. All desired features are seen to be successfully defined, and leaving a layer of polyimide around the sensors to define the flexible hinges and insulating substrate for the electrical interconnects.

Although patterning of the polyimide is successful, microscopic analysis indicated an issue with the integrity of the film. Phenomenons such as cracking and pebbling of the material were noticed on the fabrication wafers. The samples were consecutively processed in the same environmental conditions, which should produce similar results. However progression from one sample to the next provided better results, shown in Figure 3.7. Cracking of the polyimide material will most likely result in disconnects in the IMU electrical traces.
Therefore the process needs to be modified to minimize or eliminate the polyimide cracking and pebbling issue.

Because the cracking and pebbling progressively was minimized with each successive sample, the source of the problem is believed to be in the developing process during which the issue was noticed. The same solution of PA-401D developer was used for all four samples, whereas a fresh solution of PA-400R was consistently poured over the wafer during each development iteration. However some of the rinse solution remained on the sample when placing back into the developer each time. Therefore, a probable cause of the cracking and pebbling issue that changes over time is the varying concentration of rinse within the developer. One potential resolution to this problem is to add a small amount of rinse to the developer prior to the development process. Because of the polyimide patterning issues,
a new method for developing polyimide patterns was explored with a modified developer solution.

![Polyimide sample](image)

**Figure 3.8:** Polyimide re-deposited with a modified development recipe on a sample after removing the initial material which contained defects.

Polyimide in further production runs was deposited using the recipe in Appendix A.4.2, which is similar to the initial recipe in Appendix A.4.1 but with a modified developer solution that is pre-mixed with 10% of the rinse solution. A photograph of the results is shown in Figure 3.8. (Note that the discolored area in the middle of the wafer is a result of the polyimide stripping process from a prior fabrication run, but does not interfere with any existing features.) Modifications to the development procedure was done by mixing 200 ml of PA-401D developer with 20 ml of PA-400R rinse to create a 10:1 solution ratio. Using this modification, the overall results are positive. Microscopic observations indicate that no cracks or pebbling defects exist in the polyimide areas and the sensor masks are clean and free of residue, as shown in Figure 3.9(a). Additionally, thickness measurements using a physical stylus probe on a Dektak 3 tool indicates a polyimide thickness of $\approx 32 \, \mu m$, Figure 3.9(b). Overall, it is determined that by adding a small amount of rinse to the developer solution, the defects in the polyimide film observed before are successfully eliminated.

Once the polyimide is deposited and patterned, it is then cured to bake out all solvents as well as to enable extensive polymer cross-linking that provides mechanical and chemical robustness. Curing also finalizes the activation of adhesion to the silicon substrate. For
the Phase I fabrication process described in Section 2.1.4, a single layer of polyimide was fully cured directly after deposition. However, it was noticed that when using a dual-layer of polyimide in Phase II, described in Section 2.3.2, adhesion to silicon after curing is a challenge. This process in Phase I of development involved patterning and curing one layer of polyimide, followed by deposition of metal traces, and finally patterning and curing the second layer of polyimide. When two layers of polyimide are deposited in Phase II, and are both cured independently (in series), the first layer essentially is cured twice. Polyimide tends to shrink when it cures, and therefore the second layer applies additional compressive stress to the first layer during the second curing process. With this combination of stress-inducing processes, adhesion of the first layer of polyimide onto the silicon substrate cannot withstand the internal stress. For this reason, when the folded structures are released from the wafer after fabrication and soaked in acetone for cleaning, the polyimide tends to delaminate from the silicon substrate.

To address the delamination issue, the first layer of polyimide is not fully cured after deposition and patterning. Instead, a half-cure process is conducted by baking out the solvents at 200 °C for 30 minutes, but will not be exposed to the 375 °C full-cure cycle. Essentially, steps #4 and #5 are omitted from the curing recipe in Appendix A.4.3. By using this process, the solvents are baked out of the material which prevents the developer
solution from attacking the first layer when processing the second layer of polyimide. By conducting only a half-cure, the polymer cross-linking does not entirely take place, which minimizes the stress in the film. A full-cure of the polyimide is done after metal traces and the second layer of polyimide is deposited, thus curing both layers of polyimide in parallel. This results in minimization of the induced film stress on the first layer and eliminates the delamination issue experienced during cleansing of the IMU structures after fabrication. Photographs of the half-cure process results are shown in Figure 3.10(a) and Figure 3.10(b) showing a wafer-level sample and a closeup of a gyroscope. From the photographs, it is observed that the polyimide is patterned successfully and the sensor areas are free of any residue.

![Wafer with cured polyimide](image1)

![Closeup of gyroscope](image2)

Figure 3.10: Photographs of polyimide layer #1 after the half-cure process showing a wafer-level sample (a) and of a closeup of a gyroscope (b).

Thickness measurements were conducted to determine if the half cure was successful, Figure 3.11. In general, the polyimide loses approximately half of its thickness when fully cured. Plots shown indicate a thickness of $\approx 23 \, \mu m$ near the middle of the wafer, in the same location measured before in Figure 3.9b. As predicted, the variance in original thickness has been minimized after curing. Additionally, based on the initial measurement of 32 $\mu m$ and 23 $\mu m$ for the first and second sample respectively, results indicate a successful half-cure. A full-cure would show a decrease in thickness of approximately 50%, whereas the reduction in thickness for the half-cure is only a 28% reduction.
Figure 3.11: Thickness measurement of half-cured polyimide showing a thickness of approximately 23 µm.

Additional inspection of the cured polyimide layer is performed with a microscope. Figure 3.12 shows images of the first layer of polyimide after being half-cured. In Figure 3.12(a), the first photograph shows the lower right-hand corner of a bottom-face gyroscope with polyimide surrounding the sensor. It also shows a portion of the oxide sensor mask features including 5 µm comb fingers, which are free of residue indicating that the polyimide waferfully developed away in the desired areas. An alignment mark is also shown in Figure 3.12(b), indicating successful alignment of the first layer of polyimide with respect to the oxide sensor mask.

Figure 3.12: Optical microscope photographs of cured polyimide near a gyroscope (a) and an alignment mark (b).

Observation shows that no cracks or pebbling defects are existing due to the modified
developer recipe. Additionally, the layer has only been half-cured, awaiting deposition of metal interconnects and a second layer of polyimide. After which, both polyimide layers will be fully cured in parallel to minimize film stress experienced in the first layer of polyimide after curing the second layer. This eliminates the adhesion problems noticed earlier when using two layers of polyimide and cleansing the IMU samples in acetone after fabrication. The refined process for depositing and patterning successfully reduces or eliminates the delamination issues that exist in the Phase II process for creating flexible hinges with electrical interconnects on folded MEMS IMU devices.

3.3 Metal Interconnects

Following deposition of the first layer of polyimide, the next step is to perform metal lift-off patterning of the electrical interconnects. To begin the process, the wafer is cleansed by rinsing with acetone, isopropanol, and methanol, followed by a blow-dry with nitrogen as described in Appendix A.1.1. The wafer is then baked at 100 °C on a hot plate for 5 minutes for dehydration. Commonly, dehydration of wafers is done with an oven at a temperature of 120 °C for 30 minutes. But in this case a lower temperature is used to avoid any further curing of the existing polyimide features. Using AZ nLOF 2035 photoresist, specifically designed as a masking material for metal lift-off procedures, the samples are spin-coated and patterned using the recipe given in Appendix A.5.2. This type of photoresist after developing creates a negative draft angle that eliminates metal deposition on the sidewalls for directional processes such as an electron beam evaporator. Utilization of other types of photoresist commonly used for metal lift-off patterning, such as Shipley 1827, require an additional step during development such as soaking in chlorobenzene to minimize sidewall metal deposition. This process was also utilized in this work, and the recipe is described in Appendix A.5.1. A full wafer and a closer photograph of 3 IMU sidewalls are shown in
Figure 3.13: Photoresist patterned using AZ nLOF 2035 prior to metal deposition and lift-off processing of electrical interconnects.

Figure 3.13 after successfully depositing and patterning AZ nLOF 2035 photoresist.

Based on results previously experienced with patterning AZ nLOF 2035 photoresist, multiple iterations of process development have been performed. Altogether, several modifications were made compared to the recipe provided by the manufacturer. One issue that occurred in prior fabrication runs was over-development of the open features. However other issues also occurred, such as adhesion of the photoresist to polyimide, and imperfections in the sidewall angles that caused step coverage to occur during metal deposition. After making the changes shown in Table 3.1, results were significantly increased, and produces nearly 100% yield. All changes in the table have been incorporated to the recipe described in Appendix A.5.2.
<table>
<thead>
<tr>
<th>Process Step</th>
<th>Prior Recipe</th>
<th>Modifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dehydrate</td>
<td>n/a</td>
<td>15 min 110 °C on hot plate</td>
</tr>
<tr>
<td>Spread</td>
<td>500 rpm 10 s</td>
<td>500 rpm 10 s</td>
</tr>
<tr>
<td>Spin</td>
<td>1500 rpm 40 s</td>
<td>1500 rpm 30 s</td>
</tr>
<tr>
<td>Soft Bake</td>
<td>100 °C 1 min</td>
<td>110 °C 1 min</td>
</tr>
<tr>
<td>UV Exposure</td>
<td>20 s I-line light</td>
<td>22 s I-line light</td>
</tr>
<tr>
<td>Develop in AZ 300 MIF</td>
<td>60 sec</td>
<td>40 sec</td>
</tr>
</tbody>
</table>

Table 3.1: Modified deposition and patterning recipe of AZ nLOF 2035 photoresist for metal lift-off processing.

At this point, metal can be deposited onto the first polyimide layer, however there are several choices as to which type of metal is appropriate. In the Phase I of the fabrication process of folded MEMS IMUs, copper was used because it is common in current PCB manufacturing technology, has low resistivity, is inexpensive, and is simple to deposit with MEMS techniques. Analysis of the metal traces were conducted to determine if copper is the optimal solution for the application. The IMU design contains long electrical interconnects from the inertial sensors to the actual signal detection electronics which might be located several millimeters away from the actual sensing element.

Resistance measurements of the metallic traces were performed using a four-wire method with four probes and two multimeters. This technique is useful when measuring low resistances. One pair is used to apply a measured current through the trace and the second pair is used to measure the voltage drop across the unknown resistance. The measurements are taken on a copper trace on a device from Phase 0, as shown in Figure 3.14. Measuring resistance between different pairs of points labeled A through E. The total length of the longest electrical trace is 3500 µm. Because the IMU inevitably will experience a broad range of temperatures during operation, these measurements were repeated after heating the whole sample at 200 °C on a hot plate for one hour. Results of the tests are shown in Table 3.2.

As the length of the copper trace increases, the resistance measured also increases, as expected. Since the total length of the trace is known, the resistance per unit of length can
Figure 3.14: Resistance measurement test points of a single copper trace on a device created during Phase 0 of this work.

<table>
<thead>
<tr>
<th></th>
<th>Before Heat [Ω]</th>
<th>After Heat [Ω]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB</td>
<td>2.3</td>
<td>19.4</td>
</tr>
<tr>
<td>AC</td>
<td>4.2</td>
<td>44.2</td>
</tr>
<tr>
<td>AD</td>
<td>6.4</td>
<td>60.1</td>
</tr>
<tr>
<td>AE</td>
<td>8.4</td>
<td>78.8</td>
</tr>
</tbody>
</table>

Table 3.2: Four-wire resistance measurement results on a copper interconnect before and after heat treatment at 200 °C for one hour.

be obtained, and is calculated to be \(2.46 \times 10^{-3} \Omega/\mu m\). Moreover, knowing the thickness (150 nm) and the width (60 μm) of the copper trace, the resistivity of the material is calculated to be \(2.16 \times 10^{-8} \Omega\cdot m\), which is only slightly higher than the value for bulk copper of \(1.70 \times 10^{-8} \Omega\cdot m\) [42].

The resistance of another trace on a different fabrication wafer with the same design is measured at different temperatures to evaluate the temperature coefficient of electrical conductivity. These results are plotted in Figure 3.15 where a linear behavior from room temperature to 170 °C is observed. After constant exposure of the IMU to a temperature of 200 °C for one hour, results show there is an evident degradation of the copper traces which significantly increases resistance as temperatures rise.

Initially this is due to formation of cuprous oxide, and then cupric oxide as temperature
increases further. Both materials have low electrical resistance properties and causes the interconnects to decrease resistance to due heat exposure in atmospheric conditions. For temperatures above 150 °C, a larger increase in resistance takes place due to the formation of cupric oxide. Resistance of the metal trace therefore dramatically increases because cupric oxide is much less conductive than cuprous oxide. Due to the changes in properties when exposed to heat, it is determined that copper is not the optimal metal for the electrical traces on the folded MEMS IMU devices. For this reason, a different metal is preferred, and because of its lack of oxidation states, gold is potentially a better material choice. Although it is more expensive, it does not oxidize easily and maintains the other advantages provided by copper such as ease of deposition, flexibility, and common use in current PCB technology. Resistivity of gold is also lower, which benefits the use of the long traces implemented in the IMU design. Therefore gold is used to create the metal traces on the Phase I and Phase II folded MEMS IMU structures.

Direct adhesion of gold is not optimal for most surfaces, including polyimide. But it will adhere well to chrome, which in-turn adheres well to most materials, including polyimide. Adhesion of gold to chromium is known to be very good, making it an optimal adhesion layer for the electrical interconnects. Also, by using a thick, 5000 Å layer of gold, overall resistance is minimized, allowing for good feed-through of sensor signals. The first and last 50
Å of chromium is deposited at rate of approximately 0.2 Å per second to maximize adhesion and film quality. During the intermediary deposition period, the material is deposited at a faster rate of approximately 0.8 Å per second. By depositing the metal at a slow rate near the boundaries, it is hypothesized that individual atoms are allowed to fill small voids and provide better adhesion capabilities. The gold layer is deposited in the same manner, using a deposition rate of ≈0.2 Å per second for the first and last 10% of the thickness. In between these boundaries, the deposition rate is increased to ≈1.0 Å per second.

After the two layers of metal are deposited, the excess gold and chrome is removed to leave only the desired pattern. The wafers are then soaked in acetone without agitation for 24 hours to dissolve the photoresist. Nearly all of the photoresist is removed in this step, however residue still inevitably remains and must be eliminated before additional processing. Further cleansing is done by soaking and rinsing the wafers in a succession of solvents to remove the remaining photoresist residue. The procedure in Appendix A.1.1 is used for this purpose, and properly prepares the wafers for deposition of the second polyimide layer.

During metal deposition, chrome and gold is not only deposited to pattern the electrical interconnects on polyimide, but is also patterned on the sensor bond pads. Figure 3.16 shows optical photographs of critical features after metal deposition. An entire wafer, pictured in Figure 3.16(a) shows that metal is successfully patterned across the entire substrate. A closer look at a bottom-face gyroscope, Figure 3.16(b) shows that critical metal features are successfully resolved.

Using a microscope for further inspection, the metal deposition results were examined on the same bottom-face gyroscope and an alignment mark, Figure 3.17. Edges of the deposited metal are all well defined on the bond pads on the polyimide surfaces, Figure 3.17(a). Furthermore, the alignment mark photographs indicate accurate alignment of all features fabricated thus far, Figure 3.17(b).
Figure 3.16: Deposition of a chrome adhesion layer and a gold conduction layer to define electrical interconnects on top of polyimide layer #1 and sensor anchors.

Results of the process show that a 100% yield of all electrical interconnects on the large folded IMU structures is achieved. This implies that overall yield of operational folded IMU devices will not be adversely affected by the metal patterning process. For the smaller IMU devices created in Phase II of this research, shown in Figure 3.18, yield of successfully defined metal features was approximately 90% as opposed to complete success for larger devices. This is partly due to these IMU traces having significantly smaller widths, and thus a smaller adhesion area. A larger part of the problem, however, is the deposition of traces near the edge of polyimide features. Measurements have consistently shown that at the edges of the polyimide areas, the substrate is not flat, but instead has a crowned surface. The profile of the polyimide shows that this mound is very similar to the edge bead of
an emulsion after spin-coating. This non-planar area of polyimide is not optimal for metal deposition, and is avoided in the larger IMU structures. Reasoning for designing metal traces in this area for the smaller structures is to prevent compromising the width and gap sizes to avoid possible fabrication imperfections and sensor signal degradation.

Figure 3.18: Three sidewall patterns of a half-size IMU cube showing defined metal traces on top of the first layer of polyimide.

3.4 Second Polyimide Layer

At this point, fabrication has involved several steps of front-side processing including oxide sensor mask patterning, deposition of the first polyimide layer, and patterning of metal interconnects. The second polyimide layer is next patterned using the same recipe as for the first layer, given in Appendix A.4.2. By not processing a full-cure of the initial layer, adhesion to silicon should prove to be stronger because both layers will be fully cured simultaneously as discussed in Section 3.2.
Figure 3.19: Second layer of polyimide patterned onto a sample, prior to curing

The layout of the second polyimide is designed to ensure that the gold bond pads are exposed and all other metal features are encapsulated between the two polyimide layers. Otherwise, the overall layout is similar to the first polyimide layer, except that the outer dimensions are slightly smaller to prevent overlap at the edges due to slight misalignments or fabrication imperfections. Curing of the dual-layer of polyimide is done by heating the samples to evaporate the inner solvents, finalize adhesion activation, and to induce a significant amount of polymer cross-linking. A programmable nitrogen furnace was used to implement the final curing recipe given in Appendix A.4.3. After curing, the polyimide is very robust to wet solvents and dry etching. However, if exposed to certain acids, the polyimide material or the adhesion layer is attacked, or both. Therefore, once the initial layer of polyimide is deposited, the samples can no longer be directly processed with acids. Results are shown with a wafer-level photograph in Figure 3.20(a). Closer inspection of bond pads near a bottom-face gyroscope indicates successful patterning of the second polyimide layer after curing, Figure 3.20(b).

Microscopic analysis was performed to further examine the alignment results of the second layer of polyimide with respect to the existing features. An image of the corner of a gyroscope is given in Figure 3.21, which shows sensor features, bond pads on both polyimide and sensor anchors, as well as the second coating of polyimide. From the image, it is determined that
the alignment of the second polyimide layer is successful. Additionally, little or no residue is observed on the bond pads located on the first layer of polyimide, nor on the sensor features. This enables electrical connections in these locations to be made with minimal contact resistance. It is also observed that the metal traces between the bond pads is successfully encapsulated, protecting them from possible damage due to further fabrication processes.

A large challenge in processing has been achieving consistent film thickness of polyimide after deposition. Therefore an experiment was conducted with a batch of six samples being processed at the same time with identical parameters. However different results occur on each
individual wafer. Profile measurements of the six samples were measured after depositing the 
second layer of polyimide, prior to curing, Figure 3.22. Each measurement was conducted in 
the same location on each wafer to provide an optimal investigation of the variance in height 
after patterning. The measurements were taken near the center of the wafer traveling from 
the edge of an oxide sensor mask (Distance = 0 µm on the plot) across an open bond pad, 
and ending on an uncoated silicon surface for a total scan length of 3000 µm.

Results of the profile measurements indicate a non-trivial difference between samples pro-
cessed in parallel. Inconsistency in the deposition of polyimide is detrimental for fabrication,
because after curing variances in thickness can cause difficulties in later processes. These differences will negatively affect the assembly process after fabrication, and also the IMU performance capabilities. For the six wafers analyzed, the average overall thickness of the polyimide was 41.6 µm after patterning the second layer of polyimide, shown in Table 3.3. Standard deviation of the height is 5.2 µm, which is significant for samples created using the same recipe in parallel fabrication. Trench depth on average is 23.7 µm, shown in the third row of Table 3.3. This is different from the trench height shown in the second row, in that the depth is calculated by subtracting the film thickness within the trench from the overall height of the polyimide layers. The standard deviation of the trench depth is 2.4 µm, which is smaller, but is still large considering all samples were created in parallel. Therefore future work will require modifications to provide increased consistency and minimize thickness variations of batch-fabricated wafers.

<table>
<thead>
<tr>
<th>Sample</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Average</th>
<th>Std. Dev.</th>
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<tr>
<td>Max Thickness (µm)</td>
<td>44.5</td>
<td>48.7</td>
<td>41.8</td>
<td>32.9</td>
<td>40.9</td>
<td>41.2</td>
<td>41.7</td>
<td>5.2</td>
</tr>
<tr>
<td>Trench Thickness (µm)</td>
<td>19.2</td>
<td>22.0</td>
<td>20.9</td>
<td>12.2</td>
<td>16.5</td>
<td>17.0</td>
<td>18.0</td>
<td>3.5</td>
</tr>
<tr>
<td>Trench Depth (µm)</td>
<td>25.3</td>
<td>26.7</td>
<td>20.9</td>
<td>20.7</td>
<td>24.4</td>
<td>24.2</td>
<td>23.7</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Table 3.3: Polyimide film thickness measurements with averages and standard deviations for six samples prior to curing.

Despite the issues encountered with film thickness consistency, the wafers must still be fully-cured to finalize polyimide processing. Using a physical profilometer, the polyimide layers were measured and compared to the results prior to curing. These measurements were conducted at the same location on each wafer as before. From prior experience of processing many samples, a full-cure results in a 50% reduction in thickness of polyimide from patterning to curing. Results from one of the samples shows a reduced overall height of approximately 30%, and noticeable horizontal shrinkage, Figure 3.23. The reduction in height is less than expected because the first layer of polyimide was already partially cured after patterning. Although a decrease in both dimensions are expected, the horizontal compression causes internal film stress within the polyimide. Previous samples using two
layers of polyimide cured independently resulted in delamination after backside etching due to excessive horizontal shrinkage of the first layer of polyimide, but not the decrease in height. By curing both layers at once with the modified process, post-fabrication stresses are decreased and thus minimizes delamination issues of the first layer of polyimide from the underlying silicon. Overall, the modified process has proven to be successful, allowing for encapsulated metal interconnects in the polyimide hinges without the film stress experienced in prior fabrication runs.

Figure 3.23: Profile measurements of one sample before and after curing both polyimide layers with encapsulated metal interconnects.

3.5 Sensor Etch

Based on the Phase II fabrication process explained in Section 3.4, front-side processing is nearly complete. Finalizing fabrication on the device layer of each sample is completed by etching the inertial sensors using DRIE until reaching the buried oxide layer. First, however, the polyimide and metal features must be protected to prevent etching in these areas. Photoresist is therefore patterned to cover all areas of each wafer except for the sensors and the latching areas. The recipe used for this process is given in Appendix A.2.2 and provides the resolution required for this purpose. Since all the openings are designed to
be large, on the order of millimeters, a great deal of flexibility in exposure and development
time is allowed for this process. Results of the photoresist patterning procedure using this
recipe is shown on one sample in Figure 3.24, with all open areas successfully defined.

![Figure 3.24: A folded MEMS IMU wafer patterned with photoresist to prepare for DRIE
etching of sensors and latching areas.](image)

Although the latches will inevitably be etched through during backside etching, the device
layer of the SOI wafer is only 50 µm in thickness, and does not provide significant structural
support. Additionally, this layer of silicon on the latches tends to break loose during assembly
of the overall IMU and can easily cause damage to the other sensors during release and
assembly. For these reasons, the device layer of the latches is also etched in parallel with
etching the sensors. After successful masking of the mentioned areas, the inertial sensors are
etched using a DRIE process until the buried oxide layer is reached, Figure 3.25. Using the
previously defined oxide as a hard mask, the device layer is etched at an approximate rate
of 1.6 µm/min for 34 minutes to expose the buried oxide layer, which is at a depth of 50
µm. A photograph of a wafer-level sample is shown in Figure 3.25(a) after the etch. Also, a
closeup of a bottom-face gyro after etching is shown in Figure 3.25(b), indicating that the
photoresist mask was successful in preventing etching of the existing features.

Microscopic images of a gyroscope located on the folded IMU cube is shown in Figure 3.26
after sensor etching is complete. It is observed from figure Figure 3.25(a) of the corner of
a gyroscope that all fabrication processes are successful thus far, including the sensor etch.
Figure 3.25: Fabrication wafer and gyroscope photographs after DRIE etching at a rate of \( \approx 1.6 \mu m/\text{min} \) for 34 minutes to reach the buried oxide at a depth of 50 \( \mu m \).

This can be seen from Figure 3.26 because of the bright areas shown in between the sensor features that indicate that the buried oxide layer has been exposed. Areas of concern that etch slower than the rest of the sensor features are generally that of the gyroscope sense plate gaps. As designed they have a 5 \( \mu m \) separation along a 300 \( \mu m \)-length trench. This has proven to be the type of feature that etches slower than all other features, including all accelerometer features. However after etching for a total of 34 minutes, the sense plates are completely etched, shown in Figure 3.26(b) along with the rest of the sensor features.

After etching the sensors, the photoresist must be removed from the front-side to prepare for backside processing. The majority of the photoresist is easily dissolved with a five minute
soak in acetone. However residue always remains after DRIE processing that cannot be removed with this process. Oxygen plasma is therefore performed afterward to give the wafers a final clean and thus eliminating nearly all of the photoresist residue. Figure 3.27 shows an SOI wafer after undergoing five minutes of oxygen plasma at 200 W of power and a pressure of 200 mT with an oxygen flow rate of 24 sccm. Results of front-side fabrication indicate significant potential for high yield of operational sensors on the folded MEMS IMU structures.

Figure 3.26: Microscopic images of portions of a gyroscope after DRIE etching showing that the sensor features are completely etched.

Figure 3.27: Photograph of an SOI wafer with photoresist removed after the sensor etch process.
3.6 Backside Etch Preparation

Backside etching is the final process required to complete wafer-level processing. This has generally been the most challenging portion of the fabrication process. Difficulty is involved in bonding a carrier wafer onto the existing front-side topography. Multiple procedures have been utilized to perform application of the carrier wafer in attempt to prevent damage to the sensors and other front-side features during the backside etch process. Problems noticed in prior fabrication runs the past consisted of contamination of the front-side features after removing the carrier wafer, air cavities trapped in trenches causing explosion of the wafer near the end of the etch, and low thermal conductivity throughout the wafer stack which reduced selectivity of the photoresist etch mask is shown. Each of these issues cause catastrophic damage and usually compromises all IMU devices on the entire wafer. Therefore it is critical to determine a compatible method for attaching the carrier wafer to the front-side of the sample for backside etching. The main methods used for carrier wafer attachment utilized in this research are listed below and discussed in this section as well as in Section 8.2.2.

- Combination of thermal grease and low-tack tape.
- AZ P4620 photoresist only.
- Double-sided Kapton® tape.
- Combination of AZ P4620 photoresist, thermal grease, and double-sided Kapton® tape.
- Combination of AZ P4620 photoresist and double-sided Kapton® tape.
- Thermal grease mixed with silicone oil.
- Crystalbond 555 wax.
- Unity Polymer adhesive.
3.6.1 Thermal Grease and Low-Tack Tape Bonding

One process for bonding the carrier wafer utilizes AZ P4620 photoresist, low-tack dicing tape, and thermal grease. An illustration of the cross-section of this bonding approach is shown in Figure 3.28. Photoresist is first spin-coated onto the front-side features. Next, a layer of dicing tape is applied on top of the cured photoresist. By having the photoresist underneath the tape, the sensors and other features do not directly contact the tape and thus are not contaminated by its adhesive. Finally, a liberal amount of thermal grease is separately applied to the carrier wafer, which is then pressed against the front-side of the fabrication wafer. The layer of dicing tape prevents the grease from mixing with photoresist, which creates a very stubborn residue and is quite difficult to remove after fabrication.

![Cross-section illustration of a method for attaching a carrier wafer using AZ P4620 photoresist, dicing tape, and thermal grease.]

Figure 3.28: Cross-section illustration of a method for attaching a carrier wafer using AZ P4620 photoresist, dicing tape, and thermal grease.

A significant issue with the this process is the difficulty of eliminating the photoresist mask from the sensors after fabrication is complete. During the backside etch process, the temperature of the wafer is elevated to approximately 100 °C or greater, and thus bakes the photoresist during the entire etch. Because the total etch time is approximately three hours, an extensive amount of polymer cross-linking occurs in the photoresist and it cannot be entirely dissolved with solvents after fabrication. Oxygen plasma is capable of removing it, however exposure to which also etches polyimide during this process. This thins the polyimide, making it more brittle which causes breaking or tearing of the hinges during assembly. Therefore it is desired to find an alternative carrier wafer attachment material that can easily be dissolved with solvents rather than having to use oxygen plasma.
Another problem with this carrier wafer bonding process is that air pockets tend to be formed between the tape and photoresist. Thickness of the photoresist after spin-coating is approximately 28-30 µm, whereas the polyimide thickness is about 40 µm. Because of this height difference, the front-side surface is not planar. The tape is applied, but cannot conformally adhere to all areas. Pockets of air are thus trapped between the two layers. Throughout most of the backside etch process, these pockets of air do not cause much of a problem. However near the end of etching, the fabrication wafer loses structural integrity due to the wafer thinning in the etched areas. Also, pressure inside the air pockets increases when placed under heat and vacuum, and sometimes causes the fabrication wafer to burst. Once this occurs, thermal conductivity is completely lost in the affected locations and the photoresist burns, preventing any areas of the wafer to be salvaged by further etching.

3.6.2 Attachment Using Only Photoresist

A solution for the problem with the previous attachment method is to eliminate the layer of tape and simply use a thick layer of photoresist. This was performed using a double application of AZ P4620 photoresist. First one layer is spin-coated to cover the entire wafer, and baked for curing. After which, a second layer is applied to attempt to fill in areas surrounding the front-side features. This process is given in Appendix A.2.3. Although the through etch was successfully completed using this method of attachment, problems were still encountered. Mainly, separation of the carrier wafer was extremely difficult due to the extensive baking that is experienced during the backside etch process. After soaking in acetone for a significant amount of time (multiple days), the wafers could only be separated by sliding them laterally with respect to each other. This action caused significant damage to the sensors and IMU structures and therefore, AZ P4620 alone is not a viable option as a carrier wafer attachment material.
3.6.3 Photoresist and Kapton Tape

Because of the issues encountered with the above wafer attachment methods, it is desired to explore another method for bonding the carrier wafer prior to backside etching. Bonding the two wafers together can be done using two-sided Kapton® tape, which is very simple to implement. Similar to the previous methods, a double layer of AZ P4620 is first applied using the process in Appendix A.2.3 to prevent the tape from directly contacting the existing features. Kapton® tape with adhesive on both sides is then applied to the fabrication wafer on top of the photoresist layer. The carrier wafer is adhered by then removing the backing of the tape and pressing the two wafers together. A conceptual cross-section of the resulting wafer stack is illustrated in Figure 3.29. A large advantage of using this process is that use of thermal grease is eliminated. Fabrication experience has shown that the grease is a considerable source of contamination as mentioned in Section 3.6.1. By not using thermal grease, issues with contamination after fabrication are reduced.

![Figure 3.29: Carrier wafer attachment using two-sided Kapton® tape and AZ P4620 photoresist.](image)

However, disadvantages also exist with the Kapton® tape bonding process. Air pockets are still created between the tape and photoresist as experienced with the low-tack tape used in the first carrier wafer attachment method. However the Kapton® tape is much stiffer than the dicing tape used before, and therefore resists significant expansion from the heat and vacuum pressure inside the etching chamber. For this reason, the wafer does not burst near the end of the through-etch. This method also does not prevent the AZ P4620 photoresist from contaminating the sensors due to extensive baking during the backside etch process. Despite these drawbacks, using two-sided Kapton® tape is an improvement compared to
the other processes because of the elimination of thermal grease and resilience to air pockets between the wafers. However it is still desired to find another method of bonding in the future to also prevent contamination from the photoresist.

### 3.6.4 Carrier Wafer Attachment Conclusion

Although two-sided wafer fabrication is fairly common MEMS processing, this remains a challenge for folded IMU fabrication due to the front-side topography characteristics. This is mainly caused by the large thickness of the polyimide, and the small feature gaps of the sensors on the front-side surface. Several attempts have been made to determine a compatible method for attaching a handle wafer for the backside etch process. Only a few were discussed in this section because they were the most successful methods. Others that were tried, and recommended for future refinement, were listed in the beginning of this section and are further discussed in Section 8.2.2. Currently however, the best method used for the carrier wafer attachment is to use the combination of photoresist, thermal grease, and low-tack tape. This is because removal of the attachment material and thus the foldable IMU structures is sometimes successful, despite the difficulty of removing the thermal grease from the sensor features.

### 3.7 Backside Etch

Once the handle wafer has been attached using one of the multiple methods, the backside etch process can ensue. First, AZ P4620 photoresist is deposited and patterned on the front-side of the fabrication wafer using the recipe in Appendix A.2.3 to define the outlines of the folded IMU structures for etching through the wafer. Two layers must be used because the silicon etch depth achievable is not sufficient with a single-layer photoresist mask which does
not survive the entire etching process. In previous fabrication runs, a single layer was used because the etch selectivity of silicon compared to AZ P4620 photoresist has been shown to be as large as 70:1 [43, 44]. However the etch selectivity depends on several parameters and thus is not constant. A major influence is thermal conductivity throughout the stack of carrier and fabrication wafers. Active cooling of the etched wafer is done during DRIE processing from the backside of the wafer to counteract the heat induced by the plasma etching process. For the case of the folded MEMS IMU, the wafer stack consists of a silicon carrier wafer bonded to the fabrication wafer with one of the methods used in Section 3.6. Because a second wafer is necessary, and is bonded to the fabrication wafer with polymeric materials, thermal conductivity is reduced. Additionally, when using an SOI wafer, the internal layer of silicon dioxide adds another layer of reduced thermal conductivity. For these reasons, the etch selectivity is drastically reduced due to the elevated temperature of the etched surface. Excessive heating thus occurs throughout the backside etch process, which causes the photoresist to etch faster than expected, and a single layer of photoresist is eventually eliminated prior to etching through the entire wafer. Therefore, two layers of AZ P4620 photoresist are deposited for backside etching purposes, and has shown to successfully survive the through-wafer etch of the folded IMU structures. A fabrication wafer is shown in Figure 3.30 with a double layer of photoresist patterned on the backside.

Metrology was then conducted to determine the thickness of photoresist achieved. Using a Dektak 3 physical profilometer, feature heights were measured near to both the center and edge of a wafer. Results indicated from the plots shown in Figure 3.31 depict a thickness of approximately 35 µm near the center of the wafer, and 42 µm near the edge. Generally, spin-coated polymers are thicker at the center of the wafer. However, the measurements show the opposite effect after applying two layers of photoresist. This is likely caused by the solvents in the second coating partially dissolving the first layer when the liquid photoresist emulsion is initially placed on the wafer. Because it is deposited at the center of the wafer and settles for approximately 30 seconds, prior to spin-coating, some material from the first layer of
photoresist is slightly dissolved by the solvents in the second emulsion. This material is then from the first layer is pushed toward the edge while spinning, resulting in a thicker layer of photoresist near the edge of the wafer. However this does not affect the folded MEMS IMU fabrication process because the thickness achieved is sufficient for etching through the backside of the wafer, even at the thinnest photoresist areas.

As described in Section 3.1, a layer of oxide exists on the front-side of the wafer. Although this can be deposited solely on one side of the wafer, for batch fabrication it is simpler to conformally coat both sides. For this work a 1.5 µm layer of oxide was deposited on both sides of each fabrication wafer. Therefore, etching the backside of the wafer first involves removing the layer of oxide on the backside surface. This can be done with two methods: dry etching with plasma and wet etching with BOE. Both methods have been utilized in this work, however the best results, discussed in this section, have been obtained with dry etching (RIE). The advantage of this method is that issues with high surface tension involved with using BOE etching methods are avoided, which causes minimal etch rates in small trenches. Also, the etch rate of oxide is much faster with RIE plasma etching when using inductively coupled plasma. One drawback of this process is that the photoresist is also etched at a rate
Figure 3.31: Physical profile measurements of two layers of AZ P4620 photoresist patterned on the backside of a wafer showing a thickness of 35 µm near the center and 42 µm near the edge.

of 2.5:1 compared to the silicon dioxide. Therefore, approximately 0.6 µm of the photoresist mask is etched away during this process. However because of the high thickness of the photoresist mask, this is not an issue as there is a great deal of material remaining for the through-wafer etch process.

Next, 500 µm of silicon is etched to penetrate through the handle layer of the SOI wafer to reach the buried oxide. This is completed with a DRIE etch using an STS ASE, but a wide variety of tools are capable of performing this process. Differences are only that of the power, gas mixture, and inevitably the overall etch rate which can vary between 1.5-10 µm per minute. A wafer is shown in Figure 3.32 after etching through the handle wafer, exposing the buried oxide layer.

The 5 µm buried oxide layer must then be etched to continue the DRIE through-wafer etch process. Again dry etching is the preferred etching method due to the thick layer of photoresist, and has been performed on the fabrication wafers. Utilizing the same RIE process as for the initial oxide layer, the etch selectivity of oxide to photoresist is approximately 2.5:1, which eliminates approximately 2 µm of mask material while etching the 5 µm buried oxide layer.
Following the buried oxide etch, the remaining 50 µm of the silicon device layer was etched using the same DRIE process as for the initial 500 µm handle layer. Near the end of the process, inspections between short etch intervals were performed to determine when the etching is complete such that any over-etching was minimized. Specifically, the areas between the hinge fingers were observed since they are among the smallest trench widths contained in the entire design. Once these features are observed to be completely etched, it is determined that the backside etch is finalized and the DRIE process is terminated.

After backside etching is complete, the individual IMU structures are extracted from the fabrication wafer. To accomplish this, the carrier wafer bonding material needs to be removed. This is done by soaking the wafers in an acetone bath heated to 45 °C for 10-15 minutes, thereby dissolving the majority of the tape adhesive and AZ P4620 photoresist used in the bonding process. Each of the foldable MEMS IMU’s is then removed using a pair of tweezers by picking them up at hinge finger locations on the bottom sidewalls. Care must be taken to not damage the samples during removal, and excessive force cannot be induced. Therefore, it must be ensured that adhesion to the carrier wafer has been fully eliminated. Several foldable MEMS IMU samples are shown in Figure 3.33 after removal.
from a fabrication wafer.

Visual inspection of the foldable devices from several wafers indicate that approximately 85% of the inertial sensors remain completely intact, and nearly all of the folded structures survived fabrication. Additionally, the metal traces have not been damaged, and contamination of the sensors from backside processing is minimal. The backside etch mask also successfully survived the entire DRIE/RIE process, indicating that thermal conduction throughout the wafer stack is adequate for fabrication of folded MEMS IMU structures. Catastrophic failures did not occur, such as bursting of the wafer or over-etching polyimide hinges.

3.8 Contamination Removal

Many foldable structures have been successfully extracted from fabrication wafers showing good yield of both intact inertial sensors and IMU structures. However residue remains on both sides of the devices after solvent cleansing. For this reason, the samples are immersed into acetone again, this time at room temperature, for approximately one hour to remove more of the photoresist. Longer soak times have been used, up to 24 hours, however it is noticed that after one hour, there is little or no further improvement to the samples. After
removing the devices from the acetone bath, they are lightly rinsed and allowed to air dry for 10 minutes to ensure that all acetone is evaporated. Although this does not completely eliminate the remaining residue, the process significantly helps by further reducing the amount of surface residue.

Acetone has been used to its maximum extent to dissolve the left-over photoresist from the carrier wafer bonding, but did not entirely remove it, therefore more aggressive methods must be used. Although several options exist that are capable of removing such residue, nearly all will also harm the polyimide material. But the damage can be minimized if short iterations of the cleaning processes are used. Therefore a compromised method must be determined to remove the contamination while also minimizing the damage to the polyimide features. Methods explored in this work are listed below, and are described in more detail in Appendix A.

- Oxygen plasma (discussed in Section 3.6.1)
- EKC 830 photoresist remover
- Piranha etchant
- RCA cleaning
- Sulfuric acid

3.8.1 EKC 830 Photoresist Remover

One method for removing photoresist without the use of solvents is by soaking the samples in a bath of EKC 830, which is a corrosive positive photoresist remover. Heating the solution significantly increases the rate of photoresist removal, therefore the samples were initially
immersed for 10 minutes in a 70 °C bath followed by a 30 second rinse in isopropanol. However this was much too aggressive, resulting in delamination of polyimide after processing. For this reason, the process was repeated with lower temperature and a shorter immersion time. Samples were exposed to EKC 830 at a temperature of 40 °C for a period of two minutes. With this less aggressive approach, the polyimide remained adhered to the foldable structure, however the photoresist was not entirely removed. Iterations of this process was thus conducted at 40 °C to remove more of the photoresist material, however after several repetitions, polyimide delamination was again observed. Additionally, the photoresist was not entirely eliminated.

Overall, it is found that EKC 830 at a temperature of 70 °C is effective for removing all the photoresist, but causes damage to the polyimide adhesion. A less aggressive solution heated to 40 °C requires a longer immersion time to remove the photoresist, but also delaminates the polyimide. This indicates that EKC 830 is not a suitable cleanser for the folded MEMS IMU devices after fabrication.

### 3.8.2 RCA-1 Solution

More aggressive methods for removing photoresist include chemically reactive mixtures such as RCA clean. There are two stages of RCA clean, normally called RCA-1 and RCA-2. The purpose of the first cleaning process is to remove organic material, such as the tape adhesive and photoresist residue. Whereas the second process is used to remove metallic remnants. For the purpose of the foldable IMU devices, it is undesired to remove the metal, therefore only the RCA-1 process is performed, with details given in Appendix A.1.4. After drying, the samples were inspected and showed that the residue was not entirely removed, and the polyimide was beginning to delaminate. Additional exposure time would be required to fully eliminate the remaining residue, which would likely cause further delamination of the
polyimide. Therefore RCA-1 clean is not a preferred method for removing post-fabrication photoresist contamination after backside etching the folded MEMS IMU devices.

### 3.8.3 Piranha Etchant

Piranha solution was also used as a cleanser for the IMU samples after fabrication. This solution is created by combining three parts of sulfuric acid to one part of hydrogen peroxide. The mixture is then heated to approximately 100 °C to activate an aggressive chemical reaction. This reaction chemically dissolved organic material, and is commonly used to entirely remove photoresist from glass and silicon after etching. The foldable MEMS IMU devices are immersed into the piranha etchant for five minutes. Once removed, the samples are placed in DI water for another five minutes for rinsing. After completion of this process, it was noticed that the photoresist was successfully removed. However the polyimide suffered significant etching. It is thus concluded that piranha solution rapidly etches polyimide and therefore is also not an optimal solution for removing contamination from the foldable MEMS IMU samples.

### 3.8.4 Sulfuric Acid and Isopropanol

Although piranha etchant has been proven to attack polyimide, it is possible that a modified, less aggressive solution may be successful. By not adding hydrogen peroxide and just using sulfuric acid, the chemical reaction normally involved with piranha etch is avoided. Also, if the solution is not heated to high temperatures, polyimide is more stable and etches material significantly slower. It is shown that polyimide exposed to sulfuric acid at temperatures above 100 °C is rapidly etched. However at lower temperatures it tends to be etched at a lower rate and therefore can likely be exposed for a short periods of time without causing significant damage.
It was determined that sulfuric acid at a temperature of 55 °C is the optimal temperature for removing photoresist without significantly etching the polyimide. Figure 3.34 shows an IMU sample soaking in sulfuric acid showing that the photoresist is rapidly dissolving. After soaking in acid for five minutes, the samples are transferred to a bath of acetone for another five minutes. The devices are then placed in DI water for 5 minutes for a final rinse, and then allowed to air dry. But this process does not entirely remove all residue. A total duration of exposure of approximately 15 minutes is required to completely clean the devices. However long exposure to the acid at this temperature creates severe deformation of the polyimide hinges, which causes the IMU sidewalls to fold in the opposite direction from what is desired. This deformation is permanent, and thus the foldable IMU structures are catastrophically damaged. Although deformation occurs, delamination of the polyimide is not observed. For this reason, short iterations of sulfuric acid exposure are preferred so that the phenomenon of premature folding of the sidewalls can be minimized while also not causing polyimide delamination.

After approximately five iterations of repetitive treatments as described above, the majority of the residue is removed. One device that was cleaned using this process is shown in Figure 3.35 before and after removing the fabrication residue. Visual observations indicated successful removal of photoresist from between the individual latches, the bond pads on polyimide features, as well as in the inertial sensor areas. Although slight deformation occurs within the hinge areas, it is not nearly as severe as experienced with longer exposure times to the sulfuric acid. Using this iterative cleansing procedure for the foldable IMU
structures, the devices are successfully be cleaned without causing significant damage to the polyimide.

Despite exposure to sulfuric acid and solvents in multiple iterations, microscopic observations shows that a small amount of residue still remains on the IMU samples. Oxygen plasma is therefore used to eliminate the rest of the residue, albeit the possibility of further etching the polyimide material. After 10 minutes of exposure at 200 W of power and 200 mT of pressure, the photoresist is entirely removed from the sensors and electrical bond pads. Photographs are shown in Figure 3.36 after oxygen plasma exposure, showing no photoresist residue remaining on the inertial sensors of the inertial sensors as well as the rest of the
device.

Figure 3.36: Foldable MEMS IMU cube after fabrication is complete and the devices have been cleaned with sulfuric acid, acetone, and oxygen plasma.

### 3.8.5 Conclusion

Prior to releasing the SOI inertial sensors, the IMU samples must be free of extraneous front-side residue from the backside etch process. Any remaining material will cause the underlying areas of the sensor to be under-etched, or not etched at all. This is catastrophic, causing sensors on the entire device to be non-operational. Several methods have been used to remove this residue, including EKC 830, piranha solution, RCA-1 solution, sulfuric acid, and oxygen plasma. Observations indicate that polyimide or metal is damaged or delaminated when using the former three techniques. However short multiple iterations of exposure to slightly heated sulfuric acid followed by soaking in acetone is capable of removing most, if not all, the photoresist residue without causing significant damage to the polyimide. Further exposure of the samples to oxygen plasma at a pressure of 200 mT with a power of 200 W for 10 minutes is successful for performing the final clean of the bond pads and inertial sensors. Therefore it is concluded that repetitions of immersion in sulfuric acid followed by acetone rinsing is the best method for cleansing the samples in a wet solution. Additionally, when
further processed by exposure to oxygen plasma, this proves to be the optimal method for cleaning the foldable MEMS IMU devices after backside etching.

### 3.9 SOI Sensor Release

After the foldable structures were removed from the wafer and cleaned, the sensors were released by etching the underlying SOI oxide layer. This is generally done by immersion of the devices into hydrofluoric acid (HF) or a mixture of HF with other chemicals. But exposure to HF tends to attack other materials on the devices such as polyimide. Due to the presence of materials susceptible to damage from using HF, buffered oxide etch (BOE) can be used as an alternative which is more compatible with polymers such as photoresist and polyimide. Composition of BOE solution consists of HF and ammonia in varied levels of mixture ratios. When using only HF diluted with water, polymers tend to lose adhesion and delaminate from the substrate. By using a buffered mixture, delamination of polyimide from the silicon surface is minimized, yet still occurs. For these reasons, a variety of silicon dioxide etchants were utilized in an attempt to eliminate the problems experienced with the polymer and metal delamination with many fabricated devices.

Wet etchants that were used in this work for etching silicon dioxide all consist of a mixture of HF with other chemicals. As mentioned above, when polymers are present it is common to use BOE rather than HF. A comprehensive list of other possible etchants is shown in Table 3.4 provided by Transene Company, Inc. All of which do not specifically indicate compatibility with polyimide, and thus is likely they cannot be directly used as specified by the manufacturer for releasing the sensors on the foldable MEMS IMU structures. Therefore it is necessary to mask the polyimide and metal features with a material compatible with HF etching rather than re-inventing a fully-compatible etchant. The mask must be easy to remove to avoid aggressive cleaning methods after the sensors have been released, which can
be challenging. Materials considered for this purpose include AZ P4620 and SU-8 photoresist, as well as ProTEK® A2, which is a polymer coating designed for protecting substrates from HF exposure.

<table>
<thead>
<tr>
<th>Transene Etchants</th>
<th>Operating Range</th>
<th>Recommended Resist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buffered HF Improved</td>
<td>800Å/min @ 25°C</td>
<td>Positive or Negative</td>
</tr>
<tr>
<td>BD Etchant</td>
<td>Varied</td>
<td></td>
</tr>
<tr>
<td>Siloxide Etch</td>
<td>40Å/min @ 25°C</td>
<td></td>
</tr>
<tr>
<td>Timetch</td>
<td>90Å/min @ 25°C</td>
<td></td>
</tr>
<tr>
<td>Silox Vapox III</td>
<td>4000Å/min @ 22°C</td>
<td></td>
</tr>
<tr>
<td>BOE</td>
<td>Variable</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.4: Wet etchants available for removing silicon dioxide with photoresist mask material (from Transene Company, Inc.)

While all of the proposed HF mask materials are designed to be spin-coated, this is difficult for the IMU structures because they have been released from the fabrication wafer and cannot be directly mounted onto a vacuum chuck. However they can be adhered to a carrier wafer and then spin-coated, but photolithography is challenging because an exposure mask cannot directly contact all areas of the structures, due to height variances. Both AZ P4620 photoresist and SU-8 photoresist were used as a mask, but the SU-8 material was extremely difficult to remove after fabrication. Therefore, AZ P4620 photoresist is a preferred masking material because it can be removed much easier. Additionally, ProTEK® A2 is not photosensitive and is difficult to be patterned. For these reasons, each masking material is applied manually with a fine-tip applicator. The structures are first mounted to a handling wafer using small droplets of AZ P4620 photoresist underneath each sidewall. After baking on a hot plate to complete adhesion, the masking material is applied such that all polyimide features are covered. It is also applied to coat the latches and hinges to prevent penetration of HF or BOE under the sidewalls.

After using each potential option to provide a protective mask for the polyimide and metal features, using AZ P4620 exposed to 6:1 BOE performs best. However the surface
tension of the BOE solution must first be reduced by adding Novec™ 4200 to the solution, which is a surfactant designed specifically for BOE. The main advantage of this method is that it is easy to remove the photoresist using acetone after the sensor release process is complete. A disadvantage, however, is that AZ P4620 is less resistant to HF penetration compared to the other materials mentioned. Another disadvantage to this process is that it takes approximately 5 hours to complete, compare to \( \approx 50 \) minutes with 20% HF.

All areas were selectively covered with AZ P4620 photoresist where potential damage may occur due to acid exposure, leaving the sensor areas clear as shown in Figure 3.37. Different from the recommended soft bake of AZ P4620 at 90 °C in an oven for 20 minutes, the thicker material is cured at a lower temperature for a longer amount of time to prevent rapid expansion of internal solvents. Hardening of the photoresist is performed on a hot plate at 70 °C for five hours. This ensures that all photoresist is fully cured, despite the drastic increase in thickness and bake time compared to spin-coating.

![Figure 3.37: A foldable MEMS IMU with polyimide features protected with AZ P4620 photoresist and cured at 70 °C on a hot plate for five hours.](image)

Earlier, the samples were aggressively cleansed with sulfuric acid and acetone after fabrication. However residue still remained within the trenches of the sensor features. Therefore, oxygen plasma is used, as discussed in Section 3.8 to complete the cleansing process. A large majority of the residue was removed before releasing the sensors in BOE, leaving behind only a few particles which are determined to be noninvasive. Results indicate that all
inertial sensors are conceivably operational once releasing the buried oxide layer is finished. A microscopic photo of the upper-left corner of a gyroscope is shown in Figure 3.38(a) after cleaning with oxygen plasma. Another photo of an accelerometer section, Figure 3.38(b), shows clean sensor features also capable of operation after being released. Bond pads on the sensor anchors still exist but will likely be lifted off when the sensors are released. Whether present or not, the bond pads will not affect the capability of electrical connection to the sensors since both materials are compatible for wirebonding and packaging.

![Figure 3.38: Microscopic images of sensor portions after cleaning with oxygen plasma to remove remaining organic residue.](image_url)

Release time for the sensors directly depends on the etch rate of the buried oxide layer in the composition of the BOE solution. Many variables are involved in the overall etch rate including HF concentration, the aspect ratio of etched features and trenches, percentage of area to be etched, and surface tension, to name a few. While most of these properties are not controllable during release, surface tension is one that can be modified. As mentioned above, a surfactant is used to reduce this surface tension, Novec™ 4200, which inevitably increases consistency of the etch rate of silicon dioxide in high aspect ratio trenches. It has been determined that it takes approximately 300 minutes of BOE etching to fully release the folded MEMS IMU inertial sensors with enlarged etch holes and trenches. This results in an etch rate of approximately 167 Å per minute, which is quite low when compared to a rate of greater than 1000 Å per minute when using a 20% concentration of HF diluted with water.
It is shown that within small features, penetration of 6:1 BOE is not sufficient to provide a higher etch rate, despite the added surfactant. However it does offer a more consistent etch rate for features of various sizes. Also because delamination of photoresist and polyimide is reduced, BOE with the added surfactant is the preferred solution for releasing the SOI inertial sensors on the foldable MEMS IMU devices.

One challenge with etching the buried oxide layer of SOI sensors is preventing stiction of released features due to capillary drying effects. This occurs due to high surface tension of the BOE solution and also water, which while drying, attracts mobile features toward each other. When contact is made, features stick to each other if the surfaces are extremely flat. This is the case for the proof masses of the sensors, and if stuck, leave the sensors non-operational unless the structures can be mechanically freed. The devices are heated on a hot plate at a temperature of 110 °C immediately after rinsing in DI water after each iteration of HF etching. This causes the water to vaporize without inducing capillary drying effects within mobile features of the SOI inertial sensors.

Results of the etching process using AZ P4620 as an etch mask for BOE etching has proven to be successful on multiple samples. Gyroscopes have been successfully released on folded IMU structures, as shown in Figure 3.39. However, the etch mask must first be removed to provide good electrical contact to the sensor anchors and bond pads located on the polyimide substrate. Eliminating the AZ P4620 mask is performed by immersing the samples in acetone for 20 minutes, followed by a 10 minute exposure to oxygen plasma at 200 W of power and 200 mT of pressure.

Unfortunately, not all of the sensors could be fully released on all of the fabricated IMU devices. Contamination on top of the sensors prevented penetration of the HF in some locations, minimizing or eliminating the buried oxide etch rate underneath these areas. The source of contamination is likely produced from the backside etch process, which were attempted to be removed prior to the release process by using the procedures explained in
Figure 3.39: A folded MEMS IMU gyroscope fully released after etching in 6:1 BOE with Novec™ 4200 surfactant for a total exposure time of 300 minutes.

Section 3.8: After releasing the inertial sensors in BOE, the AZ P4620 photoresist is removed by immersion in acetone until the photoresist is completely dissolved. This is followed by a delicate rinse of isopropanol and drying on a hot plate at 40 °C. A photograph of the results from the cleaning process is shown in Figure 3.40.

Figure 3.40: Foldable IMU cube with released sensors after removing AZ P4620 photoresist with acetone.

Even though some polyimide delamination occurred after removing the protective photoresist, as depicted by the darker polyimide areas in Figure 3.40, adhesion remained intact in approximately half the overall area. Therefore, the foldable IMU was still capable of packaging and assembly. However, a small amount of residue remained on the inertial sensors and bond pads. Oxygen plasma was then used to eliminate this residue prior to electrical pack-
aging of the overall IMU device. Figure 3.41 shows a portion of the sense mass of one gyro, as well as the suspensions and detection electrodes. As can be seen from the photograph, no residue remains on the silicon features and thus the IMU is successfully prepared for electrical connections. Multiple methods for packaging the sensors are described in Chapter 4. After wiring the required connections on the individual sensors, the entire IMU structure can then be folded together and mounted into a DIP package to allow for external characterization in a circuit board.

Figure 3.41: A portion of a gyroscope cleaned with oxygen plasma showing sense mass, suspension and capacitive detection electrode features.

Sensors on fabricated foldable IMU samples have been released using each protective coating described in this section. Also, both BOE and HF have been used for etching the buried oxide to compare the processing time required for each. Results show that a 6:1 BOE solution releases sensors in approximately five hours, compared to 50 minutes when using 20% HF diluted in water. Based on results from the experiments performed, a solution comprised of only HF and water tends to delaminate the polyimide. This occurs when using all protective materials, either when directly exposed to HF, or when removing the protective coatings. Given the advantages and disadvantages of each, the optimal solution is to coat the polyimide features with only AZ P4620 photoresist and to use 6:1 BOE to release the sensors. However, the BOE must be combined with a surfactant, such as Novec™ 4200, to provide a uniform etch rate of the buried oxide layer underneath the mobile sensor features.
3.10 Conclusion

An approach has been explored for creating a new path toward fabrication of a high-performance MEMS IMU with a chip-scale footprint. In this chapter, the fabrication processes utilized were defined in detail to accommodate the design aspects discussed in Chapter 2. Although the details of each fabrication step has been independently explored and was successful, it is challenging to combine all processes and maintain compatibility of the materials for each subsequent step. A critical component of the overall fabrication process is the final sensor resolution capabilities. Improvements in Phase II of development have been made to reduce the sensor feature resolution to 5 \( \mu m \), compared to 8 \( \mu m \) demonstrated in previous work \[6, 8, 45, 46\]. This enhancement enables much higher theoretical performance of the sensors fabricated on the IMU structure.

It was noticed during Phase I of this research that the polyimide experienced cracking and pebbling. This created discontinuities in metal traces deposited on top of the polyimide, and therefore was a significant issue. A modified development recipe was created to eliminate this problem, and was utilized for both the first and second layer of polyimide in Phase II of this work. Another issue that was commonly observed that was when using two layers of polyimide, delamination of polyimide occurred after fabricating and cleaning the foldable IMU devices. Therefore, a curing process was specifically developed to minimize delamination when using two layers of polyimide. This involves doing a half-cure on the first layer after patterning, where the solvents are baked out but the final polymer cross-linking does not occur. After the second layer is deposited and patterned, both layers are fully cured at the same time, therefore reducing the film stress induced in the first layer compared to doing two full-cure processes. Results show that this curing process is successful in reducing delamination and was utilized during the Phase II development of the folded MEMS IMU devices.
During Phase I of this work, a metal lift-off process was utilized that included common photoresist such as Shipley 1827, Appendix A.5.1. However an extra step is required to create high-yield of successful metal traces that involves chlorobenzene. This is a toxic material, and it best to be avoided if possible. In Phase II, a metal lift-off process was used that instead uses a more modern photoresist technology in AZ nLOF 2035. This resist naturally creates sidewalls in the photoresist without the use of chlorobenzene that prevents metal deposition on the sidewalls in a directional deposition process. Also, it provides better success than the previous process, with 100% yield of traces on the large IMU devices, and approximately 90% yield on the half-sized IMU devices. Determination of the metal interconnect material is performed by analyzing the thermal and electrical characteristics, and gold is shown to be the optimal choice. Resistance measurements were conducted at various temperatures on copper traces, resulting in a large variance mainly due to oxidation. Therefore gold is preferred because of its resilience to oxidation and higher conductivity compared to copper.

For the sensor etch process, the in-house fabrication methods developed in prior research, were utilized in both phases of the folded MEMS IMU development. This process has proven to be successful during throughout the entire duration of this work. Therefore it has not been modified, except for some minor modifications recommended by cleanroom staff after etch tool repairs.

After front-side fabrication, the backside process must be done after attaching a carrier wafer. Many methods for attachment of this wafer have been utilized, as discussed in Section 3.6. Backside etching has proven to be the main bottleneck in yielding operational IMU devices. This is largely due to the fact that it is difficult to etch entirely through an SOI wafer because of the buried silicon dioxide layer. Experimental results show that the optimal solution thus far is to use two layers AZ P4620 photoresist to coat the front-side features, followed by a layer of low-tack tape. Thermal grease is then applied to the carrier wafer, followed by pressing the two wafers together while baking on a hot plate. This method tends
to reduce the amount of contamination experienced after fabrication, and is therefore preferred compared to other methods discussed. After backside processing, the contamination from photoresist masking material and tape adhesive must be eliminated. Several methods were explored for this purpose, but the challenge was to prevent simultaneous damage to the polyimide material. Results indicate that short repetitive iterations of immersion into sulfuric acid followed by acetone and isopropanol prove to be the most successful method for removing contamination from the foldable MEMS IMU devices after fabrication.

The final challenge in fabrication is releasing the SOI sensors. Several types of silicon dioxide etchants were used for releasing the sensors after the foldable IMU devices were fabricated and cleaned, as described in Section 3.9. After several experiments with different masking materials and etching solutions, a preferred method was determined. This involves AZ P4620 photoresist as a masking material for the sensors, which is manually applied, and 6:1 BOE used as an etchant. The combination of which proves to be the best available option for releasing the SOI sensors while minimizing damage to the other materials. Overall, the fabrication process developed for the foldable MEMS IMU devices shows that this approach is feasible for creating operational 3-D IMU devices on a chip-scale footprint.
Chapter 4

Packaging and Characterization

A fabrication process for manufacturing IMU devices using a folded MEMS approach has been explored and proves to be feasible for developing a new path toward creation of high-performance units on a single chip. After fabrication however, it is also necessary to package each individual device, as well as the entire IMU structure to obtain characterization results. For this work, the packaging process is a challenge on the same magnitude as fabrication. Several foldable structures have been fabricated, with sensors released, and cleaned to prepare for packaging. The individual sensors as well as the overall IMU structures must be electrically connected to signal detection circuitry to allow for characterization. Multiple well-known methods currently exist for packaging MEMS sensors [47]. Traditional wire bonding as well as more contemporary flip-chip methods [48] are both explored to determine the preferred technique for the folded MEMS application.
4.1 Packaging

Two stages of packaging are needed for the folded IMU structures. First, the sensors anchors must be bonded to the electrical bond pads located on the polyimide. This can be done either by conventional ball or wedge bonding techniques, or by using flip-chip packaging with conductive epoxy as the connection medium. The second stage involves overall packaging of the folded structure. All traces terminate at the bottom of the structure to enable flip-chip packaging onto a PCB. Alternatively, an interconnect plate can be used instead of a PCB to allow for mounting into a DIP package. By using a this type of package, or something similar, the folded IMU device can easily be removed, replaced, and recalibrated after initial implementation. The overall IMU combined with a DIP package be able to be inserted into prototype electrical detection electronics, such as a protoboard.

4.1.1 Wire Bonding

Initially, the chosen method for packaging sensors on the IMU was to wire bond the sensor anchors to the open interconnects on the polyimide. Following which, the entire structure is mounted into a larger package that can be inserted into a PCB prototype containing signal detection circuitry. However the design allows the folded MEMS IMU to be flip-chip mounted directly onto a PCB or interconnect plate.

Wire bonding of the sensors using conventional methods is challenging due to low rigidity of the polyimide substrate underneath the electrical interconnects. Therefore conductive epoxy is used as a substitute, and has been successful. The advantage of this technique is that it is possible to integrate with conventional wire bonding, as discussed below. However, a disadvantage is that the wire bonds are susceptible to damage while folding the structure together. Ideally, the wire bonds would be created after the structure is assembled to avoid
issues while assembling the structures. While this is not impossible, current technology does not easily allow for creating wire bonds on vertical or 3-D substrates.

Initial exploration of wire bonding has been done with the structures unfolded. Traditional gold ball and aluminum wedge bonding processes have thus been performed on unassembled structures. However both are not entirely compatible for bonding to the sensor terminals as well as the bond pads on the polyimide. To bond wires from the sensors to the metal traces on the polyimide, first a traditional wire bond is made with aluminum wedge bonding (using aluminum wire). However the second bond (to metal on polyimide) does not adhere using this method due to the lack of rigidity of the polyimide substrate. Therefore the broken end of the wire is then attached to the complimentary bond pad with conductive epoxy. Results of this process on a single sensor is shown in Figure 4.1.

![Accelerometer on a foldable MEMS IMU structure with the anchors of the main sensor components connected to the bond pads on polyimide.](image)

After bonding aluminum wires onto each of the bond pads, solvents are baked out of the epoxy, leaving mostly silver to act as the conductive medium. Another type of epoxy is used for burying the bonded wires on the polyimide bond pads to prevent damage during assembly of the overall structure. To ensure that this epoxy will not flow onto the sensor components prior to curing, a thick dam, created from yet another type of epoxy, is first made around
the edge of the sensor. The end result leaves very little of each wire exposed, minimizing the amount of damage that can be done while assembling the sidewalls. Completion of these tasks was carried out by FAST Semiconductor, and proves to be successful, Figure 4.2. However this method is not ideal for long-term applications of the folded MEMS IMU that may experience vibration, temperature variation, and fatigue. Therefore an improved method of packaging is desired.

Figure 4.2: Assembled IMU with sensors packaged using wire bonding underneath a protective layer of epoxy.

### 4.1.2 Interconnect Plates and Lids

While wire bonding has proven to be successful, there are inherent disadvantages related to this method. Additionally, it is desired to have each sensor protected from the environment. Therefore, encapsulation lids are designed with built-in interconnects to function as a connection medium, as well as environmental protection for the inertial sensors. Metal traces are fabricated on each lid to connect each sensor anchor to bond pads located on the polyimide. This eliminates the need for manually wire bonding each individual sensor anchor to foldable structure.
Since the accelerometers and gyroscopes require different connection schemes, encapsulation lids have been designed for both types of sensors. For the accelerometer, seven connections are necessary for full operation with the current architecture. The design for the accelerometer lid is shown in Figure 4.3(b). Gyroscopes designed for the IMU cube require a total of 11 connections for full operation, so a different design is necessary. Flip-chip lids have been created for the gyroscopes to accommodate the extra connections, shown in Figure 4.3(c).
Fabrication of both types encapsulation lids involves a single-mask process to deposit and pattern metal interconnects. This is done using the same procedure as for the IMU devices as described Section 3.3. Multiple lids are fabricated on a single 4” glass wafer, and dicing is done to separate the individual samples. The mask shown in Figure 4.3(a) includes a total of 112 lids, 68 of which are accelerometer lids and the other 44 are for gyroscopes.

The encapsulation lids for this work are created on a 500 µm D-263 glass wafer. Metal deposition is done by electron-beam evaporation with 500 Å of chrome first being deposited as an adhesion layer. This is followed by a 5000 Å layer of gold to minimize contact resistance between the conductive epoxy and the metal traces. Also, gold is not oxides nor attacked in HF solutions, it is an optimal selection. Figure 4.4 shows the fabrication wafer and closer photographs of each type of encapsulation lid before the lids are separated by dicing the wafer.

Figure 4.4: Fabrication results of glass interconnect lids for accelerometers and gyroscopes prior to dicing.

After connections are made from the metal interconnects to the sensors, the IMU can be interfaced with a PCB or other type of compatible package. All connections from the IMU sensors terminate on the bottom face to allow for connection to external circuitry. While the primary function of these terminations is to enable direct bonding to a PCB, initial testing involves an over-sized DIP package suitable for mounting into a prototype circuit.
For this reason an interconnect plate is used to provide access to the traces from an external package to the bottom terminals of the IMU. Such plates have been designed in both Phase I and Phase II of development to provide electrical connection to the IMU cube structures, as shown in Figure 4.5 for the Phase II design. A total of 40 signals are required for the three gyroscopes and three accelerometers implemented on the IMU cube. Final termination locations on the interconnect plate have been placed near to the bond pads located on the DIP package to simplify the wire bonding process. A single plate is shown in Figure 4.5(a) and is designed to fit inside of a hybrid DIP package with a 0.8”x1.9” cavity size. The plates are designed large enough to allow sufficient clearance between the IMU connections and the DIP package bond pads for the wire bonding tool-head. Because of the size of the interconnect plate, only four can fit onto a 4” wafer, as shown in Figure 4.5(b).

The process used to create the plates is identical to that of the glass encapsulation lids. The fabricated samples are then diced to separate each interconnect plate from the wafer. Cleaning of the plates is again done with the same process in Appendix A.1.1 to prepare for packaging. Fabrication of the interconnect plates was successfully completed, shown in Figure 4.6. Visual inspection depicts excellent yield because all traces are well-defined and the units are free of defects such as open or shorted connections.

In addition to electrical connection to an external package, the glass lids and interconnect plates provide some environmental protection of the inertial sensors. In the future, this process can be modified to allow for vacuum packaging the gyroscopes and accelerometers at different pressures. This would each sensor for operation at the ideal pressure to provide optimal performance. To mount the lids to the IMU sidewalls, conductive epoxy will be placed on each bonding pad, followed by the glass lids being aligned and placed on top of the sensors. The conductive epoxy will provide sufficient electrical connections for prototyping purposes. Also, it will aid in adhering the glass lid to each inertial sensor.
4.1.3 Solder Bump Packaging

One challenge to the folded MEMS IMU approach is determining a method for packaging the device. It is crucial to be able to determine a dependable method for packaging the structures for sensor characterization. With the device unassembled (flat), the sensors bond pads need to be connected to the corresponding bond pads on the polyimide substrate for each sidewall prior to assembly. As previously described, the folded IMU structures are equipped with bond pads located on the bottom face to allow for mounting to a flip-chip package or PCB. The packaging process was initially performed by and outside company, Fast Semiconductor,
using aluminum wire-bonds as well as silver-filled epoxy. The epoxy bonding process used is the same as described in Section 4.1.1. The end result leaves very little of each wire exposed, minimizing the amount of damage that can be done while assembling the sidewalls.

Fabrication of the plates is done using a glass substrate and 0.5 µm thick gold traces, as described in Section 4.1.2. One purpose of using glass material is to provide a transparent substrate, which simplifies the alignment process because the connections can be visually observed. Once all lids and the interconnect is successfully attached, the assembly can be mounted into a DIP package and wire bonded to the pin terminals so that it can be interfaced with external electronics. Since the interconnect plate on the bottom is a critical component for operation of the IMU, the solder bump attachment procedure is performed first for this aspect of the design.

Several methods are available for cube-to-plate attachment, including conventional soldering, solder bumping, and conductive epoxy bonding. A good solution for the folded
MEMS IMU device interconnect plate packaging is to use solder bumps. After applied to the glass lids and interconnect plate, the solder can be reflowed to make permanent electrical connections. Results of this process are shown in Figures 4.7 and 4.8 and are proven to be successful. Depicted in the figures are solder bumps with a diameter of 0.025” attached to the bond pads on the interconnect plate. Although an outside company was first contracted to perform this work, an in-house technique for accomplishing the same task was developed which also uses bumps of similar size. Solder spheres of 250 µm diameter are mounted onto the bond pads and held in place with solder flux prior to mounting the interconnect plate to the IMU structure. The flux acts as an adhesive after it dries and thus keeps the spheres in place while the lid is attached.

Figure 4.7(b) shows solder spheres between the IMU cube and interconnect plate prior to reflow. This photograph is taken from the underside of the assembly, through the glass substrate. After aligning the plate to the bottom of the cube, the solder bumps are quickly melted at a temperature of 250 °C to create low-resistance electrical connections. This also creates a rigid attachment of the lids or plate to the IMU structure. Results are examined using X-ray photography to determine the quality of the bonding, shown in Figure 4.8. The image is processed with a relief filter, and as it can be seen, there are no short circuit connections between solder bumps. Connections were also verified by electrical testing, resulting in no continuity between any adjacent bond pads. However some voids that are visible, which can be eliminated with further processing modifications. For the purpose of creating electrical connections on the folded MEMS IMU devices, the solder bumping process is shown to be successful. One of the resulting IMU cube structures with sensors packaged using wirebonding is shown in Figure 4.9 attached to the interconnect plate and ready for DIP packaging.
Conductive Epoxy Packaging

Different from the process in Section 4.1.3, glass lids can be adhered to the IMU sidewalls using flip-chip bonding with conductive epoxy. This eliminates the need for wire bonds from each sensor to the bond pads on polyimide. Rather than solder connections, conductive epoxy is used to reduce the temperature exposure of the fabricated IMU devices. Epoxy requires curing temperatures ranging from 25 °C to 150 °C, depending on the type of epoxy used and the amount of time allotted for the process. Then the final curing time ranges from one hour at 150 °C to 24 hours at room temperature. Flip-chip assembly is done in-house with a WestBond 7201CR die bonder with two epoxy dispensing heads and a 3-DOF vacuum
pick-up tool. Epoxy is dispensed with the die bonder onto the sensor anchors and the metal interconnect bond pads.

After removing leftover residue from fabrication, the encapsulation lids are bonded to the sensors using Ablebond® 84-1LMI silver-filled epoxy to create the electrical connections between the sensor anchors and the bond pads on the lids. It was noticed that while curing the silver-filled epoxy, the material expanded causing the lids to lift above the underlying substrate. Many bonds were unsuccessful because of this phenomenon, however a solution has been explored. Generic two-part epoxy that cures at room temperature in 10 minutes is used to maintain position of the glass lids while curing the other conductive epoxy. The following process is used to ensure successful assembly of the interconnect lids:

(I) Apply conductive epoxy to bond pads.

(II) Apply general epoxy to corners of cube.

(III) Align and place glass lid or interconnect plate.

(IV) Allow general epoxy to cure at room temperature for 10 min.

(V) Heat entire structure to 150 °C.

(VI) Hold at 150 °C for 1 hour to fully cure conductive epoxy.

The epoxy die-bonder tool enables precise placement of conductive epoxy onto the sensor anchors and polyimide bond pads. One concern with this process is overflow of conductive epoxy which can cause short-circuits between neighboring connections. However the epoxy dispensing recipe has been tuned to prevent this from occurring on the sensor anchors and interconnect bond pads. The glass lids are then aligned and placed onto the sensors to create the electrical connections. The glass lids rest on top of the polyimide, which is approximately 40 µm in height. Thus the glass lids lie slightly above the sensors which helps to reduce the
possibility of epoxy overflow onto the sensor features. Final curing is performed after the lids are attached by heating the structure at 150 °C for one hour. This evaporates the solvents from the silver-filled epoxy, leaving a permanent conductive medium between the folded IMU structure bond pads and the encapsulation lids. Utilizing this process, the encapsulation lids are mounted to each sensor, with the exception of the bottom surface, Figure 4.10.

Figure 4.10: Glass interconnect lids bonded to IMU cube sensors prior to assembling the folded structure.

Visually, inspection of the bonds indicates that the process is successful, Figure 4.11. However additional electrical characterization is necessary to determine the quality and yield of the connections. Unfortunately, the packaging design provides very few redundant connections, thus simple continuity testing cannot be performed on the electrical connections. Therefore, a more sophisticated approach is required such as capacitance testing to determine if the connections have been successfully made. Further discussion of this is given in Section 4.4 after the devices are fully packaged.

Once each lid is mounted onto each sensor and the epoxies are cured, the folded IMU structure is assembled, shown in Figure 4.12. Results of the assembly indicate that the Phase II design has several advantages compared to earlier phases of IMU development [8]. The latch design allows for simple assembly and alignment of sidewalls. Additionally, all latches fit in place with very low clearance to create a rigid interference fit which structurally maintains alignment of the sensors. Robustness of the latches is also improved due to increased
thickness compared to the Phase 0 design, thus no latches are damaged during assembly. One concern is ensuring that the lids remain adhered to the sidewalls. Because force is directly applied to the lids to maneuver the panels into place during assembly, the epoxy used must be able to withstand these forces. By using the generic epoxy reinforcements on the corners, the lids do not become detached and none of the bond pad connections are broken. Overall, the Phase II assembly process is quite successful, and is simpler and more effective than Phase 0 and Phase I of the folded MEMS development.

After assembly, the IMU cube is mounted to an interconnect plate to provide access to all connections for wire bonding to a DIP package. The interconnect plate also functions as a packaging lid for the bottom gyroscope. Assembly of the interconnect plate is done in the same manner as the sidewall lids where general use epoxy is placed on the corners for
reinforcement and conductive epoxy is applied to the bond pads. As shown in Figure 4.13, rigidity of the epoxy bonds is shown to be sufficient for adhering the large bottom interconnect plate. Based on the optical inspection of the bottom plate attachment, it is confirmed that many of the bond are observed to be successfully connected.

Figure 4.13: Assembled IMU cube attached to the bottom interconnect plate.

![Image](image1)

(a) Bottom view  
(b) Close-up

Figure 4.14: Interconnect plate attached to bottom of an IMU cube to provide electrical interconnects to the bottom sensor and the rest of the IMU.

Inspection of the epoxy connections is verified visually by viewing the bottom side of the interconnect plate after attachment, Figure 4.14(a). Adhesion strength of the epoxy reinforcements are sufficient enough to support the weight of the entire device, indicating that the epoxy bonds are rigid and fully cured. All bond pads on the sensor and polyimide are successfully aligned to the corresponding bond pads on the interconnect plate. A close-up of the connections is shown in Figure 4.14(b). Nearly all anchors on the sensors are also
connected, however some cannot be visually verified and thus electrical characterization is necessary to determine the yield and quality of successful connections.

### 4.1.5 DIP Package Integration

For initial testing purposes, DIP packaging is desired due to its simple implementation into prototype circuitry. Hybrid DIP packages are used which are capable of accepting an oversized die with up to 40 connections. The interconnect plate is designed to occupy the majority of the package area. This reduces the length of wire bonds necessary for final packaging. Large bond pads on the interconnect plate are located near the package terminals, thus simplifying the wire bonding process.

General-use epoxy is first applied to the package basin to cover the approximate area of which the bottom interconnect plate will occupy. The IMU cube with the attached interconnect plate is then placed onto the epoxy and pressure is applied while aligning it to be nearly centered with respect to the DIP package dimensions. Wire bonding is done using a WestBond model 747677E bonder equipped with aluminum wire and a deep-access bond wedge. Configured as a deep-access bonder, creating wired connections from the interconnect plate to the DIP package is done without concern of the bond head interfering with the folded structure. All connections are successfully made, Figure 4.15, resulting in a fully packaged IMU capable of integration with prototype circuitry.

Implementation into signal detection electronics requires a map of each pin to the folded IMU structure. A pin diagram labeling each electrical connection from the interconnect plate to the IMU cube is shown in Figure 4.16. Nomenclature for the convention used to make the labels is given in Table 4.1. Each pin name consists of a sequence of letters followed by a number. The first letter is either a ‘G’ or an ‘A’, depicting whether or not the pin is connected to a gyroscope or accelerometer feature, respectively. The second letter represents
Figure 4.15: Folded IMU cube packaged with interconnect lids attached to each sensor and to an interconnect plate that is wire bonded to a hybrid DIP package.

<table>
<thead>
<tr>
<th>Pin Label</th>
<th>IMU Connection Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>G#SE1</td>
<td>Sense electrodes 1 for #-axis gyro</td>
</tr>
<tr>
<td>G#SE2</td>
<td>Differential sense electrodes corresponding to G#SE1</td>
</tr>
<tr>
<td>G#TE1</td>
<td>Tuning comb drive for #-axis gyro</td>
</tr>
<tr>
<td>G#TE2</td>
<td>Opposite tuning comb drive for #-axis gyro</td>
</tr>
<tr>
<td>G#DE1</td>
<td>Drive electrode for #-axis gyro</td>
</tr>
<tr>
<td>G#DE2</td>
<td>Differential drive electrode corresponding to G#DE1</td>
</tr>
<tr>
<td>G#DM</td>
<td>Drive mass of #-axis gyro</td>
</tr>
<tr>
<td>G#SM</td>
<td>Sense mass of #-axis gyro</td>
</tr>
<tr>
<td>GZSMA</td>
<td>Sense mass of Z-axis gyro</td>
</tr>
<tr>
<td>GZSMB</td>
<td>Sense mass of Z-axis gyro (redundant connection)</td>
</tr>
<tr>
<td>A#SE1</td>
<td>Sense electrodes for #-axis accel</td>
</tr>
<tr>
<td>A#SE2</td>
<td>Differential sense electrodes corresponding to A#SE1</td>
</tr>
<tr>
<td>A#PM</td>
<td>Proof mass of #-axis accel</td>
</tr>
<tr>
<td>A#DE1</td>
<td>Drive electrode of #-axis accel</td>
</tr>
<tr>
<td>A#DE2</td>
<td>Differential drive electrodes corresponding to A#DE1</td>
</tr>
</tbody>
</table>

Table 4.1: Pin descriptions for DIP-packaged IMU.

the axis that the inertial sensor is intended to measure, with respect to the IMU body. For instance, if the letter is an ‘Z’, the sensor measures along the z-axis in the IMU body frame. In many cases, this letter is substituted with the ‘#’ symbol. This is because there are several pins that are identical in sensor function, but on a different axis. Therefore to minimize the length of the table, the sense axis is generalized. However on the pin diagram in Figure 4.16
each pin is defined independently.

As an example, the third and fourth letters describe the actual sensor feature to which the pin is connected. Sense electrodes and drive electrodes are defined with ‘SE’ and ‘DE’, respectively. Electrostatic tuning electrodes on the gyroscopes are represented by ‘TE’. Also, since the gyroscopes each have a sense mass and a drive mass, these are separately defined with ‘SM’ and ‘DM’, respectively. Because the accelerometers only have one proof mass, this is simply represented as ‘PM’. Finally, the last character is used to define opposing differential electrodes when present in the sensor architecture by using a ‘1’ or a ‘2’ for each side. This character also denotes redundant connections with an ‘A’ or ‘B’, but this only occurs for the z-axis gyroscope sense mass located on the bottom side of the IMU cube. For all other proof masses, there are no redundant connections, and by nature they do not contain differential connections. In these cases, the last character is omitted, such as for AXPM, representing the x-axis accelerometer proof mass.
4.2 Test Structure Accelerometer Analysis

Electrical characterization of the sensors is first performed on devices created separately from the folded MEMS IMU using the in-house SOI fabrication process discussed in Section 2.3.1. Due to the fact that the gyroscopes have been previously tested, the main focus of this section is on the accelerometers that were designed in Phase II of the folded MEMS IMU development process.

Finite element analysis (FEA) is performed and refined to predict the sensor performance prior to fabrication. Both a low-frequency and high-frequency accelerometer have been designed and modeled due to the advantages and disadvantages that each provides. Initially, low-frequency accelerometers were desired for the folded IMU application because of the inherent higher response to static acceleration inputs. However the final iteration of IMU design consists of high-frequency accelerometers because of lower cross-axis sensitivity. However both designs, as well as many others, can be implemented for use in different applications due to the modularity of the fabrication process.

4.2.1 Test Structure Accelerometer Modeling

The accelerometers are analyzed using FEA to predict operational sensor performance. Modeling parameters have been optimized for the devices used for the folded IMU. These parameters are used to analyze an accelerometer similar to those included in the IMU. For comparison, a device has been modeled that has existing experimental results from [8], which provides information about the accuracy of the analysis. Modal frequency results are observed in Figure 4.17, showing an in-plane natural of frequency of 444 Hz compared to the second mode of 1761 Hz. This difference shows that the first mode of vibration is significantly more dominant than the second mode. This will result in lower cross-sensitivity effects at
low frequencies compared to device with similar first and second resonance frequencies.

![Modal analysis of a low-frequency accelerometer showing the first four modes of proof mass resonance.](image)

**Figure 4.17:** Modal analysis of a low-frequency accelerometer showing the first four modes of proof mass resonance.

In addition to the low-frequency accelerometer above, a device with a higher resonant frequency has also been designed. Utilizing a very similar design as for the low-frequency accelerometer, the suspensions are modified to be much stiffer for the high-frequency unit. An FEA model was created for this accelerometer design to determine the modal frequencies, with the results shown in Figure 4.18.

As depicted in Figures 4.18(a) to 4.18(d), the first four modal frequencies are 1.726 kHz, 3.694 kHz, 5.497 kHz, and 6.948 kHz, respectively. The first mode represents the designed sense axis, showing that the majority of accelerometer response will be realized along this axis. Since the other frequencies are at least twice that of the first mode, out-of-plane sensitivities are minimized. The mesh density is increased until no noticeable change is seen in the results to best determine the accuracy of the model. The values obtained converge to
Figure 4.18: Modal analysis of a high-frequency accelerometer showing the first four modes of proof mass resonance.

It is desired to find an accurate model that can be simulated in a reasonable amount of time. Table 4.2 shows the results for all three mesh element sizes as well as the time taken for the simulation. While all values seem to differ by very little, it can be noticed that the 25 µm element size is the best choice when considering the simulation time.

Modeling of each type of accelerometer was performed to determine the in-plane and out-of-plane modal frequencies. As expected, the high-frequency device provides a larger separation of each frequency, which indicates that it is better for rejecting cross-axis sensitivity. However the low-frequency device is capable of detecting acceleration with a higher resolution. This trade-off in design indicates that the folded MEMS IMU should be specifically designed for the application in which it is implemented. Due to the modularity of
Table 4.2: Modeling results of accelerometer modal frequencies for the high-frequency design used on the folded MEMS IMU devices.

The fabrication process, substitution of devices is possible by using a different sensor mask design. Therefore a range of different types of accelerometers can be designed and tailored to the specific end-use application.

### 4.3 Folded IMU Sensor Characterization

Initial characterization of the IMU sensors is conducted by using test structures on foldable MEMS IMU structures prior to packaging. Devices characterized in this section have been successfully fabricated with the folded IMU fabrication process. Testing of the individual sensors on the IMU devices is necessary to determine quality of operation before adhering the sensor lids and assembling the entire unit. From samples that were fabricated, several intact sensors on sidewalls have been successfully released from the SOI substrate, allowing for initial characterization.

#### 4.3.1 Characterization of Accelerometer Test Structures

Design of the accelerometer consists of parallel plate sense electrodes, electrostatic comb drives, and a proof mass suspended by folded springs attached to anchors. An SEM image of the test structure, designed as an accelerometer, is shown in Figure 4.19. Resonant
detection is utilized to detect the acceleration input. This method offers advantages such as high dynamic range, quasi-digital output \([49, 51]\), and resilience to parasitic capacitance noise.

Figure 4.19: SEM image of a MEMS accelerometer test structure fabricated on a pyramidal IMU sidewall.

Accelerometer performance results are determined using a tilt stage by measuring response to gravity at pre-defined angles. The proof mass of the accelerometer is excited at a resonant frequency of 1.1 kHz using a combination of DC and AC voltage applied to the anchored drive-mode electrodes. A variable DC tuning voltage is applied to one of the opposing banks of parallel-plate sense electrodes to provide an initial displacement of the proof mass. This modifies the original capacitive gap, and thus the overall sensitivity is changed \([15, 51]\). A carrier signal is applied to the proof mass to allow for frequency modulation detection using a lock-in amplifier, Figure 4.20. The carrier frequency utilized is at 52 kHz, which is much greater than the operational frequency of the accelerometer and thus has negligible effects on the proof mass motion. The sensor output signal is amplified using a Trans-Impedance Amplifier (TIA), followed by demodulation of the carrier frequency. Vertical angles are applied in increments of five degrees to induce acceleration ranging from 0-1 g. At each position, the resonant frequency is measured to determine its shift caused by the input acceleration, with the results plotted in Figure 4.21. Using a DC bias voltage of 20 V applied to the tuning electrodes, the sensitivity is determined to be 1.8 Hz/g. When 30 V bias is used,
the scale factor is increased to 3.7 Hz/g. Therefore the scale factor can easily be modified for different performance characteristics based the application requirements. Additionally, the tuning voltage can be changed during operation, allowing for real-time adjustments to the sensor scale factor if necessary.

Figure 4.21: Measured resonant acceleration response of an accelerometer fabricated on a pyramidal IMU sidewall, using tuning voltages of 20 V and 30 V.

Inset: Photograph of an accelerometer on a pyramidal IMU sidewall.
4.3.2 Characterization of Gyroscope Test Structures

Architecture of the gyroscope consists of differential drive and sense electrodes and a large 2-DOF proof mass supported with folded suspension beams [45, 46]. A single gyroscope sense mass is driven using parallel plate actuation along the x-axis, and the inertial rotation rate is detected from differential sense electrodes on the y-axis. The frequency response of which can be seen in Figure 4.22 showing a resonant frequency of 8.55kHz. Notably, the phase response ranges from +200° to -200°. This implies that the vibration of the proof mass experiences two separate natural frequency regions, which is intuitive for a system with two degrees of freedom. This is not obvious from the magnitude response shown in Figure 4.22, however it is clearly shown in the phase response.

![Frequency response of a gyroscope test structure on a pyramidal IMU sidewall.](image)

Figure 4.22: Frequency response of a gyroscope test structure on a pyramidal IMU sidewall.

The characterization method is modified to show two clear resonant peaks by changing the parameters on the electrical equipment used to detect the signal. For this experiment, the signal is detected with a lock-in amplifier by sending a carrier frequency of 80 kHz across the proof mass at a peak-to-peak voltage of 10 VAC. However, Figure 4.22 shows a drop in magnitude near the resonant frequency that represents a possible anti-resonant peak. Therefore the second resonant peak, which is expected to closely match the first peak, may
be diminished by the anti-resonant response making it difficult to detect.

In addition to frequency response detection, the power spectrum was analyzed using a fast Fourier transform (FFT). This information shows detection of movement by depicting a peak at the natural frequency of the device. There is also a large peak at the carrier frequency, with sideband peaks occurring on either side. These sidebands are approximately the same distance away from the carrier frequency peak on either side by the amount of the natural frequency of the gyroscope (8.55kHz). The overall spectrum can be seen in Figure 4.23, where the natural frequency of the device can be seen along with the carrier frequency and resulting sidebands.

The existence of these sidebands show that the natural frequency of the gyroscope is suc-
cessfully being modulated with the carrier frequency. Because the sidebands are detectable, it is determined that the gyroscope is likely to produce a response to inertial rotation rate inputs. A closer view of the sidebands can be seen in Figure 4.24, where it is seen that the sidebands are located approximately 8.5 kHz away from the carrier frequency on either side, as expected. Additionally, the power spectrum is analyzed with the gyroscope actuation turned off to ensure that the sidebands are not being produced by an outside electronic source. In this case, the sidebands disappear, proving that the they are being generated by the gyroscope itself and not from environmental interference or other possible sources.

Angular rate performance of a gyroscope fabricated on an IMU pyramid sidewall is experimentally characterized in ambient air. Rotation rate response is then tested by mounting the structure to a computer-controlled Ideal Aerosmith 1291BR rate table. The drive mode of the gyroscope is excited into resonance at 1.6 kHz using a combination of 30 VDC bias voltage and a 5 VAC driving signal applied to the drive-mode electrodes. Separation of the useful signal from the feed-through signal is accomplished using Electromechanical Amplitude Modulation (EAM), where a carrier voltage of 3.5 Vrms at 52 kHz is applied to the

Figure 4.25: Drive and detection schematic for gyroscope characterization.
Figure 4.26: Measured rate response of a gyroscope fabricated on a pyramidal IMU sidewall.

Inset: Photograph of a pyramidal IMU sidewall fabricated with a gyroscope.

proof mass, resulting in the amplitude modulation of the motional signal. The schematic for this type of detection is shown in Figure 4.25. Two demodulations, first at the carrier frequency and then at the drive frequency, are used to extract the motional signal from the measured EAM signal \[52\]. Figure 4.26 shows the detected rate response of the gyroscope \[53\] fabricated with a scale factor of 0.43 mV/(deg/sec) over an input range of ±250 deg/s, confirming successful implementation of the folded MEMS IMU approach and the fabrication sequence described in Chapter 2.

4.4 Fully Packaged IMU

A challenge with the flip-chip packaging process used for the IMU devices is confirmation of electrical connections beneath the interconnect lids and plates. Because the bond pads are not directly accessible, it is difficult to determine if all connections are successfully made after flip-chip packaging. Silver-filled conductive epoxy is used to create the connections from the sensor to the lids, as well as the lid to the IMU backbone, as discussed in Section 4.1.4.
Some connections can be visually verified using a microscope, however others are not obvious and must be tested electrically.

One method to determine connectivity is done by observing the signal feed through strength from the lock-in amplifier output for various connections. Essentially, the lock-in amplifier functions as a capacitance measurement device. This provides information of the capacitance of each sensor feature with respect to the proof mass, and the results of the detected ‘%R’ magnitude output from the lock-in amplifier is shown in Table 4.3. Sensor elements that are successfully connected (i.e. the proof mass and drive electrodes) will have a higher capacitance compared to those that are not. This is largely due to the fact that the additional capacitance of the sensor elements is much larger than that of a disconnected bond pad. Measured by the lock-in amplifier, the ‘%R’ magnitude represents a voltage proportional to capacitance, and is therefore used to investigate the connectivity status of individual bond pads.

Results shown in Table 4.3 are all referenced to the drive-mode proof mass output pin (GZDM), which has been visually verified to be connected. Additionally, the drive mass of the gyroscope contains four redundant connections, comprised of one sensor anchor at each corner, all of which mate to bond pads on the interconnect lid. Compared to other sensor elements that contain one or two anchors, this provides a greater statistical probability that the proof mass is successfully connected. As a reference for a non-connected terminal, capacitance between the drive mass of the y-axis gyroscope, on output pin GYDM, and the drive mass of the bottom (z-axis) gyroscope was measured. Because these are designed to be on separate sidewalls, it is not possible for them to be connected, and thus acts as a control for other measurements to determine which sensor elements are connected as well as those that are not.

A strong feed-through signal of the carrier frequency is observed for the connections from pin GZDM to GZDE1, GZTE1, and GZSE2. (GZDE1 is the drive electrode bank
Table 4.3: Electrical continuity detection of IMU cube sensor features using a lock-in amplifier to measure capacitance of the z-axis gyroscope connections.

#1, GZTE1 is the tuning electrode bank #1, and GZSE2 is the sense electrode bank #2.) This either indicates that the connections have been successfully made, or depicts a short circuit connection between the proof mass and respective sensor elements. For this reason, resistance testing was also conducted to detect any shorts or open connections, represented in Table 4.4.

Table 4.4: Resistance measurement between the z-axis gyroscope drive mass and other sensor components.

Results indicate a resistance of 615 Ω for pin GZDE1, and 3.4 MΩ for pin GZSE2 (sense electrode bank #2). The low resistance between GZDE1 and GZDM was predicted due to a fabrication flaw on this particular sensor. During the packaging process, the conductive
epoxy on one of this particular feature’s bonds pad overflowed onto the drive comb structure. However this does confirm that both GZDM and GZDE1 are successfully connected to the sensor throughout the entire package, indicating feasibility of the flip-chip packaging method with conductive epoxy. Resistance across the drive mass to GZDE1 is also measured and appears to be very high, but this was expected to be an open circuit with infinite resistance. These results show that there is some connectivity observed, but is considered to be caused by a large particle, observed microscopically after testing, which is partially shorting the two sensor elements together.

Certain sensor elements are designed to be electrically connected via silicon suspensions. For instance, the sense mass and drive mass of the gyroscope is mechanically connected using silicon, and therefore should have a low-resistance connection. However continuity tests between GZSMA, GZSMB (sense mass anchor #1 and #2, respectively) and GZDM is shown to be an open circuit. Therefore it is determined that one or both anchors are not successfully connected to the interconnect plate. A summary of the capacitive and resistive testing on the current IMU cube is shown in Table 4.5. Although the procedure yields information about all connections tested, some still cannot be ultimately determined.

<table>
<thead>
<tr>
<th>Connected</th>
<th>GZDM, GZDE1, GZSE2, GZTE1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not Connected</td>
<td>GZSMA, GZSMB</td>
</tr>
<tr>
<td>Unsure</td>
<td>GZDE2, GZTE2, GZSE1</td>
</tr>
</tbody>
</table>

Table 4.5: Results of electrical connectivity testing.

After examining which terminals have been successfully connected during the packaging process, characterization of individual sensors is performed. In previous tests, the DC bias voltage applied was 20 V, and the gyroscope drive mass indicated a response at 2.60 kHz. A higher DC voltage has been used for these experiments to increase the magnitude of deflection of the proof mass. This enables a larger response signal and thus is easier to detect a frequency response. However the trade-off is a modified resonant frequency occurring due to a decrease in the effective suspension stiffness induced by a larger DC voltage that inevitably
changes the frequency of resonance during operation. A frequency response measurement of the drive mass is obtained using 40 VDC added to the 2.0 VAC carrier signal, with the results shown in Figure 4.27. As predicted, the frequency response represents a curve more indicative of testing in air, and the resonant frequency is observed to be 2.43 kHz. A weak response is noticed from the analysis from the drive mass connection, likely due to the device being tested at ambient pressure. However it is determined that the fabrication, packaging, and testing processes in this work are feasible for manufacturing operational folded MEMS IMU devices.

![Figure 4.27](image)

Figure 4.27: Frequency response of the drive mass on a gyroscope on the bottom of a folded MEMS IMU cube, indicating that the entire fabrication process is capable of successfully creating operational IMU devices.

![Figure 4.28](image)

Figure 4.28: Sense mass frequency response of the same gyroscope a resonant peak at 4.38 kHz.
Similar to the drive mass, the sense mass of the bottom gyroscope is also characterized. A peak at 4.381 kHz is observed in all ranges of frequency sweeps, and is predicted to be the out-of-plane mode of the sensor. While peaks are not observed at lower frequencies (indicative of in-plane modes), the experiments show that the sense mass is electrostatically responding. A plot of the frequency response is shown in Figure 4.28 depicting a response peak at 4.381 kHz. Although the frequency response is not ideal compared to sensors tested independently, it does depict that the device is active. Possible reasons for poor detection is the resistance of long electrical traces, low resistivity of conductive epoxy connections, and parasitic capacitance induced by packaging lids. These results support that the approach for creating IMU devices presented in this work are capable of producing an operational unit.

4.5 Conclusion

Fabrication of samples capable for packaging have been created for Phase I and Phase II developments of this work. However, both the individual sensors and the entire IMU must be packaged in order to characterize the entire device. Multiple packaging methods have been explored for the folded MEMS IMU structures. One method is to conduct flip-chip attachment of interconnect lids on top of each sensor. The lids also provide environmental protection from the environment. Additionally, a similar type of approach can be utilized to provide vacuum packaging of all sensors, which will significantly improve performance. Packaging with solder spheres proved to be an acceptable method as well. Using this method, lids are attached using solder flux, and then the substrate of the IMU is heated to the melting point of the solder. Both types of packaging processes have yielded successful results after the fabrication and packaging processes are completed.

Initially in Phase I, the fabrication process was capable of a minimum of 8 µm sensor feature resolution. This process was able to produce positive results, as shown in Figures.
and [126]. However, higher performance is possible by decreasing the resolution of sensor features manufactured with the Phase II fabrication process. Both processes have resulted in sensor responses after fabrication and packaging.

Packaging of the assembled structure requires an interconnect plate capable of integration into prototype signal detection electronics. Once the entire device is packaged using flip-chip packaging methods for all sensors, the entire assembly is mounted into a DIP package. Wire bonds are made from the interconnect plate bond pads to the connections on the DIP package. This allows for simple integration into a prototype circuitry integrated with signal detection electronics. Capacitive detection of each connection using a lock-in amplifier shows that multiple connections have been successfully created. Continuity testing was also performed, and it was determined that the majority of the connections are isolated. Overall, the flip-chip interconnect lid bonding process was successful for approximately 50% of the connections attempted. With further process refinement, it is feasible that this packaging process is suitable for the folded MEMS IMU devices.

With current sensor designs, the performance is much better when using resonant detection methods as opposed to capacitive detection. A main advantage of this type of detection is that the effects of ambient temperature changes are eliminated. A gyroscope was tested which shows to be fully operational, and is highly likely to be capable of rotation rate detection. After assembling the packaging lids and bottom interconnect plate, results indicate that sensors are responding at the expected resonant frequency. However the frequency response depicts an issue with the packaging process. Although the interconnect plate and packaging lids are successfully connected, the magnitude of gyroscope response of the gyroscope is not as large as expected from independent measurements. This result indicates that the packaging process must be improved to enable fabrication of a high-performance folded MEMS IMU for consumer applications. However, the overall process proves to be a feasible method for creating an operational chip-scale IMU device.
Chapter 5

Structural Reinforcement of IMU Assemblies

A general challenge in manufacturing inertial measurement units is maintaining rigid alignment of each sensor after fabrication and assembly \[55\text{–}57\]. Small displacements of sensors cause signal bias and drift errors, resulting in incorrect outputs. For this reason the overall structure of any IMU must be very rigid at all times to avoid having to regularly recalibrate the device. Structural reinforcement thus far on the folded IMU structures has been done with general-use epoxy. For light application loads, this is an adequate technique. However, to allow for a wider variety of uses for the IMU device, more robust methods have been explored to enhance the rigidity. The ideal method is to use silicon-to-silicon welding to fuse the sidewall edges, creating a pure silicon bond between each sidewall.
5.1 Methods of Reinforcement

Several options are available for solidifying the folded MEMS IMU structures, such as epoxy bonding, soldering the latching areas, and silicon welding. These methods involve significant trade-offs between difficulty and resulting performance. For instance, epoxy bonding is simple and quick to perform, however provides the least amount of structural rigidity. Conversely, silicon welding is the most difficult, but if successful, will create extremely rigid IMU devices. As a compromising medium, eutectic solder can be applied to the latches and reflowed at fairly low temperatures to enable metal reinforcement of the structure. This provides a significant improvement in rigidity compared to epoxy. However due to thermal expansion concerns, using different materials from that of the substrate will cause a variance in thermal properties. All of the mentioned rigidity reinforcement materials have been explored, beginning with epoxy bonding, eutectic solder bonding, as well as silicon welding of the folded IMU latches.

Once the folded MEMS IMU structures have been manufactured, the initial structural reinforcement method is to use epoxy applied to all eight corners and the vertical latching locations. This provides sufficient rigidity enhancement compared to using only the silicon latches themselves. Application of the epoxy is done after the IMU devices are assembled by using a fine-tip applicator to place dots of adhesive on all eight corners. Additionally, the epoxy is deposited along the exposed latching sidewall edges, excluding the bottom edges to prevent adhering the structure to the platform used during epoxy deposition. After packaging, the bottom sidewall is adhered to either an interconnect plate or PCB, and therefore is not required for reinforced. Using the same two-part general epoxy for reinforcement of the packaging lids described in Section 4.1.4, the cubic IMU structures are structurally reinforced. First the epoxy mixture is created using equal parts of the adhesive and catalyst. Before the epoxy mixture cures, it is applied to the IMU corners and latches and allowed to dry for approximately 10 minutes. This allows for a full-cure of the epoxy, which secures
the initial position of the sidewalls after assembly. While this enables adequate rigidity for low-level applications, a more robust method for structural reinforcement is desired using other materials.

Eutectic soldering is also explored as an improved method for structural reinforcement compared to epoxy bonding. However, solder does not wet directly to elemental silicon. Therefore, a folded MEMS silicon structure sample was assembled and gold was deposited on the latches to explore the capabilities of eutectic solder reinforcement. Solder paste was then applied onto the gold-plated latches, at which point the entire structure was heated to above 183°C, the melting point of the solder paste. The results are shown in Figure 5.1.

![Figure 5.1: Eutectic soldering reinforcement process of an assembled pyramidal IMU structure.](image)

The solder paste applied is successfully melted onto the latches, wetting the areas covered by gold. This shows that the process is feasible for providing added rigidity of the IMU structures. It is known that long-term rigidity and thermal properties are more consistent with silicon than a combination of metal materials [33]. Therefore, it is hypothesized that for the purposes of creating an extremely rigid IMU platform, silicon is the preferred bonding material. For this reason, welding of the latches is explored using laser heating and resistive heating.
5.2 Silicon Welding Exploration

Performance of an IMU directly depends on the rigidity of the overall supporting structure. Inertial sensors mounted to a structure with low rigidity will result in measurement of the deflections of the structure itself. Therefore, the minimum resolution and bandwidth of the IMU is limited not only by the performance of the sensors, but by the structural integrity of the entire system. For this reason, methods for maximizing the stiffness of the folded IMUs have been explored. Although epoxy bonding and eutectic soldering have proven to be a feasible reinforcement method, both involve addition of a foreign material. However, welded folded IMU devices are comprised primarily of silicon, which has similar thermal properties compared to the overall structure. This minimizes misalignment and signal errors experienced due to temperature fluctuations. Welding of silicon is therefore explored using both resistive heating and laser techniques to explore this possibility.

Like other materials, silicon can be welded with resistive heating using electric current, discussed in Section 5.3, or by laser heating, discussed in Section 5.4. Welding of various materials is a highly researched field usually pertaining to metals and their respective alloys. However in the MEMS field, semiconductors are often used to create devices and structures. For this work, it is desired to permanently fuse bulk silicon features to each other. For bulk silicon, the voltage and power necessary for resistive welding are very large due to the potentially high resistivity of silicon such as in the handle layers of the SOI wafers used for this work. Likewise, laser welding of bulk silicon requires a large amount of optical power of approximately 12-25 Watts. Due to the high power required for both methods, welding of silicon is quite challenging. However each method is explored to determine the optimal technique for the folded MEMS IMU structures.

A high-power laser is required to heat the welding area to a temperature above the 1414 °C melting point of silicon. Therefore, a 23 W copper vapor laser (CVL) is used which
emits wavelengths of 510.6 nm and 578.2 nm at a pulse rate of 10 kHz. Silicon absorbs approximately 65% of the light at these wavelengths for a net weld power of 15 W. These results indicate that laser welding of silicon is feasible, if exposed for the required duration of time to melt the individual latches. As an alternative, resistive welding of silicon is also explored. However no quantitative results were arrived - only qualitative results are shown to be successful. Refer to Section 5.3.3 for details on the resistive welding apparatus and results.

Previous exploration of silicon-to-silicon welding has been done, however has only been demonstrated on a small scale (50 µm and lower). One example of extremely small scale welding has been demonstrated in nanowires using an electrochemical technique [58]. This approach uses lithium ions with are induced and then extracted from the nanowires, which creates a high-strength bond. Additionally, this is used for self-healing of broken nanowires for use in lithium ion batteries. In a similar application, a high-intensity electron can be used to weld nanowires of various materials together, including silicon [59]. Although both of these techniques have shown to be successful, they are not feasible for welding bulk pieces of silicon, such as the latches on the folded MEMS IMU structures.

Larger scale welding has been done to fuse borosilicate glass and silicon. One method utilizes a 1558 nm wavelength laser to weld 100 µm diameter spots in the internal layer of a glass and silicon wafer stack [60]. Even though this method is capable of also welding silicon-to-silicon, it is difficult because a transparent material is required on the top of the stack to focus the laser. A similar method that also provides glass-to-silicon welds at the internal wafer boundaries has also been done with a 1045 nm optical source [61]. Both methods provide larger scale welding than that of nanowires, but still is on the order of approximately 100 µm in weld area. These techniques, and others that are similar, require a transparent substrate above the welding area, and thus is not compatible with the folded IMU devices.
The most relevant prior art related to this topic involves welding portions of SOI devices to permanently fuse sensor features [62]. In this work, inertial sensors features very similar to the devices on the folded MEMS IMU devices have been welded together using resistive heating. However the devices used for this purpose consist of very low-resistivity silicon (approximately 0.001 - 0.003 $\Omega$-cm). The bulk silicon substrate of the folded IMUs generally is constructed of high-resistivity silicon, greater than 1000 $\Omega$-cm. Additionally, the device layer for the devices being welded was only 50 $\mu$m in thickness. The latches on the folded IMU cubes and pyramids are created from the entire 500 $\mu$m thickness of the wafer, and are approximately 200 $\mu$m wide. For each method discussed, only spot welding has been performed rather than linear seams. Therefore a new technique must be developed for welding the sidewall latches to create a silicon IMU with a very rigid inertial sensor platform.

5.3 Resistive Silicon Welding

Previous work regarding silicon welding have included both resistive and laser heating methods. For the folded MEMS IMU fabrication process, resistive welding is preferred because it is likely that it can be directly integrated into the fabrication process. Therefore, resistive welding is explored using fabricated IMU sidewalls created of pure silicon (not SOI substrates). This section describes the development process of resistive welding, beginning with modeling, followed by manufacturing an appropriate power supply, and concluding with welding results of the fabricated silicon samples.

5.3.1 Modeling

Simulations of resistive and laser silicon welding using FEA have been performed using a model with ideal thermal and electrical contact at the boundary between a single pair of
latches. However, in reality the surface will not be perfectly flat, and will produce a non-ideal contact area. For this reason, additional simulations were performed with a modified interface between each individual latch. Non-ideal contact between latches is caused by several issues, however the main problematic parameters have been identified as follows:

- Etching imperfections
- Misalignment at welding area
- Thin layer of silicon dioxide at interface created while etching

Of the three items mentioned, the etching imperfections are believed to be the largest cause of creating a non-ideal contact interface. This is largely due to the DRIE process which creates scallops on the vertical surfaces of etched silicon. The scallops are produced because during the DRIE process, iterations of etching and passivating are done to create a semi-vertical etch. Therefore the vertical surfaces of silicon are not perfectly flat, and the contact area between the latches for welding is reduced. Rather than modeling the actual dimensions of the scallops which includes small curves and sharp edges, a set of grooves is instead created at the interface. This simplifies the analysis by reducing the required mesh density at the weld area while also inducing a non-ideal contact between latches. Each groove is 50 µm in width and 20 µm in depth, resulting in contact area of half that of the ideal contact interface. Using COMSOL FEA software, simulations are combined to simulate resistive heating effects as electrical current flows through the latches. Modeling is done using a mesh with 9,017 elements and 31,730 degrees of freedom. Current is applied by setting one of the outer-most boundaries at 1.0 V of potential and the other at ground. A transient analysis is conducted up to 1.5 seconds with decreasing time steps from 0.1 - 0.01 s to determine the necessary weld time to successfully bring the latches up to the melting temperature of silicon.
Results indicate that the maximum temperature is 1419°C after an exposure time of 1.35 seconds, shown in Figure 5.2, which is just above the 1414°C melting point of silicon. A minimum temperature of 1402°C is experienced at the outer boundaries of the modeled sample. These results do not significantly differ from the ideal contact boundary model where the maximum and minimum temperature of 1424°C and 1408°C, respectively. Exposure time required for the a model with ideal contact between latches was 1.2 seconds, which is lower than that of the non-ideal model, but is not significant. Therefore, it is determined that the contact area between latches will not drastically effect resistive welding results.

![Figure 5.2: Resistive welding analysis of a single pair of latches with non-ideal contact.](image)

Current density analysis is also performed to determine the required electrical energy to weld individual latches. Additionally, this also functions as an analysis method to ensure the simulation is providing accurate values. Results of the simulation, shown in Figure 5.3, indicate that the largest amount of current passes through the corner contact area nearest to each amount of bulk silicon. Although this result is inherently expected, it shows that the simulation is conducted properly because the maximum temperature also exists at the same location. Analyzing the boundaries at which 1.0 V of potential is applied, it is calculated that 2 A of current is required to perform welding over a period of 1.35 seconds.

Comparing the results from laser and resistive silicon welding simulations, it is determined that the difference between the two is negligible. Because resistive welding can be accom-
plished in a simpler manner than laser welding by applying current through the contact area, this method is further explored. Due to limited power capabilities of most DC voltage supplies, a capacitive discharge current supply has been designed, with the electronic circuit shown in Figure 5.4.

Using this configuration, voltage is applied through a mechanical switch to charge a bank of four 25 mF capacitors for a total of 100 mF capacitive capability. With all capacitors involved, a current pulse of 2.8 A for a duration of 2.6 s can be achieved, Figure 5.5. From the circuit simulation results, this is suitable for resistive bulk silicon welding. Current is controlled by the voltage applied to the power transistor gate. Also, by varying the amount of capacitance using a selector switch will provide a user option of applying incrementally larger amounts of electrical energy through the weld. For initial testing purposes, the designed circuit will be built and experimental welding will be performed on pure silicon samples.

5.3.2 Power Supply Manufacturing

As described above, resistive welding is a better choice for final integration, and therefore is explored for the purpose of folded MEMS IMU structural rigidity enhancement. Modeling
Figure 5.4: Electronic circuit design for capacitive welding of silicon latches to enable bulk welding of the folded MEMS IMU structures.

Figure 5.5: Current and voltage results obtained from the circuit simulation showing a theoretical current pulse of 2.8 A for 2.6 seconds.

has been done showing that for the folded MEMS IMU latch geometry, resistive welding can be done in approximately one second with the appropriate power source. Depending
on the resistivity of the silicon substrate, a different amount of current must be applied to successfully create the weld (range of 2-35 A). Because of these voltage and current requirements, exploration of silicon welding using joule heating must be done using a power supply capable of providing sufficient power. This power supply should also be adjustable so that it is suitable for welding silicon of various resistivity values.

Figure 5.6: Power supply model and terminal block layout for back panel component wiring.

Using a charged bank of capacitors and a control circuit, such a power supply has been designed. A modeled layout of the unit is shown in Figure 5.6. With the circuit designs and proper components, this power supply will allow for an output pulse time from 0-5 seconds, current output of 0-10 A, and a variable welding voltage up to 120 VDC. Further development has been conducted to manufacture the designed power supply. An enclosure must be implemented for mounting of internal components, which involves attaching parts to the back and front panels of the enclosure. Terminal blocks and wireway are both to be mounted to the back panel using screws and tapped holes in the back panel of the enclosure. Machining the back panel using a CNC mill was done to create the tapped holes in precisely defined locations.

After machining of the back panel was complete, it was cleaned and deburred to prepare
for assembly. Using screws with an 8-32 thread size, wireway and terminal blocks were mounted to the panel. Final design plans include four 12 mF capacitors, a high-power 200 Ω resistor, and a high-power transistor. This provides a total of 48 mF of capacitance to allow for a high-current output pulse that lasts for several seconds to allow for welding of bulk silicon.

Manufacturing of the front panel of the enclosure was performed in a similar manner, involving CNC machining and component assembly. Results of machining the front panel of the enclosure were successful. Holes for the LED indicators, switches, knobs, and control PCB mounts were created. Sharp edges were deburred, all debris removed, and the enclosure was prepared for front panel assembly.

A traditional 555 timer is used in a monostable mode to create the output pulse signal for welding. By connecting one of the variable resistor knobs from the front panel, the output pulse time can be varied from 0-5 seconds. Another control knob on the front panel provides control over the amount of current transferred through the weld joint by the high power transistor. All of the comparator circuits consist of LM311 comparator ICs that activate LEDs based on various states of the power supply. Such states indicated are as follows:

- Fully charged
- 50% charged
- Charging
- Discharging
- Discharged
- Welding

All ICs, resistors, capacitors, and internal wires were assembled and soldered onto a
prototype circuit board as per the electrical schematic design, Figure 5.7. Interfacing the PCB with the overall power supply requires connection through the terminal blocks. Inputs and outputs required for the PCB include supply power, capacitor voltage, front panel potentiometer connections, the weld activation switch and the output current pulse to the high power transistor for welding.

![Figure 5.7: All components assembled onto the PCB showing the I/O terminal block connection configuration.](image)

Including the switches, knobs, and PCB with LEDs, the front panel was populated with components. The assembled PCB was mounted such that the LEDs protrude through the front of the enclosure. Mounting of the LEDs to the PCB was done on the backside, using the machined front panel as a jig. Soldering of the LEDs was performed while resting in the front panel holes, eliminating potential issues with assembly alignment.

After mounting components to the back and front panels of the power supply, further manufacturing was conducted to complete the unit. Capacitors were mounted rigidly to the sidewalls of the enclosure using Velcro™ and metal mounting strap material. To mount the straps, aluminum standoffs with a height of 1.5 inches and 1/4”-20 female threads were installed onto the sidewalls of the enclosure. A thin strip of sheet metal strap was then cut and shaped to match the form-factor of each capacitor and mounting standoffs. Additional support for each capacitor was provided by Velcro™ material applied underneath, on the back panel. The purpose of this is to prevent the capacitors from shifting in the event that
the metal mounts loosen due to long-term fatigue.

Wiring of the overall power supply was performed after installation of the capacitors, PCB, switches, terminal blocks, and wireway. All input and outputs to the PCB were wired to the front panel and back panel components. Due to the size of the PCB terminals, 22 gage wire was used for all PCB connections. High power internal wiring was done with 16 gage wire to allow for large short-term current applications. Figure 5.8 shows the internal assembly of the resistive welding power supply after manufacturing is complete.

![Power supply with the cover open showing internal components such as capacitors, switches, PCB, and wiring.](image)

All wiring that could potentially experience high-voltage and high-current electrical power are yellow in color to advise caution to anyone performing maintenance on the unit. However, the entire unit should be discharged using the front panel switches prior to opening the internal components of the power supply. Green wiring indicates the grounded terminals of each component, and red indicates a positive 15 Volts for PCB power. Black wires used for the PCB inputs indicate grounds for the PCB, which is internally coupled with the high voltage ground, which is green in color. Other colors such as white, blue, and brown indicate internal signals for low-voltage connections to the PCB.
During operation, the power supply cover must be securely closed for safety reasons. Therefore, input and output terminals are required for external voltage sources, welding contacts, as well as a 10 A fuse. Patch cables with banana plug end terminations and a 12 gage width are used for all external inputs and outputs. Shown in Figure 5.9 is the bottom side of the welding power supply with proper patch cables attached. One of the welding cables in the figure is not attached, however this was done to conduct functional testing without performing high-current operations.

![Figure 5.9: Bottom side of power supply showing input and output power terminals and a 10 Amp fuse connection.](image)

Testing the overall operation of the power supply was conducted after successfully installing all internal components and wiring. Initially, the PCB power was applied to test the operation of the LED indicators on the front panel. Individual testing of LED’s proved to be successful. Shown in Figure 5.10 is the power supply indicator lights after the capacitors are fully charged. Note that the “50% Charged” and “Fully Charged” indicator lights are lit. The “Charging” light is off which indicates that current is no longer being absorbed by the capacitors.

High-power operational testing of the welding power supply was performed by attaching a 16 Ω load capable of dissipating 4 Watts continuously. Welding current is passed through the load by pressing the “Weld” button, thus applying voltage to the gate of the high-power MOSFET to pull current through the load. Proper functionality was determined
Figure 5.10: Operational test showing the unit is fully charged as indicated by the LED’s on the front panel.

by observing the indicator lights on the front panel, noting that the “Fully Charged” light quickly turns off, and the “50% Charged” light turns off after a short time longer. This indicates that the capacitors are discharging through the load and the indicator lights are functioning properly. Figure 5.11 shows a snapshot of the LED indicators immediately after pressing the weld button. The photo was taken after the “Fully Charged” indicator light had turned off, but prior to the “50% Charged” turning off. These tests, accompanied by other
more tedious and repetitive testing, shows that the power supply is functioning properly in all aspects of design.

5.3.3 Experimental Research

Due to the small size of the weld compared to the entire piece of silicon, handling of the samples after welding is challenging. Samples are easily broken while removing them from the setup. Clamps have been designed to firmly hold the samples in place during the experiments, as well as to provide a simple method for removal without destroying the samples, Figure 5.12(a). Consisting of two plastic parts to create the upper and lower parts of each clamp, the overall design offers a significant advantages. Three screws are included in the design: one for clamping the silicon samples, another for fastening the rear of the top and bottom clamps together, and the third for mounting the entire clamp to a manipulator stage, Figure 5.12(b). Two strips of metal foil are included in between the two clamps to provide a low-resistance connection to the silicon sample, allowing for use in resistive welding experiments. The clamps can also be removed from the mounting stage with the sample firmly held in place for analysis after welding.

![Image of custom welding clamp](image)

(a) Assembled clamp
(b) Exploded view

Figure 5.12: Conceptual design of a custom welding clamp to be used for resistive and laser welding experiments.

Fabrication of the clamps was done using fused deposition modeling (FDM), a method of
rapid prototyping. Although this process is not capable of high precision, it is suitable for creating the bulk of the clamp components. The only features that cannot be produced with FDM are the 6-32 tapped holes in the bottom piece. However most rapid prototyping techniques are also not capable of accurately manufacturing screw threads, so post-fabrication machining is inevitably required.

After completing fabrication of the plastic clamp components, metal strips were added in between the clamps to provide electrical connection to the silicon samples for resistive welding. Using heavy gage stainless steel foil, strips were first cut to the approximate size of the clamp. Epoxy was used to adhere the strips to the surfaces of the clamps. Once the epoxy is cured and all excess metal foil is removed has been removed, manufacturing of the clamp components is finished, shown in Figure 5.13.

![Figure 5.13: Fabricated welding clamp components with screw threads tapped on the bottom piece and heavy gage metal foil adhered to both parts.](image)

The clamps are then assembled together using the screws, shown in Figure 5.14. In the middle, the large hole allows access to a screw for mounting the assembled clamp to a positioning stage. The screw on the rear of the clamp not only fastens the top and bottom together, but will also function as the electrical connection point for resistive welding. The third screw, on the front of the clamp, is the mechanism used to apply holding pressure to the welding samples. As it can be seen in the figure, the clamp is capable of firmly holding a piece of silicon in the jaws.
Figure 5.14: Assembled silicon welding clamp with a silicon IMU sidewall mounted in the front between the two clamping jaws.

Utilizing the clamps in the resistive welding setup, two samples are mounted such that the hinge fingers are in contact. A 5-DOF manipulator stage is used to position one silicon sample while the other is fixed. The welding electrodes provided by the output welding terminals of the power supply are connected to the clamps. The positive connection is applied to one sample, and the negative connection is applied to the other. Using a charge of approximately 80 V on the power supply capacitors, a pulse of electrical current is applied to the weld joint for one second. As shown in Figure 5.15, the two hinge fingers in contact are welded together. This is determined by observing the melted material on the touching hinge fingers. Although the welded area seems to be mostly on the top surface of the substrates, the missing material from the hinge finger on the right indicates that silicon from this portion was absorbed into the weld joint.

After the welding experiment was conducted, an attempt to remove the samples from the clamps was performed. However, due to the mechanical play in the setup, all welded samples were broken. While this is disadvantageous for quantitative testing, the sample still provides positive results. After breakage occurred upon removal, it is obvious from Figure 5.16 that a portion of one panel is still fused to the other. This indicates that the strength provided by the resistive welding process is similar to that of the elemental silicon material. Therefore it is concluded that bulk silicon features have successfully welded together. This result
5.4 Laser Welding

Although welding of bulk silicon has been proven to be successful with resistive heating, it may be difficult to achieve on assembled folded IMU devices. For instance, the power required for welding needs to transmitted through heavy-duty electrical connections. This is difficult to achieve on latches that are only 200 µm in width. Another concern is that with resistive welding, the FEA simulations show that heat is spread to areas that would
inevitably contain polyimide and metal features. For these reasons, laser welding is also explored which would provide a non-physical welding interface, and possibly more localized heating. Due to the high melting point of silicon, a high power laser must be used to reach the appropriate temperature. Additionally, it is important to choose a wavelength that is mostly absorbed by silicon. For this purpose, a copper vapor laser is used which emits wavelengths of 510.6 nm and 578.2 nm with a pulse rate of 10 kHz. The particular laser used is capable of 23 Watts maximum output power. Silicon absorbs approximately 65% of the light at these wavelengths.

5.4.1 Modeling

Welding of a pair of latches is simulated using a laser beam varying from 100 µm to 500 µm. Thermal properties are equivalent to that of resistive welding, however electrical properties can be ignored. The main difference in the model is the boundary that defines the laser spot. This area is defined to have a heating input equal to that of the laser power, measured to be 23 Watts. Because the laser impinges the latches at a 45° angle to share the laser load equally on both latches, the heat input per area is adjusted using a cosine multiplier. Also, it is known that at the wavelength produced by a copper vapor laser, silicon absorbs approximately 65% of the light. Both of these effects are taken into account in the heat input definition at the laser spot. Assuming ideal contact between the contacting latch surfaces, results of the modeling for each beam size is shown in Figure 5.17.

Comparing each analysis, it is determined that the amount of time to create the weld is approximately 0.44 seconds and is independent of the laser beam size. Additionally, to successfully melt the entire latch, the nearby sidewall areas reach a temperature of approximately 1375 °C, which is also independent of the beam size. However it can be seen that reducing the diameter increases the maximum temperature. Plotting the maximum and
Figure 5.17: Transient modeling results of laser welding using a beam size ranging from 100-500 µm. All images show temperature at 0.44 seconds of laser exposure.

Minimum temperature versus beam size shows that the difference in temperature significantly decreases as the beam diameter increases, Figure 5.18. Although the temperature of the nearby silicon is still very high, it is lower than that of the resistive welding simulation results. Therefore it is preferred to use laser welding to minimize damage to nearby features.
However it is still apparent that a cooling mechanism must be used on the sidewalls for production of operational IMU devices. This can be done by using a heat sink or forced convection to reduce the temperature to a tolerable level of approximately 200 °C.

![Temperature vs. Beam Diameter (at 0.44 s exposure)](image)

Figure 5.18: Simulated maximum and minimum temperatures experienced for 100 µm to 500 µm diameter laser beam sizes.

Using the same non-ideal contact between latches as for resistive welding analyses, additional laser welding simulations are conducted. Similar to the above modeling results that assume ideal contact between latches, the beam size of the laser varies from 100-500 µm. Results of a simulation with a laser diameter of 500 µm is shown in Figure 5.19. Maximum and minimum temperatures are observed to be 1457 °C and 1344 °C, with a laser exposure time of 0.44 seconds. Temperature of the latches are above the melting point of silicon while the surrounding areas remain below melting temperature. Compared to the prior modeling with ideal contact between latches, results are similar. Modeling was done with a mesh containing 18,792 elements and 31,288 degrees of freedom. Heat input was simulated using the measured power of the copper vapor laser, 23 W, and dividing by the area exposed, then multiplying by the cosine of the incidence angle and the 65% silicon absorption coefficient for the provided wavelengths.

Tabulation of maximum and minimum temperatures for all beam diameters was recorded
Figure 5.19: Laser welding FEA simulation using a 500 µm beam diameter and an exposure time of 0.44 seconds.

Figure 5.20: Maximum and minimum temperatures versus laser beam size for ideal and non-ideal (with grooves) contact between latches. 

and plotted in Figure 5.20. On the same plot, both results with ideal and non-ideal contact area with grooves are shown as a comparison. As observed, it is determined that non-ideal contact produces a larger difference between maximum and minimum temperatures of the latches and outer boundary areas. However, the difference is only a matter of dozens of degrees, and therefore is considered insignificant. Additionally, the surrounding silicon temperature remains high, which will still cause damage to the polyimide and metal features on the IMU sidewalls.
5.4.2 Laser Welding Experiments

Initial Testing on Silicon Samples

An experimental welding setup was created using the custom clamps described in Section 5.3.3 as shown in Figure 5.21. In addition to the clamps, several manipulator stages were utilized to allow for several degrees of freedom for sample and beam positioning. For resistive welding, the setup contained a 5-DOF stage for alignment and positioning of one sample with respect to another fixed sample. However, the laser welding setup includes another 2-DOF stage that was added to the previously fixed sample to allow for precise x- and y-axis translation. Also, the focusing lens was placed into a 2-DOF lens mount to allow for x- and z-axis positioning of the beam. Altogether, the setup consists of a total of 9-DOF which enables significant flexibility in position and orientation of the samples as well as the incident beam target location.

![Image of laser welding setup with 9-DOF for sample and beam positioning.]

Two silicon samples, both in the shape of IMU cube sidewalls, are mounted into the clamps and positioned such that the latches are interdigitated. The angle between the sidewalls is approximately 90°, with each sidewall oriented at 45° with respect to the laser beam, as...
shown in Figure 5.22. Because of the multiple translational degrees of freedom of the beam itself, the entire length of the weld from top to bottom of the sidewalls can be performed by moving the beam instead of the samples. This mitigates the challenge of precisely moving two silicon samples simultaneously during the welding process, without breaking any previous welds. With the clamps installed and the samples in place, the welding setup is complete and welding experiments can be conducted.

Figure 5.22: Silicon IMU cube sidewall samples held by clamps and ready for laser welding of the interdigitated latches.

Focusing of the laser is performed by manipulating the distance between the convergent lens and the target samples. A beam dump is placed in the path of the laser beam to reduce the laser power by approximately 90% during the focusing process. This prevents premature welding of undesired features. It was observed, however, that even with the beam dump in place, the plastic portions of the clamps are heated above the material melting temperature.

Once the beam is properly focused and centered on the interdigitated latches, the lens manipulator is used for vertical translation of the laser beam. Initially, the beam is focused to a diameter of approximately 500 µm at the bottom portion of the intended weld seam. Once the setup is fully prepared, the beam dump is removed to allow the full power of the laser to impinge the welding area. Welding was then performed by opening the laser shutter and slowly translating the beam upward along the 10 mm length of the latch area. Although it was hypothesized that the heating area would be localized to the silicon, the
clamps suffered significant damage to the temperature of the weld. As shown in Figure 5.23, the front portions of the clamps were melted and charred where in contact with the silicon samples. Additionally, the stainless steel foil was also melted, creating a mixture of fused plastic and metal around the silicon samples.

Figure 5.23: Photograph of the front of the clamps after welding showing damage due to heat, causing the material to melt and burn.

Because of the damage done to the clamps, the silicon samples were difficult to remove from the setup. Some of the plastic material had melted around the edges of the samples preventing them from easily slipping out of the clamps. Inevitably, the samples were broken apart during removal. Although this prevented inspection of the welds while intact, results were still obtained by observing the broken latches. Cleaning of the samples was done by rinsing in isopropanol to remove the charred residue from the burnt ABS plastic. One of the samples is shown in Figure 5.24 and it is observed that the latches were successfully melted.

Figure 5.24: One sidewall after laser welding and being extracted from the clamps, showing that latches were successfully melted.

Observing the corresponding sidewall sample after cleaning, it is noticed that several
Latches from the first sample are still fused, as shown in Figure 5.25. On the left side of the photograph, nearly all latches from the same portion of the other sample remain. This portion of the welded samples was the bottom of the welding area in the experimental setup. Conversely, the right of the figure has several unsuccessful welds. During the welding experiment, the bottom portion of the samples were passed over twice with the laser to compare total laser exposure time to the quality of welding. Laser exposure time of the bottom portion was approximately 2 seconds for each latch pair, compared to 1 second per latch pair for the top portion.

![Figure 5.25](image)

Figure 5.25: The opposite silicon sample after welding, indicating that several latches from the other sidewall are fused to the latches.

These results show that laser welding of the silicon was successful, despite the damage to the clamps. Because the bottom area of the latches were broken from one sample yet remained fused to the other, the strength of the weld meets or exceeds the strength of the raw silicon. Additional characterization of the welding samples will require modifications to the clamps. Specifically, the clamps should be manufactured with a material with a higher melting temperature and better heat dissipation characteristics. Using a similar design, clamps made from such a material will enable easier handling of the samples after welding without breaking the samples or damaging the clamps.

**Laser Welding of Folded IMU Structures**

The experimental setup for laser welding assembled IMU structures consists of the CVL, optics for reducing the beam size, and a manipulator stage on which to mount the samples, similar to previous experiments. However for these experiments, the laser output was reduced...
to 12.5 Watts of power in attempt to reduce damage to nearby polyimide and metal features. The laser is directed through a convergent lens to reduce the beam diameter to $\approx 500 \, \mu m$. An additional lens is then used to further reduce the diameter of the beam to $\approx 150 \, \mu m$, which approaches the physical limits of convergence for 510.6 nm light waves. Welding was done on IMU pyramid structures by focusing the laser to maximize power density and quickly melt the silicon substrate. In some experiments, powdered silicon or silicon carbide was added as a filler material. With or without the filler material, sidewalls of the structure were successfully fused, Figure 5.26.

![Figure 5.26: Laser welding of a folded IMU pyramid using a 12.5 W copper vapor laser focused down to a 150 $\mu$m beam diameter and silicon powder filler material.](image)

Although the welding process with 12.5 W of laser power resulted in structures reinforced with silicon welding, there are a few drawbacks. First, the beam size must be reduced to a very small diameter to raise the power density to a suitable level for welding. This requires the use of two lenses and both need to be carefully aligned to create the desired beam diameter in the appropriate location. The focal length is also quite small, making it challenging to focus the beam on the welding area. Additionally, because the latches are 500 $\mu$m in thickness, a beam size of 150 $\mu$m is significantly smaller than the welding area. For these reasons, it is desired to use the full 23 W of laser power to allow for welding with a larger beam size and minimize the effort needed for alignment.
By increasing the laser power, this allows for use of a single lens to reduce the beam size to \( \approx 500 \, \mu m \) while still producing enough power density to melt silicon. Two single-crystal silicon panels identical to those on the IMU cube were stacked on top of each other to test the new setup, as shown in Figure 5.27. The panels were aligned such that the outline of the latches on the top layer matched that of the bottom layer. With this configuration, individual pairs of latches can be welded.

Laser welding of an individual pair of latches was performed successfully using the simplified setup with only one lens. Welding of silicon was confirmed by removing the panels from the mounting platform and observing that they were mechanically attached. The panels were broken apart and each of the welded latches were independently analyzed with an SEM to further examine the welded area. Observing the top latch showed that the substrate material was melted after laser exposure, as shown in Figure 5.28. This indicates that the larger beam size of 500 \( \mu m \), along with higher laser output power of 23 W, is capable of melting the bulk silicon weld joint without vaporizing the material.

Analysis of the second latch, which was underneath the first latch during welding, yielded more interesting results. An SEM image of the broken area shows that the weld joint was fractured within the raw silicon, Figure 5.29. The isometric view in Figure 5.29(a) shows that all of the melted silicon is no longer attached and the fracture occurs along a constant angle. Additionally, the surface of the fractured area has very few ridges, indicated that

![Figure 5.27: Laser welding setup with 20 W of power and a single lens with a resulting beam diameter of \( \approx 500 \, \mu m \) to weld latches on two stacked IMU panels.](image-url)
the break occurred along one of the silicon crystalline planes. Although it was not directly measured, it can be concluded from the image that the surface is likely that of the (110) plane of silicon because the top surface is known to be the (100) plane. Within the weld, the crystalline planes of the silicon are ruined, and therefore the weld fracture is determined to be within the raw, non-welded material due to the clean break. It can be inferred that the welded joint is stronger than that of the substrate. Although this is heavily influenced by the additional cross-sectional area of the weld, this result shows that this method of laser welding bulk silicon is capable of creating joints of a strength comparable to the raw material.

Figure 5.29: SEM images of the second latch showing that the fracture occurs in the raw, non-welded silicon.

Figure 5.30 shows an IMU pyramid with the laser properly aligned onto the top section of the latches. Results of the welding show that the latches can successfully be fused together with a copper vapor laser. Samples of welded sets of latches are shown in Figure 5.31. One
set of latches is shown prior to welding in Figure 5.31(a). After welding, the latches are combined to create a rigid structural joint, as shown in Figures 5.31(b) and 5.31(c). From the visual photographs, it appears that the use of a silicon carbide powder filler material produces better results. However these experiments were conducted with the laser output power at 12.5 Watts, and should prove to be much better when using the full 23 Watts of power.

Figure 5.30: IMU pyramid with laser aligned and focused before welding.

(a) Before welding

(b) Welded - no filler material

(c) Welded - SiC filler material

Figure 5.31: Latches on IMU pyramid before welding, after welding, and welded with silicon carbide filler material.

Because some of the silicon vaporizes while welding, a filler material is added to potentially provide better quality welds. For rigidity purposes, silicon carbide powder offers an ideal solution. Using a 400 grit powder mixed with a small amount of water, a silicon carbide
filler mud is applied to the welding area. When heated with the laser, the water is quickly vaporized and the powder is melted along with the underlying silicon latches, as shown in Figure 5.31(c).

Figure 5.32: Folded IMU pyramid with welded together using a copper vapor laser.

An entire assembled IMU pyramid was welded together using a 23 Watt copper vapor laser and silicon carbide filler material. All four sidewalls were fused together using this procedure, with the result shown in Figure 5.32. It can be seen that the heating of the weld compromised the integrity of the nearby polyimide and metal traces. Additionally, a significant amount of silicon dioxide is produced (seen as white areas of Figures 5.31(c) and 5.32). To resolve these issues, a steady flow of inert gas should be applied to the active welding area to cool the structure and minimize oxidation. However without active cooling applied to the structures, welding has been shown to be possible with a high-power laser. Latches on the folded structures have been fused together with and without filler material. However observational inspection indicates that better results occur when using a filler material such as silicon carbide. Overall, results show that utilizing a 23 W CVL, it is feasible to welding silicon features as large as 200 x 500 µm, which is much larger than previously accomplished.
5.5 Structural Characterization

Environmental testing was done on folded IMU pyramid structures after laser welding of the sidewalls. Temperature variation, shock, and constant acceleration tests were performed on IMU pyramid samples. For vibrational testing, the results were compared to that of epoxy bonded structures to show the increase in overall rigidity. Temperature testing was done by exposing assembled IMU structures to extreme cold and hot environmental temperatures. The structures were first cooled to a temperature of -10 °C, and then ramped up to over 150 °C. Over the entire temperature range, the structures survived, showing capability of a platform for inertial measurement purposes at various temperatures.

Analysis of structural parameters on the IMUs has continued by performing mechanical shock tests on another IMU pyramid with welded sidewalls. Testing was first performed by mounting the IMU pyramid to a vertical shaker unit capable of applying up to 40 g shock acceleration. A laser vibrometer was used to measure the response of the IMU during the experiments. The laser was focused onto a top edge of the pyramid where maximum deflection is expected to occur. Figure 5.33 shows the acceleration and velocity response of an IMU pyramid during a half-sine 40 g shock test with a 3.5 ms pulse width. The structure survived all tests, and it can be seen from the plot that the acceleration at the top of the IMU pyramid experienced a 40 g maximum value. Results indicate that after welding, the folded IMU structures are able to survive shock tests of at least 40 g of acceleration.

For many applications, survival of 40 g shock levels is not sufficient [64]. Therefore additional shock testing has been done with higher acceleration values using a steel bar and an impact hammer. Characterization of the setup shows that it is capable of producing up to 2000 g of acceleration onto a sample mounted onto the end of the apparatus. A welded IMU pyramid structure was tested on this device and showed to survive at least 262 g of acceleration with a pulse width of approximately 0.5 ms, as shown in Figure 5.34. However
it is believed to survive much higher shock values once the welding reinforcement process is refined.

Vibrational characterization was also performed on a vertical shaker producing vibrations from 20 Hz to 20 kHz. A laser vibrometer detected the motion of a top point of the pyramidal IMU structure during the experiments. An IMU pyramid was mounted to the shaker at a 60° angle using a brass substrate such that one face of the pyramid was perpendicular to
the vertical axis. First, the laser vibrometer was focused onto the brass substrate during the vibration sweep to detect the frequency response of the mounting jig. This result was compared to the acceleration output detected from the pyramid sidewall for each the epoxy-bonded and silicon welded structures. Vibration testing shows that the resonant modes detected on pyramidal IMU structures are shifted above 10 kHz after laser silicon fusion of the latches is performed, Figure 5.35. The results were compared to that of an epoxy bonded structure, which has resonant peaks below 10 kHz, specifically at 970 Hz, 3.80 kHz, 5.42 kHz, and 8.02 kHz. Because the mass of the structure is not significantly changed, this indicates a significant increase in overall structural stiffness of the structure after welding is performed. It is demonstrated that epoxy adhesives as well as silicon fusion are both adequate for creating a rigid 3-D platform for MEMS devices, however silicon welding is proven to enhance the integrity of the structures.

Figure 5.35: Frequency response of assembled IMU pyramids comparing epoxy bonding and silicon welding showing an increase in overall structural stiffness for the welded structure.

Overall, testing shows that the folded IMU structures can survive exposure to temperature changes, acceleration, and shock. The results are summarized in Table 5.1. Vibration testing of the structure was performed and measured over a range of 20 Hz to 20 kHz with a
Table 5.1: Environmental testing results of folded laser welded pyramidal IMU structures.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Test Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration</td>
<td>20 Hz - 20 kHz, 5 g max</td>
</tr>
<tr>
<td>Shock</td>
<td>262 g</td>
</tr>
<tr>
<td>Temperature</td>
<td>-10 °C to 150 °C</td>
</tr>
</tbody>
</table>

maximum of 5 g of acceleration. Constant acceleration tests were performed along each of the three independent axes at a maximum of 30 g, however the structures should easily survive much higher acceleration loads. Shock testing proved that the structures can survive up to at least 262 g of acceleration with a 0.5 ms pulse width. Temperature testing of the structures was also done and showed that the folded IMUs can withstand a range of -10 °C to 150 °C and is believed to survive a much wider array of temperature after silicon welding is conducted.

### 5.5.1 Environmental Sensor Misalignment Measurements

Initial alignment of the folded IMU sensors after assembly and packaging are designed to be positioned along pre-defined each intended sense axis. However, due to fabrication and assembly imperfections that cause errors in alignment, calibration is necessary to fully characterize the complete IMU. Once calibrated, slight misalignments of the sensors will cause errors in inertial signal detection. Therefore, performance of an IMU directly depends on the ability of the supporting architecture to rigidly maintain the initial sensor alignment. Characterization of structural integrity is performed by measuring misalignment of the IMU sidewalls before and after various environmental loads are applied. A comparison is made between epoxy bonding and eutectic soldering to determine the performance of each reinforcement technique in varying environmental conditions. Structures reinforced with silicon welding were not able to be tested in this section due to the damage experienced during the welding process.
Figure 5.36: Optical measurement setup for alignment characterization of folded IMU sensor axes.

An optical characterization method was developed to precisely measure the relative misalignments of the pyramid sidewalls, Figure 5.36. Folded 3-D structures are rotated using a precision-controlled dual-axis Ideal Aerosmith 2102 rate table with an angular accuracy of 0.15 mrad and repeatability of 0.05 mrad. At the same time, reflection of a collimated laser beam from the pyramid sidewalls is observed using a calibrated detection screen at a 1.5 m distance. The following procedure is used to obtain misalignment data from each sidewall before and after each environmental condition is applied:

(I) Mark the position of the laser beam reflected off of sidewall 1. This acts as a reference for later measurements.

(II) Precisely rotate the pyramid by 90° and mark the position of laser beam reflected off of sidewall 2.

(III) Repeat Step 2 for sidewalls 3 and 4.

(IV) Remove the IMU pyramid and conduct environmental testing.

(V) Place the IMU pyramid back onto the test stage and adjust the rate table, such that the sidewall 1 beam location is very near the original reference mark.
(VI) Mark the new position of the laser beam reflected off of sidewall 1 as the second reference.

(VII) Measure the distance between the two reference marks from sidewall 1.

(VIII) Precisely rotate the pyramid by 90° and mark the position of laser beam reflected off of sidewall 2.

(IX) Measure the distance between the respective two marks for sidewall 2.

(X) Subtract the sidewall 1 distance from the sidewall 2 distance and multiply by the calibrated sensitivity of the detection grid to calculate misalignment.

(XI) Repeat Steps 8, 9 and 10 for sidewalls 3 and 4.

**Elevated temperature**

For static thermal testing, IMU pyramid structures are placed on a miniature heater located on the dual-axis rate table. Prior to heating, the initial angular position of each sidewall is measured. Temperature of the pyramid is then elevated to 85 °C over a period of 25 minutes. Temperature is held at 85 °C for 25 minutes to allow for steady-state conditions. Misalignment data from each sidewall is extracted at the elevated temperature using the above procedure, yielding a maximum variance of 1.7 mrad for an epoxy-bonded IMU pyramid.

**Temperature cycles**

Misalignment of IMU pyramid structures is measured after thermally cycling from room temperature to -40 °C and 85 °C, respectively. Before testing, angular position of the sidewalls is measured. The IMU structure is then mounted inside a thermal chamber (TestEquity
model 107) and heated to 85 °C. After holding the temperature for 25 minutes, the IMU is gradually cooled to room temperature. Once steady-state temperature of the folded structure is reached, detection of misalignment is conducted to determine the effects of the process. The same process was performed and the corresponding misalignment data obtained after thermally cycling the IMU from room temperature to -40 °C. Results indicate a maximum angular sidewall variance for an epoxy-bonded IMU structure of 1.6 mrad and 3.0 mrad for heating and cooling cycles, respectively.

**Temperature shock**

Thermal shock is also performed on the folded IMU pyramids, both for cold and hot temperatures. After measuring the initial angular position of each sidewall, the structures are transferred into an 85 °C environment with a transition period of approximately 3 seconds. Temperature is maintained for 25 minutes to ensure the entire structure is at steady-state. The pyramid is then transferred to room temperature within approximately 3 seconds to apply a negative thermal shock. Utilizing the same procedure, folded IMU pyramids are exposed to thermal shock from room temperature to -40 °C, then back to room temperature. Each experiment is repeated three times consecutively for each the hot and cold temperature tests to determine the effects of multiple cycles. Misalignment data from each sidewall on an epoxy-bonded pyramid results in a maximum variance of 3.0 mrad and 3.5 mrad for the 85 °C and -40 °C thermal experiments, respectively.

**Constant acceleration**

For applications in which acceleration loads are constantly applied, folded MEMS IMU structures must withstand the forces involved. To determine suitability for such purposes, constant acceleration is applied to IMU pyramids by rotating the devices on a centrifuge with
a known rotation rate. Loading is applied to the folded structure along three independent axes by mounting the IMU at orthogonal angles for each experiment. The setup is capable of providing up to 60 g of acceleration on the test sample. Misalignment of the sidewalls is measured before and after the experiment, yielding a maximum angular variance of 1.8 mrad between sidewalls for an epoxy-bonded IMU structure.

Results Summary

Results of all alignment stability tests comparing epoxy and solder-bonded IMUs is shown in Table 5.2. Structures reinforced with epoxy show a maximum alignment drift of 3.5 mrad or less under each applied environmental condition. In contrast, the soldered structures provide stability better than 0.2 mrad. The lower limit of detection of the measurement setup is approximately the same, therefore the misalignment of the solder-bonded structures is likely much lower than the measured data. Moreover, further development of silicon welding should prove to provide more rigidity compared to eutectic soldering. These results indicate feasibility of reinforced 3-D folded MEMS structures for a wide variety of environmentally robust IMU applications.

5.6 Conclusion

High-performance IMUs not only depend on the quality of the sensors, but also on the quality of the structure on which they are mounted. Therefore, it is desired to maximize the structural rigidity of the folded MEMS IMU devices to enable high-performance operation of the overall unit. Several methods have been explored for reinforcement of the assembled IMUs, including epoxy bonding, eutectic soldering, and silicon welding. However silicon welding offers the maximum amount of rigidity compared to the others, and thus is desired...
Table 5.2: Measured angular misalignment of folded MEMS IMU sensor axes for epoxy and solder reinforcement approaches

<table>
<thead>
<tr>
<th>Environmental Test (vs. initial position at 25 °C)</th>
<th>Max. Misalignment (mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Epoxy</td>
</tr>
<tr>
<td>25 ºC → 85 ºC elevated temperature</td>
<td>1.7 ± 0.2</td>
</tr>
<tr>
<td>25 ºC → 85 ºC → 25 ºC thermal cycle, 25 min</td>
<td>1.6 ± 0.2</td>
</tr>
<tr>
<td>25 ºC → -40 ºC → 25 ºC thermal cycle, 25 min</td>
<td>3.0 ± 0.2</td>
</tr>
<tr>
<td>25 ºC → 85 ºC → 25 ºC thermal shock, 3 s, 3 cycles</td>
<td>3.0 ± 0.2</td>
</tr>
<tr>
<td>25 ºC → -40 ºC → 25 ºC thermal shock, 3 s, 3 cycles</td>
<td>3.5 ± 0.2</td>
</tr>
<tr>
<td>Constant acceleration 60 g for 1 min for each axis</td>
<td>1.8 ± 0.2</td>
</tr>
</tbody>
</table>

(*limit of the alignment detection system is 0.2 mrad)

for the folded MEMS IMU application. Prior literature shows that only small portions of pure silicon have been successfully welded, from the nanometer scale up to 50 µm in thickness. Therefore to implement silicon welding on the folded IMU devices, further development was performed enable silicon welding of material up to 500 x 500 µm in size.

Simulations of welding silicon have been performed for resistive and laser heating methods, and indicates that the optimal laser exposure time is approximately 44 seconds. Also, it is shown that this is independent of the laser beam size at the welding location. Therefore, the requirement to control the welding exposure time is much more important than being able to precisely focus the laser onto the target. This is particularly advantageous for the pyramidal IMU structures with latches that are fabricated at a non-vertical angle. It is shown that theoretically, laser welding and resistive welding are fairly equivalent when comparing the temperature of the latches versus temperature of the internal portions of the sidewalls. For the purpose of initial investigation of bulk silicon welding, the heating is considered to be an insignificant issue. However, for future implementation of operation IMUs, active cooling
will be necessary to prevent damage to the polyimide, metal, and sensor features on the sidewalls during the welding process.

Environmental testing was performed on folded MEMS IMU structures to determine survivability of the devices in various conditions. Results of thermal testing, thermal shock, acceleration, vibration, and mechanical shock were evaluated for structures reinforced with eutectic solder. The results indicate that the structures are capable of withstanding a large array of environmental conditions without compromising structural integrity. However it is believed that the devices will survive much higher accelerations after refining the welding process.

Vibration testing was then performed, again on the controllable shaker, and frequencies were applied ranging from 20 Hz to 20 kHz with a maximum of 6 g of acceleration. Structural response was detected with a laser vibrometer to measure the modal frequencies of a structural sidewall. Both epoxy bonded structures and silicon welded structures were analyzed, showing that epoxy bonded structures have several resonance modes detected below 10 kHz. Results of an identical structure with welded sidewalls shows that frequencies of all modes are shifted above 10 kHz, which is adequate for nearly all practical IMU applications. All experiments indicate that silicon welding is not only feasible for the folded MEMS IMU structures, but also provides much better overall structural integrity compared to the other reinforcement methods.
Chapter 6

Coordinate Transformation for Inertial Navigation

Integration of an IMU into a complete inertial navigation system (INS) requires an analysis of the sensors and geometry in which they are configured. A variety of sensors are generally used in an IMU, including accelerometers and gyroscopes as discussed in Chapter 2. But also magnetometers and pressure sensors can be included to provide valuable information for navigation. Magnetometers are used to aid in determining heading by sensing the magnetic field of the earth, much like a compass. Altitude information can be provided by pressure sensors, allowing calculation of gravity independent of the inertial sensors.

6.1 Introduction

Full inertial detection requires at least three axes of acceleration detection and three axes of rotation rate detection. However in many cases, redundant sensors are also included to improve performance of the IMU as well as monitor errors of other sensors. Multiple
independent IMUs are also often combined to detect failure of each individual unit [65]. For instance, if three IMUs are combined, a difference in the signals from each IMU can be compared to the others. When it is detected that one is reading a different signal than the other two, then that unit is considered to be inaccurate and thus is ignored. Utilizing two IMUs doesn’t provide this capability because it cannot be determined which one is providing false signals. However, the signals can be combined and averaged to improve INS performance.

A common problem with IMUs is instability of signals causing drift in the signal outputs, which provide false navigational information. For this reason, another reference is generally desired to update position and attitude periodically. A common method for providing the updates is to use GPS information. Therefore an IMU is not independently a complete INS, but must be integrated into a system of position, heading, and attitude detection systems to provide reliable navigation data.

Individual sensors of the IMU exist in their own coordinate frames, independent of the application, number of degrees of freedom for the IMU, or redundancy of IMU devices. Each sensor must be correlated to a coordinate frame useful for navigation purposes. Therefore, coordinate transformations must be performed for each sensors to map the sense vectors to the external frame of the IMU body. Discussed in this chapter is an algorithm for performing transformations from the sensors themselves to desired orthogonal axes for navigational purposes. This first involves compensating for misalignments of the sensors compared to the designed IMU configuration. This is followed by transformation from the IMU form factor to an orthogonal coordinate system related to the external IMU body. Because this has been a consistent process in development of IMUs for several generations, the majority of this work is derived from various existing sources, [55, 66, 67]. Using the information provided in literature, an algorithm for a proper coordinate transformation procedure has been developed specifically for folded MEMS IMUs.
6.2 Coordinate Transformation of Sensor Signal Vectors

Arbitrary coordinate frames have been used in the vector definitions described in Appendix B for general use of any IMU. Specific coordinate frames have been defined, and will be used to describe the algorithms explained in the following sections. Three individual coordinate frames, \( s \), \( i \), and \( b \) are defined as follows:

- **s frame**: Coordinate frame for an individual sensor, regardless of fabrication misalignments and the designed spatial configuration of the overall IMU.

- **i frame**: Coordinate frame of a sensor IMU form factor with regards to the ideal IMU form factor without misalignments.

- **b frame**: Orthogonal coordinate frame of the external IMU body, disregarding the original ideal sensor orientation and number of sensors. This frame can be directly transformed to the navigation frame for the specific application in which the IMU is being utilized.

Considering a sense vector \( r \) in the sensor frame \( s \), a transformation to the ideal IMU configuration frame \( i \) can be obtained as defined in Equation (6.1). Rotation transformation matrices are defined as \( C \) matrices, which are discussed in Appendix B. A general expression is given in Equation (6.1) for converting a sense vector from the sensor frame to the ideal IMU form factor alignment frame.

\[
R^{i} = C_{s}^{i}(\theta_{m}, \phi_{m}, \psi_{m})R^{s} = C_{s}^{i}r^{s}(\psi_{m})C_{s}^{s'}(\phi_{m})C_{s}^{s'}(\theta_{m})R^{s} \tag{6.1}
\]

The misalignment angles (\( \theta \), \( \phi \), and \( \psi \)), denoted with a subscript \( m \) to indicate a misalign-
ment angle, must be determined by quantitative measurement of the folded MEMS IMU geometry after fabrication and assembly. Equation (6.1) provides an algorithm for compensating for sensor misalignments on any IMU device. Given that the misalignment angles, $\theta_m$, $\phi_m$ and $\psi_m$ are experimentally determined for each of the sensor platforms, the angles are inserted into the Equation (6.1).

It is inevitable that all of the sensors will have small misalignments after assembly compared to the ideal form factor. Therefore additional notations must be used to specify to which sensor the expression is applied. For this reason, a subscript, $n$, is added to the $r$ vectors to indicate which sensor’s coordinate frame is being transformed. Similarly, the misalignment angles, $\theta_m$, $\phi_m$ and $\psi_m$, and the transformation matrices are also given an additional subscript $n$ that corresponds with that of the sense vectors. Using this additional notation, the expression now becomes

$$r_n^i = C^{\text{sn}}_{\psi_m n}(\psi_m)C^{\text{sn}}_{\phi_m n}(\phi_m)C^{\text{sn}}_{\theta_m n}(\theta_m)r_n^s,$$

where $n$ is an integer ranging from one to the total number of sensors included in the IMU design. In the case of a cubic IMU with a single sensor on each sidewall, there are a total of six expressions and thus $1 \leq n \leq 6$. This is also true for an IMU pyramid with four sidewalls, each containing a single axis accelerometer or gyroscope, with an additional gyroscope and accelerometer on the bottom face. However the definition of $n$ largely depends on the IMU form factor design and the number of sensors included on each sidewall. In either case, a general expression has been determined for misalignment compensation of each sensor on folded MEMS IMU structures of various form factors.

Once the misalignment transformation of each sensor are conducted by the algorithm above, further discussed in Appendix B.1, the sense vectors are all referenced to the ideal IMU frame, $i$, for the specific form factor. Another transformation is necessary to convert...
the IMU sensor vectors to the orthogonal IMU body frame, $b$. This procedure requires a specific definition of the ideal IMU geometry. With the sense vectors, $r^i_n$, referenced to the ideal alignment of the folded IMU sidewalls, the designed sidewall angles must be taken into consideration. Each coordinate frame must be transformed to the orthogonal IMU body frame coordinates to provide a common reference usable for inertial navigation purposes.

### 6.2.1 Pyramidal IMU Configuration

Alternatively to a cubic structure, a pyramidal IMU form factor is also explored as mentioned above. A coordinate transformation algorithm is specifically created considering this type of structure with four sidewalls, each at a 30° angle with respect to the vertical $z_b$ axis, Figure 6.1. After accounting for misalignments from the ideal design to transform the vectors

![Figure 6.1: Folded MEMS IMU pyramid inertial and body coordinate frames.](image)

Figure 6.1: Folded MEMS IMU pyramid inertial and body coordinate frames.

to the $i$ frame, each sensor axis must then be referenced to the orthogonal IMU body frame, $b$. For sensor #1, the transformation requires only one rotation about the $x_{1,i}$ axis at an angle of -60°, shown below.

$$ r^b_1 = C_{i1}^b r^i_1 = C_x(-60°) r^i_1 $$

(6.3)
Following the same procedure with the remaining sensors on the IMU pyramid sidewalls, the coordinate transformations are as follows.

\[ r_2^b = C_{i2} r_2^i = C_z(-90^\circ)C_x(-60^\circ)r_2^i \] 

(6.4a)

\[ r_3^b = C_{i3} r_3^i = C_z(180^\circ)C_x(-60^\circ)r_3^i \] 

(6.4b)

\[ r_4^b = C_{i4} r_4^i = C_z(90^\circ)C_x(-60^\circ)r_4^i \] 

(6.4c)

\[ r_5^b = I r_5^i \] 

(6.4d)

\[ r_6^b = I r_6^i \] 

(6.4e)

In the case of the pyramidal IMU configuration in this work, the \( r_1 \) and \( r_2 \) vectors represent y-axis accelerometers with the sensor coordinate frame defined as shown in Figure 6.1. Sensor vectors for \( r_3 \) and \( r_4 \) represent z-axis gyroscopes, with respect to the sensor frame. For the \( r_5 \) and \( r_6 \) vectors, they are designated as an x-axis accelerometer and a z-axis gyroscope, respectively. For this reason, these two vectors need no coordinate transformation. For completeness, a transformation using the identity matrix is shown in Equation (6.4e) using the identity matrix, \( I \), for these two vectors.

### 6.2.2 Cubic IMU Configuration

Alternatively for the IMU cube form factor, the process is very much the same. First, the coordinate systems for each sidewall must be defined, as shown in Figure 6.2. For the system shown, sensors 1-4 are located on the vertical sidewalls. The top and bottom sidewalls contain sensors 5 and 6, respectively. Second, misalignments of the sensors after fabrication and assembly of the IMU must be accounted for to project the sense vectors from the sensor frame, \( s \), to the ideal IMU form factor frame, \( i \). This results in the expression shown below.
Once the misalignments have been accounted for, the general sense vectors, $r^i_n$, must be mapped to the coordinate frame of the orthogonal IMU body, $b$. For this process, each transformation varies for each sidewall of the IMU. Referring to Figure 6.2, the transformations for each sensor is computed as follows:

$$r^i_n = C_{s,n}^{in} (\psi_n) C_{s,n}^{in} (\phi_n) C_{n}^{in} (\theta_n) r^s_n \quad \text{for} \quad 1 \leq n \leq 6$$

$$= C^i_s (\psi_n, \phi_n, \theta_n) r^s_n$$

Once the misalignments have been accounted for, the general sense vectors, $r^i_n$, must be mapped to the coordinate frame of the orthogonal IMU body, $b$. For this process, each transformation varies for each sidewall of the IMU. Referring to Figure 6.2, the transformations for each sensor is computed as follows:

$$r^b_1 = C_{i1}^{b} r^i_1 = C_x(-90^\circ) r^i_1$$

$$r^b_2 = C_{i2}^{b} r^i_2 = C_y(-90^\circ) C_x(-90^\circ) r^i_2$$

$$r^b_3 = C_{i3}^{b} r^i_3 = C_y(180^\circ) C_x(-90^\circ) r^i_3$$

$$r^b_4 = C_{i4}^{b} r^i_4 = C_y(90^\circ) C_x(-90^\circ) r^i_4$$

$$r^b_5 = I r^i_5 \quad \text{(no transformation needed)}$$

$$r^b_6 = C_{i6}^{b} r^i_6 = C_x(180^\circ) r^i_6$$
As notated in the list of equations, the fifth sidewall does not need a transformation because it is located on top of the folded MEMS IMU cube structure. This is because the ideal alignment frame, $i$, of this sidewall is the same as the IMU body frame $b$. The other transformations shown are for the general case and apply to any type of sensor and any sense vector direction. Also, the transformations are independent of whether or not the sensors are single- or multi-axis devices. However for the cubic IMU described in this research, there is a specifically defined configuration of single-axis accelerometers and gyroscopes, given as follows:

**Sensor 1:** y-axis accelerometer

**Sensor 2:** x-axis accelerometer

**Sensor 3:** z-axis gyroscope

**Sensor 4:** z-axis gyroscope

**Sensor 5:** x-axis accelerometer

**Sensor 6:** z-axis gyroscope

Using the sensor configuration listed, the generalized vectors can be transformed to reflect the actual sensor signals provided by the folded MEMS IMU cube. The $r_n^b$ vectors are defined as $a_n^i$ and $w_n^i$ vectors to respectively describe the IMU acceleration and rotation rate vectors. Because the numbered system shown in Figure 6.2 ranges from 1 to 6, this notation is carried through to the actual sensor vectors to minimize confusion. However, this leads to sensor vectors with sporadic numbering. Specifically, vectors $w_1^i, w_2^i, w_5^i, a_3^i, a_4^i,$ and $a_6^i$ are not defined. This is because each sidewall only contains one sensor, and therefore only six sense vectors exist. For example, there are no acceleration vectors numbered the same as the gyroscopes. On the cubic IMU structure, sensors #1, #2, and #5 are accelerometer vectors,
and sensors #3, #4, and #6 are gyroscope vectors, as shown in Equation (6.7b).

\[
\begin{align*}
  r_1^i &= \begin{bmatrix} \alpha_{cx1} \\ \alpha_{y1} \\ \alpha_{cz1} \end{bmatrix} = a_1^i \\
  r_2^i &= \begin{bmatrix} \alpha_{x2} \\ \alpha_{cy2} \\ \alpha_{cz2} \end{bmatrix} = a_2^i \\
  r_3^i &= \begin{bmatrix} \omega_{cx3} \\ \omega_{cy3} \\ \omega_{cz3} \end{bmatrix} = w_3^i \\
  \quad \quad \text{(6.7a)}
\end{align*}
\]

\[
\begin{align*}
  r_4^i &= \begin{bmatrix} \omega_{cx4} \\ \omega_{cy4} \\ \omega_{cz4} \end{bmatrix} = w_4^i \\
  r_5^i &= \begin{bmatrix} \alpha_{x5} \\ \alpha_{cy5} \\ \alpha_{cz5} \end{bmatrix} = a_5^i \\
  r_6^i &= \begin{bmatrix} \omega_{cx6} \\ \omega_{cy6} \\ \omega_{cz6} \end{bmatrix} = w_6^i \\
  \quad \quad \text{(6.7b)}
\end{align*}
\]

These equations represent acceleration and rotation rate vectors defined with respect to the ideal IMU frame, without consideration of any misalignments. Included in the vectors are cross-axis sensitivities specific to the IMU cube, denoted by a subscript, \(c\). It is necessary for the different form factors to map these vectors to the IMU body coordinate frame, \(b\), using the \(C^b_{in}\) similar to the pyramidal IMU coordinate transformation matrices defined in Equations (6.6a) to (6.6f). Both cubic and pyramidal transformations have been derived, and the resulting algorithm can be utilized for any IMU form factor.

Since it can be confusing to retain the numbers when converting to the body frame vectors, \(a_n^b\) and \(w_n^b\), the notation system is changed to reflect the sensor vectors with respect to the orthogonal IMU body frame with subscripts \(x\), \(y\), and \(z\). These directions correspond with the sensor axes with respect to the overall IMU. By applying this new notation and performing the proper coordinate transformations, the generalized vectors are converted to sensor vectors that can be easily applied to a defined navigational frame. The following calculations are done by multiplying the same \(C^b_{in}\) matrices defined specifically for each
IMU form factor studied in this work.

\[
\begin{align*}
a^b_x &= C^b_{i5}a^i_5 \\
a^b_y &= C^b_{i2}a^i_2 \\
a^b_z &= C^b_{i1}a^i_1 \\w^b_x &= C^b_{i4}w^i_4 \\
w^b_y &= C^b_{i3}w^i_3 \\
w^b_z &= C^b_{i6}w^i_6 \\
\end{align*}
\]

(6.8a)

(6.8b)

All sensor data for the folded IMU cube is transformed to the IMU body frame, and thus single vectors can be defined for the overall accelerations and rotation rates by summing the sensor data from vectors in Equation (6.8b). Calculation of the vectors \( a^b \) and \( w^b \) in the following expressions are used to define the total acceleration and rotation rate information experienced by the folded MEMS IMU devices.

\[
\begin{align*}
a^b &= \begin{cases} 
\alpha_{x,tot} \\
\alpha_{y,tot} \\
\alpha_{z,tot} 
\end{cases} 
= a^b_x + a^b_y + a^b_z \\
w^b &= \begin{cases} 
\omega_{x,tot} \\
\omega_{y,tot} \\
\omega_{z,tot} 
\end{cases} 
= w^b_x + w^b_y + w^b_z 
\end{align*}
\]

(6.9)

(6.10)

Total acceleration and rotation rate is now calculated for a folded MEMS IMU device with three accelerometers and three gyroscopes, all of which are single axis devices. Information from all inertial sensors has been utilized, including cross-axis sensitivities to maximize the amount of data in the final vectors. Cross-axis sensitivities are included in the equations later produced. Inclusion of this error will increase the overall performance of the IMU by being able to predict the misalignments due to acceleration, temperature variation, and assembly.
6.3 Vibration Compensation

All calculations explored thus far have only considered the folded MEMS IMU in a static environment. However, when utilized in any application, the environment will be dynamic. This involves vibrations, thermal variations, mechanical shock, and other phenomena. Each of which will affect the IMU by actively changing the alignment of each sidewall. Even though the dynamic misalignments may be small compared to the overall dimensions of the IMU, any variations decrease the performance capabilities. Therefore it is desired to be able to actively compensate for these variations.

Due to the complex geometry of the folded MEMS IMU structures, it is difficult to predict the response to each phenomena analytically. For instance, thermal expansion and contraction depends on the reaction of all materials on the device, as well as the quality of adhesion between sidewalls. In the case of mechanical shock, directionality of the applied forces is completely arbitrary. This makes it extremely difficult to predict in the medium of analytical exploration. In fact, for most physical phenomena that will affect sensor alignment, empirical testing is required. Such experiments can be performed either by testing on existing physical devices, or with finite element analysis. However in the case of dynamic vibration during operation, there is some useful analysis that can be done analytically. This is because the first couple of frequency modes can be easily predicted, compared to the other effects that can be applied along any arbitrary direction. This section describes an estimated response for folded MEMS IMU sidewalls experiencing vibration, with assumptions defined to derive solvable expressions of sensor misalignments.
6.3.1 Cubic IMU

Consider a single IMU cube sidewall adhered to the overall structure on two opposing edges. For the actual structures, the sidewall is adhered along all four edges. However effective stiffnesses on either side can be calculated to provide a single stiffness coefficient that includes the effects from the distributed stiffness from the top and bottom edges. These effective stiffnesses are depicted as $k_1$ and $k_2$, shown in Figure 6.3.

![Figure 6.3: Free body diagram of an IMU cube sidewall with vibrations about the y-axis.](image)

The mass of the sidewall is notated as $m$, and vibration is applied as a torsional force, $F$, applied to each edge. The first mode of vibration is likely to occur with both springs deflecting identically, resulting in a vertical motion of the sidewall. However in this situation, the sensor axis remains unchanged with respect to the external IMU body frame. Therefore for the purpose of vibration analysis, this vibration mode can be ignored. The second mode of vibration will likely involve a torsion of the sidewall, with the deflection of each spring being opposite of each other. In this case, the sensor axis experiences a rotation with respect to the IMU body frame. Misalignment of the sidewall in this configuration is depicted by $\beta$, which defines the angle of the sidewall induced by vibrations. Length of the sidewall is defined as $L$, which is the same as the out-of-plane sidewall dimension in the case of a cubic IMU structure. A dynamic equation of motion can then be defined about the y-axis using...
the following expression.

\[ I\ddot{\beta} - \frac{L^2}{4}(k_1 + k_2)\sin \beta = F\frac{L}{2}\sin(\omega t) \] (6.11)

Although this equation accurately depicts the free body diagram (FBD) shown in Figure 6.3, the second term that includes \( \sin \beta \) makes it non-linear. Due to the light weight, small form factor, and rigidity of the IMU structure, it is fair to assume that \( \beta \) is small. In order to solve the equation with usual methods, \( \sin \beta \) is replaced simply by \( \beta \) in accordance with the small angle approximation. This change is reflected in the modified equation.

\[ I\ddot{\beta} - \frac{L^2}{4}(k_1 + k_2)\beta = F\frac{L}{2}\sin(\omega t) \] (6.12)

Solving this equation involves two parts: determining the homogeneous solution and particular solution. Each part is then added together to obtain the overall solution for the angle \( \beta \) about the y-axis. For the homogeneous solution, the forcing function of the equation is assumed to be zero. This results in a solution for \( \beta_h \), given below.

\[ \beta_h = e^{\sqrt{\frac{L^2}{4}(k_1 + k_2)} I} \] (6.13)

While this is sufficient assuming no physical forcing, it does not depict the solution when experiencing actively imposed vibrations. Therefore another analysis is required to determine the particular solution. The sum of the homogeneous solution and particular solution provide a complete expression for \( \beta \) when an IMU cube sidewall is vibrating in the second frequency mode. For this analysis, we assume that \( \beta_p \) has a similar form of the forcing function with unknown amplitude, \( B \).

\[ \text{Let } \beta_p = B\sin(\omega t) \] (6.14)

Inserting this expression into Equation (6.11) and solving once again, the amplitude \( B \) can
be determined as follows.

\[ B = \frac{-FL}{2[I\omega^2 + \frac{L}{4}(k_1 + k_2)]} \] (6.15)

Substituting this expression for the amplitude \( B \) results in the particular solution \( \beta_p \) below.

\[ \Rightarrow \beta_p = \frac{-FL \sin(\omega t)}{2[I\omega^2 + \frac{L}{4}(k_1 + k_2)]} \] (6.16)

The complete solution for the angle \( \beta \) is achieved by adding the homogeneous and particular solutions together. After doing so, the resulting expression is

\[ \beta = \beta_h + \beta_p = \left( e^{\sqrt{\frac{L^2}{4}(k_1+k_2)}} \right) - \left( \frac{FL \sin(\omega t)}{2[I\omega^2 + \frac{L}{4}(k_1 + k_2)]} \right) \] (6.17)

Up to this point, the solution is independent of the sidewall geometry, except for the placement of the springs on each edge. To apply the result specifically for the IMU cube form factor, the moment of inertia, \( I \), must be defined for a square-shaped sidewall. Neglecting the latches and hinge fingers along the edges, the moment of inertia is defined as

\[ I_y = \frac{ml^2}{12} \text{ where } l = 10\text{mm} \] (6.18)

The mass can be calculated using the density of silicon multiplied by the volume of an individual sidewall. Again neglecting the latches and using a sidewall thickness of 550 \( \mu \), the mass, \( m \) of the silicon is determined.

\[ m = \rho V = (2.33 \cdot 10^{-6} \frac{kg}{mm^3})((10\text{mm})^2 \cdot 0.550\text{mm}) = 1.28 \times 10^{-4}kg \] (6.19)

Using the mass calculated above, the moment of inertia about the \( y^s \)-axis can now be determined.

\[ I_y = \frac{(1.28 \times 10^{-4}kg) \cdot ((10\text{mm})^2)}{12} = 1.068 \times 10^{-3}kg \cdot mm^2 \] (6.20)

Knowing that \( L \) in Equation (6.17) is 10 mm, again neglecting the geometry of the latches,
all known values can be inserted into the expression. Because the spring constants \( k_1 \) and \( k_2 \) can vary due to different types of structural reinforcement, they are left as undefined variables. These values need to be determined experimentally for each folded IMU after being fabricated and assembled. Additionally, the value for \( \omega \) is also left undefined since a wide range of vibration frequencies and induced forces \( F \) will inevitably be experienced during operation. With these floating constraints combined with the defined values for the length \( L \) and moment of inertia \( I_y \), the expression is specified to define the angular deflection \( \beta \) for the folded IMU cube form factor.

\[
\beta = \left( e^{\sqrt{\frac{(10\text{mm})^2}{4} \frac{(k_1+k_2)}{1.068 \times 10^{-3} \text{kg} \cdot \text{mm}^2}}} \right) - \left( \frac{F \cdot 10\text{mm} \cdot \sin(\omega t)}{2\left[(1.068 \times 10^{-3} \text{kg} \cdot \text{mm}^2) \omega^2 + \frac{(10\text{mm})^2}{4}(k_1+k_2)\right]} \right) \quad (6.21)
\]

Because of the IMU cube form factor being considered, the solution for the angle about the \( x^s \)-axis is nearly identical. Rotation due to vibration about this axis will likely be the second or third frequency mode, depending on the spring constant values. Therefore it is important to consider both modes, and in most cases, combining the two to provide a more accurate determination of sidewall deflection due to environmental excitation. For the purpose of keeping variables independently defined, the induce angle is denoted as \( \alpha \) rather than \( \beta \) as before. Additionally, the spring constants are inherently different due to the geometry, and thus \( k_1 \) and \( k_2 \) are replaced with \( k_3 \) and \( k_4 \) respectively. However the mass of the sidewall, \( m \) and the moment of inertia \( I_x \) is identical. Using the same process as before, the expression for angular deflection about the \( x^s \)-axis is defined.

\[
\alpha = \left( e^{\sqrt{\frac{(10\text{mm})^2}{4} \frac{(k_3+k_4)}{1.068 \times 10^{-3} \text{kg} \cdot \text{mm}^2}}} \right) - \left( \frac{F \cdot 10\text{mm} \cdot \sin(\omega t)}{2\left[(1.068 \times 10^{-3} \text{kg} \cdot \text{mm}^2) \omega^2 + \frac{(10\text{mm})^2}{4}(k_3+k_4)\right]} \right) \quad (6.22)
\]
Angular deflection has been defined as $\alpha$ and $\beta$ for vibration excitation of each folded MEMS IMU sidewall about the $x^s$-axis and $y^s$-axis respectively. However to actively accommodate for these deflections, additional sensors are required. By combining this information with the data obtained from the IMU, vibrations can be computationally eliminated to increase the overall IMU performance.

### 6.3.2 Pyramidal IMU

A detailed algorithm for determining the effects of vibration for a folded MEMS IMU cube have been defined. However for other form factors, such as an IMU pyramid, the expressions must be modified. While the overall process is the same, the geometry, mass, moment of inertia, and spring constants are different. Therefore an additional analysis is required to describe the angular deflections for a pyramidal IMU. Following the process described in Section 6.3.1, vibration compensation can be analyzed for any IMU form factor. Based on the geometry, the mass and moment of inertia are defined. Spring constants, however, still must be determined experimentally or by FEA modeling, or more likely a combination of both. Using the procedure previously described, angular deflection for a pyramidal IMU form factor is discussed in this section.

![Image of a free body diagram of an IMU pyramid sidewall experiencing vibration about the x-axis.](image)

Figure 6.4: Free body diagram of an IMU pyramid sidewall experiencing vibration about the x-axis.
Considering the design of an IMU pyramid constructed for this research, the population of latches exists primarily on the top half of each sidewall with the bottom edge anchored to the base. Therefore the FBD in this case is redefined to show a spring located at a distance of \( \frac{L}{4} \) from the top and another spring at the bottom edge of the sidewall, Figure 6.4. Otherwise, the method for determining the angle, \( \alpha \), is identical to the above process used for the IMU cube vibration angles. First, the equations of motion are defined based on the figure.

\[
I_x \ddot{\alpha} - \left( \frac{H}{2} \cdot k_3 \frac{H}{2} \sin \alpha \right) - \left( \frac{H}{4} \cdot (k_1 + k_2) \frac{H}{4} \sin \alpha \right) = \frac{F \cdot H}{2} \sin(\omega t) \quad (6.23)
\]

As before, the expression is non-linear due to the \( \sin \alpha \) terms. Using the small angle approximation, \( \sin \alpha \) can be replaced by \( \alpha \) to make the differential equation solvable. Making this substitution and simplifying the expression by combining like terms yields the following.

\[
I_x \ddot{\alpha} - \left( k_3 + \frac{1}{4} \cdot (k_1 + k_2) \right) \frac{H^2}{4} \alpha = \frac{F \cdot H}{2} \sin(\omega t) \quad (6.24)
\]

Instead of going through the details of solving for each the homogeneous solution and particular solution individually, these steps are not included in this discussion. The complete solution for the angle \( \alpha \) is shown below.

\[
\alpha = \left( e^{\sqrt{\frac{H^2}{4I_x} \left[ k_3 + \frac{1}{4} (k_1 + k_2) \right]}} \right) \left[ \frac{F \sin(\omega t)}{\frac{2I_x \omega^2}{H} + \frac{H}{2} \left[ k_3 + \frac{1}{4} (k_1 + k_2) \right]} \right] \quad (6.25)
\]

The above expression for the angle \( \alpha \) gives an approximated vibration perturbation for an IMU pyramid sidewall given an excitation force \( F \). This is to predict the reaction of the pyramidal IMU structures in a torsional resonance mode due to environmental turbulence or other sources of vibration about the \( x^s \)-axis, in the sensor coordinate frame. However, unlike for the IMU cube, the FBD considering rotational vibration about the \( y^s \)-axis is not the same as for the \( x^s \)-axis. Because the IMU sidewalls are supported along the trapezoidal edges, the reaction forces induced by the springs cannot be determine at the edges. The geometry
of each sidewall and the application area of the reinforcement areas where reinforcement would be performed, an accurate approximation of the spring positions is determined to be a quarter of the distance from each edge. Viewing an IMU pyramid sidewall from the bottom edge the FBD for vibration about the $y^s$-axis is shown in Figure 6.5 with respect to the sensor coordinate frame.

![Free body diagram of vibration excitation of a pyramidal IMU sidewall about the y-axis in the sensor coordinate frame.](image)

Figure 6.5: Free body diagram of vibration excitation of a pyramidal IMU sidewall about the y-axis in the sensor coordinate frame.

Following suit with the previous analyses, the equations of motion are first defined without considering any assumptions. The form of the equation is similar to the definition of the system for vibration about the $x^s$-axis, with some minor modifications. Because the structure is adhered on the bottom, as well as along the latches along the edges near the top, two spring constants are used to differentiate between each adhesion location. Defining the rotation angle due to vibration as $\beta$, the equations of motion for the system is defined.

$$I \ddot{\beta} - \frac{L}{4} \left( \frac{L}{4} \sin \beta \right) (k_4 + k_5) - \frac{L}{4} \left( \frac{L}{4} \sin \beta \right) (k_6 + k_7) = F \frac{L}{2} \sin (\omega t) \quad (6.26)$$

By making the assumption that the rotation angle is small, $\sin \beta$ can be replaced with $\beta$ to make the system linear. Additionally, like terms are combined and the equation is simplified, resulting in the following expression.

$$I \ddot{\beta} - \frac{L^2}{16} (k_4 + k_5 + k_6 + k_7) \beta = F \frac{L}{2} \sin (\omega t) \quad (6.27)$$
As before, the homogeneous and particular solutions are derived separately and then added together to yield the overall solution for $\beta$ about the $y^s$-axis due to active vibrations.

$$\beta = \left( e^{\sqrt{\frac{L^2}{16\pi^2}}} (k_4 + k_5 + k_6 + k_7) \right) - \left( \frac{F \sin(\omega t)}{\frac{2I_y\omega^2}{L} + \frac{L}{8} (k_4 + k_5 + k_6 + k_7)} \right)$$  \hspace{1cm} (6.28)

Expressions for rotation angles due to vibration have been defined about the $x^s$-axis and $y^s$-axis for an IMU pyramid sidewall. There is an additional mode of vibration that can be predicted about the $z^s$-axis, however the sidewalls are adhered along the edges at several points for both cubic and pyramidal structures. Therefore the deflection of this mode is assumed to be much smaller than the other modes and thus is neglected for the purpose of this study. If required for certain applications to further increase performance, the process of determining the rotation angle will be the same as for the first two modes described.

6.3.3 Integration into Coordinate Transformations

Expressions for the rotation angles due to environmental vibration effects have been determined for both the cubic and pyramidal IMU form factors. Two modes of vibration have been accounted for, along the $x^s$-axis and $y^s$-axis with respect to sensor coordinate frame for each sidewall. In order to make the information useful for navigation purposes, it must be converted to the external IMU body coordinate frame $b$. This can be done with two different methods:

(I) Transforming the vibration data separate from the sensor vectors, and then adding them together in the IMU body frame.

(II) Including the vibration data in the overall coordinate transformation expression of the sensor vectors.
Both methods will yield accurate results, however the first method requires more computations than the second method. Not only are the transformations from each frame to another repeated twice, but there is an additional summing step required afterward. Therefore in this research, the second method is preferred to minimize the computational power needed while the IMUs are in operation.

Notation for the vibration angle matrices must first be defined before further modeling to ensure consistency throughout the error model analysis. The notation will be defined similar to that used for the DCMs used in Appendix B to maintain mathematical congruity. However instead of using $C$, the letter $V$ will be used to describe a rotation matrix containing vibration information. Superscript letters will still be used to define the reference coordinate frame, and numerals or the letter $n$ defines the index integer of each individual sidewall. For example, the matrix $V_{s2}^{s2}$ describes the vibration of sidewall #2 with respect to the sensor frame of the same sidewall. While in most cases the coordinate frame of the vibration information will be the same as for the individual sensor, this notation gives flexibility for other options. For instance it may be desired to translate the vibration of one sidewall to the coordinates of a different sidewall. This can be shown as $V_{s3}^{s1}$, where the vibration information of sidewall #3 is given with respect to the coordinate frame of sidewall #1. Within the scope of this work, the vibration matrices will be referenced to the sensor frame upon which the vibration data is calculated, and thus the numeric index in the subscript and superscript will be identical. However there is flexibility for extrapolation of this study to discuss vibrations in other frames if required for specific applications.

Using the either method described above for the cubic or pyramidal IMU form factor, the first process is to define rotation matrices with the $\alpha$ and $\beta$ angles. With the diagrams displayed and the solutions completed, $\alpha$ and $\beta$ are defined about the $x^s$-axis and $y^s$-axis respectively. Additionally, since the resulting matrix depends on time, this is included in the definition as a dependent variable. Therefore a rotation about the $x^s$-axis and $y^s$-axis due
to vibration is expressed respectively as follows:

\[ V_x^s(\alpha, t) = R_x(\alpha(t)) \]  \hspace{1cm} (6.29a)
\[ V_y^s(\beta, t) = R_y(\beta(t)) \]  \hspace{1cm} (6.29b)

However including the total time-dependent vibration matrices for inclusion into the coordinate transformation algorithm, these matrices must be multiplied. Instead of using \( x \) and \( y \) as the subscripts, the notation can thus be changed to \( n \) or an integer selective to each individual sensor. Still using \( t \) as a dependent variable, this defines a total transformation matrix due to environmental vibrations including motion in two frequency modes. Also, the notated index, \( n \), is carried through to the sensor coordinate frame notation as well as the angles \( \alpha \) and \( \beta \) solved for the vibration response for each sidewall previously described.

\[ V_n^s(\alpha_n, \beta_n, t) = V_{y,n}^{s,n}(\beta_n, t)V_{x,n}^{s,n}(\alpha_n, t) \]  \hspace{1cm} (6.30)

At this point, the total vibration matrix has been defined with the angles dependent on time. While this definitions are not expressed specifically for either of the transformation methods nor the IMU form factor, they can now be included for the transformations for the cubic and pyramidal IMUs from the sensor frame, \( s \), to the IMU body frame, \( b \). Using an unspecified sensor vector in the sensor frame, \( r^s \), and converting it to another vector, \( r^b \), the transformation including vibration is defined as follows.

\[ r_{bn} = C_{bn}^{sn}C_{in}^{sn}V_n^{sn}(\alpha_n, \beta_n, t)r_{sn} \]  \hspace{1cm} (6.31)

As defined for the IMU form factors earlier in this chapter, this transformation can be applied to one or more sensors on each sidewall. Because these definitions would be repetitive and mundane, each accelerometer and gyroscope sense axis will not be specifically defined. However using the notation and definition of IMU sidewalls, it is straightforward to convert
the general expression in Equation (6.31) for the designed IMUs discussed in this research. For example, an accelerometer on sidewall #1 of a cubic IMU would indicate that the $n$ be replaced by the integer 1, as well as the variable $r$ replaced by $\alpha_n$. Conversely, for gyroscopes, the variable $r$ will be replaced by $\omega_n$.

### 6.4 Conclusion

For each of the IMU designs considered, coordinate transformations have been determined to translate the sensor signals to the frame of the overall chip package in which it is mounted. Different frames of reference have been defined for the coordinate transformation calculations, discussed in Section 6.2. Transformation algorithms have been defined for gyroscopes and accelerometers and translated from the sensor frame, $s$, to the IMU body frame, $b$, for both pyramidal and cubic IMU form factors. These expressions are defined in Equation (6.6f) Equation (6.4e) respectively for the IMU cube and pyramid.

Vibration analysis was also conducted assuming that the most influential frequency modes involve rotation about the $x_s$-axis and $y_s$-axis of each sidewall in the sensor coordinate frame. Dynamic equations have been solved based on free-body diagrams (FBDs) using active forces and varying spring constants for both cubic and pyramidal sidewalls Equations (6.11), (6.14), (6.25) and (6.28). These derivations are an estimate of the sidewall reaction due to vibration. Therefore the reaction may be different for the fabricated IMU assembly. Each of the expressions derived in this chapter can be used to actively estimate and compensate for dynamic vibration and sensor misalignment of folded IMU devices during operation. However the total error would not be able to be completely eliminate because other errors also exist that are inherent to inertial sensors. These errors are discussed independently in Appendices C and D.
Chapter 7

Sensor and System Error Model

In the previous chapter, the focus of the mathematical algorithms was to create a coordinate transformation for folded MEMS IMU devices with various form factors. Specifically, expressions were derived for the cubic and pyramidal structures currently developed with the fabrication process in Chapter 2. However, the coordinate transformation does not include sensor- and system-level errors involved with IMUs. An error model for any IMU device is needed to understand the advantages and limitations of its navigational capabilities. Therefore, an error model has been created and is described in this chapter for the folded IMU devices.

Due to the compact density of sensor area for the given chip-scale footprint, the folded MEMS IMU devices have an inherent advantage compared to current technology. This chapter explores an error model customized to the folded IMU devices based on the definitions of each type of error. Calculations involved generally apply to both the cubic and pyramidal form factors. However, the procedures for implementing each error apply to any form factor with sensors fabricated on the sidewalls. Other fabrication technologies and sensor designs can be used on the folded IMU devices due to the modularity of the process, and thus the
error model may need further customization if the sensors implemented involve a significantly
different fabrication process than what is presented in this work. Notation for the terms and
expressions defined in this chapter are consistent with the previous chapter, but do contain
additional variables for each error, each of which is defined in the following sections.

Errors discussed include a collection of known sources induced by the sensors and the
overall IMU configuration. White noise is discussed first because of the similarity for both
gyrosopes and accelerometers. Each other type of error discussed in this chapter is defined
independently. Anisoelasticity error and tilt misalignment and system error due to gyroscope
bias are also discussed for the folded IMU sensors. The overall error model is graphically
shown as a block diagram, and supplemented with system-level equations to express the
effects of all considered errors for pyramidal and cubic folded IMU form-factors.

7.1 Introduction

Many error sources exist for each individual sensor, as well as for the overall IMU system.
Many of which are discussed in this chapter for accelerometers, gyroscopes, and overall
IMU Systems. All inertial sensors suffer from inherent errors such as bias drift and random
walk, but environmental conditions also affect the performance of an inertial navigation
system. Overall the performance of each inertial sensor relies on the errors contributed
from bias, temperature misalignment, scale factor, asymmetry, white noise, as well as other
unpredictable sources \cite{55,57,66,68}. Each known type of error is summarized in Table 7.1
and discussed in the following sections for SOI sensors capable of being fabricated on the
folded IMU structures.
<table>
<thead>
<tr>
<th>Error Level</th>
<th>Type of Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerometer</td>
<td>Bias Error</td>
</tr>
<tr>
<td></td>
<td>Misalignment</td>
</tr>
<tr>
<td></td>
<td>Scale Factor Error</td>
</tr>
<tr>
<td></td>
<td>Asymmetry</td>
</tr>
<tr>
<td></td>
<td>White Noise</td>
</tr>
<tr>
<td>Gyroscope</td>
<td>Bias Error</td>
</tr>
<tr>
<td></td>
<td>Misalignment</td>
</tr>
<tr>
<td></td>
<td>Scale Factor Error</td>
</tr>
<tr>
<td></td>
<td>Asymmetry</td>
</tr>
<tr>
<td></td>
<td>White Noise</td>
</tr>
<tr>
<td></td>
<td>Anisoelasticity</td>
</tr>
<tr>
<td>System Level</td>
<td>Tilt Misalignment</td>
</tr>
<tr>
<td></td>
<td>System Error from Gyroscope Bias</td>
</tr>
</tbody>
</table>

Table 7.1: Error sources considered for accelerometers, gyroscopes, and the overall IMU system.

### 7.2 Sensor Error Sources

Because there are separate errors for accelerometers and gyroscopes as well as the entire system, this chapter is comprised of multiple subsections. Each of which describes a different type of error. Errors associated with the individual accelerometers and gyroscopes are discussed first, and system errors will follow in Appendix D. Definitions of each error discussed are generally similar for both accelerometers and gyroscopes, and therefore they are combined for each subsection. One main difference between the two types of sensors is the units of the original error and the number of time integrations needed to convert the error to navigational-frame units. For example, the accelerometer errors need to be integrated twice with respect to time to achieve distance units, whereas the gyroscope errors only need one integration to provide angular units. In general, this means that the gyroscope errors propagate slower than the accelerometer errors. But because gyroscopes are more complicated devices, the errors are generally larger at the sensor-level compared to accelerometers. For this reason the magnitudes of each type of error is comparable for both types of sensors.

Each of the errors listed Table 7.1 are discussed and expressions are given for existing ac-
CELEROMETERS and gyroscopes with known specifications. While most errors are solely related to individual sensors, white noise error could be interpreted as a system-level error. However, since it affects each sensor individually, it is not included in the system error section but rather is explained as a sensor-level error. Algorithms presented in this chapter, supplemented with Appendix B, can be applied to any IMU form factor by tailoring the notation and definitions of the coordinate transformation matrices. Specifically, the error definitions in this work are applicable to cubic and pyramidal configurations. The procedures of which can pertain to any geometric IMU form factor developed with the folded IMU fabrication process described in Chapter 2.

7.3 Complete IMU Error Model

As discussed earlier in this chapter, several errors for accelerometers and gyroscopes have been discussed. Specifically, bias, scale factor, and temperature misalignment errors are evaluated for the individual sensors, as well as the resulting effects on the entire IMU system. However to provide a complete error model, all error terms must be combined into a single algorithm. A block diagram of this algorithm for the IMU pyramid is shown in Figure 7.1, which includes gyroscope errors, accelerometer errors, and the CEP rate calculation.

Each type of error is calculated separately using experimental values from existing sensors compatible with the folded MEMS IMU fabrication process. Gyroscope bias is assumed to be 0.9°/hr as reported in [40], which represents the fundamental minimum level of detection under ideal conditions. This error is constant, and thus is populated into a matrix to enable coordinate transformation and direct addition to the overall error after integration. Initially, the reported value is converted to rad/s, and is then integrated with respect to the total time that the IMU is operating. In this example, the duration is 146 seconds. After integrating, the bias error matrix multiplied by a coordinate transformation matrix to convert the values
Figure 7.1: System error model block diagram for an IMU pyramid including all errors and coordinate transformations considered
from the IMU pyramid form to orthogonal coordinates with a sidewall angle of $\theta_{sw}$. This calculation assumes a $60^\circ$ angle of each sidewall with respect to the baseplate. However other angles can be implemented for other tetrahedral IMU designs.

Bias error for accelerometers is calculated in the same fashion. A compatible accelerometer has been experimentally determined to provide a bias error of $6 \, \mu g$ [69]. Once converted to $m/s^2$, the matrix values are all integrated twice with respect to time to obtain total distance error. A coordinate transformation is then applied to convert the bias error values from the pyramidal IMU body frame to the orthogonal frame of the vessel. The figure shows a transformation matrix for the IMU pyramid form factor, and is also applicable to the IMU cube form factor by using identity matrices in place of the coordinate transformations shown.

Scale factor error is also calculated for gyroscopes and accelerometers. For gyroscopes, the scale factor error utilized in the simulation is 1 ppm [70]. This value is first converted to units that can be directly multiplied by the actual input data to the IMU system. Actual rotation rate and acceleration matrices are provided by the trajectory definition. Next, the vectors of each matrix are integrated with respect to time, and afterward added to the initial rotation rate and acceleration values. Then the matrices are transformed from the IMU body to the orthogonal frame. For the IMU cube, these transformations are defined to be the identity matrix, and thus is not separately shown.

Accelerometer scale factor error is calculated using a value of 0.52% [69]. This value is multiplied by the acceleration values obtained from the trajectory definition after converting from percent to an equivalent multiplication factor by dividing the value by 100. Initial velocities are added after the first integration, and the second integration converts the values to the total amount of distance error due to accelerometer scale factor error.
Temperature cycles

Misalignment of IMU pyramid structures is measured after thermally cycling from room temperature to -40 °C and 85 °C, respectively. Before testing, angular position of the sidewalls is measured. The IMU structure is then mounted inside a thermal chamber (TestEquity model 107) and heated to 85 °C. After holding the temperature for 25 minutes, the IMU is gradually cooled to room temperature. Once steady-state temperature of the folded structure is reached, detection of misalignment is conducted to determine the effects of the process. The same process was performed and the corresponding misalignment data obtained after thermally cycling the IMU from room temperature to -40 °C. Results indicate a maximum angular sidewall variance for an epoxy-bonded IMU structure of 1.6 mrad and 3.0 mrad for heating and cooling cycles, respectively.

Temperature shock

Thermal shock is also performed on the folded IMU pyramids, both for cold and hot temperatures. After measuring the initial angular position of each sidewall, the structures are transferred into an 85 °C environment with a transition period of approximately 3 seconds. Temperature is maintained for 25 minutes to ensure the entire structure is at steady-state. The pyramid is then transferred to room temperature within approximately 3 seconds to apply a negative thermal shock. Utilizing the same procedure, folded IMU pyramids are exposed to thermal shock from room temperature to -40 °C, then back to room temperature. Each experiment is repeated three times consecutively for each the hot and cold temperature tests to determine the effects of multiple cycles. Misalignment data from each sidewall on an epoxy-bonded pyramid results in a maximum variance of 3.0 mrad and 3.5 mrad for the 85 °C and -40 °C thermal experiments, respectively.
Constant acceleration

For applications in which acceleration loads are constantly applied, folded MEMS IMU structures must withstand the forces involved. To determine suitability for such purposes, constant acceleration is applied to IMU pyramids by rotating the devices on a centrifuge with a known rotation rate. Loading is applied to the folded structure along three independent axes by mounting the IMU at orthogonal angles for each experiment. The setup is capable of providing up to 60 g of acceleration on the test sample. Misalignment of the sidewalls is measured before and after the experiment, yielding a maximum angular variance of 1.8 mrad between sidewalls for an epoxy-bonded IMU structure.

Results of all alignment stability tests comparing epoxy and solder-bonded IMUs is shown in Table 5.2. Structures reinforced with epoxy show a maximum alignment drift of 3.5 mrad or less under each applied environmental condition. In contrast, the soldered structures provide stability better than 0.2 mrad. The lower limit of detection of the measurement setup is approximately the same, therefore the misalignment of the solder-bonded structures is likely much lower than the measured data. These results indicate feasibility of reinforced 3-D folded MEMS structures for a wide variety of environmentally robust IMU applications.

Figure 7.2: Optical photograph of a MEMS gyroscope integrated on the pyramid IMU sidewall.
Mechanical shock

Utilizing the FEA model described, shock loading is simulated for the pyramidal IMU structures. Shock is applied using gun-hard parameters with an amplitude of 30,000 g over an interval of 7 ms. Applying these parameters to the model along each X, Y and Z directions yields a maximum misalignment of 0.5 mrad and stress of 200 MPa. Comparing the stress induced to the 7000 MPa yield strength of silicon, the structure will not fail under gun-hard conditions. For most applications, the slight misalignment produced during the simulation will not adversely affect the IMU data. Shock was also applied experimentally using an impact bar and a striker, with the pyramid under test mounted to the end of the bar. A Polytec laser vibrometer is focused onto the top of the pyramid to measure the acceleration induced into the structure. Tests show that the structures are capable of surviving up to 389 g of acceleration over a 0.5 ms time interval. It is believed that the structures will survive higher values of acceleration, however the test setup is capable of approximately 400 g.

7.3.1 Misalignment in Simulated Error Model

The majority of the errors discussed above require a very sophisticated algorithm involving many parameters if desired to be included in the mathematical error model. For example, it is difficult to mathematically describe the effects on the IME structure over time as is described for thermal cycling. However one error considered in the simulation is misalignment due to temperature change. For both gyroscopes and accelerometers, this error is experimentally determined to be 0.0002 rad for solder-reinforced structures. Because this error occurs similarly for pyramidal and cubic IMU geometries, errors from each type of sensor are calculated with the same value. This measurement is done with the IMU structures heated to a temperature of 80°C (60°C above room temperature of 20°C), with δ representing the
angular error factor. This information is extrapolated to estimate misalignment at 150°C, which is a common maximum operating temperature of existing devices. This conversion is done prior to multiplication of the rotation matrices needed to convert the IMU pyramid data to the orthogonal vessel frame. Determination of the total error induced requires multiplication by the input rotation rate or acceleration values provided by the trajectory definition. The resulting error is then added to the actual inertial input to obtain total distance and angle estimates from the folded IMU system. Finally, these values are transformed from the IMU body frame to the orthogonal frame (coordinate transformation for cubic IMU’s is defined as the identity matrix). Worst-case scenario operation is determined by utilizing the absolute value of the resulting data since some errors counteract each other. This algorithm for temperature misalignment error calculation is included in Figure 7.1.

Since the gyroscopes are informing the IMU of the current orientation, the accelerometer signals are calculated on an axis that differs from that of the actual trajectory. Hence the sensed acceleration is calculated along the orientation axes defined by the gyroscopes. This introduces a system-level error that causes an increase in the distances measured by accelerometers. Gyroscope error is added to the accelerometer error algorithm similar to other accelerometer errors. First the gyroscope error data is transformed to the IMU body frame by an array of rotation matrices. Then it is multiplied by the actual acceleration values and integrated with respect to time. Initial distance and velocity are included in this calculation. The result is added to the overall distance error computed in the simulation for a folded MEMS IMU system.

A standard for evaluating IMU performance can be observed using the circular error probable rate error. Generally this value is calculated statistically from tested projectiles and the distance from which they land compared to the target location. In this situation, the CEP rate error is determined by counting the number of projectiles that terminate within a radius that is 50% of the maximum variance. However for this work, statistical data is
not possible. Therefore the calculation for the CEP rate is performed by assuming that the area of the circular area of termination points is half of that of the circular area defined by the worst-case distance from the targeted location. For this reason, the total distance variance between that of the actual data and the IMU calculations is multiplied by a factor of $\sqrt{2}$, which is equivalent to a circle with 50% of the area of that by a circle with a radius of the maximum error. The total distance is also divided by time to obtain a rate value. A conversion is then performed to obtain a CEP rate error in units of nautical miles per hour. This value can be used to evaluate the overall performance of the IMU for the given vessel trajectory.

7.4 Error Model Implementation

It is necessary to determine how the folded IMU approach would perform in an end-use application to compare the folded IMU approach to that of current devices with a similar footprint area. Because of the modular capability of the folded MEMS approach, it allows for a wide variety of sensor designs that have well-known characteristics [40, 54, 69]. However the characteristics measured do not include all types of error described. In addition to bias and scale factor behavior, measurements have also been performed to provide information on how the folded structure reacts under various temperature conditions [45, 46]. With this data provided as described in Section 5.5.1 it makes it possible to simulate an operational folded IMU for pyramidal and cubic folded IMU form-factors to determine the accumulated errors of each. This chapter discusses a computational model created in Matlab utilizing data from existing sensors with known error parameters. Error data is collected from SOI sensor designs that are compatible with the folded IMU fabrication process [40, 69, 70].

Several different sources of error are known for inertial sensors as described within this chapter and in more detail in Appendices C and D. However many are not commonly mea-
sured or published. Therefore there are only a small collection of errors that can be considered in order to compare overall performance of the folded IMU devices to similar existing devices. In the Matlab model used for this work, the implemented errors include effects from bias, scale factor, and misalignment due to temperature. Errors induced into the overall IMU system are also included in the simulation calculations, such as that defined in Appendix D.

Table 7.2 shows the values used for each sensor on the cubic and pyramidal folded IMU structures. Each of these values are based on measured values for existing devices that are compatible with the folded MEMS IMU fabrication process.

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Measured Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gyroscope Bias</td>
<td>0.9 °/hr</td>
</tr>
<tr>
<td>Gyroscope Scale Factor</td>
<td>1 ppm %</td>
</tr>
<tr>
<td>Accelerometer Bias</td>
<td>6 µg</td>
</tr>
<tr>
<td>Accelerometer Scale Factor</td>
<td>0.52 %</td>
</tr>
<tr>
<td>Temperature Misalignment at 85 °C</td>
<td>0.2 mrad</td>
</tr>
</tbody>
</table>

Table 7.2: Error values included in computational error model [40, 45, 46, 69, 70]

7.4.1 Error Calculations

Many of the errors being considered have been previously derived, with the details shown in Appendixes C and D. The implementation of each into a computational simulation is quite similar to the process of derivation. Each error must be transformed to the correct coordinate frame and then integrated to determine the cumulative attitude and position errors. Overall, the goal is to compare the effects of temperature misalignment to the bias and scale factor errors. Theoretically, the silicon skeleton that houses the folded IMU sensors is more robust to changes in temperature when compared to other fabrication methods. Data has been collected for sidewall misalignment of the folded IMU structures under a known temperature change from 25 °C to 85 °C, as shown in Table 7.2. Additionally, because of the large amount of usable sensor area provided by the folded MEMS approach, the sensors are capable of
much higher performance compared to other chip-scale IMU devices. It is hypothesized that
the combination of these design aspects, the folded IMU units are capable of performing
much better than other devices with a similar footprint area.

**Misalignment Due to Temperature**

As mentioned above, a main goal of this study is to compare a structurally ideal IMU to a
realistic device, specifically with temperature misalignment effects. For an ideal structure
that is not affected by temperature effects, only bias and scale factor errors induced by the
sensors are considered in the simulation. Data has been obtained on how the folded IMU
structures react to thermal expansion due to an increase in temperature. Results show that
for structures reinforced with epoxy, a temperature increase from 25 °C to 85 °C causes an
angular deflection of 1.7 mrad for each sidewall. However when reinforced with solder, this
value is reduced to less than 0.2 mrad [45, 46]. Assuming a linear relationship of angle versus
temperature, this can be expressed as shown below for all axes of each individual sensor.

\[
\theta_{TM,n}^n = K_{TM,x} \cdot \frac{T - 25}{60} \quad (7.1)
\]

\[
\phi_{TM,n}^n = K_{TM,y} \cdot \frac{T - 25}{60} \quad (7.2)
\]

\[
\psi_{TM,n}^n = K_{TM,z} \cdot \frac{T - 25}{60} \quad (7.3)
\]

In these equations, \( \theta_{TM,n}^n \) represents the angle about the x-axis of the \( n^{th} \) sensor on the
IMU sidewall. The same follows for \( \phi_{TM,n}^n \) and \( \psi_{TM,n}^n \) for the angles about the y-axis and z-axis
of each sensor. The coefficient \( K_{TM} \) is the angle measured at 85 °C and \( T \) is the temperature
of the IMU in degrees Celsius. Once these misalignments are calculated, they are added to
the error model using similar equations to those previously derived in Appendix C.2.

\[
\vec{E}_{ma,n}^b = \int \int \vec{e}_{ma,n}^b \, d^2t = \vec{v}_{0,n} \cdot t + \frac{1}{2} \vec{e}_{ma,n}^b \cdot t^2
\]  \hspace{1cm} (7.4)

\[
\vec{E}_{mg,n}^b = \int \vec{e}_{mg,n}^b \, dt = \vec{\psi}_{0,n} + \vec{e}_{mg,n}^b \cdot t
\]  \hspace{1cm} (7.5)

### 7.4.2 Error Model Algorithm

Several errors have been discussed for the folded IMU sensors. A selection of known errors are used to create a simulated model. This first task involves defining an appropriate trajectory. For this work, it is assumed that the vessel of concern is a guided projectile. While most of the journey is likely controlled by GPS navigation, it is often that the satellite signal transmissions are jammed when approaching the target site [72]. When this occurs, the responsibility of the IMU is to provide guidance for the remainder of the trip.

In order to compare the potential performance of a folded MEMS IMU with other devices traveling along the same trajectory, a standard unit of measure must be defined. This is done by comparing the circular error probable (CEP) radius and rate measurements, which is generally determined statistically from the resulting termination point of several samples guided toward a specific trajectory. The radial diameter from the ideal endpoint of the trajectory to the actual termination point of each projectile is measured. The CEP radius is defined as the radius inside which 50% of the projectiles land. Since statistical information is not available for this work, it is assumed that the CEP radius is \(\sqrt{2}\) multiplied by the worst-case scenario distance error. Calculating the CEP rate is then done by dividing the CEP radius by the amount of time that the IMU is governing navigation and then converting it to nautical miles per hour to compare with well-published standards for other IMU devices.
(a) Front view: sensors #1 and #4  
(b) Back view: sensors #2 and #3  
(c) Two sidewalls removed to show sensors #5 and #6 on bottom panel

Figure 7.3: Locations of sensors on the pyramidal IMU three accelerometers and three gyroscopes.

7.4.3 Simulated Trajectory Definition

For simulation purposes, a path of travel has been defined to determine the overall error induced into the system during operation. A potential application for the folded IMU devices is tracking position and orientation of a vessel when GPS navigation is not available. This could be due to lack of satellite signal strength, a malfunction of the GPS navigation system, or from the GPS signals being jammed by a separate party. For this work, a temporary lapse in GPS navigation is assumed to occur for approximately 2-3 minutes. For this duration of time, navigation capabilities are dependent upon the IMU for tracking position and attitude of the vessel. This situation is not uncommon in the defense industry when a vessel is being guided toward a target. When nearing the target location, the GPS signals can be jammed with known techniques, and all navigation guidelines rules on the IMU sensors for the last few minutes of flight.

Considering the situation described, an appropriate trajectory is defined as an arched path going from zero altitude, then rising and undergoing various course corrections, and finally decreasing altitude and terminating near the intended target. Defining navigation trajectories in Matlab has been conducted by others in the field, and therefore a third-party source was utilized for the purpose of defining an applicable flight path [73]. Using this algorithm, acceleration and rotation rates are calculated which are used for inputs to
the IMU simulation model. The specific file, obtained from www.instk.org, that is used for the trajectory definition is ‘PathGen_v003.mat’, and requires an input matrix, ‘mot_def’, which is used to define the motion path. This function requires an input consisting of a list of course corrections in the proper format to define the input motion matrix. It assumed in this algorithm that the positive x-axis direction is aligned with the forward travel and the positive z-axis is upward, both with respect to the vessel orientation. The positive y-axis corresponds to the proper direction using the right-hand rule. With this information considered, the course corrections are defined as follows:

(I) Initial orientation of 45° about the y-axis, -45° about the z-axis, and an initial x-axis velocity of 100 m/s

(II) Rotation of 15° about the y-axis

(III) Rotation of 30° about the y-axis, and a rotation of 15° about the z-axis

(IV) Rotation of -10° about the y-axis, and a rotation of -30° about the z-axis

(V) Rotation of 15° about the y-axis, and a rotation of 15° about the z-axis

(VI) Rotation of 15° about the x-axis, rotation of 15° about the y-axis and a rotation of 15° about the z-axis

(VII) Rotation of -15° about the x-axis, and a rotation of 30° about the y-axis

Each of the course corrections occur at approximately 20 second intervals, resulting in a total time of 146 seconds for the flight. The initial velocity, along the x-axis direction, is not changed throughout the entire trajectory. This is done to simulate a vessel powered with a constant forward thrust, reaching steady-state velocity after the first several seconds of travel. It is likely that the IMU will not be utilized until later in the flight when GPS signal detection is lost. The course corrections above are defined such that all inertial sensors
in the IMU are utilized, and thus their corresponding error is added to the total measured trajectory error. Figure 7.4 shows a 3-D plot of this trajectory, which reflects the data that will be used as a basis for the various errors being considered for the folded IMU devices.

![3-D plot of trajectory](image)

Figure 7.4: Ideal trajectory path defined for a vessel with a travel time of approximately 2.5 minutes

### 7.4.4 Results

Utilizing the above trajectory for the simulation, a Matlab model is used to determine the measured paths of travel for both the pyramidal and cubic folded IMU devices. Because different methods of IMU reinforcement have been explored, results are produced for each approach. Misalignment measurements were previously conducted for solder-reinforced and epoxy-reinforced IMU structures, and both are considered in the simulations using the values given in Table 7.2 [45, 46].

With the error calculation algorithms derived in this chapter, errors are calculated for
the folded IMU devices in the simulated model. These errors are then added to the ideal trajectory to show the error-induced deviation from the actual path of the vessel. Many errors that have been described in this chapter are known to exist, but some are commonly not reported or measured by the manufacturers. Examples of which would be scale factor asymmetry and anisoelasticity of gyroscopes and accelerometers. Therefore, the only errors included in the Matlab simulation model are bias, scale factor, and misalignment due to temperature changes. An ambient temperature of 150°C is utilized as the worst-case scenario because it is a common maximum operating temperature for chip-scale devices. Figure 7.5 shows the simulation results for an IMU cube with temperature misalignment error compared to scale factor and bias error, as well as the ideal trajectory of the vessel.

Because bias error and scale factor error occur in the sensor frame, the errors from each are combined. However since temperature misalignment error affects the entire IMU body, it is considered separately. This is done to differentiate the individual sensor errors from that of the IMU structure errors. Structural evaluation due to an elevated temperature of the folded IMU devices can be determined using the measured values in Table 7.2. The measurement process details for obtaining these errors is discussed in Section 5.5.1. Using these values in the simulation, effects of error from the folded MEMS silicon skeleton can be compared to other devices independent of sensor performance.

Simulation results for an IMU cube reinforced with solder is shown in Figure 7.5(a). Observing the figure, it is noticed that there is a minimal amount of error induced by misalignment due to exposure to a temperature of 150°C. In this case, the CEP radius and rate are respectively calculated to be 367 m and 4.91 nautical miles per hour, Table 7.3. Note that the CEP rate is calculated by dividing the CEP radius by the total time of the flight trajectory (146 s). In contrast, results from the same simulation considered the IMU cube reinforced with epoxy, shown in Figure 7.5(b), yield values of 552 m for the CEP radius, and 7.46 nmi/hr for the CEP rate. For this case, the error induced from temperature
misalignment is much larger for that of an epoxy-reinforced folded MEMS IMU structure.

When analyzing the pyramidal IMU devices in the same manner, the results indicate slightly better performance. For epoxy-reinforced IMU pyramid structures, the simulation at 150°C, shown in Figure 7.6(b), gives a CEP radius of 482 m and a CEP rate of 6.45 nmi/hr. However for a solder-reinforced pyramidal structure shown in Figure 7.6(a), the values are calculated to be 362 m and 4.85 nmi/hr. While this shows that the IMU pyramid devices seem to perform better, the difference in results from that of the cube are minimal.
When comparing the results at an elevated temperature of 150°C versus room temperature operation, the results are inevitably better as reported in Table 7.3. But it is not reasonable to assume that the IMU will be exposed to constant room temperature. Therefore the results for elevated temperature are assumed to be more accurate. Also, it is to be noted that the values in Table 7.3 for the room-temperature simulations are the same for epoxy- and solder-reinforced structures. This is due to the fact that the reinforcement method does not affect the error if elevated temperature is not considered. As expected and shown by the simulations, the devices reinforced with epoxy are not able to perform as well as folded
MEMS IMU’s reinforced with solder. Therefore with solder-reinforced IMU structures, it is determined that the silicon skeleton is suitable for MEMS IMU devices with suitable performance for short-term navigation \[57\].

Results from the simulation indicate that the pyramid and cube are similar in performance based on the calculated CEP rate values. Error induced from temperature misalignment is determined to be insubstantial for the solder-reinforced structures, Figure \[7.6(a)\]. However for the epoxy-reinforced pyramid results shown in Figure \[7.6(b)\] the error from temperature misalignment is observed to be comparable to the bias and scale factor errors. Additionally, the CEP rate error values for each form-factor are comparable to existing high-performance devices that use silicon MEMS technology \[57\]. Therefore it is determined that the folded silicon structure is an adequate platform for inertial measurement purposes.

<table>
<thead>
<tr>
<th>Reinforcement Material:</th>
<th>CEP Radius (m)</th>
<th>CEP Rate (nmi/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cube, bias and SF error only</td>
<td>348</td>
<td>348</td>
</tr>
<tr>
<td>Cube, add temperature error</td>
<td>552</td>
<td>367</td>
</tr>
<tr>
<td>Pyramid, bias and SF error only</td>
<td>347</td>
<td>347</td>
</tr>
<tr>
<td>Pyramid, add temperature error</td>
<td>482</td>
<td>362</td>
</tr>
</tbody>
</table>

Table 7.3: Calculated CEP radius errors (m) and CEP rate errors (nautical miles/hr) for pyramidal and cubic IMUs reinforced with epoxy and solder.

Further determination of the performance for cubic and pyramidal folded IMU structures is done by observing the overall CEP rate, as defined in Section \[7.4.2\]. Each simulation also calculates a CEP rate value by finding the radius of a circle that has an area of one-half of a circle defined by final distance error measured. All resulting CEP rate values for each type of simulation are reported in Table \[7.3\].
7.5 Conclusion

A simulation has been created to determine the overall performance of the folded IMU devices with different reinforcement methods (solder and epoxy). Models for each the cubic and pyramidal form-factor have been implemented using Matlab. Evaluation of performance for both IMU geometries and both reinforcement methods have been simulated by calculating the CEP radius and rate values for each worst-case possibility. Results indicate that at room temperature, the pyramidal folded IMU predicted to perform nearly equal to that of a cubic IMU configuration. However at an elevated temperature of 150 °C, the pyramidal form-factor performs slightly better, as reported in Table 7.3. Each of the CEP rate values fall between that of medium- and low-performing IMUs [57]. Considering that existing silicon MEMS IMU devices are included in the low-performance category, the values achieved for the folded MEMS IMU’s appear to be better than those using similar fabrication and computational techniques. Therefore, the folded MEMS IMU approach integrated within an overall IMU system is capable of higher accuracy compared to existing chip-scale devices.

Considering the calculated CEP rate errors, a comparison is made between cubic and pyramidal IMU form-factors. Because the bias and scale factor errors occur in the sensor frame, the reinforcement method does not affect the final error induced by the IMU assembly. Results are summarized in Table 7.3 and indicate a significantly larger CEP rate value for epoxy-reinforced folded IMU structures, as is expected. Conversely, solder-reinforced IMU structures have a relatively insignificant effect on the overall error results because it is more robust under temperature changes. Comparing the solder-reinforced cubic and pyramidal IMU structures, the pyramidal geometry has a slight performance advantage at higher operating temperatures compared to a cubic geometry.
Chapter 8

Conclusions and Future Work

8.1 Summary of Results

Several aspects of developing an innovative method for manufacturing MEMS IMU devices have been explored through an approach that uses folded MEMS structures. One focus of this approach was to fabricate in-situ single-axis SOI inertial sensors onto a folded silicon skeleton which would then be folded into a 3-D structure to enable 6-DOF detection. A fabrication process has been created after multiple iterations of development, described in Chapter 2. Utilizing the fabrication processes presented in this work, operational accelerometers and gyroscopes are fabricated on the folded IMU structures and then characterized, Chapter 4. Frequency modulation was used for acceleration detection, and frequency-amplitude modulation was used for gyroscopes to detect rotation rate. Accelerometer results yielded a sensor scale factor of 3.7 Hz/g, and the gyroscope testing yielded a scale factor of 0.43 mV/(deg/sec), Section 4.3. Signals of this level are easily detected with current electronics. Therefore the characterization results indicate feasibility of the overall fabrication process to be used for creating operational folded MEMS IMU devices.
Pyramidic and cubic IMU geometric configurations have been investigated and created using the fabrication processes presented in Chapter 2. Rigidity of the structures was analyzed, and methods for reinforcement were explored using additive epoxy or solder for reinforcement materials, as well as silicon welding. Alignment stability of epoxy- and solder-bonded IMUs was experimentally investigated under environmental loads including constant acceleration, temperature, thermal cycling, and thermal shock, Chapter 5. Reinforcement with epoxy results in modal frequencies occurring above 10 kHz, which is suitable for most inertial measurement applications. Bonding with eutectic solder provides much higher rigidity, with the first mode occurring above 50 kHz and therefore will be implemented in harsh vibrational environments. Although a pyramidal shape has been initially explored, other polyhedral form factors can also be implemented. Experimental results confirm feasibility of the proposed folded MEMS IMU approach, and may enable new integrated architectures for other multi-axis dynamic sensors.

A complicated packaging sequence must be performed after fabrication is complete to enable experimental characterization of the sensors on the IMU sidewalls. Anchors located on the sensors need to be connected to the bond pads located on the polyimide substrate that subsequently connect to the bottom of the cube. This can be done using glass lids fabricated with electrical interconnects and flip-chip bonded to the sensors. After assembly of the lids, the overall IMU is mounted to an electrical interconnect plate that brings all electrical connections out to bond pads accessible with a wirebonder. The interconnect plate also functions as a lid for the bottom sensor.

To finalize the packaging process, the IMU cube with the interconnect plate attached was mounted inside a DIP package and wirebonded. A minimum number of 40 connections is required for all six sensors to function properly. The size of the DIP package must also be rather large, therefore 40-pin over-sized packages have been utilized.

In addition to creating a fabrication process and developing physical folded MEMS IMU
devices, analytical analysis has also been performed. The mathematical simulation translates
the single-axis sensor signals to the coordinate frame of the chip. The algorithms provided
in this work are specifically related to a cubic and pyramidal IMU form factor. Given
the modularity of the fabrication process, the capacity of possible form factors is limitless.
However the procedure described is applicable to any other shape implemented with folded
MEMS technology. All that is needed is a mathematical description of the geometry in
which the IMU is created. Included in this coordinate transformation algorithm is mapping
of the sensor signals to the chip coordinate frame, misalignment of sensors after fabrication,
and also misalignment due to dynamic vibration. Other misalignments, such as thermal
expansion, are not described because the complex form factor complicates analytical analysis
of such errors. However for predictable misalignments and defined IMU shape geometries,
this algorithm can easily be implemented into a navigational computer for implementation
in nearly any application.

A more detailed description of error sources has also been explored which considers not
just misalignment, but other sources of errors as well. These errors mostly pertain to the
sensors themselves, but some also influence the entire IMU system. Existing literature
presents many different types of errors, and this work describes the errors applicable for
single-axis MEMS sensors and are tailored to the folded MEMS IMU approach. Sensor-
level errors explored include bias, dynamic misalignment, scale factor errors, noise, and
anisoelasticity. On the system-level, tilt misalignment and the effect of gyroscope bias on
the entire system were described.

A simulation has been created to predict the performance of the folded MEMS IMU
devices for a defined trajectory. In nearly every case, the folded IMU theoretically is capable
of much smaller error sources than when compared to existing chip-scale IMU technology.
This is largely due to the fact that the amount of surface area versus the footprint size
is larger than other devices that are currently available. Another advantage of the folded
MEMS devices is the capability of silicon welding after fabrication. This largely increases
the rigidity of the structure, which significantly increases the performance capabilities of the
IMU system. In a large majority of the errors described, these advantages prove that the
folded MEMS IMU technology has a large potential to create inertial navigation devices that
have higher performance than existing devices, with the same chip-level footprint area.

8.2 Future Work

A large bottleneck in the development of a reliable fabrication process for creating folded
IMU structures is backside etching. Several samples in the past have experienced cata-
strophic failure during processing or suffer from stubborn contamination after fabrication is
complete. Both situations are determined to be caused by improper selection of handle wafer
attachment material. Results using a combination of AZ P4620 photoresist, protective tape,
and thermal grease show that yield of operational devices is very low. Thus the challenge
must be addressed. An on-going effort is continued to determine the optimal material for
attaching a handle wafer that performs well during DRIE etching, and can be easily removed
afterward without contaminating the devices.

While the above process is suitable for fabrication of SOI sensors, it is not entirely com-
patible with the fabrication of the folded IMU devices. Due to the existence of polyimide
and metal on the samples, a different process must be explored for releasing SOI devices.
One challenge is preventing the metal and polyimide from being damaged due to exposure
to hydrofluoric acid. In general, HF causes delamination of the polyimide from the silicon
substrate, and for longer exposures also effects the adhesion of metal traces to the polyimide.
Three possible solutions are:

(I) Use an oxide etchant compatible with polyimide and metal
(II) Mask the damaged areas with a material compatible with oxide etchants

(III) Increase adhesion between polyimide and silicon substrate

8.2.1 Increased Polyimide Adhesion

As mentioned above, an additional idea for eliminating delamination of polyimide during sensor release involves improving adhesion of polyimide to silicon. Motivation for developing this process arises from being able to define electrical interconnects directly onto sensor bond pads rather than having to use wirebonding to provide connections. Moreover, this technique can also improve polyimide adhesion in two manners:

(I) Increasing surface roughness of the substrate due to aggressive DRIE etching of silicon.

(II) Minimizing exposure to the adhesion layer by burying it 20-30 µm beneath the substrate surface.

While the rough surface provides much better adhesion, sidewall protection of the polyimide features will further minimize etchant penetration, eliminating delamination effects currently being experienced.

8.2.2 Handle Wafer Attachment Methods

Thermal Grease and Silicone Oil

Another alternative method for carrier wafer bonding is to use a mixed solution of thermal grease and silicone oil on top of two layers of photoresist. A layer of LOR 10A photoresist is first applied, which is compatible with higher temperatures. This prevents sensor
contamination from the AZ P4620 photoresist because the contaminants will be deposited onto the LOR 10A. Additionally, it should be easily removed with multiple types photoresist developers, which should lift-off the AZ P4620 photoresist residue without the use of oxygen plasma for removal. After spin-coating the photoresist layers, approximately equal portions of grease and oil are mixed together and applied to the fabrication wafer. A consistent, flat layer of the emulsion is created by horizontally smoothing the surface with a flat tool. The carrier wafer is then placed onto the wet surface and pressure is applied to adhere the two wafers. Figure 8.1 shows a cross-section illustration of the wafer stack using this potential bonding method.

![Figure 8.1](image)

Figure 8.1: Two layers of photoresist and thermal grease mixed with silicone oil to adhere a carrier wafer to the front side of fabrication samples.

Rather than using thermal grease in its original form, mixing it with oil makes it much easier to remove after etching. By immersing the sample in acetone, the oil and grease should be dissolved to reduce the contamination previously noticed. Another advantage of this process is that no tape is required. Without the use of tape, air pockets that were observed earlier will not be an issue with this process. One concern, however, is that thermal grease is directly contacting photoresist, and could mix to create a stubborn residue. While this is likely not an issue during backside etching, it may cause a problem when dissolving the grease/oil mix and AZ P4620 in solvents. Another challenge is maintaining the properties of the LOR 10A photoresist when dissolving the wafer stack after backside etching is complete. Acetone cannot be used because it chemically reacts with the photoresist to create a different type of polymer not easily removed with developer. For this reason, the carrier wafer release process should be done using isopropanol rather than acetone. Although certain challenges
exist with this process, eliminating the use of protective tape is a significant advantage over other bonding methods.

**Crystalbond 555 HMP Wax**

A third solution for bonding a carrier wafer to the IMU fabrication samples is to use Crystalbond 555 HMP wax on top of photoresist. Similar to the method of using oil mixed with thermal grease, a layer of LOR 10A can be used to prevent potential contamination of the wax after fabrication. However instead of using a thick layer of AZ P4620, a layer of wax should be melted and spin-coated on top of the LOR 10A photoresist. Once coated and cooled to room temperature, the fabrication wafer can be placed on a hotplate to melt the wax again. While wet, the carrier wafer should be adhered and the entire stack removed from the hot plate to cool at room temperature. A cross-section of this proposed attachment method is illustrated in Figure 8.2.

![Diagram of Crystalbond 555 HMP wax attachment](image)

Figure 8.2: Attachment of carrier wafer using Crystalbond 555 HMP wax on top of LOR 10A photoresist.

A thick layer of wax is capable of being deposited using this process, and will entirely encapsulate all existing front side features. An advantage of this is that the layer of AZ P4620 photore sist would no longer be needed, and contamination of the front side features should be reduced. During bonding at elevated temperature, the surface of the carrier wafer will mount flush to the wax. With pressure applied during bonding, the top surface of the wax will directly contact all areas of the carrier wafer and flow to create consistent contact over the entire wafer area. Because of this, the need for thermal grease is eliminated. Removal of
the wax is done using hot water, which offers yet another advantage for folded IMU fabrication. After backside etching of the wafers is completed, the carrier wafer can be removed using water, which does not affect the LOR 10A photoresist beneath it. Subsequently the photoresist can be removed with developer after extracting each foldable IMU structure.

Potential difficulties with this process, however, are not avoided. One concern is that the melting temperature of the Crystalbond 555 HMP wax is 66 °C, which can be exceeded during the backside etch process. Most existing processes that utilize this material as a carrier wafer attachment method are done with surface-to-surface contact of each wafer. For this reason, only a small amount of wax is needed. Topology of the folded IMU samples, however, prevents direct wafer contact, and much more wax material is required. If temperature of the wafer stack exceeds the melting temperature of the wax while etching, material will extrude out from between the wafers and into the plasma chamber. This can be prevented, however, by conducting several etches of short durations to ensure the fabrication wafer remains below the flow temperature of the wax. Despite these disadvantages, Crystalbond 555 HMP wax offers multiple advantages over other carrier wafer attachment methods.

**Unity Polymer**

A more contemporary material for attaching the carrier wafer is Unity Polymer ASR-X5610. This polymer is designed as a sacrificial material that can be baked out rather than exposing samples to harmful solvents or plasma. It can also be dissolved in toluene or xylene as a wet removal process. For use in attaching the carrier wafer, it can be spin-coated directly onto the front side of the fabrication wafer. Solvents are baked out by then heating the wafer on a hot plate at 120°C. Bonding of the carrier wafer should be done thereafter by applying pressure and heat (170°C) to the wafer stack. Debonding can be performed after fabrication by heating to a higher temperature which greatly reduces the bond strength. Figure 8.3 shows a cross-section of the wafer stack using Unity Polymer ASR-X5610 as a
potential carrier wafer attachment material.

Figure 8.3: Cross-section of wafer attachment method using Unity Polymer ASR-X5610.

A main advantage of this process is that this particular model of the Unity Polymer, ASR-X5610, can be spin-coated at a thickness of up to 70 µ using one spin. This allows the front side features to be fully encapsulated, eliminating the need for a thick protective photoresist layer. Contamination from photoresist can therefore also be eliminated from the backside etch process. Additionally, thermal grease and protective tapes are not needed which further reduces the possibility of sensor contamination.

Unfortunately, for the folded IMU structures, the polymer cannot be baked out as instructed by the manufacturer. Temperatures necessary for bake-out of the ASR-X5610 Unity Polymer exceed the survivable polyimide temperature. Therefore it must be removed with solvents such as toluene or xylene. Exposure to these solvents may cause delamination of metal traces from polyimide as well as polyimide from the silicon sensor panels. Even though these challenges exist, this method provides significant advantages compared to other options.

8.2.3 Silicon Welding

For further characterization of the laser-welded silicon, samples must be created and their strength tested quantitatively. However, handling of the samples is quite difficult due to the fragility of the welded area. In most instances, the welded joint is broken upon removal of the samples from the welding setup. Improvements must be made to the current method
of mounting samples for welding experiments to allow easy removal afterward. Currently, custom clamps are used to firmly hold individual samples in place and folded structures are mounted to an aluminum block using double-sided tape. Along with the mechanical forgiveness of the manipulator stages, these methods have a lot of mechanical play in the processes of mounting and removing the samples. The motion induced from the mounting apparatus causes the samples to prematurely break while removing them from the test setup. Therefore a modified method needs to be determined for mounting the samples during welding.

Additional exploration should also be performed with various filler materials for laser welding the folded IMU latches. In this work, both silicon and silicon carbide was used in powder form. However other materials can also be used, ensuring that the thermal expansion properties are similar to that of silicon. For instance, another possible material is borosilicate glass, which has a nearly identical thermal expansion coefficient as that of silicon. An advantage of this material is that its melting point is much lower than silicon. Although it is transparent to light at the wavelength of a copper vapor laser, the silicon substrate can be heated to a temperature that melts the glass around the latches. With this method, the structure is essentially brazed together using a material with similar thermal properties. Moreover, utilizing a material with lower melting temperature than silicon, potential damage to nearby polyimide and metal is minimized.

8.3 Conclusion

A new method of creating chip-scale IMUs has been explored using folded MEMS structures rather than chip-stacking or single-die implementations. Multiple phases of fabrication have been developed to create 3-D silicon structures with SOI sensors located on each sidewall [8], resulting in a US patent [7]. Because the sensor fabrication process uses SOI technology,
almost any type of sensor design compatible with SOI fabrication can be integrated into the folded structures using the same process. This modularity aspect of the folded MEMS approach also allows for fabrication of other transducers instead of inertial sensors. Compared to other 3-D fabrication technologies, this is the first approach used that includes in-situ fabrication of SOI single-axis inertial sensors in the same process used for creating foldable silicon structures [25, 27, 29, 31].

A large challenge in the folded MEMS approach is packaging of the sensors after fabrication. Inertial test structures were designed and implemented on the IMU structures. Conventional packaging methods have been used such as wirebonding and flip-chip die attachment. Both methods have proven to be successful in the initial stages of development, and each approach yielded sensor responses. With the wirebonding method, frequency-modulated responses for gyroscopes and accelerometers were able to be measured. The scale factors were found to be 0.43 mV/°s for the gyroscopes and 3.7 Hz/g for the accelerometers, Figures 4.21 and 4.26. Both responses are easily detected with excellent resolution using current signal detection technology. Due to the infancy of integration of flip-chip packaging with the folded MEMS fabrication process, the results of this method were not as successful when compared to wirebonding. However the sensors did indicate response to electrical excitation, as described in Section 4.4. Despite being less successful, the detection of signals show that with further refinement the process could be successful. This also provides a path to use flip-chip packaging to fully encapsulate each sensor in a vacuum. Overall it seems that both methods are suitable for packaging the folded MEMS IMU sensors. However the flip-chip method is preferred due to the potential for full environmental protection and vacuum packaging of the sensors.

Another concern with the folded MEMS approach is the possible lack of overall rigidity of the structure due to its large size, which causes significant errors that are mainly due to environmental changes. Therefore, various methods were explored for reinforcement of
the 3-D structures, including solder application and silicon welding of the sidewall seams. Vibration test results indicate that the silicon welding provides significantly more rigidity than solder reinforcement, which is to be expected based on the material properties. As discussed in Section 5.5, the welded structures can withstand shock accelerations of over 260 g, and have a first-mode resonant frequency above 10 kHz. Additional structural testing indicates that the integrity of the welded structures is suitable for housing an IMU capable of performing well in most end-use applications [57].

Due to the 3-D form factors produced by the folded IMU process, the sensor axes will inevitably not be perfectly aligned with the desired navigational coordinates in any end use application. Therefore a coordinate transformation has been defined to translate the inertial sensor vector axes to the navigational frame. Such transformations were created for each the pyramidal and cubic folded IMU structures, Section 6.2. When comparing the resulting inertial acceleration and rotation rate matrices, it is observed that the cubic form factor has a theoretical advantage. Because each sensor axes are orthogonal to each other, data detected along the x-, y-, and z-axis utilize the full capability of the individual sensors. Alternatively, for the pyramidal IMU, a tradeoff is involved that causes some of the z-axis data to be transferred to the other detection axes. This is due to the trigonometric projection of the sense axis onto both the y- and z-axis of the navigational frame which can be observed by Equation (6.4e). While this might not be ideal for some applications, it could be advantageous in others. An example of which is for surface navigation purposes where the x- and y-axes of detection are of more concern than z-axis detection such as on the Earth’s surface.

Results discussed show that the folded MEMS fabrication approach is capable of producing operational sensors on the IMU sidewalls. Inertial test structures were evaluated and produced detectable results, but were also conservatively designed and not meant for high-performance but rather to test the feasibility of the approach. A simulated error model
was produced that evaluates the detection capabilities of the IMU over a given trajectory to determine the overall performance potential of operational end-use devices. The sensor characteristics used in the model are based on measurements from existing high-performance SOI sensors that are compatible with the folded MEMS fabrication process. Errors included in the model consist of bias error, scale factor error, and temperature error. Total CEP values and rates were determined based on a defined trajectory. The calculations consider various types of reinforcement methods for both the cubic and pyramidic form factors.

Comparing epoxy and solder reinforcement methods, the CEP rate calculations show that solder is superior in performance. For the cubic IMU, the CEP rates were determined to be 4.91 nmi/hr and 7.40 nmi/hr for solder and epoxy reinforcement methods respectively. Alternatively, the pyramidic IMU was determined to have similar respective CEP rates of 4.85 nmi/hr and 6.45 nmi/hr. These results indicate that overall, the pyramidic form factor performs slightly better than the cubic configuration. The resulting values show that the solder reinforcement method is significantly better than using epoxy. Using generally defined performance parameters for an IMU, the folded MEMS process shows to be capable of producing moderate-performance devices \[57\]. Silicon welding is theorized to provide higher structural rigidity and thus lower CEP rate values are expected compared to epoxy and solder reinforcement. Combined with the future potential for vacuum packaging with encapsulation lids and modularity of sensor designs that can be utilized, it is foreseeable that the folded MEMS process could be capable of creating high-performance chip-scale IMU devices.

A fabrication process has successfully been developed to manufacture folded IMU devices that have a footprint area of \(< 1 \text{ cm}^2\) with operational SOI sensors on the sidewalls. By using a 3-D structure, the available area for sensor construction is much larger than that of 2-D IMU chip devices. This allows for use of single-axis sensors, which naturally provide better performance than multi-axis devices. Structurally, using silicon has an advantage over several other materials because of its high rigidity-to-density ratio \[15\]. Packaging methods used for
the folded IMU sensors include conventional wirebonding, as well as flip-chip attachment with custom-fabricated encapsulation lids. While the wirebonding method provides better results at this point in development, flip-chip packaging offers a future path for full encapsulation and vacuum packaging of the inertial sensors.

A performance estimation of the capabilities of the folded MEMS IMU devices was simulated with a mathematical error model. The resulting calculated CEP rates indicate that the device is capable of moderate navigational performance in the current state of development. Implementation of silicon welding reinforcement and sensor vacuum packaging is possible, which would increase overall IMU performance and likely be able of producing a high-performance IMU [57]. An additional advantage to the fabrication approach is that by using SOI technology, it is a modular platform allowing for a wide variety of sensors other than accelerometers and gyroscopes [7]. Virtually any sensor that can be fabricated with SOI technology can be implemented on the folded structure sidewalls. Considering all of the results discovered and challenges encountered, the folded MEMS concept has shown that the approach provides new path for manufacturing high-performance chip-scale IMU devices.
Appendices

A Fabrication Recipes

A.1 Wafer Cleaning Recipes

A.1.1 Solvent Cleanse

1. Soak in acetone for 5 minutes.

2. Rinse with acetone for 30 seconds.

3. Before sample is dry, rinse with isopropanol for 30 seconds.

4. Before sample is dry, rinse with methanol for 30 seconds.

5. Dry with nitrogen gun, with flow toward tweezers.

6. Bake at 120°C for 30 minutes to dehydrate.

A.1.2 Plasma Cleanse: for wafers with organic residue

1. Clean with solvents as described above

2. Use oxygen plasma environment
3. Expose sample to plasma for 5-15min depending on residue amount

4. Bake at 120°C for 30min to dehydrate

A.1.3 EKC 830 Photoresist Remover

1. Heat EKC 830 solution to 40 °C in a glass dish.
   
   *Use higher temperatures for more aggressive cleansing.*

2. Immerse foldable IMU device into solution for 2 minutes.

3. Remove and place in acetone for 2 minutes.

4. Repeat steps 2 and 3 until photoresist is removed.

5. Do a final rinse in acetone for 2 minutes, followed by isopropanol for another 2 minutes.

6. Dry gradually by placing on a cleaning wipe on top of a hot plate at a temperature of 40 °C.

A.1.4 RCA-1 Cleaning Process

*Note: This process was obtained from the UCI INRF standard operating procedures.*

1. Add 325 ml of water, 65 ml of 27% ammonium hydroxide, and 65 ml of hydrogen peroxide to a glass dish.

2. Heat solution to 70 °C on a hot plate.

3. Once the solution bubbles rapidly for a few minutes, place the sample to be cleansed into the solution.

4. Keep the sample immersed for approximately 10 minutes.
5. Remove from solution and place in container with DI water constantly over-flowing.

6. After 10 minutes, remove from DI water and dry on a hot plate at 40 °C on a clean wipe.

A.1.5  HF Acid Cleanse: to remove oxide

1. Use 6:1 BOE, or create 20% HF mixture with water

2. Immerse wafer into acid for 30-60s

3. Rinse wafers with copious amounts of water and dry with nitrogen

4. Bake at 120°C for 30min to dehydrate

A.1.6  Surface Preparation for Photolithography

1. Bake wafers at 120 °C for a minimum of 30 minutes

2. Expose to oxygen plasma at 200 W for 5 minutes

3. Deposit HMDS onto the wafer in a vacuum oven at 100 °C using pump and purge iterations

   Requires ≈30 minutes

4. Apply lithography emulsion immediately

   Do not delay processing for more than 10 minutes to prevent absorption of humidity and excessive native oxide growth
A.2 AZ P4620 Photoresist Patterning

A.2.1 Sensor Patterning

1. Spread photoresist at 500 rpm for 10 seconds.

2. Spin photoresist at 5000 rpm for 40 seconds.

3. Bake in an oven at 90 °C for 20 minutes.

4. Expose using with I-line at light 10 mW/cm² of power for 25 seconds.

   This was performed on a Karl Suss MA6 mask aligner with a calibrated lamp intensity.

5. Develop in AZ 400K, diluted 3.5:1 with water, for 2.5 minutes, or until visibly observed that development was completed.

   Agitate every 15-20 seconds during development.

A.2.2 Sensor Open Mask Patterning

1. Spread photoresist at 500 rpm for 10 seconds.

2. Spin photoresist at 2000 rpm for 40 seconds.

3. Bake in an oven at 90 °C for 20 minutes.

4. Expose using with I-line at light 10 mW/cm² of power for 40 seconds.

   This was performed on a Karl Suss MA6 mask aligner with a calibrated lamp intensity.

5. Develop in AZ 400K, diluted 3.5:1 with water, for ≈3 minutes, or until visibly observed that development was completed.
Agitate every 15-20 seconds during development.

A.2.3 Dual Layer Photoresist Process

1. Spin on photoresist at 2000 rpm for 40 sec
2. Bake at 90°C in oven for 20 min
3. Repeat steps 2 and 3 to add a second layer of photoresist
4. Expose using an I-line lamp with 10 mW/cm² of energy for 100 sec
5. Develop in AZ 400K diluted 3.5:1 in water for 8 min

A.3 Application of LOR 10A Photoresist

A.3.1 Blanket Coating for Front Side Protection

1. Pour photoresist onto wafer such that nearly the entire wafer is puddled
2. Spread at 200 rpm for 10 seconds
3. Spin at 1000 rpm for 30 seconds
4. Bake at 180 °C on a hotplate for 5 minutes

A.4 Polyimide Deposition HD-4110

A.4.1 Initial recipe, which produced cracks in the polyimide

1. Ensure that the HD-4110 is frozen unless being used
2. Thaw polyimide for at least four hours, preferably overnight.

   *If the bottle is opened before being completely thawed, moisture will contaminate the polyimide and cause unpredictable results.*

3. Dehydrate wafer at 120°C for 30 minutes.

4. Puddle adhesion promoter VM-652 onto entire wafer, let sit for 10 seconds.

5. Spin dry at 2500 rpm for 30 seconds.

6. Activate by baking on a hot plate at 120°C for 1 minute.

7. Pour HD-4110 polyimide emulsion onto wafer.

8. Spread polyimide at 500 rpm for 10 seconds.

9. Spin polyimide at 1500 rpm for 40 seconds.

10. Bake on hot plate at 120°C for 12 minutes.

11. Expose with I-line light for 60 seconds.

   *Using a Karl Suss MA6 mask aligner with 10 mW lamp intensity.*

12. Bake after exposure on hot plate at 120°C for 5 minutes.

13. Soak sample in PA-401D developer for 2 minutes.

14. Spray sample with PA-400R rinse for 30 seconds.

15. Repeat steps 13 and 14 until pattern is fully developed (3-4 iterations).

16. Blow dry with nitrogen.
A.4.2  Modified recipe to prevent cracks in polyimide

1. Dehydrate wafer at 120°C for 30 minutes.

2. Puddle adhesion promoter VM-652 onto entire wafer, let sit for 10 seconds.

3. Spin dry at 2500 rpm for 30 seconds.

4. Activate by baking on a hot plate at 120°C for 1 minute.

5. Pour on liquid polyimide resin in a liberal amount.

6. Remove bubbles or push to edge of wafer with tweezers.

7. Spread at 500 rpm for 10 seconds.

8. Spin at 1500 rpm for 40 seconds.

9. Bake at 120°C for 12 minutes on hot plate.

10. Expose with I-line light for 60 seconds (10 mW intesity).

11. Bake at 120°C for 5 minutes on hot plate.

12. Immerse in solution of 200 ml PA-401D and 20 ml of PA-400R 2 minutes.

13. Spray PA-400R rinse on sample for 30 seconds in separate dish.

14. Repeat steps 12 and 13 until fully developed.

15. Blow dry with nitrogen (do not rinse with water).

A.4.3  Polyimide Curing Process

1. Prepare a nitrogen environment with ¡500 ppm of oxygen by purging.
Purge time required depends on the furnace size and nitrogen flow rate. However, a total of 6 times the volume of the furnace must be displaced.

2. Ramp from room temperature to 200°C at 7°C per minute.

3. Hold at 200°C for 30 minutes.

4. Ramp from 200°C to 375°C at 7°C per minute.

5. Hold at 375°C for 60 minutes.

6. Gradually cool to room temperature.

A.5 Metal Lift Off Recipe

A.5.1 Using Shipley 1827 Photoresist

1. Spin Shipley 1827 Photoresist onto sample at 2000rpm for 30s

2. Expose using MA-6 for 25s (much thinner than AZ4620, and can see alignment eatures underneath)

3. Develop using MF-319
   
   Soak for 1min, agitating every 15s, examine.

   Examine, if an extra 15s of development is needed, perform as above

4. Deposit metal (up to 0.25μm)

5. Soak sample in acetone overnight, remove extraneous material with squirt bottle

6. Dry with air or nitrogen
A.5.2 Using AZ nLoF 2035 Photoresist

1. Dehydrate on a hot plate at 110°C for 15 minutes.

2. Spread at 500 rpm for 10 seconds.

3. Spin at 1500 rpm for 30 seconds.

4. Bake at 110°C for 60 seconds on a hot plate.

5. Expose with 10 mW I-line light for 22 seconds using a MA6 Mask Aligner.

6. Bake again at 110°C for 60 seconds on a hot plate.

7. Develop in AZ 300 MIF for 40 seconds.

A.6 ProTEK A2 Removal

1. Prepare two baths of ProTEK Remover 200 at 70°C.

2. Immerse sample in bath #1 for 30 minutes.

3. Immerse sample in bath #2 for 30 minutes.

4. Rinse in isopropanol for 5 minutes.

5. Rinse in water for 5 minutes.

6. Allow to air dry completely (do not blow dry).
B Rotation Matrices and Notation

Coordinate transformations are conducted with a matrix that maps a vector from one coordinate frame to another. This is accomplished by defining an appropriate transformation considering the application at hand. Dimensions of the vector and mapping matrix can be infinite, however for the case of navigation, it is desired to use a system with three dimensions. Any spatial vector can be fully defined with such a system, and therefore the concentration of this study will follow suit. A general transformation using a mapping matrix $A$ to transform a vector $x$ to an alternative vector $b$ in a different coordinate frame is performed in the common simple equation below.

$$Ax = b$$

(B.1)

In the case of navigational calculations, $A$ is a 3x3 matrix with $x$ and $b$ both three-dimensional vectors. Creating the transformation matrix for spatial coordinates can be described in a sequential multiplication of rotation and translation transformation multiplied to create a single matrix. In the application of converting IMU signals to useful navigation data, direction of the vectors is of most importance. Therefore translation modifications are not usually necessary. Thus the focus of this research is focused on mapping vectors from one coordinate frame to another using only rotation transformations. While the definition of such rotation matrices is commonly known, they are defined below for the purpose of being thorough in this investigation.

$$C_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & \sin \theta \\ 0 & -\sin \theta & \cos \theta \end{bmatrix} C_y = \begin{bmatrix} \cos \theta & 0 & -\sin \theta \\ 0 & 1 & 0 \\ \sin \theta & 0 & \cos \theta \end{bmatrix} C_z = \begin{bmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

(B.2)

The rotation matrices describe coordinate frame rotations about $x$, $y$, and $z$ axes notated as $C_x$, $C_y$ and $C_z$, respectively. These matrices are useful in describing total transformations.
contrived in this chapter. Because the matrices are defined in a general format relating to a
single angle, \( \theta \), they must be modified to accommodate varied angles defined by the geometry
of the IMU. Because each rotation angle will inevitably have a different value, additional
variables are required to clarify information within the overall algorithm. Therefore it is
declared that a rotation about the x-axis is \( \theta \), a rotation about the y-axis is \( \phi \), and about
the z-axis is \( \psi \). Additionally, the rotation matrices can be defined as a function of each
respective angle to obtain

\[
C_x(\theta), \quad C_y(\phi) \quad \text{and} \quad C_z(\psi)
\]

where

\[
C_x(\theta) = \begin{bmatrix}
1 & 0 & 0 \\
0 & \cos \theta & \sin \theta \\
0 & -\sin \theta & \cos \theta
\end{bmatrix}
\]  
\[\text{(B.3)}\]

\[
C_y(\phi) = \begin{bmatrix}
\cos \phi & 0 & -\sin \phi \\
0 & 1 & 0 \\
\sin \phi & 0 & \cos \phi
\end{bmatrix}
\]  
\[\text{(B.4)}\]

\[
C_z(\psi) = \begin{bmatrix}
\cos \psi & \sin \psi & 0 \\
-\sin \psi & \cos \psi & 0 \\
0 & 0 & 1
\end{bmatrix}
\]  
\[\text{(B.5)}\]

Inertial navigation coordinate transformations can be created by successive multiplica-
tions of the rotation matrices in Equations (B.3) to (B.5). Any coordinate from can be
mapped to another with a combination of three multiplications using these matrices to re-
sult in a single transformation matrix. However the above definitions do not contain notation
information regarding the initial coordinate frame and the resultant coordinate frame. For
this reason, another notation definition is required. Subscripts and superscripts are included
in the definition of the matrix to allow this information to be portrayed. The superscript
denotes the resulting coordinate frame and conversely, the subscript denotes the original frame. For example, a transformation matrix for mapping vectors from frame \( a \) to frame \( b \), constructed of three successive multiplications of rotation matrices would be written as

\[
C^b_a = C_z(\psi)C_y(\phi)C_z(\theta)
\]  

(B.6)

where the rotation matrices correspond to the initial coordinate frame \( a \). While this definition is adequate for portraying the notation utilized for coordinate transformation matrices, it must be noted that the individual rotation matrices themselves must also include similar notation. This is due to the fact that after one rotation, the coordinate frame is different from the original frame. Figure B.4 shows successive rotations of frame \( a \) using angles \( \theta \), \( \phi \), and \( \psi \) to transform it to frame \( b \). After the first rotation about the x-axis by an angle \( \theta \), the coordinate system is no longer aligned to the original frame, and therefore is notated as \( a' \). Two labels are used for the original x-axis, \( a_x \) and \( a'_x \), to show that this axis is not modified by the first rotation. The second rotation is performed about \( a'_x \) at an angle of \( \phi \). Similar to the first rotation, the \( a'_y \) axis is not changed and thus is also labeled as \( a''_y \).
Following suit with the third and final rotation about \( a_z'' \) at an angle \( \psi \), the transformation to coordinate frame \( b \) is complete. Because the last rotation is about the \( a_z'' \), this axis is not modified and therefore also labeled as \( b_z \) in the figure. Using the notation defined above, the transformation \( C^b_a \) is more appropriately defined as follows.

\[
C^b_a = C^b_{a''} (\psi) C^{a''}_a (\phi) C^{a'}_a (\theta)
\] (B.7)

In addition to the transformation matrices, directional vectors within each frame also must be depicted with a notation to show which reference frame used for the coordinates of the vector. For instance, consider a vector \( r \) in frame \( a \). The reference frame is depicted as a superscript, \( r^a \). Similarly, the same vector would be denoted as \( r^b \) when referenced to the \( b \) coordinate frame. A transformation of this vector from frame \( a \) to frame \( b \) would then be calculated by multiplying \( r^a \) by the matrix \( C^b_a \).

\[
r^b = C^b_a r^a = C^b_{a''} (\psi) C^{a''}_a (\phi) C^{a'}_a (\theta) r^a
\] (B.8)

Arbitrary coordinate frames have been used in the definitions above to describe general usage. However for the folded IMU structures, specific coordinate frames must be defined. These frames will be used to describe the algorithms explained in the following sections. Three individual coordinate frames, \( s, i, \) and \( b \) are defined below.
**s frame:** Individual coordinate frame for an individual sensor, regardless of fabrication misalignments and the designed spatial configuration of the overall IMU.

**i frame:** Indicates the coordinate frame of a sensor IMU form factor with regards to the ideal IMU form factor without misalignments.

**b frame:** Orthogonal coordinate frame of the external IMU body, disregarding the original ideal sensor orientation and number of sensors. This frame can be directly transformed to the navigation frame for the specific application in which the IMU is used.

This exploration provides a foundation for the inertial navigation algorithm developed for the folded MEMS IMU devices. Rotation matrices have been defined, as well as notation for coordinate frames used for the algorithms presented in this chapter. General coordinate transformations have also been defined based on previous studies from a variety of sources. The following portions of the chapter will apply these definitions to compensate for misalignment of sensors after IMU fabrication, mapping the sensor vectors to a useful frame for navigational purposes, and accounting for vibration of the IMU structures while in use. Although it is recommended that the reader be previously familiar with such mathematics, the above explanation provides a basis for the algorithms presented in the following sections.

### B.1 Sensor Misalignments

For any IMU form factor, an ideal theoretical alignment of sensors is defined by the design. However, when manufactured, ideal alignment is never achieved. Therefore, misalignments must be compensated for during operation to maximize the performance of the inertial navigation system. Misalignment of the folded MEMS IMU sidewalls compared to the
ideal design can be directly measured to provide the angles of rotation needed for calibration.

Three coordinate frame rotations must be performed to transform individual sensor vectors from the sensor frame itself, \( s \), to the ideal alignment frame, \( i \) defined by the IMU form factor design. Using each direction cosine matrix (DCM) defined in Section 6.1, the sense vector of a single-axis sensor is converted to the inertial frame. First the individual rotations are defined about each orthogonal axis.

\[
C_{\theta_m}^s C_{\phi_m}^{s'} C_{\psi_m}^{s''} \quad C_{\theta_m}^i C_{\phi_m}^{i'} C_{\psi_m}^{i''} (B.9)
\]

These DCMs when multiplied together provide a full transformation from the sensor frame to the ideal IMU skeletal frame. Considering a sense vector \( r \) in the sensor frame \( s \), a transformation to the ideal IMU configuration frame \( i \) can be obtained as follows:

\[
r^i = C_{\theta_m}^i C_{\phi_m}^{i'} C_{\psi_m}^{i''} (B.10)
\]

The misalignment angles, denoted by a subscript \( m \), are determined by quantitative measurement of the folded MEMS IMU structure after fabrication and assembly. This equation provides a simple algorithm for compensating for sensor misalignments on any IMU form factor, given that the angles, \( \theta_m \), \( \phi_m \) and \( \psi_m \) have been determined and thus can be inserted into the equation. Methods for measuring these angles can be evaluated by use of such devices as a coordinate measuring machine (CMM), laser scanning device, or optical inspection. Depending on the application, the necessary precision of alignment may vary. However higher precision of misalignment measurement requires additional time. For this reason a balance of performance to time and unit cost must be determined.

The expression in Equation (6.1) is a general expression for a sensor on any sidewall of a folded MEMS IMU. However it is inevitable that each sensor will have different misalignment angles. Therefore additional notation must be used to specify which sensor the expression is
applied to. For this reason, a subscript \( n \) is added to the \( r \) vectors to indicate which sensor coordinate frame is being transformed. Similarly, the misalignment angles, \( \theta_m \), \( \phi_m \) and \( \psi_m \), and the transformation matrices are also given an additional subscript \( n \) that corresponds with that of the sense vectors. Using this additional notation, the expression now becomes

\[
r^i_n = C_{sn}^{in}(\theta_{mn}, \phi_{mn}, \psi_{mn})r^s_n = C_{sn}^{in}(\psi_{mn})C_{sn}^{in}(\phi_{mn})C_{sn}^{in}(\theta_{mn})r^s_n
\] (B.11)

where \( n \) is an integer ranging from one to the number of sensors included in the IMU design. In the case of a cubic IMU with a single sensor on each sidewall, there are a total of six expressions and thus \( 1 \leq n \leq 6 \). Alternatively for an IMU pyramid with four sidewalls, each containing a single axis sensor, \( 1 \leq n \leq 4 \). However the definition of \( n \) largely depends on the IMU form factor design and the number of sensors included on each sidewall. In either case, a general expression has been developed for misalignment compensation for each sensor after fabrication and assembly of a folded MEMS IMUs with various form factors.

**B.2 Acceleration and Rotation Rate IMU Vector Calculation**

For an actual IMU, the sensor signals will be comprised of acceleration and rotation rates oriented in various directions. Specifically for in-plane single-axis accelerometers, the sense vectors will be expressed as acceleration vectors with respect to the sensor frame.

\[
a^s_x = \begin{bmatrix} \alpha_x \\ 0 \\ 0 \end{bmatrix} \quad \text{or} \quad a^s_y = \begin{bmatrix} 0 \\ \alpha_y \\ 0 \end{bmatrix}
\] (B.12)

Because the accelerometers used for the IMUs described in this work operate in-plane, there is no need for defining an acceleration vector along the z-axis. In general, an x-axis accelerometer and a y-axis accelerometer have identical designs, with the difference being
a 90° rotation of the entire device. For other applications, out-of-plane sensors may be employed and thus it would be required. Moreover, if a multi-axis accelerometer is utilized, the vectors will have additional components along other axes. Similar to the accelerometers, the gyroscopes used for the folded MEMS IMU devices operate in-plane. However due to the dynamics of the gyroscopes, rotation rate is detected out-of-plane along the z-axis. With respect to the sensor frame, s, the rotation rate vectors can be expressed with one z-axis component.

\[
\omega_s^z = \begin{cases} 
0 \\
0 \\
\omega_z 
\end{cases}
\] (B.13)

Although the inertial sensors implemented on the folded MEMS IMUs are designed to detect motion along a single axis, cross-axis sensitivities inevitably exist. The above definitions describe ideal sensors and do not take into account the cross-axis sensitivities. Therefore the acceleration and rotation vectors are modified to include non-ideal sensor components in all directions.

\[
a_s^x = \begin{cases} 
\alpha_x \\
\alpha_{cy} \\
\alpha_{cz} 
\end{cases}, \quad a_s^y = \begin{cases} 
\alpha_{cx} \\
\alpha_y \\
\alpha_{cz} 
\end{cases} \quad \text{and} \quad w_s^z = \begin{cases} 
\omega_{cx} \\
\omega_{cy} \\
\omega_z 
\end{cases}
\] (B.14)

In this definition, the cross-axis sensitivities are denoted with a c in the subscript of the non-ideal sensor components. Experimental characterization is done to determine the sensitivity components and thus can be directly inserted into the definitions. With the sensor vectors defined for acceleration and rotation rate, the coordinate transformations are performed using the algorithm described for the general r vectors. Transformation from the sensors frame, s, to the IMU body frame, b, for in-plane accelerometers is performed using
the following expressions.

\[
\begin{align*}
\text{x-axis accelerometer:} & \quad a^b_x = C^b_{ix} C^i_{sx} a^s_x \\
\text{y-axis accelerometer:} & \quad a^b_y = C^b_{iy} C^i_{sy} a^s_y
\end{align*}
\]  \hspace{1cm} (B.15)

Similarly for the z-axis gyroscopes, the transformation is as follows.

\[w^b_z = C^b_{iz} C^i_{sz} w^s_z\]  \hspace{1cm} (B.16)

With the accelerometer and rotation rate vectors defined with respect to the IMU body frame, \(b\), the expressions can now be applied to the individual sensors on the IMU pyramid. Rather than using \(x\), \(y\), and \(z\) to denote the vectors, integers can be used that correspond to Figure 6.1. Also, as discussed above, it is assumed that there is a single-axis gyroscope and a single-axis accelerometer located on each sidewall. Rather than defining each sensor individually, a subscript \(n\) is used to create one general expression for each type of sensor.

\[
\begin{align*}
a^b_n &= C^b_{in} C^i_{sn} a^s_n \\
wx^b_n &= C^b_{in} C^i_{sn} wx^s_n
\end{align*}
\]  \hspace{1cm} (B.17)

Overall detection capabilities of the entire IMU is achieved by adding the acceleration and rotation rate data from each sensor. For a pyramidal IMU containing four accelerometers and four gyroscopes in the designed form factor produces the following expressions for the total acceleration and rotation rate data.

\[
a^b = \begin{bmatrix} \alpha_{x,\text{tot}} \\ \alpha_{y,\text{tot}} \\ \alpha_{z,\text{tot}} \end{bmatrix} = \sum_{n=1}^{4} a^b_n
\]  \hspace{1cm} (B.18)
\[ w^b = \begin{cases} 
\omega_{x,tot} \\
\omega_{y,tot} \\
\omega_{z,tot} 
\end{cases} = \sum_{n=1}^{4} w^b_n \quad (B.19) \]

For a folded MEMS IMU pyramid designed as shown in Figure 6.1, the above transformation apply to any configuration and orientation of sensors. Various types of sensor alignment may be used for different applications, however the algorithm still applies. Typical configurations would include all accelerometers aligned to sense the y-axis with respect to the sensor frame, or having two accelerometers aligned to the x-axis with the other two aligned to the y-axis. However it may also be beneficial to align the accelerometers at an angle, such as $45^\circ$ to allow each sensor to detect partial motion in all three axes of the IMU body frame. In any case, the algorithm has been defined to accommodate a wide variety of accelerometer orientations. Conversely, when considering the gyroscopes implemented in this exploration, each will have a a sense vector along the z-axis with respect to the sensor frame. Rotation of such gyroscopes makes no difference in the sense vector, limiting the flexibility to one configuration independent of sensor rotation. However in the case of multi-axis gyroscopes integrated onto the folded MEMS IMU structures, the algorithm defined is still applicable.
C  Review of Inertial Sensor Errors

C.1  Bias Error

An error that exists for any accelerometer or gyroscope designed with any technology is bias error. This error relies on the design of the inertial sensor, as well as the signal detection electronics that are used to calculate the inertial input \[55, 57, 66, 68\]. Bias error is measured in units of acceleration or rotation rate, hence it must be integrated with respect to time to achieve distance or angular units. This is necessary because during navigation, distance or angle data is preferred when using an IMU for navigational purposes. During this research, capacitive detection is utilized for the accelerometers and gyroscopes, however the fabrication process allows for multiple types of devices, given that they can be created with the fabrication process described in Chapter 2. After measuring the individual bias errors for the implemented accelerometers designed specifically for the IMU, they must be converted from the sensor frame \(s\) to the inertial frame \(i\), and then to the IMU body frame \(b\) using Equation (C.20).

\[
\vec{e}^b_{Ba,n} = C^i_{i,n} C^s_{s,n} \vec{e}^s_{Ba,n}
\]  \hspace{1cm} (C.20)

In this equation, \(n\) depicts the specific \(n^{th}\) accelerometer, \(e^s_{Ba,n}\) represents the original acceleration bias error of the specific accelerometer, \(C^i_{s,n}\) is the coordinate transformation matrix from the sensor frame to the inertial frame, \(C^i_{i,n}\) represents the transformation matrix from the inertial frame to the IMU body frame, and \(e^b_{Ba,n}\) is the bias error acceleration after the coordinate transformation, in the IMU body frame of reference. This algorithm can be applied to any IMU device built with any technology in any form factor, and is not specific to the folded IMU design. This directly applies to this research for the sensors implemented on the IMU sidewalls, and therefore is included in the overall error model. However the data must be integrated to achieve bias error values in units of distance, as
given in Equation (C.21).

\[ \vec{E}_{Ba,n}^b = \int \int \vec{e}_{Ba,n}^b d^2 t = \frac{1}{2} \vec{e}_{Ba,n}^b \cdot t^2 \]  

(C.21)

Here, \( E_{Ba,n}^b \) represents the distance error integrated twice from the accelerometer bias error. This calculation provides a formula that can be used to compensate for accelerometer bias distance error in the navigational frame. Coordinate transformations are then performed to convert the data to useful navigational data. These transformations for the IMU devices are embedded in the overall coordinate transformation matrices, which are different for each type of form-factor and are discussed in Chapter 6. Using the same type of algorithm used for accelerometers and applying it to the gyroscopes, the bias is error with respect to the IMU body frame is given in Equation (C.22) which applies to both the cubic and pyramidal IMU form factors.

\[ \vec{e}_{Bg,n}^b = C_{i,n}^b C_{s,n}^i \vec{e}_{Bg,n}^s \]  

(C.22)

The bias error in the sensor frame for each gyroscope, \( \vec{e}_{Bg,n}^s \), is measured in units of rotation rate during calibration. However computing the angular error requires some simple manipulation of the data. First it is mapped to the IMU body frame, as shown above, using coordinate transformation matrices defined in Chapter 6. The transformed bias vector is then integrated once over time to obtain angular error, as expressed in Equation (C.23), and is typical for any type of IMU form factor.

\[ \vec{E}_{Bg,n}^b = \int \vec{e}_{Bg,n}^b dt = \vec{e}_{Bg,n}^b \cdot t \]  

(C.23)

In this expression, \( E_{Bg,n}^b \) represents the angular error due to the bias of the \( n \)th gyroscope with respect to the IMU body frame, and \( \vec{e}_{Bg,n}^b \) is the rotation rate bias error after being transformed from the sensor frame to the IMU body frame. This, and the acceleration bias
error can be incorporated into the overall error model using these calculations.

One method to reduce bias error for an accelerometer or gyroscope is to increase the mass of the sensing element to increase the Coriolis effect \[75\]. With a larger proof mass, the inertial signal is inherently stronger compared to the bias error. A direct advantage that the folded MEMS IMU approach has is a large sensor area compared to current IMU devices with similar footprint areas. Therefore the sensors are capable of being much larger and thus the bias error is inherently reduced. Other designs with more complexity can also be implemented that are specifically intended for reducing bias error. With the current designs, each of the sensors are designed to detect inertial input along a single axis. Therefore the bias error is generally lower than that of multiple-axis devices utilized for currently available chip-scale IMUs. For these reasons, the folded MEMS approach has an advantage over existing IMU devices of comparable size.

C.2 Sensor Misalignment

Current IMU technology relies on gyroscopes and accelerometers, which do not directly measure distance and angle as desired for navigational purposes. Integration of the signals must be conducted, thus errors induced by the system can rapidly propagate. Contributors of this error is misalignment of the structure with respect to the original shape, as well as shifts with respect to the initial installation orientation. Static misalignment arising from fabrication imperfections, assembly of the folded structures, and differences in orientation after installation are addressed in Appendix B.1. Static misalignments are often minimized during the calibration process. However this does not account for dynamic misalignment of the system while in operation.

Many factors can cause misalignment, such as vibration, thermal effects and large accelerations, as well as differences in environmental conditions \([56, 66, 67]\). Therefore expressions
must be derived to compensate for these types of post-calibration misalignments. Figure C.5 shows an accelerometer vector in the sensor frame that is misaligned with respect to the sensor’s z-axis.

![Figure C.5: Accelerometer misalignment about the z-axis](image)

In the figure shown, $m$ depicts the term misalignment, $a$ represents that it is an accelerometer error, again $n$ is the index number for the specific accelerometer on the folded MEMS IMU structure. Additionally, $\tilde{a}_x$ shows the actual acceleration detected along the $x$-axis, which is typical for the $y$ and $z$ axes. Only the $x$-axis is shown due to the fact that the algorithm is identical for all coordinate axes. Measured acceleration is depicted with a tilde ($\tilde{\cdot}$), and as an example for the $x$-axis shown as $\tilde{a}_x$, Equation (C.24).

$$\vec{e}_{ma,n}^s = \tilde{a}_x [2 - \cos(\psi_{ma,n}) - \cos(\psi_{ma,n})] \quad (C.24)$$

Because this error calculation occurs in the sensor frame, it must be converted to the IMU body frame in order to be useful for a navigational calculations. This transformation is shown in Equation (C.25) as follows.

$$\vec{e}_{ma,n}^b = C_{i,n}^b C_{s,n}^i \vec{e}_{ma,n}^s \quad (C.25)$$

In this equation, $\vec{e}_{ma,n}^b$ represents the acceleration bias error with respect to the IMU body frame. Next, the overall distance error due to dynamic misalignment must be determined. In this case, the initial velocity $\vec{v}_{0,n}$ must be considered because it significantly affects the
total accumulated misalignment error, as shown in Equation (C.26).

\[
\vec{E}_{ma,n}^b = \int \int \vec{e}_{ma,n}^b d^2 t = \vec{v}_{0,n} \cdot t + \frac{1}{2} \vec{e}_{ma,n}^b \cdot t^2 
\]  
(C.26)

Calculating the dynamic misalignment error for gyroscopes follows a similar procedure. Figure C.6 shows misalignment of a z-axis gyroscope about the y-axis. The angle of misalignment is given as \(\phi_{mg,n}\), the actual rotation rate vector is represented by \(\omega_z\), and the measured rotation rate is shown as \(\tilde{\omega}_z\). This figure also applies to misalignment about the x-axis by simply changing the notation.

Figure C.6: Gyroscope measuring z-axis rotation misaligned about the y-axis.

Misalignments along the other sensor axes also affect each error and thus are included in the overall calculations. The error expressions in this section are derived referencing Figures C.5 and C.6. The algorithm presented is fairly typical for other types of errors on the folded IMU structures. For this reason, a similar algorithm is derived for other errors, with specific modifications made for each IMU form-factor.

Misalignment error is first calculated in the sensor frame. Vector \(\vec{e}_{mg,n}^s\) in Equation (C.27) represents the misalignment error of the nth gyroscope in its own sensor frame. All gyroscopes currently being considered for implementation on the folded IMU devices measure rotation rate with respect to the inherent z-axis of each individual sensor. The misalignment error is calculated in Equation (C.27) using the measured rotation rate, \(\tilde{\omega}_z\), and the misalignment angles from Figures C.5 and C.6, which would be determined during initial
calibration.

\[ \vec{e}_{mg,n}^s = \hat{\omega}_z [2 - \cos(\phi_{mg,n}) - \cos(\theta_{mg,n})] \]  \hspace{1cm} (C.27)

In this equation, \( n \) represents the specific gyroscope on the IMU structure, \( \phi_{mg,n} \) is the angle of misalignment rotation about the \( y \)-axis, and \( \theta_{mg,n} \) is the misalignment angle about the \( x \)-axis, both with respect to the sensor frame. Next, this error is transformed to the IMU body frame, \( \vec{e}_{mg,n}^b \), using same type of expression with coordinate transformation matrices for the accelerometer, and thus is not discussed. The error is then integrated with respect to time to obtain angular error, \( \vec{E}_{mg,n}^b \), shown in Equation (C.28).

\[ \vec{E}_{mg,n}^b = \int \vec{e}_{mg,n}^b dt = \vec{\psi}_{0,n} + \vec{e}_{mg,n}^b \cdot t \]  \hspace{1cm} (C.28)

Use of single axis sensors on the folded MEMS structures minimizes this error for all IMU form factors designed with the fabrication processes developed in this work. Data from the accelerometers can be used to compute misalignments of the structure and thus can be compensated for in a navigational computer. However the performance parameters for such sensitive sensors may not meet the specifications required by the end-use application, and therefore implementation of alternative sensor designs and configurations would be necessary. Also, the size of the sensors plays a major role in the severity of misalignment error because a large proof mass increases the signal-to-noise ratio from inertial input and thus aids in masking the error [75]. The folded IMU design maximizes the amount of footprint area provided for each sensor with respect to the footprint of the entire device. Compared to other available IMUs with similar mounting areas, the folded MEMS design approach provides a large advantage for this reason. Misalignment error can be greatly minimized due to the fact that the single-axis sensors being implemented are inherently designed for larger signal-to-noise ratios of detection, and thus capable of higher performance than the multi-axis sensors commonly used in existing devices.

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C.3 Scale Factor Error

Another known source of error in inertial sensors arises from changes in the scale factor that relates the sensor output signal to the magnitude of inertial input. Over time, the scale factor can vary for multiple reasons, and thus induces detection errors in the navigational system [66]. Moreover, this type of error tends to be more prevalent for MEMS sensors due to their small size and susceptibility to environmental effects. As an example, a change in temperature will generally cause a direct change in the sensor scale factor. One method to minimize this effect is to heat the sensors to a known temperature above that of the maximum operating temperature. This technique is known as ovenization and is commonly used in current applications. Acceleration inertial inputs can also cause a change in a gyroscope scale factor because it applies a load on the proof mass suspension. This alters the resonant frequency of the sensor, much like a guitar string, and thus effects performance. Other factors also cause a change in scale factor, such as suspension spring degradation over time, as well as changes in day-to-day operation [56, 57]. However calibrating an IMU for these types of influences is difficult, if not impossible. Discussed in this section is an algorithm for calculating errors based on scale factor variances that can be calibrated for signal error compensation. Changes in scale factor is required to be measured for each sensor during the initial calibration process so that they are known while actively being compensated for by a navigational computer.

Ideally, the scale factor will be linear with respect to the inertial input. Though in reality scale factors of both accelerometers and gyroscopes add error to the sensed trajectory due to non-linearities. An expression is given in Equation (C.29) that is applicable to accelerometers at any point in time in which the scale factor differs from the calibrated linear response:

$$\vec{e}_{sfa,n} = \frac{\Delta K_{a,n}}{K_{a,n}} \vec{a}_n$$  \hspace{1cm} (C.29)
where $\vec{e}_{sfa,n}$ represents the scale factor error for the $n$th accelerometer with respect to the sensor frame, $K$ is the scale factor for that particular sensor, and $\vec{a}_n$ is the applied acceleration. Like other errors, the scale factor error must be converted from the sensor frame to the IMU body frame. Equation (C.30) the coordinate transformation matrices associated with the individual sensor and the spatial configuration of the IMU as discussed in Chapter 6.

$$\vec{e}_{sfa,n}^b = C_{b,i,n}^b C_{i,s,n}^i \vec{e}_{sfa,n}^s$$  \hspace{1cm} (C.30)

Finally, the error is integrated to achieve distance error with respect to the IMU body frame. Similar to the dynamic misalignment error, the initial velocity needs to be considered because it adds to the distance error realized for navigational purposes, Equation (C.31).

$$\vec{E}_{sfa,n}^b = \int \int \vec{e}_{sfa,n}^b d^2t = \vec{v}_{0,n} \cdot t + \frac{1}{2} \vec{e}_{sfa,n}^b \cdot t^2$$ \hspace{1cm} (C.31)

Similar to the accelerometer, scale factor error is represented for gyroscopes as $\vec{e}_{sfg,n}^s$, shown in Equation (C.32) below. The notation in the subscript denotes a $g$ to indicate gyroscope error rather than an $a$ for accelerometer error. Likewise, $K_{g,n}$ is the gyroscope scale factor and is multiplied by the input rotation rate $\vec{\omega}_n$. Then the error vector is transformed to the IMU body frame using the coordinate transformation matrices calculated for each individual gyroscope on both the pyramidal and cubic IMU spatial configurations. The error is then transformed from the sensor frame into the IMU body frame using Equation (C.33).

$$\vec{e}_{sfg,n}^s = \frac{\Delta K_{g,n}}{K_{g,n}} \cdot \vec{\omega}_n$$ \hspace{1cm} (C.32)

$$\vec{e}_{sfg,n}^b = C_{b,i,n}^b C_{i,s,n}^i \vec{e}_{sfg,n}^s$$ \hspace{1cm} (C.33)

As with the accelerometer scale factor error, the error for the gyroscope must be inte-
grated with respect to time. However the difference is that only one integration is necessary, Equation (C.34). Due to the single integration, the gyroscope scale factor error is proportional to \( t \), rather than \( t^2 \) for accelerometers. Therefore the scale factor error for gyroscopes theoretically is less significant than that of accelerometers.

\[
\vec{E}_{sfg,n}^b = \int \vec{e}_{sfg,n}^bd t = \vec{\alpha}_{0,n} + \vec{e}_{sfg,n}^b \cdot t
\]  

(C.34)

Overall distance error induced by a change in accelerometer scale factor in the IMU body frame is defined as \( \vec{E}_{sfa,n}^b \). Similarly, \( \vec{E}_{sfg,n}^b \) represents the accumulated angular error from gyroscope scale factor changes, also in the IMU body frame. In these expressions, \( \vec{e}_{sfa,n}^b \) and \( \vec{e}_{sfg,n}^b \) represent the scale factor error of the \( n \)th gyroscope and accelerometer, respectively. Both have been transformed into IMU body frame coordinates using the matrix algorithms defined in Chapter 6. Generally, the scale factor error from predictable sources is measured during the calibration process, and is inevitably different for each individual sensor. In particular for this type of error, the initial velocity and angular acceleration, \( \vec{v}_{0,n} \) and \( \vec{\alpha}_{0,n} \), must be considered in the calculation which adds to the accumulated error, making scale factor error a very significant issue for inertial sensor manufacturing.

The overall design advantages of the folded MEMS IMU are capable of reducing scale factor error compared to existing chip-scale devices. Foremost, there is a large amount of surface area available for the sensing elements due to the 3-D form factor. For this reason, single-axis sensors can be utilized instead of multi-axis sensors and thus the proof masses can be much larger in size compared to sensors on other available chip-scale IMU devices. This results in a larger overall scale factor for each axis, which aids in masking the level of error. Additionally, the amount of area provided for each sensor allows for complex high-performance designs that are focused toward suppressing different types of error for various applications.
Another method for minimizing the scale factor error is to use a phase-locked loop in the signal detection electronics. This method is used to actively and precisely measure the resonant frequency of a vibratory inertial sensor [70]. During calibration, the scale factor of each sensor can be calibrated with respect to its own natural operational frequency and thus scale factor errors can be compensated during operation. The folded MEMS IMU design allows for each of these error reduction techniques to be utilized in various end-use applications due to the modularity of the process and large amount of sensor area compared to existing devices.

C.4 Scale Factor Asymmetry

Another source of scale factor error is due to performance differences for positive and negative inertial inputs [57, 66]. A significant cause of this arises from fabrication imperfections of the sensors induced during manufacturing [56]. For the SOI sensors on the folded IMU structures, the suspensions and other sensor features have a minimum feature size is on the order of approximately 4-5 microns. The sensor elements are thus very susceptible to imperfections caused by fabrication. Photolithography and etching errors inevitably causes variations in the thicknesses of the sensor features. This also creates variations in the spring constants of each suspension included in the sensor designs. Location of each sensor element on a fabrication wafer also causes a difference in the fabrication results [63, 76]. Additionally, non-linear spring deflections and stiffnesses causes asymmetry in the positive and negative scale factors. By design, the non-linear region of spring deflection is generally avoided. However there are always small non-linear effects which can be ignored for error calculation purposes in this application because the scale factor largely overshadows the level of error. For every inertial sensor, the scale factor symmetry is never ideally defined. Each sensor must be individually characterized to determine the asymmetry properties. This section discusses expressions for scale factor asymmetry calculations of gyroscopes and accelerometers.
Beginning with the accelerometers, equations are defined for calculating the error caused by scale factor asymmetry. The process is similar for the gyroscope calculations as well. Below is an equation, Equation (C.35), that includes different scale factors for positive and negative inertial inputs of an accelerometer. When the inertial input is negative, the term $\varsigma^-$ is the only variable utilized and $\varsigma^+$ is defined as zero. Conversely, $\varsigma^+$ is used for positive inertial inputs and $\varsigma^-$ is defined to be zero. Because the current IMU configurations gyroscopes and accelerometers have the same designs, this equation is typical for each accelerometer on the folded MEMS IMU structures.

$$\vec{e}_{saa,n}^s = \left[ (K_{a,n}^+ \cdot \varsigma^+ + K_{a,n}^- \cdot \varsigma^-) - K_{a,n} \right] \vec{a}_n \over K_{a,n} \quad \text{(C.35)}$$

The scale factor asymmetry error for the $n$th accelerometer with respect to the sensor frame is defined as $e_{saa,n}^s$. Similar to the other errors, the scale factor asymmetry error is converted to the IMU body frame as shown in Equation (C.36).

$$\vec{e}_{saa,n}^b = C_{i,n}^b C_{s,n}^i \vec{e}_{saa,n}^s \quad \text{(C.36)}$$

The error is then integrated twice to achieve distance error, adding the effects of initial velocity in the calculation, resulting in the expression for $\vec{E}_{saa,n}^b$ shown in Equation (C.37). With this calculation, a navigational computer can provide compensation of the error.

$$\vec{E}_{saa,n}^b = \int \int \vec{e}_{saa,n}^b d^2t = \vec{v}_{0,n} \cdot t + \frac{1}{2} \vec{e}_{saa,n}^b \cdot t^2 \quad \text{(C.37)}$$

Similar to scale factor asymmetry for the accelerometers, the gyroscopes have the same type of error. The calculation of which is also similar. The notation is changed, however, showing a subscript ‘$g$’ instead an ‘$a$’ to depict gyroscope error rather than accelerometer
error, as follows in Equation (C.38).

\[ \vec{e}_{sag,n}^s = \left[ (K_{g,n}^+ \cdot \zeta^+ + K_{g,n}^- \cdot \zeta^-) - K_{g,n} \right] \frac{\vec{\omega}_n}{K_{g,n}} \]  

(C.38)

In this expression, \( \vec{e}_{sag,n}^s \) represents the scale factor asymmetry error at the sensor level in units of rotation rate. Like the expressions given above for accelerometers, \( K_{g,n}^+ \) is the scale factor when the rotation input is positive, and \( K_{g,n}^- \) is the scale factor for negative rotation rate input. Also, \( \zeta^+ \) and \( \zeta^- \) are alternatively set to zero based on the direction of the rotational inertial input. Mapping the scale factor asymmetry error to the IMU body frame is necessary so that it can be integrated to angular units useful for navigation. Equation (C.39) uses coordinate transformations defined in Chapter 6 for both cubic and pyramidal folded IMU form factors that converts the error from the sensor frames to the body frame. Angular error is then achieved by integrating the original error source over time as followed in Equation (C.40).

\[ \vec{e}_{sag,n}^b = C_{i,n}^b C_{s,n}^i \vec{e}_{sag,n}^s \]  

(C.39)

\[ \vec{E}_{sag,n}^b = \int \vec{e}_{sag,n}^b dt = \vec{\psi}_{0,n} + \vec{e}_{sag,n}^b \cdot t \]  

(C.40)

The expression for \( \vec{E}_{sag,n}^b \), which is the angular error due to scale factor asymmetry of the \( n \)th gyroscope, is dependent on the initial angle, \( \vec{\psi}_{0,n} \) in which the sensor is positioned prior to calculation. Thus it is included in the integration and significantly adds to the overall error produced from scale factor asymmetry. This expression is typical for other gyroscopes on different axes using the same formula with different angles such as \( \vec{\theta}_{0,n} \) and \( \vec{\phi}_{0,n} \) for the \( x \)-axis and \( y \)-axis, respectively.

Using experimental measurements during the sensor calibration process, the scale factor

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error from predictable sources is able to be minimized. Because this error is dependent upon $t^2$ for accelerometers, the error will propagate rapidly if no compensation is provided. While this is only dependent upon $t$ for gyroscopes due to a single integration, the error still accumulates quickly with respect to time. However, the inherent higher design complexity for gyroscopes creates more susceptibility for error. Thus the magnitude of integrated error for the gyroscopes may be comparable to that of the accelerometers, depending on the design of each type of sensor.

It is necessary to calibrate all sensors prior to implementation to determine the asymmetry error of each sensor so that computational compensation can be performed. Otherwise, the navigation information provided by the IMU will constantly need to be updated using an external source, such as a GPS or a gimballed set of gyroscopes. In the case of the folded MEMS approach, the sensors can be made very large compared to the sizes provided by existing units. This property of the folded MEMS IMU sensors allows for a significantly larger scale factor, minimizing the effects of asymmetry errors. Also, each sensor implemented on the folded IMU is designed to be symmetric about the $x$-axis and $y$-axis, which further minimizes asymmetry.

\section*{C.5 White Noise}

A type of error that plagues all sensors and can never be completely eliminated is white noise. This error is induced by surrounding signals of many different sources and frequencies. White noise is defined to have an equal intensity throughout the entire frequency spectrum. This best represents the random noise detected by the inertial sensors. Any signal generated from an inertial input that falls below this noise level cannot be accurately detected. Therefore the minimum measurable inertial input response is governed by the amount of white noise that exists within the navigation system electronics and surrounding environment. Factors that
cause white noise error to be induced into a sensor signal depends on many factors, such as
nearby electronics, environmental acoustics, and atomic interaction within the sensing
element itself [55, 66, 68]. Although it cannot be completely eliminated or compensated,
white noise interference can be measured. This data can then be used to determine the
resolution of each accelerometer and gyroscope on the folded MEMS IMU. Final distance
and angular error due to white noise is calculated using the algorithms discussed in this
section.

Generally measured as a power spectral density, white noise has units of acceleration with
respect to $\sqrt{Hz}$ for accelerometers, and rotation rate with respect to $\sqrt{Hz}$ for gyroscopes
[55, 66, 68]. Equation (C.41) below is used to convert white noise error from power spectral
density units to that of acceleration.

$$\vec{e}_{wa,n}^s = \sqrt{\frac{\vec{N}_{a,n}}{\tau_{sa,n}}} \cdot \delta(t - \tau_{sa,n}) \quad (C.41)$$

The white noise associated with the $n$th accelerometer with respect to the sensor frame
is represented as $e_{wa,n}^s$, while $\vec{N}_{a,n}$ is the power spectral density of the white noise associated
with that particular sensor. The term $\tau_{sa,n}$ is the sample averaging time, and $\delta(t - \tau)$ is the
Dirac delta function applied at time $\tau_{sa,n}$. The white noise error is then mapped to the IMU
body frame and integrated twice to obtain the resulting distance error, $\vec{E}_{wa,n}^b$.

$$\vec{e}_{wa,n}^b = C_{i,n}^{b} C_{s,n}^{i} \vec{e}_{wa,n}^s \quad (C.42)$$

The white noise error is then integrated twice with respect to time to achieve units of
distance, rather than acceleration, shown in Equation (C.43). In this particular case, the
initial velocity is not used in the calculation because the white noise is independent of
velocity.
\[
\vec{E}_{wa,n}^b = \int \int \vec{e}_{wa,n}^b d^2t = \frac{1}{2} \sqrt{\frac{N_{a,n}}{\tau_{sa,n}}} \cdot t
\]  
(C.43)

Calculations of white noise error for gyroscopes is quite similar to that of the accelerometers. First the noise level is predicted within the sensor frame using Equation (C.44). In this expression, \( \vec{e}_{wg,n}^s \) represents the white noise error for the \( n \)th gyroscope with respect to the sensor frame.
\[
\vec{e}_{wg,n}^s = \sqrt{\frac{N_{g,n}}{\tau_{sg,n}}} \cdot \delta(t - \tau)
\]  
(C.44)

Transforming the error to the IMU body frame is also nearly identical to that of the accelerometer white noise calculations. The main difference being that the coordinate transformation matrices are defined for the specific gyroscope, not accelerometer, for which white noise is being calculated. It is then integrated, only once instead of twice for the accelerometers, to achieve the white noise error in units of angular rotation, represented as \( \vec{E}_{wg,n}^b \) as follows in Equation (C.45).
\[
\vec{E}_{wg,n}^b = \int \vec{e}_{wg,n}^b dt = \sqrt{\frac{N_{g,n}}{\tau_{sg,n}}}
\]  
(C.45)

Although white noise exists for nearly all types of sensors, the inertial sensors on the folded IMU can be designed such that the effects of noise interference are small compared to the scale factor of each sensor. One way of accomplishing this is to make the sensors very large, which increases the magnitude of the scale factor. However for chip-scale inertial measurement units, this is a difficult task to achieve. In the case of the folded IMU design, and as mentioned earlier, the sensing elements can be designed to be much larger than most other chip-scale devices because of the 3-D structural platform. This allows for minimized white noise signal interference based solely on the design approach.
Each of the current sensors are also designed to only detect motion along a single axis, so the white noise induced by each sensor only affects that respective axis. With other IMUs that have multi-axis sensors, white noise affects all axes of detection. These effects are also not necessarily equal in proportion. By using a collection of single-axis sensors, with each accelerometer and gyroscope of identical designs, white noise is approximately equal along all axes. Therefore the minimum level of detection is also approximately the same, providing consistency for each IMU axis. These advantages of the folded MEMS process are significant when considering the negative effects of sensor resolution due to white noise interference.

C.6 Anisoelasticity

Another type of error that may affect the large suspended proof masses on the folded MEMS IMU sensors is caused by anisoelasticity. This occurs when the x-axis and y-axis suspension stiffnesses are slightly different than each other due to fabrication imperfections or spring degradation over time. This causes the principle axis of elasticity to be different than what is intended by design. Therefore, when an acceleration is applied, the proof mass deflects at a slightly different angle than what is expected. In general, this causes larger errors for gyroscopes than for accelerometers due to the natural higher complexity of design. For capacitive sensors, such as the ones implemented on the folded IMU device, anisoelasticity will cause a false output that will register as a rotation rate [56, 66, 77, 80]. This error must therefore be measured during the calibration process for each sensor. With the anisoelasticity errors known, they can be compensated for by a navigational computation algorithm when accelerations are experienced. Below, Figure C.7 shows a diagram representing deflection of a gyroscope proof mass when influenced by in-plane acceleration along an arbitrary direction.

In the figure shown, $m$ represents the proof mass of the gyroscope, $a$ is the applied acceleration, $F$ is the resultant acceleration force, $k$ represents the spring constants of the
suspension, $\alpha$ is the angle of which the acceleration is applied, $\theta_{ai,gn}$ and $\phi_{ai,gn}$ are the anisoelasticity angles, and $x', y'$ are the true deflection axes due to anisoelasticity effects.

![Figure C.7: Free body diagram considering anisoelasticity of a gyroscope proof mass with acceleration applied along a random direction](image)

**Figure C.7**: Free body diagram considering anisoelasticity of a gyroscope proof mass with acceleration applied along a random direction

![Figure C.8: Gyroscope anisoelasticity vector diagram about the z-axis of a single-axis gyroscope](image)

**Figure C.8**: Gyroscope anisoelasticity vector diagram about the z-axis of a single-axis gyroscope

The effect of anisoelasticity is graphically shown in Figure C.8. Based on the diagrams shown above, which are typical for all gyroscopes on the folded MEMS IMU for each axis of detection, expressions are derived for anisoelasticity error. A matrix representation of this expression is shown below in Equation (C.46).

$$
\vec{d} = \begin{pmatrix}
  d_x \\
  d_y
\end{pmatrix} = \begin{pmatrix}
  \frac{1}{k_x} ma \cos(\alpha) \\
  \frac{1}{k_y} ma \sin(\alpha)
\end{pmatrix} + \begin{bmatrix}
  0 & k_z \tan(\phi_{ai,gn}) \\
  k_z \tan(\theta_{ai,gn}) & 0
\end{bmatrix} \begin{pmatrix}
  x \\
  y
\end{pmatrix}
$$  (C.46)

This deflection causes a change in capacitance for the sensors implemented on the folded IMU structures. Therefore the error, calculated in Equation (C.47), is detected as a false
rate of rotation rate and negatively impacts sensor performance.

\[
\vec{e}_{\text{aig},n}^s = K_{c,n}^\omega K_{d,n}^c \cdot \vec{d}_{\text{err},y,gn}
\]  

(C.47)

In this equation, \(\vec{e}_{\text{aig},n}^s\) represents the anisoelasticity error for the \(n\)th gyroscope with respect to the sensor frame, and \(K_{d,n}^c\) is the scale factor for converting proof mass deflection to a change in capacitance. Similarly, \(K_{c,n}^\omega\) is the scale factor to convert capacitance into rotation rate. Integrating and mapping the error to the IMU body frame, like with the other errors, results in anisoelasticity error in units of angular rotation are defined in Equation (C.48).

\[
\vec{E}_{\text{aig},n}^b = C_{i,n}^b C_{s,n}^i K_{c,n}^\omega K_{d,n}^c \cdot \vec{d}_{\text{err},y,gn} \cdot t
\]  

(C.48)

While anisoelasticity effects on inertial sensors cannot be completely avoided, the sensor architecture can be designed to minimize the error. Due to the large surface area provided for sensors on the folded IMU devices, complex geometries can be implemented that are less susceptible to anisoelasticity error. The method used in the current design of the gyroscopes provides separate drive and sense masses [54]. All rotation rate detection is done with the sense mass, which is intentionally smaller than the drive mass. Anisoelasticity error is only induced by the smaller sense mass. Therefore when acceleration is experienced, the induced error is much when less compared to that of a single-mass gyroscope. Also due to the large sensor area available, the suspensions can be placed at the corner edges of the proof masses, significantly far apart from each other. This provides increased symmetry compared to existing IMU devices that utilize smaller multi-axis or single-axis sensors. Theoretically, this results in minimized anisoelasticity error compared to alternative sensors. Single-axis sensors generally provide large out-of-plane stiffness and low in-plane stiffness for the \(x\)– and \(y\)–axis sensors. Fabrication imperfections thus have a reduced effect on the performance of the sensors included on the folded MEMS IMU structures. A natural aspect of single-axis
inertial devices with a large surface is that they are generally very symmetric. Therefore, anisoelasticity error on the folded IMU devices is theoretically expected to be less than that of current chip-scale IMU devices.
D System Error Sources

While most of the error that is realized in an IMU arises from the individual sensor errors, there are some that also affect the overall IMU system. For instance, some of the errors from one sensor will add to the error from other sensors after computation in a navigation system. Once specific example is tilt misalignment which is caused by errors in inertial sensor signals which then cause errors observed in all other sensor calculations, and thus affects the overall IMU performance.

While all system errors cannot necessarily be known or analytically determined prior to installation in the end use application, the total system error from gyroscope bias and tilt misalignment can be estimated during the initial calibration procedure. White noise can also be considered as a system error since it is often influenced by the ambient environment in which the IMU is incorporated. Although it generally affects all local sensors similarly, white noise calculations are derived independently for each sensor in Section 7.2 The major difference is in the magnitude of error, which is significantly different for gyroscopes compared to accelerometers due to the number of integrations required for each.

D.1 Tilt Misalignment

Accuracy of orientation internally calculated by an IMU is limited by the detection of each gyroscope [56]. The orientation of the vessel is slightly miscalculated within the navigational computer. This attitude calculation is used for distance detection derived from accelerometer signals. Results of which cause trajectory errors to accumulate over time due to variances in rotation rate detection within the resolution limits of each gyroscope. Unfortunately, this error cannot be separated from bias error due to the gyroscopes because it causes the same type of error for the accelerometers [56, 57, 81]. The main of bias error calculations are
Tilt misalignment error will inevitably be induced into an IMU system comprised of MEMS sensors. Alternatively, a precision altimeter or gimballed set of gyroscopes can be used in addition to the IMU for compensation. These devices periodically update the self-detected orientation calculated by the IMU with a much more precise measurements. But this is not practical for the intended applications of the folded MEMS IMU due to size constraints. This occurs to some extent on all inertial devices, independent of the size of each individual sensor as well as the manufacturing process. A graphical depiction of the tilt misalignment effect induced by a $y$-axis gyroscope is shown in Figure D.9. However both $x$-axis and $z$-axis gyroscopes must also be considered for the overall system performance. The algorithms discussed in this section describe tilt misalignment induced by all gyroscopes. Although Figure D.9 depicts error for a $y$-axis gyroscope, the $x$- and $z$-axis gyroscope errors are typical to the figure. Derivation of the calculations based on the figure are shown below for the $y$-axis gyroscope, but are similar for the other axes which will be included later in matrix-form.

![Diagram of a folded MEMS IMU cube showing measured acceleration errors induced by the $y$-axis gyroscope tilt misalignment error.](image)

Terms shown in Figure D.9 include $e_{tmy,xx}^b$, defined as tilt misalignment error from the $y$-axis gyroscope reflected to the measured $x$-axis acceleration from the $z$-axis acceleration.
vector. This error also induces a false acceleration detection in the z-axis direction, $e_{tmy,zz}^b$. Other error terms are calculated in a similar manner, such as $e_{tmy,xx}^b$ and $e_{tmy,xz}^b$, with the notations modified to indicate the tilt misalignment error induced by each gyroscope into the acceleration measurements. Another term shown in the figure is $\beta_{tmy}^b$, which represents the angle of miscalculation from the y-axis gyroscope. This error is due to the individual characteristics of each sensor as well as signal processing techniques used for inertial detection. Other terms in the figure, such as $a_x$ and $\tilde{a}_x$ have been previously defined, and represent the actual and measured acceleration along the x-axis, respectively.

Each of the tilt misalignment errors, $e_{tmy,xx}^b$ and $e_{tmy,xz}^b$, are calculated as follows based on the cubic geometry shown in Figure [D.9]. Calculations for tilt misalignment error for other axes are completed in the same manner. The only difference being that alternative tilt misalignment angles are utilized that represent each of the gyroscope axes.

\[
e_{tmy,xx}^b = -a_x (1 - \cos(\beta_{tmy}^b)) \tag{D.49}
\]

\[
e_{tmy,xz}^b = a_z \sin(\beta_{tmy}^b) \tag{D.50}
\]

The total tilt misalignment error, considering all axes, contains a total of 12 terms, and is shown in horizontal vector form combined into one overall error term, $\vec{e}_{tm}^b$, shown in Equation (D.51).

\[
\vec{e}_{tm}^b = \begin{bmatrix}
e_{tmy,xx}^b + e_{tmy,xz}^b + e_{tmz,xx}^b + e_{tmz,xy}^b \\
e_{tmx,yy}^b + e_{tmx,yz}^b + e_{tmz,yy}^b + e_{tmz,yx}^b \\
e_{tmx,zz}^b + e_{tmx,zy}^b + e_{tmy,zz}^b + e_{tmy,zx}^b
\end{bmatrix} \tag{D.51}
\]

Substituting each expression of the errors calculated in Equations (D.49) and (D.50),
as well as similar expressions for the x- and z-axis gyroscope error terms, the total tilt misalignment error vector becomes as follows in Equation \((D.52)\).

\[
\vec{e}_{tm} = \begin{cases} 
-a_x(1 - \cos(\beta_{tmx})) + a_z \sin(\beta_{tmz}) - a_x(1 - \cos(\beta_{tmz})) + a_y \sin(\beta_{tmz}) \\
-a_y(1 - \cos(\beta_{tmz})) + a_z \sin(\beta_{tmx}) - a_y(1 - \cos(\beta_{tmz})) + a_z \sin(\beta_{tmx}) \\
-a_z(1 - \cos(\beta_{tmz})) + a_y \sin(\beta_{tmx}) - a_z(1 - \cos(\beta_{tmx})) + a_x \sin(\beta_{tmx}) 
\end{cases}
\]

\((D.52)\)

Because each error term is defined with respect to the IMU body frame, which is considered cubic for these calculations, no coordinate transformation is necessary. However the error must be integrated to convert of acceleration measurements into units of distance. For the pyamidic IMU form-factor, both a coordinate transformation and integration is necessary, but is not shown in these calculations. Integrating the total tilt-misalignment error from each gyroscope is performed using Equation \((D.53)\). This is again typical for all tilt-misalignment errors induced by each gyroscope fabricated on the folded IMU devices.

\[
\Rightarrow \vec{E}_{tm} = \int \int \vec{e}_{tm} \, d^2t = \vec{v}_{0,n} \cdot t + \frac{1}{2} \vec{e}_{tm} \cdot t^2
\]

\((D.53)\)

The term \(\vec{E}_{tm}\) represents the total integrated error due to a gyroscope signal detection error that cause a false calculation in attitude. As determined from this equation, the magnitude of error is dependent upon a factor of \(t^2\) and thus will increase quickly over time. Therefore it is important to minimize this error by utilizing high-quality signal detection methods.

Detection of tilt misalignment error is directly dependent on gyroscope resolution which is limited by noise. This can be minimized by using high-performance gyroscopes and state-of-the-art signal detection techniques. However in the end, there is still some inertial detection information lost due to tilt-misalignment error because the error induced cannot be filtered out from gravitational detection of the accelerometers without the use of additional devices.
such as an altimeter. In regards to the folded IMU, there are specific advantages offered when considering tilt misalignment error. First, single-axis sensors are utilized on the folded IMU, which minimizes tilt misalignment when compared to multi-axis sensors with higher cross-axis sensitivity. Also, similar to other errors, tilt misalignment is further reduced by using larger sensor footprint areas. The folded IMU design allows for sensor areas that is much larger than conventional chip-level IMUs. This also inherently increases the signal-to-noise ratio of each sensor. Larger sensors generally have better resolution than smaller sensors and thus are less susceptible to influence of errors including that from tilt misalignment, resulting in more accurate inertial detection. Hence the folded IMU design is theoretically capable of lower tilt misalignment error when compared to existing IMU devices with a similar footprint.

D.2 System Error from Gyroscope Bias

Similar to tilt misalignment error that arises from resolution limits of each gyroscope, bias error from the gyroscopes also affect the IMU system alignment measurements. Gyroscope bias induces angular error not only into the gyroscope signals, but also into the accelerometer measurements. This error is realized by the acceleration measurements just as for the tilt misalignment error. Thus it is difficult to determine which error is causing a more significant drift in the accelerometer signals. However both types of error can be predicted if the characteristics of each individual sensor are known and experimentally calibrated. Calculations of the system error due to gyroscope bias are discussed in this section.

The algorithm described applies to the cubic folded IMU form factor due to its direct orthogonal alignment of the IMU body frame with the navigational frame. However the same overall procedure can be used for the pyramidal IMU with the addition of the trigonometric calculations involved with the geometry. As defined in Appendix C.1, the angular bias error
from a z-axis gyroscope with respect to the IMU body frame is given as $E_{Bg,z}^b$ below.

$$E_{Bg,z}^b = e_{Bg,z}^b \cdot t$$  \hspace{1cm} (D.54)

This results in an $x$-axis acceleration error and similarly a $y$-axis acceleration error as shown in Equations (D.55) and (D.56). In the expressions, $e_{Bg,z,x}^b$ represents the error induced to the $x$-axis accelerometer vector from the $z$-axis gyroscope, and $e_{Bg,z,y}^b$ represents the error induced into the $y$-axis accelerometer vector from the same gyroscope.

$$e_{Bg,z,x}^b = -a_y \sin(E_{Bg,z}^b) - a_x (1 - \cos(E_{Bg,z}^b))$$  \hspace{1cm} (D.55)

$$e_{Bg,z,y}^b = a_x \sin(E_{Bg,z}^b) - a_y (1 - \cos(E_{Bg,z}^b))$$  \hspace{1cm} (D.56)

Expressions for acceleration error from the $y$-axis and $x$-axis gyroscope bias errors are calculated in similar fashion, resulting in the following four expressions. The first two, Equations (D.57) and (D.58), represent the $x$-axis and $z$-axis acceleration errors due to the $y$-axis gyroscope bias. Similarly, the latter two, Equations (D.59) and (D.60), represent the $y$-axis and $z$-axis acceleration errors due to the $x$-axis gyroscope bias.

$$e_{Bg,y,x}^b = a_z \sin(E_{Bg,y}^b) - a_x (1 - \cos(E_{Bg,y}^b))$$  \hspace{1cm} (D.57)

$$e_{Bg,y,z}^b = -a_x \sin(E_{Bg,y}^b) - a_z (1 - \cos(E_{Bg,y}^b))$$  \hspace{1cm} (D.58)

$$e_{Bg,x,y}^b = a_x \sin(E_{Bg,x}^b) - a_y (1 - \cos(E_{Bg,x}^b))$$  \hspace{1cm} (D.59)
\[ e_{Bg,x,z}^b = a_y \sin(E_{Bg,x}^b) - a_z (1 - \cos(E_{Bg,x}^b)) \] (D.60)

These errors are then combined into matrix form to be useful for computational compensation purposes. Additionally, each error must be multiplied by the acceleration input along each axis. The resulting expression is given below, defining the vector \( \vec{e}_{Bga}^b \), which represents the total system error due to the gyroscope biases for all axes.

\[
\vec{e}_{Bga}^b = \begin{bmatrix}
(1 - \cos(E_{Bga}^b)) - (1 - \cos(E_{Bga}^b)) & -\sin(E_{Bga}^b) & \sin(E_{Bga}^b) \\
\sin(E_{Bga}^b) & -(1 - \cos(E_{Bga}^b)) - (1 - \cos(E_{Bga}^b)) & \sin(E_{Bga}^b) \\
-\sin(E_{Bga}^b) & -\sin(E_{Bga}^b) & -(1 - \cos(E_{Bga}^b)) - (1 - \cos(E_{Bga}^b))
\end{bmatrix}
\begin{bmatrix}
a_x \\
a_y \\
a_z
\end{bmatrix}
\] (D.61)

Because gyroscope bias errors are generally considered to be small with respect to the magnitude of the scale factors, it can be mathematically assumed that the angular errors that affect the calculated acceleration axes are also small. Using a small angle assumption and substituting the expressions for the \( E_{Bga,n}^b \) terms in Equation (D.61), the following matrix is produced, shown in Equation (D.62).

\[
\Rightarrow \vec{e}_{Bga}^b = \begin{bmatrix}
0 & -\vec{e}_{Bga,z}^b \cdot t & \vec{e}_{Bga,y}^b \cdot t \\
\vec{e}_{Bga,z}^b \cdot t & 0 & \vec{e}_{Bga,x}^b \cdot t \\
-\vec{e}_{Bga,y}^b \cdot t & -\vec{e}_{Bga,x}^b \cdot t & 0
\end{bmatrix}
\begin{bmatrix}
a_x \\
a_y \\
a_z
\end{bmatrix}
\] (D.62)

Notice that this is a skew-symmetric matrix, which can be expected because it is essentially a rotation vector translated to a 3x3 matrix. However the error must be integrated from acceleration units into distance units, resulting in the following expression for \( \vec{E}_{Bga}^b \). Equation (D.63) shown a matrix of distance errors induced into the acceleration axes from
gyroscope bias influences.

\[ \Rightarrow \vec{E}_{Bga}^b = \frac{1}{6} \begin{bmatrix} 0 & -\vec{e}_{Bg,z} \cdot t^3 & \vec{e}_{Bg,y} \cdot t^3 \\ -\vec{e}_{Bg,z} \cdot t^3 & 0 & \vec{e}_{Bg,x} \cdot t^3 \\ -\vec{e}_{Bg,y} \cdot t^3 & -\vec{e}_{Bg,x} \cdot t^3 & 0 \end{bmatrix} \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} \] (D.63)

It is observed that this error is dependent on a factor of \( t^3 \), which will significantly increase with respect to time and thus can be a large source of error. This is yet another example indicating that gyroscope bias must be minimized as much as possible to increase performance of any IMU system. Although this error can never be completely avoided, flexibility of design and operation schemes that can be implemented on the folded MEMS IMU devices are able to minimize bias error using existing high-performance configurations \[54, 70\].

The folded MEMS fabrication approach is advantageous for multiple reasons when considering system effects from gyroscope bias error. First, the large size of each sensor allows for minimal error influence, including that of gyroscope bias error and many others previously discussed. Second, by using single-axis sensors rather than multi-axis sensors which are common among current chip-scale IMUs, bias error is further reduced for each axis of detection. Additionally, for the cubic IMU configuration, the sensors are orthogonal to one another. Therefore bias error from each sensor affects independent axes of detection in the navigational frame. Although bias error cannot be completely eliminated, it can be calibrated and then compensated for during operation. This can further reduce the bias error effects on the entire IMU system. Overall, the folded MEMS approach, even in these early stages of development, has the capability of meeting or exceeding the current state-of-the-art technology.
E Matlab Code for Error Model

The error model in this work is implemented using a Matlab program to approximate the errors from various sources. Source code for each file is included below. Each type of error calculation is approximated and then converted to the navigational frame. Individual programs have been created for the errors being considered. The calculated errors are determined by the following files. The 'Main File' controls the sequence of operations, and approximates the overall CEP error based on a defined trajectory.

E.1 Main File

```matlab
%% %%%%%%%%% DEFINITIONS AND ERROR INPUTS %%%%%%%%%
%% PUT YOUR DESIRED OUTPUT FOLDER HERE, MAKE SURE IT ALREADY
%% EXISTS, AND HAS A "\" AT THE END, LIKE BELOW.
pyr_angle = 60;
DirOut = 'C:\IMU Cube\Error Model\Matlab\Bias\Output\';
Pinit = [0;0;0];
Vinit = [0;0;0];
Ainit = [0;0;0];
accel_biasX = 6;
% Units of micro-g (from Alex's paper "Silicon Accel with Diff. Freq Mod..."
accel_biasY = accel_biasX;
accel_biasZ = accel_biasX;

gyro_biasX = 0.9;
% Units of deg/hr (from Igor's paper "Sub-Degree-per-Hour Silicon MEMS..."


```
PyramidToOrthoMapGyro = inv(OrthoToPyramidMapGyro);

%% XXXXXXXXXXXXX PATH DEFINITIONS XXXXXXXXXXXXXXXXXXXX

% motion definitions
mot_def(1,:)=[3 0 -45*D2R 45*D2R 10 100];
mot_def(2,:)=[3 0 15*D2R 0*D2R 0 100];
mot_def(3,:)=[3 0 30*D2R 15*D2R 0 100];
mot_def(4,:)=[3 0 -10*D2R -30*D2R 0 100];
mot_def(5,:)=[3 0 15*D2R 15*D2R 0 100];
mot_def(6,:)=[3 15*D2R 15*D2R 15*D2R 0 200];
mot_def(7,:)=[3 -15*D2R 30*D2R 0*D2R 0 100];

TESTER = 1;

%% XXXXXXXXXXX GENERATE TRAJECTORY XXXXXXXXXXX

% INPUTS: PathGen_v003_noErr (dir_name, ini_pva, mot_def, out_typ, sim_mode)
% mimu outputs: (index, accelX, accelY, accelZ, gyroX, gyroY, gyroZ)
% mnav outputs:
% (index, 2, 3, 4, v_x(5), v_y(6), v_z(7), ang_x(8), ang_y(9), ang_z(10))

%% %%%%%% EXTRACT ACTUAL TRAJECTORY VALUES %%%%%%%

% These values are all in the frame of the vessel, assuming a strapdown IMU with the x-axis oriented toward the front of the vessel, and the z-axis upward.

TimeVals = OutputDataActual(:,1);
AccelDataActual_X = OutputDataActual(:,2);
AccelDataActual_Y = OutputDataActual(:,3);
AccelDataActual_Z = OutputDataActual(:,4);
VelDataActual_X = OutputDataActual(:,5);
VelDataActual_Y = OutputDataActual(:,6);
VelDataActual_Z = OutputDataActual(:,7);
DistDataActual_X = OutputDataActual(:,8);
DistDataActual_Y = OutputDataActual(:,9);
DistDataActual_Z = OutputDataActual(:,10);
AngRateDataActual_X = OutputDataActual(:,11);
AngRateDataActual_Y = OutputDataActual(:,12);
AngRateDataActual_Z = OutputDataActual(:,13);

% CHANGE TO PYRAMID SENSOR COORDINATES %%%%%%%

AccelDataActualPyr = CoordTrans(AccelDataActual,OrthoToPyramidMapAccel);
VelDataActualPyr = CoordTrans(AccelDataActual,OrthoToPyramidMapAccel);
DistDataActualPyr = CoordTrans(AccelDataActual,OrthoToPyramidMapAccel);

%% COMPUTE GYROSCOPE ERRORS %%%%%%%

GyroAngleBias = BiasErrGyroPyr(gyro_biasX,TimeVals,AccelDataActualPyr,...
VelDataActualPyr,DistDataActualPyr,PyramidToOrthoMapGyro);
GyroAngleSF = GyroSFErrPyr(gyro_SFerrX,TimeVals,AngRateDataActualPyr,...
AngRateDataActualPyr(:,1),PyramidToOrthoMapGyro);
GyroAngleTMA = TempMAErrGyro(tma_const,AngRateDataActualPyr,TimeVals,...
TempMADistVals,PyramidToOrthoMapGyro);

%% COMPUTE ACCELEROMETER MISALIGNMENT ERROR DUE TO TEMPERATURE %%%%%%%

TempMDistVals = TempMAErrAccelPyr(tma_const,TimeVals,AccelDataActualPyr,...
VelDataActualPyr,DistDataActualPyr,PyramidToOrthoMapAccel);

% XXXXXXXXXXXXXXXXXX COMPUTE ACCELEROMETER MISMATCH ERROR DUE TO TEMPERATURE XXXXXXXXXXXXXXXXXX

TempMADistVals = TempMAErrAccelPyr(tma_const,TimeVals,AccelDataActualPyr,...
VelDataActualPyr,DistDataActualPyr,PyramidToOrthoMapAccel);

% Uncomment if you want to print the values to the command window
% disp('Temperature Values:'); disp(TimeVals);
% disp('Accel Data Actual:'); disp(AccelDataActual);
% disp('Dist Data Actual:'); disp(DistDataActual);
% disp('Ang Rate Actual:'); disp(AngRateDataActual);
% disp('Gyro Angle Bias:'); disp(GyroAngleBias);
% disp('Gyro Angle SF:'); disp(GyroAngleSF);
% disp('Gyro Angle TMA:'); disp(GyroAngleTMA);
% disp('Temp MDist Vals:'); disp(TempMDistVals);

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AccelDistTMA = TempMADistVals(:,3);

%% %%%%%%%%%%%% COMPUTE BIAS ERRORS %%%%%%%%%%%%
AccelDistBiasPyr = BiasErrAccelPyr(accel_biasX, TimeVals, VelDataActualPyr(:,1,:),
    DistDataActualPyr(:,1,:), PyramidToOrthoMapAccel);

%% %%%%%%%%% COMPUTE SCALE FACTOR ERRORS %%%%%%%%%
AccelDistSF = AccelSFErrPyr(accel_SFerrX, TimeVals, AccelDataActualPyr,
    VelDataActualPyr(:,1,:), DistDataActualPyr(:,1,:), PyramidToOrthoMapAccel);

%% %%%%%%%%% COMPUTE TOTAL DISTANCE ERRORS %%%%%%%%%
GyroDistErrTotalSFBias = AngleToDistPyr(TimeVals, GyroAngleErrTotalSFBias,
    AccelDataActual, VelDataActual, DistDataActual);
GyroDistErrTotalWMA = AngleToDistPyr(TimeVals, GyroAngleErrTotalWMA,
    AccelDataActual, VelDataActual, DistDataActual);
AccelDistErrTotalSFBias = AccelDistBiasPyr + AccelDistSF;
AccelDistErrTotalWMA = AccelDistErrTotalSFBias + TempMADistVals;
DistDataWErrSFBias_X = DistDataActual(:,1) + AccelDistErrTotalSFBias + GyroDistErrTotalSFBias;
DistDataWErrTMA_X = DistDataActual(:,1) + GyroDistErrTotalWMA + AccelDistErrTotalWMA;
DistDataWErrSFBias_Y = DistDataActual(:,2) + AccelDistErrTotalSFBias + GyroDistErrTotalSFBias;
DistDataWErrTMA_Y = DistDataActual(:,2) + GyroDistErrTotalWMA + AccelDistErrTotalWMA;
DistDataWErrSFBias_Z = DistDataActual(:,3) + AccelDistErrTotalSFBias + GyroDistErrTotalSFBias;
DistDataWErrTMA_Z = DistDataActual(:,3) + GyroDistErrTotalWMA + AccelDistErrTotalWMA;

%% %%%%%%%%%%%%%%%%%% 3-D PLOT %%%%%%%%%%%%%%%%%%
% Create axes
TrajPlotFig = figure('Color',[1 1 1]);
axes1 = axes('Parent', TrajPlotFig);
ylim(axes1,[0 1000]);
view(axes1,[-82 36]);
grid(axes1,'on');
hold(axes1,'all');

% Create 3D trajectory
TrajPlot = plot3(DistDataActual_X, DistDataActual_Y, DistDataActual_Z,'Parent',axes1,'LineWidth',2);
set(TrajPlot(1), 'DisplayName', 'True Trajectory');
set(TrajPlot(2), 'DisplayName', 'With Scale and SF Error');
set(TrajPlot(3), 'DisplayName', 'Add Temperature Misalignment Error');

% Create x label
xlabel('X- Displacement (m)', 'FontSize', 12);

% Create y label
ylabel('Y- Displacement (m)', 'FontSize', 12);

% Create z label
zlabel('Altitude (m)', 'FontSize', 12);

% Create legend
legend1 = legend(axes1, 'show');
set(legend1, 'Position', [0.539 0.703 0.331 0.141],
    'FontSize', 12);

%% %%%%%%%%%%%%%%%%%% COMPUTE CEP VALUE %%%%%%%%%%%%%%%%%
vecsize = length(TimeVals);
finaldisterr = sqrt(((DistDataWErrTMA_X(vecsize) - DistDataActual_X(vecsize))^2 + ...
    (DistDataWErrTMA_Y(vecsize) - DistDataActual_Y(vecsize))^2 + ...
    (DistDataWErrTMA_Z(vecsize) - DistDataActual_Z(vecsize))^2))
CEPerr = finaldisterr * 0.707
CEPrateErr = finaldisterr * 0.707 / (TimeVals(vecsize)/3600)*(1/1852)
% CEP error in nautical mi/hr

% Create legend
legend1 = legend(axes1, 'show');
set(legend1, 'Position', [0.539 0.703 0.331 0.141],
    'FontSize', 12);

% 3-D PLOT
% %%%%%%%%%%%%%%%%%% 3-D PLOT %%%%%%%%%%%%%%%%%
% Create axes
TrajPlotFig = figure('Color',[1 1 1]);
axes1 = axes('Parent', TrajPlotFig);
ylim(axes1,[0 1000]);
view(axes1,[-82 36]);
grid(axes1,'on');
hold(axes1,'all');

% Create 3D trajectory
TrajPlot = plot3(DistDataActual_X, DistDataActual_Y, DistDataActual_Z,'Parent',axes1,'LineWidth',2);
set(TrajPlot(1), 'DisplayName', 'True Trajectory');
set(TrajPlot(2), 'DisplayName', 'With Scale and SF Error');
set(TrajPlot(3), 'DisplayName', 'Add Temperature Misalignment Error');

% Create x label
xlabel('X- Displacement (m)', 'FontSize', 12);

% Create y label
ylabel('Y- Displacement (m)', 'FontSize', 12);

% Create z label
zlabel('Altitude (m)', 'FontSize', 12);

% Create legend
legend1 = legend(axes1, 'show');
set(legend1, 'Position', [0.539 0.703 0.331 0.141],
    'FontSize', 12);

% 3-D PLOT
% %%%%%%%%%%%%%%%%%% 3-D PLOT %%%%%%%%%%%%%%%%%
% Create axes
TrajPlotFig = figure('Color',[1 1 1]);
axes1 = axes('Parent', TrajPlotFig);
ylim(axes1,[0 1000]);
view(axes1,[-82 36]);
grid(axes1,'on');
hold(axes1,'all');

% Create 3D trajectory
TrajPlot = plot3(DistDataActual_X, DistDataActual_Y, DistDataActual_Z,'Parent',axes1,'LineWidth',2);
set(TrajPlot(1), 'DisplayName', 'True Trajectory');
set(TrajPlot(2), 'DisplayName', 'With Scale and SF Error');
set(TrajPlot(3), 'DisplayName', 'Add Temperature Misalignment Error');

% Create x label
xlabel('X- Displacement (m)', 'FontSize', 12);

% Create y label
ylabel('Y- Displacement (m)', 'FontSize', 12);

% Create z label
zlabel('Altitude (m)', 'FontSize', 12);

% Create legend
legend1 = legend(axes1, 'show');
set(legend1, 'Position', [0.539 0.703 0.331 0.141],
    'FontSize', 12);
E.2 Gyroscope Bias Error Function

```matlab
function [GyroBiasAngleOut] = BiasErrGyroPyr(gyro_bias, TimeArr, AccelValsMat, VelValsMat, DistValsMat, CoordMap)

%% DEFINE INITIAL VALUES AND CONVERSIONS %%%%
size = numel(TimeArr);
gyro_biasRS = (gyro_bias/3600)*(pi/180); % convert from deg/hr to rad/s
GyroBiasVec(1:size) = gyro_biasRS;
GyroBiasMat = [GyroBiasVec', GyroBiasVec', GyroBiasVec'];

%% INTEGRATE BIAS DATA FROM RATE TO ANGLE %%%%
BiasErrAngle(:,1) = cumtrapz(TimeArr, GyroBiasMat(:,1));
BiasErrAngle(:,2) = cumtrapz(TimeArr, GyroBiasMat(:,2));
BiasErrAngle(:,3) = cumtrapz(TimeArr, GyroBiasMat(:,3));

%% MAP VALUES TO VESSEL FRAME %%%%
GyroBiasAngleOut = abs(CoordTrans(BiasErrAngle, CoordMap));
% using absolute value to assume worst-case
```

E.3 Accelerometer Bias Error Function

```matlab
function [DistValsOut] = BiasErrAccelPyr(accel_bias, TimeArray, InitVel, InitDist, CoordMap)
% accel_bias = const bias (micro-g), TimeArray = time values,
% This is done in the sensor frame, then is transformed to the IMU body
% frame. No need for applying vessel-frame Dist and Vel vals now.
size = length(TimeArray);
accel_biasMS2 = accel_bias*(9.81/1000000); % accel_bias is units of micro-g, convert to m/s^2
AccelBiasVec(1:size) = accel_biasMS2;
AccelBiasMat = [AccelBiasVec', AccelBiasVec', AccelBiasVec'];
DistValsOutPyr = AccelToDistPyr(TimeArray, AccelBiasMat, InitVel, InitDist);
DistValsOut = abs(CoordTrans(DistValsOutPyr, CoordMap));
```

E.4 Gyroscope Scale Factor Error Function

```matlab
function [AngleErrOut] = GyroSFErrPyr(perK, TimeArray, AngleRateMat, InitAngs, CoordMap)
% perK = percent SF error
% TimeArray = time array (in seconds)
% AngleRateMat = matrix of rotation rates
% InitAngs = vector of initial angles

SFerr = perK/100;
% convert from percent to actual error value in degrees/hr
RotRateMatSF = SFerr * AngleRateMat;
AngleErrOutPyr(:,1) = InitAngs(1) + cumtrapz(TimeArray, RotRateMatSF(:,1));
AngleErrOutPyr(:,2) = InitAngs(2) + cumtrapz(TimeArray, RotRateMatSF(:,2));
AngleErrOutPyr(:,3) = InitAngs(3) + cumtrapz(TimeArray, RotRateMatSF(:,3));

%% MAP TO VESSEL FRAME %%%%
AngleErrOut = abs(CoordTrans(AngleErrOutPyr, CoordMap));
```
E.5 Accelerometer Scale Factor Error Function

```matlab
function [DistErrOut] = AccelSFErrPyr(perK, TimeArray, AccelMat, ...
    InitVels, InitDists, CoordMap)
    % perK = percent SF error
    % TimeArray = time array (in seconds)
    % AccelMat = matrix of actual acceleration
    % InitVels = vector of initial velocities
    % InitDists = vector of initial distances
    SFerr = perK/100; % convert from percent to actual error value
    eSFanbA = SFerr * AccelMat; % Transform from sensor frame to vessel frame
    AccelSFValsMatAdj = CoordTrans(eSFanbA, CoordMap);
    % AccelSFError = AccelSFValsMatAdj - AccelMat
    DistErrOut = abs(AccelToDistPyr(TimeArray, AccelSFValsMatAdj, ...
        InitVels, InitDists));
```

E.6 Gyroscope Temperature Misalignment Error Function

```matlab
function [OutputVals] = TempMAErrGyro(temp_const, AngleRateVals, ...
    TempVals, TimeArray, PyrMap)
    % AngleRateVals = Angular rate input matrix in sensor frame (rad/s)
    % TempVals = Temperature values (celsius)
    % TimeVals = time array (s),
    %% %%%% DEFINE VARIABLES AND ANGLE MATRICES %%%% 
    size = numel(TimeArray);
    ThetaErr = (TempVals - 25)*(temp_const/60); % 1.7mrad (epoxy) or 0.2mrad (solder) misalignment for change
    PhiErr = ThetaErr;
    PsiErr = ThetaErr;
    GyroValsMatAdj = zeros(size,3);
    %% %%%%%%% TRANSFORM FROM MISALIGNMENT TO SENSOR FRAME %%%%%
    for i =1:size
        GyroValsMatAdj(:,i) = (RotX(ThetaErr(i)) * RotY(PhiErr(i)) ...
            * RotZ(PsiErr(i))) * AngleRateVals(i,:)';
    end
    %% %%%%%%% SUBTRACT ORIGINAL VALUES TO DETERMINE ERROR VALUES %%%%%
    GyroValsMatAdjErr = GyroValsMatAdj - AngleRateVals;
    %% %%%%%%% TRANSFORM FROM SENSOR FRAME TO VESSEL FRAME %%%%%
    GyroValsMatAdjOrtho = CoordTrans(GyroValsMatAdjErr, PyrMap);
    %% %%%%%% CONVERT ROTATION RATE VALUES TO ANGLE VALUES %%%%% 
    AngleOutX = cumtrapz(TimeArray, GyroValsMatAdjOrtho(:,1));
    AngleOutY = cumtrapz(TimeArray, GyroValsMatAdjOrtho(:,2));
    AngleOutZ = cumtrapz(TimeArray, GyroValsMatAdjOrtho(:,3));
    %% %%%%%% DEFINE OUTPUT VALUES %%%%%
    OutputVals(:,1) = abs(AngleOutX);
    OutputVals(:,2) = abs(AngleOutY);
    OutputVals(:,3) = abs(AngleOutZ);
```
E.7 Accelerometer Temperature Misalignment Error

```matlab
function [TempMAerrDist] = TempMAErrAccelPyr(tma_const, TimeArray,...
    TempVals, AccelValsMat, VelocityValsMat, DistValsMat, PyrMap)
% TimeArray = time array (in seconds)
% AccelValsMat = matrix of acceleration values in ideal IMU BODY frame
% VelocityValsMat = matrix of velocity values in ideal VESSEL frame
% DistValsMat = matrix of distance values in ideal VESSEL frame
% TempVals = vector of temperature values (Celsius)

%% %%% DEFINE VARIABLES AND ANGLE MATRICES %%%%
size = numel(TimeArray);
ThetaErr = (TempVals - 25)*(tma_const/60);
% tma_const is 0.0017 rad (epoxy) or 0.0002 rad (solder) misalignment
% for change in temp from 25C to 85C (Monthly report from 101201)
PhiErr = ThetaErr;
PsiErr = ThetaErr;
AccelValsMatAdj = zeros(size,3);

%% %%%%%%% ADD MISALIGNMENT TO ACCEL %%%%%%%%
for i = 1:size
    AccelValsMatAdj(i,:) = (RotX(ThetaErr(i)) * RotY(PhiErr(i)) * ...
                              RotZ(PsiErr(i))) * AccelValsMat(i,:);
end

%% %%%%%%% SUBTRACT ORIGINAL VALUES TO FIND ERROR %%%%%%%%
TotalErrAccel = AccelValsMatAdj - AccelValsMat;

%% %%%%%%% TRANSFORM FROM SENSOR FRAME TO VESSEL FRAME %%%%%%%%
TotalErrAccelOrtho = CoordTrans(TotalErrAccel, PyrMap);

%% %%%% CONVERT ACCELERATION VALUES TO DISTANCE VALUES %%%%%
% VelocityValsMat and DistValsMat in vessel frame
% Absolute values are considered to assume worst-case
TempMAerrDist = abs(AccelToDistPyr(TimeArray, TotalErrAccelOrtho,...
    VelocityValsMat(:,1), DistValsMat(:,1)));```

E.8 Coordinate Transformation Function

```matlab
function [OutputMat] = CoordTrans(MatrixVals, CoordMap)
size = length(MatrixVals);
for i = 1:size
    OutputMat(i,:) = CoordMap * MatrixVals(i,:);'
end```

E.9 Function to Integrate Acceleration into Distance

```matlab
function [DistVals] = AccelToDistPyr(TimeVals, AccelVals,...
    InitVel, InitDist)
% AccelVals = array of acceleration vals (m/s^2)
% TimeVals = time array (s)
% InitVel = Initial velocity vector
% InitDist = Initial distance vector
% No coordinate transformation as this is just an integral function.

VelVals(:,1) = cumtrapz(TimeVals, AccelVals(:,1))+InitVel(1);
DistVals(:,1) = cumtrapz(TimeVals, VelVals(:,1))+InitDist(1);
VelVals(:,2) = cumtrapz(TimeVals, AccelVals(:,2))+InitVel(2);
```
\[ \text{DistVals}(:,2) = \text{cumtrapz}(\text{TimeVals}, \text{VelVals}(::,2)) + \text{InitDist}(2); \]
\[ \text{VelVals}(::,3) = \text{cumtrapz}(\text{TimeVals}, \text{AccelVals}(::,3)) + \text{InitVel}(3); \]
\[ \text{DistVals}(::,3) = \text{cumtrapz}(\text{TimeVals}, \text{VelVals}(::,3)) + \text{InitDist}(3); \]

### E.10 Rotation Matrix Functions

**function** \([ \text{RotMatX} ] = \text{RotX} (\theta) \)

% \theta = rotation about x-axis

\[ \text{RotMatX} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta) & \sin(\theta) \\ 0 & -\sin(\theta) & \cos(\theta) \end{bmatrix}; \]

**function** \([ \text{RotMatY} ] = \text{RotY} (\phi) \)

% \phi = rotation about y-axis

\[ \text{RotMatY} = \begin{bmatrix} \cos(\phi) & 0 & -\sin(\phi) \\ 0 & 1 & 0 \\ \sin(\phi) & 0 & \cos(\phi) \end{bmatrix}; \]

**function** \([ \text{RotMatZ} ] = \text{RotZ} (\psi) \)

% \psi = rotation about z-axis

\[ \text{RotMatZ} = \begin{bmatrix} \cos(\psi) & \sin(\psi) & 0 \\ -\sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix}; \]
F Vendors and Suppliers

F.0.1 Ultra-sil

Nearly all wafers used in this research were obtained from Ultra-sil. This company is capable of providing a wide variety of wafers as well as custom orders. Pure silicon wafers were significantly utilized for the purpose of creating test structures and evaluating fabrication process results. For the folded MEMS IMU devices, fabrication was performed on SOI wafers with a 500 µm handle layer and a 50 µm device layer. The majority of each type were purchased from Ultra-sil.

- Contact: Raymond Duque
- Phone Number: (510) 266-3700
- Website: www.ultrasil.com

F.0.2 FineLine Imaging

During this research several fabrication masks have been utilized due to the large number of development iterations. FineLine offers quick turn-around for glass masks and were used several times during this work. Multiple types of masks are offered with different resolution levels and is a useful source for several applications.

- Contact: Rich Sayer
- Phone Number: (719) 268-8319
- Website: www.fineline-imaging.com
F.0.3 PhotoSciences

Another company was also used for mask fabrication for several masks that were utilized for this work. One specialty of Photosciences is fabricating masks with very small minimum features with high resolution. In general, masks for the sensors were obtained from Photosciences due to the critical 5 µm features and gaps contained in the sensor design. Masks were also ordered for batch SOI sensor fabrication runs with up to 400 devices on a single wafer.

- Contact: Kiomi Hamada
- Phone Number: (310) 784-7460
- Website: www.photo-sciences.com

F.0.4 Capitol Scientific

Photoresist was a key ingredient in many of the fabrication steps performed in this work. For the most part, AZ P4620 photoresist was used due to it’s thickness properties and ease of lithographic patterning. However many other materials are available from Capitol Scientific for a wide variety of applications.

- Contact: Misty Hull
- Phone Number: (800) 580-1167
- Website: www.capitolscientific.com

F.0.5 Mays Chemical

Several types of materials are available from Mays Chemical including photoresist and developers. Some batches of photoresist and developer used for the folded MEMS IMU process
was purchased from Mays Chemical. This company and Capitol Scientific are both useful for acquiring cleanroom materials and supplies.

- Contact: Beena Siddiqui
- Phone Number: (317) 558-2262
- Website: www.mayschem.com

F.0.6 HD Microsystems

Multiple types of polyimide were used throughout the development process. In general, polyimide was utilized, obtained from HD Microsystems. Developer solutions were also purchased, which enabled lithographic patterning of polyimide on the folded MEMS structures.

- Contact: Jean Reed
- Phone Number: (800) 346-5656
- Website: www.hdmicrosystems.com

F.0.7 Micromanipulator

For accurate inspection and maneuvering of sensor features and small packaging features, probes were used that have a movement resolution of approximately 1 µm. Multi-degree-of-freedom probes were utilized on a microscopic observation platform to probe and position critical portions of the folded MEMS IMU structures. Various tools such as probe needles, probe station parts, cables, and other items have been purchased from Micromanipulator.

- Contact: Randy Davis
- Phone Number: (949) 481-7133
- Website: www.micromanipulator.com

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F.0.8 Spectrum Micromechanical

During the sensor development stages of research, a large amount of wafer dicing was needed to individualize each sensor from each other for extraction from the fabrication wafer. A large amount of the dicing work was carried out by Spectrum Micromechanical. For protection, wafers were first covered with photoresist to prepare for the dicing process. Spectrum Micromechanical proceeded to dice the wafers with excellent precision to individualize sensors. After removing the photoresist with an extensive cleaning and releasing the underlying oxide layer, the individual sensors were then operational and capable of inertial detection.

- Contact: Jeff Olson
- Phone Number: (858) 395-2264
- Website: www.spmmi.com

F.0.9 West:Bond

Wirebonding and epoxy bonding process were integral components of the folded MEMS IMU packages. Tools obtained from West-Bond aided in packaging structures after wafer-level fabrication of the IMU devices. Such tools include a 747677E wirebonder capable of wedge and ball bonding, as well as a 7201-CR die-bonder for epoxy bonding. Parts can also be purchased from West-Bond, and the materials and specific bonding tools were obtained from other manufacturers.

- Contact: Chet Brannen
- Phone Number: (714) 978-1551
- Website: www.westbond.com
F.0.10 DeWeyl

Throughout the packaging process development, multiple types of wire-bonding and epoxy-bonding were utilized. Tools for the bonding equipment were largely purchased from DeWeyl for bonding with aluminum and gold wire. Epoxy-bonding equipment was also obtained from DeWeyl which was used for flip-chip attachment of the encapsulation lids.

- Contact: Johanna Palmer
- Phone Number: (707) 765-5779
- Website: www.deweyl.com

F.0.11 Henkel

Various types of epoxy were used during the development of the folded MEMS IMU for structural purposes as well as for creating electrical connections. Conductive epoxies from Henkel were used with the West:Bond 7201-CR die-bonder for accurate application onto bond pads on the sensors and encapsulation lids.

- Contact: Froilan Mendoza
- Phone Number: (310) 761-4866
- Website: www.henkel.com

F.0.12 So-Low

Multiple types of polyimide and conductive bonding epoxy were used during this research, and most required a storage temperature of -40 °C for a maximum lifetime. Because most batches of these substances were utilized multiple times in small quantities, stability of each was critical. For this reason, a sub-zero degree freezer was purchased from So-Low capable
of a -40 °C storage temperature. Other freezers are also available for purchase, including small bench-top freezers and larger units capable of storing larger quantities of material.

- Contact: Dan Hensler
- Phone Number: (517) 772-9410
- Website: www.so-low.com

F.0.13  FAST Semiconductor

FAST Semiconductor, Inc. provides a wide variety of services including manufacturing and packaging of miniature devices. This company’s services were utilized for the initial flip-chip packaging of the folded IMU devices after fabrication. Solder bumps were adhered to an interconnect plate, mounted to the sensors, and the solder re-flowed to create the connections. They also offer services such as miniature CNC manufacturing, wirebonding, metal coating, etc.

- Contact: Roger Young
- Phone Number: (714) 528-2550
- Website: www.fastsemi.com

F.0.14  Oxford Laser

For the laser silicon welding work, a 20W copper-vapor laser was utilized and successfully was capable of melting silicon. This laser was obtained from Oxford Laser by Prof. Dunn-Rankin and use was permitted for the purpose of laser welding. Supplies such as copper refills can be obtained from Oxford for this particular laser, and other laser systems are also available.

- Contact: Jim Bishop
F.0.15  RapidTech

Many types of rapid prototyping technologies are available at RapidTech, which is located in Engineering Tower. Prototypes were produced for this work for various reasons including reinforcement, silicon welding, and for aiding in assembly of the folded IMU sidewalls. Reinforcement inserts were created using stereolithography in the shape of the inner cavity of each IMU geometry. Similarly, parts were fabricated to fill the inner cavity of the structure, but also to allow for vacuum connection to hold sidewalls in place during the assembly process. Clamps were also created using FDM technology to create non-conductive clamps for holding silicon samples while undergoing laser or resistive welding. Several other rapid prototyping techniques are available at RapidTech which allows for a wide variety of parts to be made with different materials and resolution capabilities.

• Contact: Ed Tackett
• Phone Number: (949) 824-4938
• Website: www.rapidtech.org
Bibliography

[1] Honeywell Aerospace. HG-9900 IMU.


