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DETERMINISTIC SENSOR CALIBRATION METHODS FOR
DISTRIBUTED INERTIAL NAVIGATION SYSTEMS

BY

JACOB KRAFT

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Aerospace Engineering
in the Graduate College of the
University of Illinois Urbana-Champaign, 2022

Urbana, Illinois

Adviser:

Associate Professor Timothy Bretl

ABSTRACT

In this thesis, we explore a method used to perform deterministic calibration of the accelerometers and gyroscopes on the Distributed Inertial Sensor Integration (DISI) Kit. We develop a set of hardware testing requirements, procedures, and analyses for each of the sensors integrated on the motherboard and daughterboards of this distributed inertial navigation system (DINS). We present various means of hardware testing methods and sensor calibration improvements for the inertial measurement unit (IMU). These requirements cover testing ranges for frequency response tests, static and dynamic tests, thermal, vacuum, and electromagnetic field tests as well as data collection methods that are used during these tests. Sensor calibration improvements to increase accuracy of the relationships developed are presented.

To my parents, for their love and support.

ACKNOWLEDGMENTS

I would like to acknowledge a number of individuals from the Bretl Research Group for their contributions without which I could not have completed this work: Professor Tim Bretl, who provided me with the opportunity to participate in this research project and kept the entire research team striving towards our goals; Dave Hanley, who not only designed the daughterboards that were tested for this thesis, but who also guided me as I was introduced to the project and provided constant feedback and insight into any issues I encountered; Jongwon Lee, who directly contributed to the work outlined in this thesis by writing the robot operating system code that allowed the streaming and recording of sensor data via Teensy; Su Yeon Choi, who provided answers to sensor calibration related questions whenever they arose; all of the above individuals again for taking the time to read my thesis and offer feedback as necessary in preparation to submit.

I would also like to thank the DISI Kit team at CU Aerospace for allowing the Bretl Research Group to contribute to this project as well as providing continuous guidance and feedback on the work the team was performing.

I would finally like to thank my friends and family for all of their continued support. In particular, I would like to thank my parents and my brothers for never letting me forget how proud they are of me. Lastly, I would like to thank Courtney Trom, Aldo Montagner, and Oscar Ortiz for repeatedly motivating me to persist through restless semesters as well as lending an ear on the occasions where I needed to explain my thoughts on a given problem.

This work was funded by a subaward from CU Aerospace on a NASA-funded Phase II STTR entitled "Scalable and Distributed Inertial Navigation Systems" (Contract #80NSSC20C0020).

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LIST OF ABBREVIATIONS

ACS	Attitude Control System
ADCS	Attitude Determination and Control System
BRG	Bretl Research Group
CSV	Comma-Separated Values
CUA	Champaign-Urbana Aerospace
CSL	Coordinated Science Laboratory
CSLI	CubeSat Launch Initiative
DB	Daughterboard
DINS	Distributed Inertial Navigation System
DISI Kit	Distributed Inertial Sensor Integration Kit
DNS	Domain Name System
GOES	Geostationary Operational Environmental Satellite
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
IP	Internet Protocol
JWST	James Webb Space Telescope
LiPo	Lithium Polymer
MEMS	Microelectromechanical Systems
NASA	National Aeronautics and Space Administration
NGS	National Geodetic Survey

NOAA	National Oceanic and Atmospheric Administration
NTP	Network Time Protocol
NUC	Next Unit of Computing
PC	Personal Computer
ROS	Robot Operating System
SPI	Serial Peripheral Interface
TPU	Teach Pendant Unit
TTL	Transistor-Transistor Logic
TVAC	Thermal Vacuum
UIUC	University of Illinois Urbana-Champaign
URL	Uniform Resource Locator
USB	Universal Serial Bus

CHAPTER 1

INTRODUCTION

Attitude determination and control systems (ADCS) are an integral part of all modern-day spacecraft. They are used to detumble and stabilize a spacecraft upon being inserted into a given orbit, to estimate the orientation of a spacecraft at any given point in time with respect to some reference frame, and to command and implement corrections to the attitude of a spacecraft as necessary throughout a mission [1]. Accurate attitude determination and control is required for spacecraft with strict pointing requirements such as remote sensing or communications missions. For Earth-pointing instruments like those on the Geostationary Operational Environmental Satellite (GOES) series satellites jointly designed by the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA), pointing accuracy and pointing stability requirements are as low as hundreds of microradians [2]. Networks of satellites that need to communicate optically with one another in space also have a need for accurate pointing to close the link [3].

Spacecraft attitude determination is accomplished by an inertial navigation system (INS) that consists partially of a series of force and inertial angular velocity sensors [4]. Accelerometers provide a measure of the specific force being applied along a given axis as experienced by the sensor [5]. Gyroscopes provide a measure of the angular rate experienced by the sensor about a given axis [5]. Magnetometers provide a measure of magnetic field strength along a given axis experienced by the sensor [6]. It is common in navigation systems for accelerometer, gyroscope, and occasionally magnetometer sensors to be grouped together during the manufacturing process into a single inertial measurement unit (IMU) for ease of interfacing between individual sensors as well as allowing data collection by a single central hub.

Such devices are continuously being improved by decreasing their mass, volume, and cost while also improving performance. As a means of promot-

ing the development of new space applications, NASA created the CubeSat Launch Initiative (CSLI) in 2010. Compared to the primary payloads launched by NASA and other United States-based launch providers that have a mass of hundreds or even thousands of kilograms and exceed tens of cubic meters in volume [7–11], CubeSats are significantly smaller. The standard unit CubeSat dimension, or 1U, is 10 cm x 10 cm x 10 cm and has a mass of less than 2 kilograms [12]. CubeSat sizes today range from 1U to 16U [13].

The power systems, sensors, interfacing mechanisms, actuators, and other components required to power, communicate with, command, and reorient a CubeSat have benefited from miniaturization. One class of miniature components, known as microelectromechanical systems (MEMS), comprise four subcategories: micro-structures, micro-sensors, micro-actuators, and micro-electronics [14]. These components are fabricated at a micro (e.g., μm or 10^{-6}m) scale. Miniaturized accelerometers, gyroscopes, magnetometers, and more are now readily available for use by CubeSat designers. These sensors measure changes to a system’s environment and output that information to micro-electronics that process data and generate commands for micro-actuators to react and change the system in some way [15]. However, as compared to higher-cost, higher-performance IMUs that are used by the military or NASA, MEMS IMUs have a significantly lower performance and higher random noise as a result of mass production techniques used in their manufacturing [16,17]. As a result, sensor performance models must be properly examined to calibrate the systems that rely on MEMS IMUs, and many seek to further improve upon low-cost IMU calibration via unconventional test apparatus and procedures, sensor networks, and Kalman filtering [18–22].

Graduate student researchers of the Bretl Research Group (BRG) have worked alongside Champaign-Urbana Aerospace (CUA) to design the Distributed Inertial Sensor Integration (DISI) Kit. The idea behind this distributed inertial navigation system (DINS) is to position a series of IMUs across the entire body of a system with the principal goal of achieving higher-accuracy pose estimation, greater system redundancy and flexibility, and new state observation such as jitter identification. The system consists of a single motherboard along with a variable series of daughterboards, each board equipped with its own set of force and inertial angular velocity sensors: a single three-axis IIS3DWB accelerometer from STMicroelectronics, a single one-axis CRM100 from Silicon Sensing for z-axis measurements, and

two one-axis CRM200s from Silicon Sensing for x- and y-axis measurements. Images of the current design iteration of DISI Kit motherboard as well as the prototype and revised versions of the DISI Kit daughterboards that are tested in this thesis are presented in Figures 1.1, 1.2, and 1.3, respectively. The daughterboards interface with the motherboard via a 4-pin and a 5-pin DF-13 connector. Power and sensor communication take place over the 5-pin DF-13 connector whereas chip selects take place over the 4-pin DF-13 connector. The daughterboards are powered by the motherboard and the daughterboards communicate their sensor readings back to the motherboard using serial peripheral interface (SPI) communication. The motherboard communicates that incoming data along with its own sensor readings to the satellite bus using transistor-transistor logic (TTL) communication. These sensor readings are then used for pose estimation and attitude corrections. As such, each of the individual sensors across the entire DISI Kit must be accurately calibrated to provide the highest possible performance to the system in which the DINS is integrated.

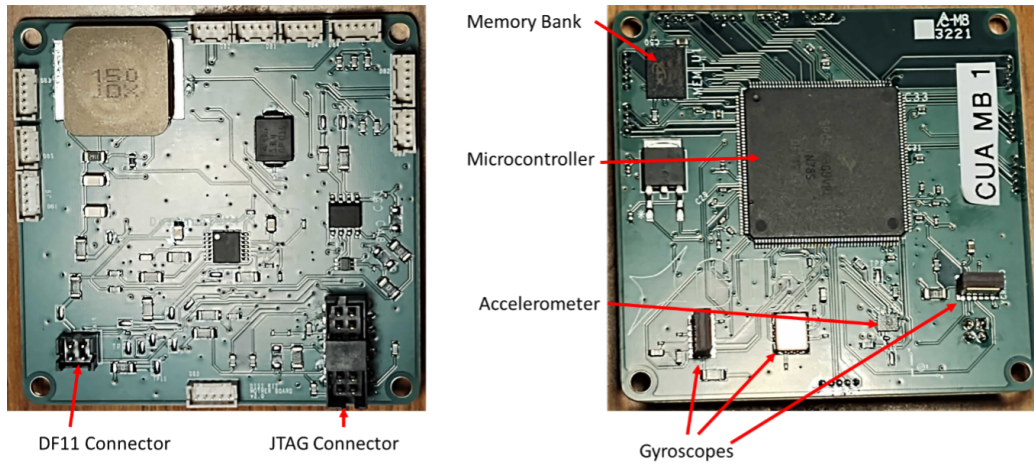


Figure 1.1: The DISI Kit motherboard is the central hub which powers and communicates with all DISI Kit daughterboards via a series of DF-13 connectors.

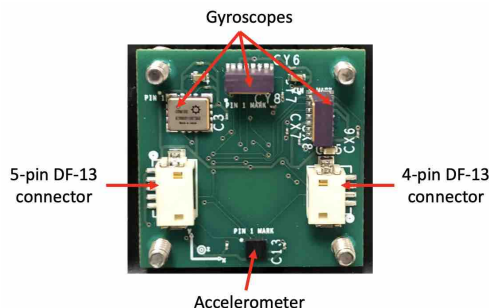


Figure 1.2: The DISI Kit prototype daughterboards are the subject of the first round of accelerometer multi-position testing and gyroscope rate testing. In this thesis, they are denoted by a single-digit identifier preceded by DB or daughterboard (e.g., DB1).

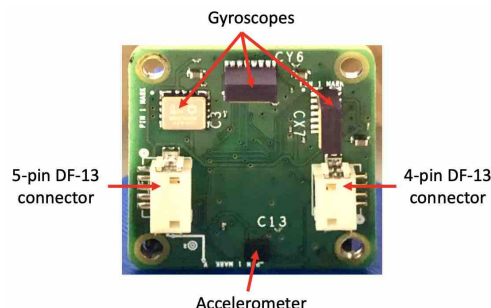


Figure 1.3: The DISI Kit revised daughterboards are the subject of the second round of accelerometer multi-position testing and gyroscope rate testing. In this thesis, they are denoted by a two-digit identifier preceded by DB or daughterboard (e.g., DB03).

1.1 Outline

The thesis begins with an overview of IMU error models and individual error parameters in Chapter 2. In Chapter 3, the multi-position testing conducted to determine the fixed bias, scale factor error, and axis misalignment of the IIS3DWB accelerometer integrated into each DISI Kit daughterboard is discussed. In Chapter 4, we examine the angular rate testing conducted using a robotic arm to determine the fixed bias, scale factor error, and axis misalignment of the one CRM100 and two CRM200 gyroscopes integrated into each DISI Kit daughterboard. A discussion of future work through sensor calibration platform improvements followed by final concluding statements is provided in Chapter 5.

CHAPTER 2

INERTIAL MEASUREMENT UNIT ERROR MODELS

Every sensor has a unique set of performance parameters. These parameters are categorized as being either stochastic or deterministic. Stochastic errors represent a random deviation originating from inconsistencies in the electrical signal communicated by electronics that make up the sensors as well as the wiring used to transfer those signals [23]. These inconsistencies create sensor noise that can result in error propagation in an INS [24]. Stochastic errors include, but are not limited to, Gaussian white noise, quantization noise, random walk, and bias and scale factor instability. Deterministic errors represent a measurable and quantifiable deviation resulting from imperfections in the manufacturing process of a particular sensor [25]. Deterministic errors include, but are not limited to, bias, scale factor error, and axis misalignment. This thesis focuses on a subset of the deterministic set of sensor errors.

Each deterministic performance parameter is defined differently based on the context of which sensor is being referred to. Bias is simply defined as the error in the output of a sensor related to the current dynamic state of the sensor. However, bias can also be characterized as the sum of a set of individually identified biases. Fixed bias is defined as the sensor output when a sensor is at rest. For an accelerometer, this refers to the specific acceleration output when the sensor is at rest. For a gyroscope, this refers to the angular rate output when the sensor is at rest. Acceleration-dependent, or g-dependent, bias is defined as the sensor output when the sensor axis is aligned with Earth's gravitational field. This error is only present in gyroscopes and essentially refers to the measured bias with respect to the current angular rotation applied to the gyroscope that subjects the sensor to both tangential and centripetal accelerations. Scale factor, also known as sensitivity, is defined as the ratio of the change in the output of a sensor to the change in the input applied to that sensor. Errors in this ratio are referred to as scale factor errors and need to be calibrated to achieve higher IMU

performance accuracy. Axis misalignment, also known as cross-axis sensitivity, is defined as the error in the orthogonality of a multi-axis sensor system. Axis misalignment results in off-sensitive test axes compounding non-zero measurements when the dynamical input is not with respect to them. Unlike the name suggests, cross-axis sensitivity does exist in single-axis sensors as well as multi-axis accelerometers, gyroscopes, or systems which integrate multiple single-axis accelerometers or gyroscopes together into one IMU. For a perfectly accurate sensor system, the axis misalignment would equal zero as the axes of the system would be perfectly orthogonal and no off-sensitive axes would measure a non-zero output from zero dynamical input [5]. A simplified IMU error model that includes all of the above deterministic error parameters is given by

$$\tilde{a} = (1 + S + \delta S)a + B + \delta B + n \quad (2.1)$$

$$\begin{aligned} \begin{bmatrix} \tilde{a}_x \\ \tilde{a}_y \\ \tilde{a}_z \end{bmatrix} &= \begin{bmatrix} 1 + S_x + \delta S_x & M_{xy} & M_{xz} \\ M_{yz} & 1 + S_y + \delta S_y & M_{yz} \\ M_{zx} & M_{zy} & 1 + S_z + \delta S_z \end{bmatrix} \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} \\ &+ \begin{bmatrix} B_x + \delta B_x \\ B_y + \delta B_y \\ B_z + \delta B_z \end{bmatrix} + \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} \end{aligned} \quad (2.2)$$

$$\tilde{\omega} = (1 + S + \delta S)\omega + B + \delta B + B_g a + n \quad (2.3)$$

$$\begin{aligned} \begin{bmatrix} \tilde{\omega}_x \\ \tilde{\omega}_y \\ \tilde{\omega}_z \end{bmatrix} &= \begin{bmatrix} 1 + S_x + \delta S_x & M_{xy} & M_{xz} \\ M_{yz} & 1 + S_y + \delta S_y & M_{yz} \\ M_{zx} & M_{zy} & 1 + S_z + \delta S_z \end{bmatrix} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \\ &+ \begin{bmatrix} B_x + \delta B_x \\ B_y + \delta B_y \\ B_z + \delta B_z \end{bmatrix} + \begin{bmatrix} B_{g,x} & 0 & 0 \\ 0 & B_{g,y} & 0 \\ 0 & 0 & B_{g,z} \end{bmatrix} \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} + \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} \end{aligned} \quad (2.4)$$

where Equations 2.1 and 2.3 represent the error model for an individual single-axis accelerometer and gyroscope, respectively, whereas Equations 2.2 and 2.4 represent the error model for a three-axis accelerometer and gyroscope or a system of three orthogonal single-axis accelerometers and gyroscopes, respectively [26]. The following list defines the symbols present in these equations:

- $\tilde{a}$ represents the accelerometer output for a single-axis accelerometer
- $\tilde{a}_i$ represents the accelerometer output for the i^{th} axis of a three-axis accelerometer
- a represents the actual acceleration for a single-axis accelerometer
- a_i represents the actual acceleration for the i^{th} axis of a three-axis accelerometer
- B represents the fixed bias for a single-axis sensor
- B_i represents the fixed bias for the i^{th} axis of a three-axis sensor
- δB represents the bias instability for a single-axis sensor
- δB_i represents the bias instability for the i^{th} axis of a three-axis sensor
- B_g represents the g-dependent bias for a single-axis gyroscope
- $B_{g,i}$ represents the g-dependent bias for the i^{th} axis of a three-axis gyroscope
- M_{ij} represents the axis misalignment between the i^{th} and j^{th} axes of a three-axis sensor
- n represents the sensor noise for a single-axis sensor
- n_i represents the sensor noise for the i^{th} axis of a three-axis sensor
- S represents the scale factor error for a single-axis sensor
- S_i represents the scale factor error for the i^{th} axis of a three-axis sensor
- δS represents the scale factor instability for a single-axis sensor
- δS_i represents the scale factor instability for the i^{th} axis of a three-axis sensor
- $\tilde{\omega}$ represents the gyroscope output for a single-axis gyroscope
- $\tilde{\omega}_i$ represents the gyroscope output for the i^{th} axis of a three-axis gyroscope
- ω represents the actual angular rate for a single-axis gyroscope

- ω_i represents the actual angular rate for the i^{th} axis of a three-axis gyroscope

As this thesis focuses on the deterministic error parameters of the overall IMU error model, the bias and scale factor instability as well as noise parameters are ignored. Simplifying Equations 2.1-2.4 to remove stochastic error parameters reduces the IMU error model to a fully deterministic sensor error model described as follows [27]:

$$\tilde{a} = (1 + S)a + B \quad (2.5)$$

$$\begin{bmatrix} \tilde{a}_x \\ \tilde{a}_y \\ \tilde{a}_z \end{bmatrix} = \begin{bmatrix} 1 + S_x & M_{xy} & M_{xz} \\ M_{yz} & 1 + S_y & M_{yz} \\ M_{zx} & M_{zy} & 1 + S_z \end{bmatrix} \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} + \begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} \quad (2.6)$$

$$\tilde{\omega} = (1 + S)\omega + B + B_g a \quad (2.7)$$

$$\begin{bmatrix} \tilde{\omega}_x \\ \tilde{\omega}_y \\ \tilde{\omega}_z \end{bmatrix} = \begin{bmatrix} 1 + S_x & M_{xy} & M_{xz} \\ M_{yz} & 1 + S_y & M_{yz} \\ M_{zx} & M_{zy} & 1 + S_z \end{bmatrix} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} + \begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} + \begin{bmatrix} B_{g,x} & 0 & 0 \\ 0 & B_{g,y} & 0 \\ 0 & 0 & B_{g,z} \end{bmatrix} \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix}. \quad (2.8)$$

As will be discussed in Chapter 4, for the purpose of gyroscope rate testing, care is taken to mount the test hardware such that it is aligned with the axis of rotation. An assumption is made that the gyroscope sensors are approximately aligned with the axis of rotation during testing. This causes the resulting centripetal acceleration to hold constant at zero (i.e., 0g) for the duration of the test. Given that data sampling takes place during portions of the test where the angular rate is held constant, the tangential acceleration is also zero. Jumps in rate subject the system to tangential acceleration, but datapoints that exist in those jumps are ignored during analysis. As a result, if the sensor is experiencing 0g (i.e., it is assumed to solely rotate during testing), g-dependent bias is non-existent. The deterministic IMU error model can be simplified further to account for this assumption. The procedures that allow this assumption to hold weight are outlined in Chapter 4.

Without the g-dependent bias term in the deterministic gyroscope error model, Equations 2.5 and 2.7 show that the single-axis sensor error model is

equivalent to the slope-intercept form of the equation of a line, $y = mx + b$, where y is represented by the sensor output, m is represented by the sum $(1 + S)$, x is represented by the actual dynamics experienced by the sensor, and b is represented by the fixed bias. Linear interpolation is used to calculate both the scale factor error and the fixed bias. By plotting the dynamics to which the sensor is subject in the x axis and the sensor output in the y axis and performing linear interpolation to estimate all of the datapoints in between those tested, the magnitude of the scale factor error is found to be the slope minus one of the resulting line and the magnitude of the fixed bias is found to be the y-intercept of the resulting line.

Simpler methods of calculating a sensor's fixed bias and scale factor error as well as the axis misalignment between two measurement axes are as follows:

$$B_{\text{accel}} = \frac{\tilde{a}_{\text{up}} + \tilde{a}_{\text{down}}}{2} \quad (2.9)$$

$$S_{\text{accel}} = \frac{\tilde{a}_{\text{up}} - \tilde{a}_{\text{down}} - 2g}{2g} \quad (2.10)$$

$$M_{\text{accel},ij} = \frac{\tilde{a}_{j,\text{up}} - \tilde{a}_{j,\text{down}}}{2g} \quad (2.11)$$

$$B_{\text{gyro}} = \frac{\tilde{\omega}^+ + \tilde{\omega}^-}{2} \quad (2.12)$$

$$S_{\text{gyro}} = \frac{\tilde{\omega}^- - \tilde{\omega}^+ - 2\omega}{2\omega} \quad (2.13)$$

$$M_{\text{gyro},ij} = \frac{\tilde{\omega}_j^+ - \tilde{\omega}_j^-}{2\omega} \quad (2.14)$$

where Equations 2.9 and 2.12 show how to calculate the fixed bias for a given axis of an accelerometer and gyroscope, respectively, whereas Equations 2.10 and 2.13 show how to calculate the scale factor error for a given axis of an accelerometer and gyroscope, respectively [28], and Equations 2.11 and 2.14 show how to calculate the axis misalignment for a given pair of axes of an accelerometer and gyroscope, respectively [27].

In these equations, the tilde over a symbol still represents a sensor output whereas a symbol with no tilde represents the true dynamical input condition. The up and down subscripts on the accelerometer outputs represent the

output when the test axis is pointing up and down, respectively, whereas the plus and minus superscripts on the gyroscope outputs represent the output when the system is rotating in the positive (counterclockwise) and negative (clockwise) directions, respectively. In Equations 2.10 and 2.11, g represents the local gravity constant. This term is calculated using a number of online charts or calculators. Using a National Geodetic Survey (NGS) calculator from NOAA [29] and inputting a latitude of $40.115082607049686^\circ\text{N}$ and longitude of $88.22669804437446^\circ\text{W}$ for the Coordinated Science Laboratory (CSL) as defined by Google Maps as well as a sea level altitude of 728 feet as defined as the average elevation in Urbana, Illinois, the local gravity magnitude at the test location is found to be $980,117 \pm 3$ milligals or approximately 9.80117 m/s^2 solved from the following conversion calculation:

$$\begin{aligned}
& 980,117 \text{ milligals} \left(\frac{1 \text{ gal}}{1000 \text{ milligals}} \right) \left(\frac{1 \frac{\text{cm}}{\text{s}^2}}{1 \text{ gal}} \right) \left(\frac{1 \text{ m}}{100 \text{ cm}} \right) \\
& = \mathbf{9.80117 \frac{m}{s^2}} \approx \mathbf{0.999441g}.
\end{aligned} \tag{2.15}$$

Equations 2.9 and 2.12 once again show that the fixed bias of a sensor can be calculated as the y-intercept of the linear interpolation of the datapoints relating the dynamics experienced by the sensor and the corresponding sensor output. If the dynamics are plotted in the x axis and the sensor output is plotted in the y axis, the average between the maximum and minimum dynamics equals zero as the maximum and minimum dynamics are equal in magnitude but opposite in sign. The resulting averages shown in Equations 2.9 and 2.12 are then the y-intercept of the resulting linear interpolation. For greater accuracy in the subsequent sensor error model, more datapoints are included in the linear interpolation which then ignores the fixed bias equations presented. Equations 2.10 and 2.13 stray from the slope-intercept form discussed as these equations represent the relative error rather than the absolute error. It is common to calculate the scale factor error as a percent error which is accomplished by multiplying the relative error by 100%.

These deterministic performance parameters can vary between multiple units of the same sensor model due to minute changes in the manufacturing process. Deterministic sensor errors are also prone to variations in environmental conditions such as thermal or barometric changes as well as variations in local magnetic field strength. Slight misalignment in the axes of a multi-axis accelerometer or gyroscope can result in more severe levels of cross-axis

sensitivity that also need to be calibrated. Although an average or expected scale factor error, fixed bias, and axis misalignment for a particular sensor are generally all provided on a manufacturer's product specifications sheet, it is worthwhile to perform a personal evaluation using a set of static, dynamic, and environmental tests in order to derive an accurate deterministic sensor error model for a given sensor.

CHAPTER 3

ACCELEROMETER MULTI-POSITION TESTING

This chapter covers the multi-position testing performed to derive the deterministic fixed bias, scale factor error, and axis misalignment of the IIS3DWB accelerometer integrated within the DISI Kit design. Based on Equations 2.9-2.11, the minimum number of measurement positions required to calculate the fixed bias, scale factor error, and axis misalignment is two: $+1g$ and $-1g$ (i.e., $\tilde{a}_{up}$ and $\tilde{a}_{down}$, respectively). The minimum number of measurement positions in practice is four after the addition of the two $0g$ measurement positions separated by 180 degrees. However, typical accelerometer multi-position testing is referred to as an “eight-position test” as it generally involves collecting measurements across eight angular positions spaced evenly from 0 degrees to 360 degrees (i.e., every 45 degrees). This ensures that measurements are taken for each axis for at least $0g$, $+1g$, and $-1g$. To achieve angular positional accuracy during testing, a precision dividing head is used. When mounted to a precision dividing head, accelerometers can have their sensitive axis rotated to an accuracy on the order of arcseconds [5] allowing the user to develop a model of the current orientation of the accelerometer and the output signal communicated by the sensor. An accelerometer’s fixed bias, scale factor error, and axis misalignment are calculated by analyzing data from multi-position testing. These deterministic performance parameters are then used to better calibrate the system on which the accelerometer is to be integrated, or in the case of this thesis, the DISI Kit system.

3.1 Test Apparatus

A precision dividing head is made up of three integral components: an indexing plate, a crank, and a workpiece chuck. An annotated image outlining this design is presented in Figure 3.1. The indexing plate is used to measure out

a given angular rotation. The crank is used to manually rotate the dividing head as well as lock the dividing head into a given position via the holes on the indexing plate. The workpiece chuck is used to mount a given piece of hardware. The gear system within a precision dividing head is designed such that a set number of crank rotations results in a full rotation of the chuck. For a typical dividing head, this ratio is either 40:1, 60:1, or 90:1. From this ratio, the angular change can be calculated for a given rotation of the crank that is used for high-level angular changes. For fine tuning, the indexing plate is used. As shown in Figures 3.1 and 3.2, the indexing plate on a dividing head has a number of circular rings which consist of a series of equally-spaced holes. Each of these rings has a different radius as measured from the crank mount. For a given desired angular rotation, there is a set ring that should be used as well as a set number of holes that the crank should traverse to rotate the chuck by said angle. As precision dividing heads are generally used for precision machining of parts, there exist reference sheets that outline which ring should be used based on the model of dividing head being used and the desired number of cuts around a part which can be translated to a set angular rotation [30]. As an example, if a 45-degree rotation is desired (equivalent to eight divisions across 360 degrees) and a 40:1 precision dividing head is being used, reference sheets say that any of the indexing ring circles can be used as eight goes into 40 five times so the individual holes are not actually required. If the same rotation is desired but a 60:1 precision dividing head is being used, reference sheets say that the 16-hole circle should be used and the crank rotation should traverse seven full turns plus eight holes. A brief calculation showing such a derivation is as follows:

$$\begin{aligned}
& \frac{360^\circ/\text{full rotation}}{60 \text{ crank turns}/\text{full rotation}} = 6^\circ/\text{crank turn} \\
& \Rightarrow \frac{45^\circ}{6^\circ/\text{crank turn}} = 7.5 \text{ crank turns} \\
& \Rightarrow (0.5)(16\text{-hole circle}) = 8 \text{ holes} \\
& \Rightarrow \textbf{Total rotation: seven crank turns plus eight holes.}
\end{aligned} \tag{3.1}$$

Using the technique shown in Equation 3.1, a precision dividing head can achieve arcsecond accuracy on a variety of desired rotations. For this series of testing, a VEVOR precision dividing head configured with a Sanou K11-125



Figure 3.1: Shown are each of the three main components of a precision dividing head [31].



Figure 3.2: This precision dividing head is used for the multi-position testing.

three-jaw self-centering lathe chuck is used. This model of precision dividing head is shown in Figure 3.2. This particular model of precision dividing head has a 40:1 reduction ratio meaning that 40 full crank rotations results in a full rotation of the lathe chuck.

3.2 Test Overview

A DISI Kit daughterboard integrated with a single IIS3DWB three-axis accelerometer is clamped to the lathe chuck on the precision dividing head via the three jaws as well as a test mount that the board is directly mounted to. The first mounting position has the desired axis pointing upward as denoted by the engraved axes on the board (i.e., the test axis will be mounted such that it outputs $+1g$ or $\sim 9.80117 \text{ m/s}^2$). Keeping the precision dividing head stationary, output data are streamed and recorded for a set period of time. After a sufficient amount of time has passed, the data stream is terminated and the data saved. The precision dividing head is rotated clockwise to the next test angle, 45 degrees from the previous test angle. From the discussion in Section 3.1, a 45-degree rotation for a 40:1 model precision dividing head requires five turns of the crank. Any circular ring of holes can be used so long as the hole into which the crank is locked stays consistent between each test. The same procedures for data streaming and recording are repeated for the new test angle. These steps are followed until the test angle has reached 360 degrees, equivalent to the first zero-degree test angle. These steps are then followed for all three measurement axes for each daughterboard.

3.3 Test Considerations

When designing the multi-position test plan that is used to collect the data necessary to calibrate the accelerometer sensors, one choice needs to be considered: how much data should be collected for a single angle of each test axis of each daughterboard? More specifically, at what rate should data be collected and how long should data be collected for a single angle of each test axis of each daughterboard? Each of the daughterboards is configured with a STMicroelectronics IIS3DWB ultra-wide bandwidth 3-axis accelerometer. An image of the IIS3DWB can be seen in Figure 3.3. Accelerometer multi-position tests last anywhere from several seconds to several minutes depending on the number of positions at which measurements are collected [32–35]. These tests then extend into the realm of long-term stability once the duration of the test has reached hours, days, and beyond [5]. As this particular multi-position test is a static test that is simply looking for an average sensor output over a short duration for a given input condition (i.e., for a given attitude) in order to calculate the scale factor error and fixed bias, and given the testing conducted for this thesis includes eight measurement positions, an arbitrary sampling rate of 100 Hz and test duration of 60 seconds will be used. This results in approximately 6000 datapoints for a given angle.

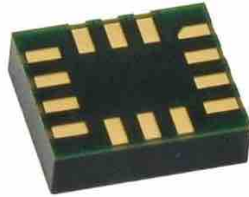


Figure 3.3: The IIS3DWB is responsible for three-axis accelerometer measurements on the DISI Kit daughterboards [36].

3.4 Test Plan

The accelerometer multi-position test using the VEVOR precision dividing head proceeds as follows:

1. The daughterboard is mounted and the precision dividing head is ro-

tated such that the test axis is pointing upwards (i.e., the axis is parallel with but in the opposite direction of Earth’s gravity vector).

2. Data streaming and recording is initiated and allowed to continue for 60 seconds while the precision dividing head and mounted hardware remain stationary.
3. After 60 seconds, the data streaming and recording is terminated and the data are saved.
4. The precision dividing head is rotated 45 degrees by turning the crank a full eight rotations and relocking the crank shaft into the correct indexing plate hole.
5. Steps 2-4 are repeated for all angles up to 360 degrees.
6. Steps 1-5 are repeated for all three axes of each daughterboard.

As small vibrations could excite the data and cause inaccuracies in calculating the deterministic performance parameters, interaction with the precision dividing head or the surface to which the dividing head is mounted is avoided.

3.5 Test Setup and Procedures

Another consideration is how the daughterboard is mounted onto the precision dividing head. The daughterboards are thin and not designed to be subject to large magnitudes of compression, so it is not ideal to clamp the daughterboards with the lathe chuck jaws directly as this could significantly damage the boards. Test mounts that the daughterboards could be mounted on are used as the mounting adaptor between the precision dividing head and the boards. For the first round of testing using the prototype daughterboards, two different 3D-printed test mounts are used, one for x- and y-axis testing and one for z-axis testing. As these 3D-printed test mounts require the daughterboards to be secured via tape which introduces the possibility for significant error in resulting data, the subsequent round of testing changed to allow for more secure fastening of the boards. For the second round of testing using the revised daughterboards, a Thorlabs AB90A/M aluminum

right-angle bracket is used [37]. This change was made as a single right-angle bracket could be used for all testing and the daughterboards could be fastened to the bracket using bolts and nuts rather than an adhesive like that used on the 3D-printed mounts.

Upon finalizing all decisions pertaining to mounting test hardware, the test is set up and run as follows:

1. Secure the daughterboard to the mounting adaptor such that the test axis is aligned with the gravity vector and facing upward.
 - (a) For the 3D-printed adaptor, the daughterboard is secured to the part using an adhesive. Electrical tape is used for this round of testing as shown in Figure 3.4.
 - (b) For the Thorlabs right-angle bracket, the daughterboard is secured to the part using a set of 4/40 socket cap bolts each outfit with a 4/40-to-M6 thread adaptor and a 4/40 hex nut as shown in Figure 3.5.

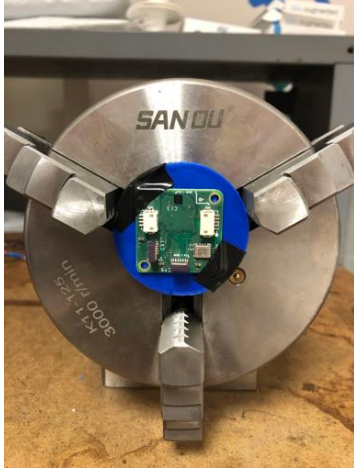


Figure 3.4: In the first round of testing, a 3D-printed mounting adaptor with electrical tape is used to secure the daughterboard.



Figure 3.5: In the second round of testing, a Thorlabs AB90A/M aluminum right-angle bracket with compatible fasteners is used to secure the daughterboard.

2. Rotate the precision dividing head such that one of the jaws is at the bottom-most point (i.e., when mounting hardware, the jaw sits below the component). This gives the hardware something to rest on as it is secured into the jaws of the lathe chuck as shown in Figure 3.4.

3. Loosen the jaws enough such that the mounting adaptor with hardware configured slides into the area between the jaws.
4. Place the mounting adaptor in between the three lathe chuck jaws such that the test axis is pointed vertically upward.
5. Tighten the jaws to clamp on the mounting adaptor as shown in Figure 3.6. The mounting adaptor is adjusted as necessary such that all three jaws contact the part and that the hardware does not move when a force is applied to it by the user.

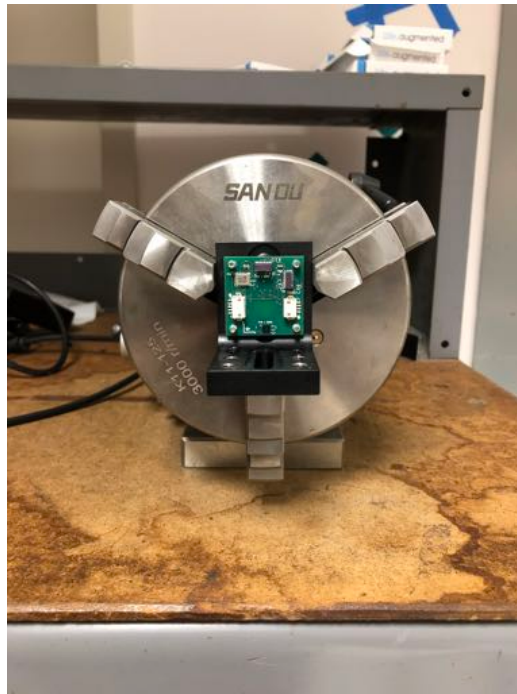


Figure 3.6: The hardware is mounted and rotated such that the test axis is pointing vertically upward. The hardware should not move at all when fully secured in the jaws of the lathe chuck.

6. Rotate the precision dividing head as needed to ensure that the test axis is pointed vertically upward. Then lock the precision dividing head crank into the corresponding hole on the indexing plate and take note of this hole as this is the same hole into which the crank is locked for all following angles for this test axis.
7. Connect a universal serial bus (USB) port on the Intel Next Unit of Computing (NUC) device to the microUSB port of the Teensy board.

8. Plug the 4-pin and 5-pin DF-13 connectors from the red electronics breadboard into their respective 4-pin and 5-pin DF-13 sockets on the daughterboard as shown in Figure 3.7.

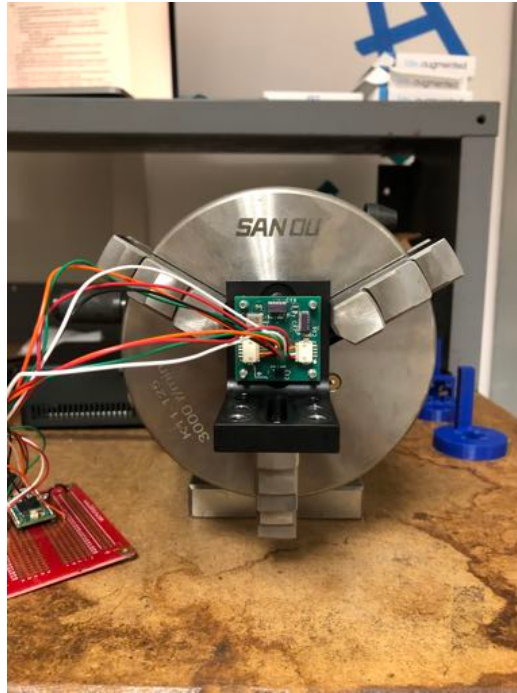


Figure 3.7: Once the daughterboard is mounted, the DF-13 connectors which interface with the Teensy are plugged into the daughterboard.

9. Plug the Intel NUC into a power source. Either an external wall outlet or a lithium polymer (LiPo) battery with corresponding voltage connector is used.
10. Power on the Intel NUC.
11. Remote desktop into the Intel NUC using NoMachine on an external device.
12. Open a command prompt terminal. Run the appropriate robot operating system (ROS) commands necessary to log into the ROS system, to connect the device to the Teensy interface, and to stream and record sensor data. Further details are provided in Appendix A.
13. Leave the setup to run for one minute. Take note not to interact with the precision dividing head or the surface to which it is mounted as small vibrations could impact the incoming data.

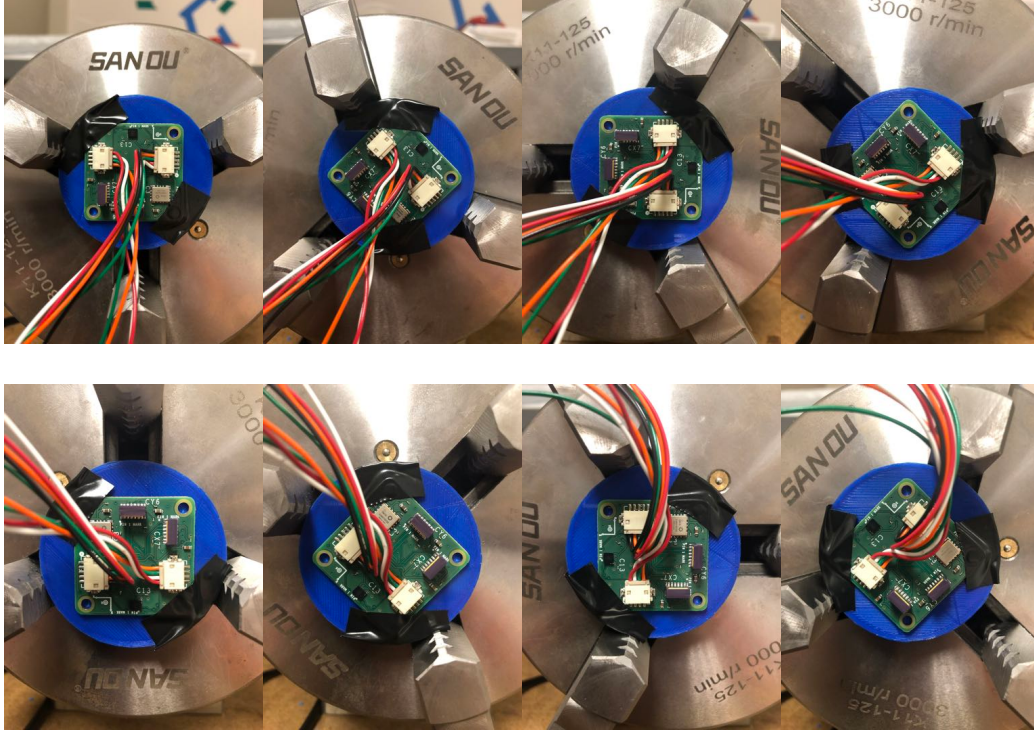


Figure 3.8: The daughterboard is rotated about the z axis every 45 degrees between zero and 360 degrees. The x- and y- axis tests can occur simultaneously as they exist on the same plane. The only difference is that the angles for each axis are 90 degrees apart (i.e., when the y axis points upward at zero degrees, the x axis points at 90 degrees).

14. When one minute has passed, stop the data recording on the Intel NUC and convert the ROS bag file (.bag) to which the data were saved into a text file (.txt) and comma-separated values file (.csv). Further details are provided in Appendix A.
15. Repeat these steps for all axes of each DISI Kit daughterboard to be tested as shown in Figures 3.8 and 3.9.

3.6 Prototype Hardware Test Results

Plotted accelerometer multi-position test data for prototype daughterboard 1 are presented in Figure 3.10. The left column of plots shows the entire dataset for each individual angle of each individual axis test. The images

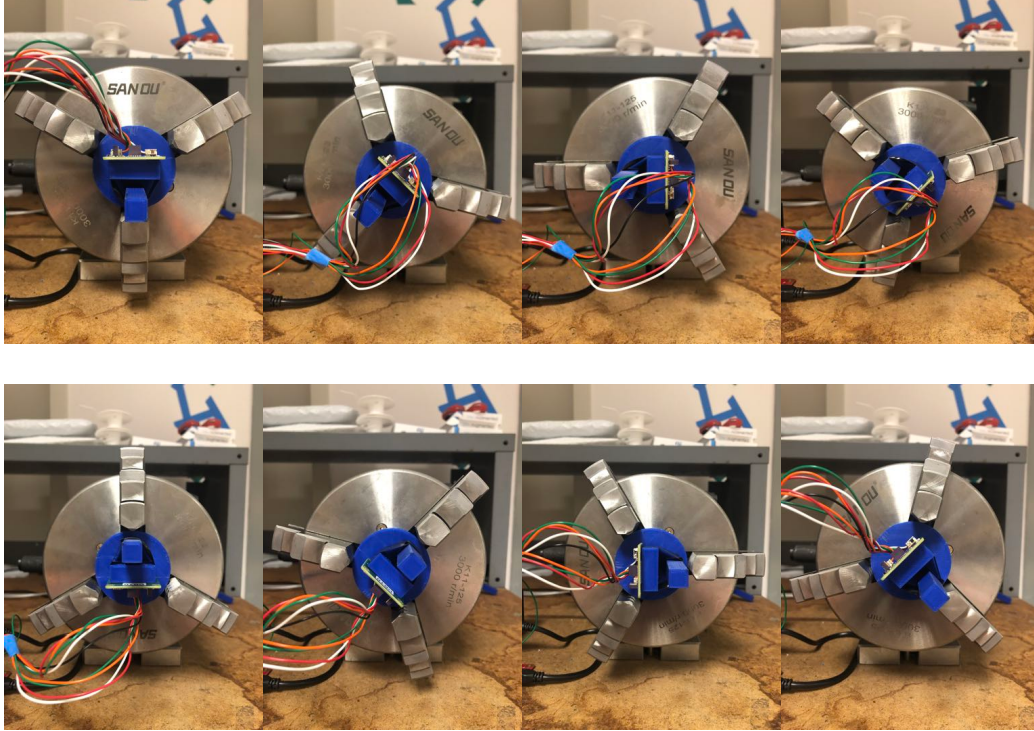


Figure 3.9: The daughterboard is once again rotated every 45 degrees between zero and 360 degrees, but this time about the x or y axis.

show two axes making significant changes in measured acceleration as the board is rotated while one axis holds nearly constant at zero meters per second squared. The stationary measurement axis corresponds to the axis of rotation (i.e., the board rotates about this axis and thus is always orthogonal to Earth's gravity vector) whereas the mobile measurement axes represent the two axes which lie in the same plane as Earth's gravity vector. In all cases, the magnitudes of the two mobile measurement axes are separated by 90 degrees as all three measurement axes are orthogonal. The resulting numerical data presented in Table 3.1 and Equation 3.2 show a slight fixed bias in the x axis and a more significant fixed bias in both the y and z axes with magnitudes slightly over half a meter per second squared, or approximately 5.8% of the magnitude of local gravity. The scale factor error in the x and y axes are both less than 0.15% whereas the scale factor error in the z axis is nearly 0.6%, or about 6000ppm. Numerical data for other prototype daughterboards are found in Tables 3.2-3.3 and Equations 3.3-3.4. Plots for other prototype daughterboards are left out of this chapter for conciseness. Detailed plots of

other datasets are found in Appendix E.

Table 3.1: Prototype Daughterboard 1 Accelerometer Multi-Position Test Results

Prototype Board #	1		
Test Axis	X	Y	Z
Accelerometer Fixed Bias [m/s ²]	0.204	−0.568	0.525
Accelerometer Scale Factor Error [%]	0.134	−0.0776	0.597

$$M_{\text{accel, Prototype DB1}} = \begin{bmatrix} 0 & -2.06 & -0.0269 \\ 2.01 & 0 & -1.01 \\ -2.48 & 0.508 & 0 \end{bmatrix} \quad (3.2)$$

Table 3.2: Prototype Daughterboard 2 Accelerometer Multi-Position Test Results

Prototype Board #	2		
Test Axis	X	Y	Z
Accelerometer Fixed Bias [m/s ²]	0.202	−0.633	−0.202
Accelerometer Scale Factor Error [%]	0.00525	−0.340	0.0938

$$M_{\text{accel, Prototype DB2}} = \begin{bmatrix} 0 & -2.40 & 1.99 \\ 2.28 & 0 & -0.769 \\ -1.11 & 0.0109 & 0 \end{bmatrix} \quad (3.3)$$

Table 3.3: Prototype Daughterboard 3 Accelerometer Multi-Position Test Results

Prototype Board #	3		
Test Axis	X	Y	Z
Accelerometer Fixed Bias [m/s ²]	0.0969	−0.356	−0.437
Accelerometer Scale Factor Error [%]	0.101	−0.0314	0.207

$$M_{\text{accel, Prototype DB3}} = \begin{bmatrix} 0 & -0.530 & 0.667 \\ 0.434 & 0 & 1.79 \\ 1.05 & 0.0508 & 0 \end{bmatrix} \quad (3.4)$$

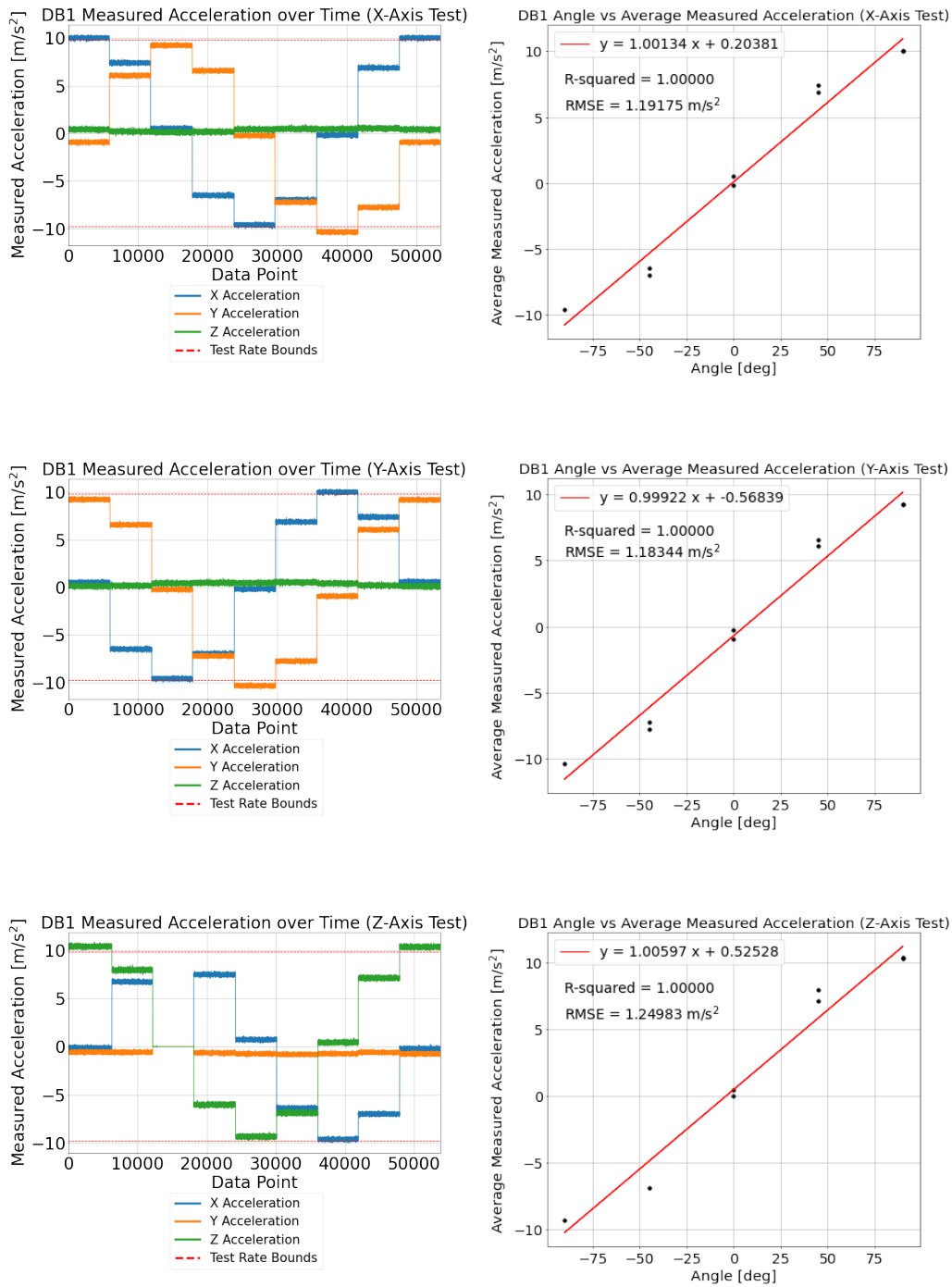


Figure 3.10: DB1 accelerometer multi-position test results: The left column plots show the full dataset for each individual axis test of prototype DB1. The right column plots show the average data for each individual step of each axis test of prototype DB1 along with a best fit line representing the sensor deterministic error model for fixed bias and scale factor error.

Table 3.4 and Equations 3.5-3.6 present a compiled analysis of the accelerometer multi-position tests for all three prototype daughterboards. Table 3.4 also makes a comparison between the deterministic error parameters of the IIS3DWB sensors across all prototype daughterboards and the ranges for these same error parameters as given by the manufacturer. Looking at both the fixed bias and the scale factor error together, the average magnitude of each of these parameters across all axes is well within the datasheet ranges [36]. The highest mean magnitude of fixed bias exists in the y axis with a mean bias magnitude of just over half a meter per second squared. The maximum magnitude of fixed bias according to the manufacturer is 180mg or 0.18g. From the local gravity magnitude, this comes out to approximately 1.8 meters per second squared. The highest magnitude fixed bias calculated across all three prototype daughterboards is the y axis of prototype daughterboard 2 with a fixed bias magnitude of 0.633 meters per second squared, or approximately 35% of the datasheet value. The highest mean magnitude of scale factor error exists in the z axis with a mean scale factor error of 0.299%. The maximum scale factor error according to the manufacturer is 2%. The highest magnitude scale factor error across all three prototype daughterboards is the z axis of prototype board 1 with a scale factor error of 0.597%, or approximately 30% of the datasheet value.

Looking at the accelerometer axis misalignment across all prototype daughterboards, none of the misalignment matrices exactly follow the skew symmetric form expected of a misalignment matrix. Given that the symmetric terms represent the misalignment between the same axes but in the opposite reference frame, these terms should be equal in magnitude but opposite in sign. These deviations from the skew symmetric form can be attributed to random noise and stochastic error in the system.

Table 3.4: Prototype Daughterboard Accelerometer Results Statistics

Parameter	Fixed Bias [m/s ²]			Scale Factor Error [%]		
Test Axis	X	Y	Z	X	Y	Z
Mean	0.168	-0.519	-0.0377	0.0801	-0.150	0.299
Std Dev	0.118	0.808	0.409	0.0547	0.136	0.215
IIS3DWB [36]	[-1.8, 1.8]			[-2, +2]		

$$M_{\text{accel, Prototype Avg}} = \begin{bmatrix} 0 & -1.66 & 0.878 \\ 1.57 & 0 & 0.00350 \\ -0.846 & 0.190 & 0 \end{bmatrix} \quad (3.5)$$

$$M_{\text{accel, Prototype Std Dev}} = \begin{bmatrix} 0 & 0.812 & 0.838 \\ 0.813 & 0 & 1.27 \\ 1.45 & 0.226 & 0 \end{bmatrix} \quad (3.6)$$

3.7 Revised Hardware Test Results

Plotted accelerometer multi-position test data for revised daughterboard 03 are presented in Figure 3.11. The left column of plots shows the entire dataset for each individual angle of each individual axis test. Like with the plots for prototype daughterboard 1, the images show two axes making significant changes in measured acceleration as the board is rotated while the axis about which the board is rotating holds close to zero meters per second squared as this axis stays orthogonal to Earth's gravity vector. The resulting numerical data presented in Table 3.5 and Equation 3.7 show a wide range of fixed bias magnitudes across all three axes with the x-axis fixed bias magnitude less than 0.02 meters per second squared, the y-axis fixed bias magnitude of just under half a meter per second squared, and a z-axis fixed bias magnitude of approximately 0.636 meters per second squared. Even with some larger fixed biases, all of these magnitudes lie within the range of fixed biases for the IIS3DWB. The scale factor error for revised daughterboard 03 is much less significant with the largest magnitude existing in the x axis at just over 0.25% and the smallest magnitude existing in the z axis at 0.0161%. Once again, all of these scale factor error magnitudes lie within the range outlined in the manufacturer datasheet. Numerical data for other revised daughterboards are found in Tables 3.6-3.9 and Equations 3.7-3.11. As with the prototype daughterboards, plots for other revised daughterboards are left out of this chapter for conciseness. Detailed plots of other datasets are found in Appendix E.

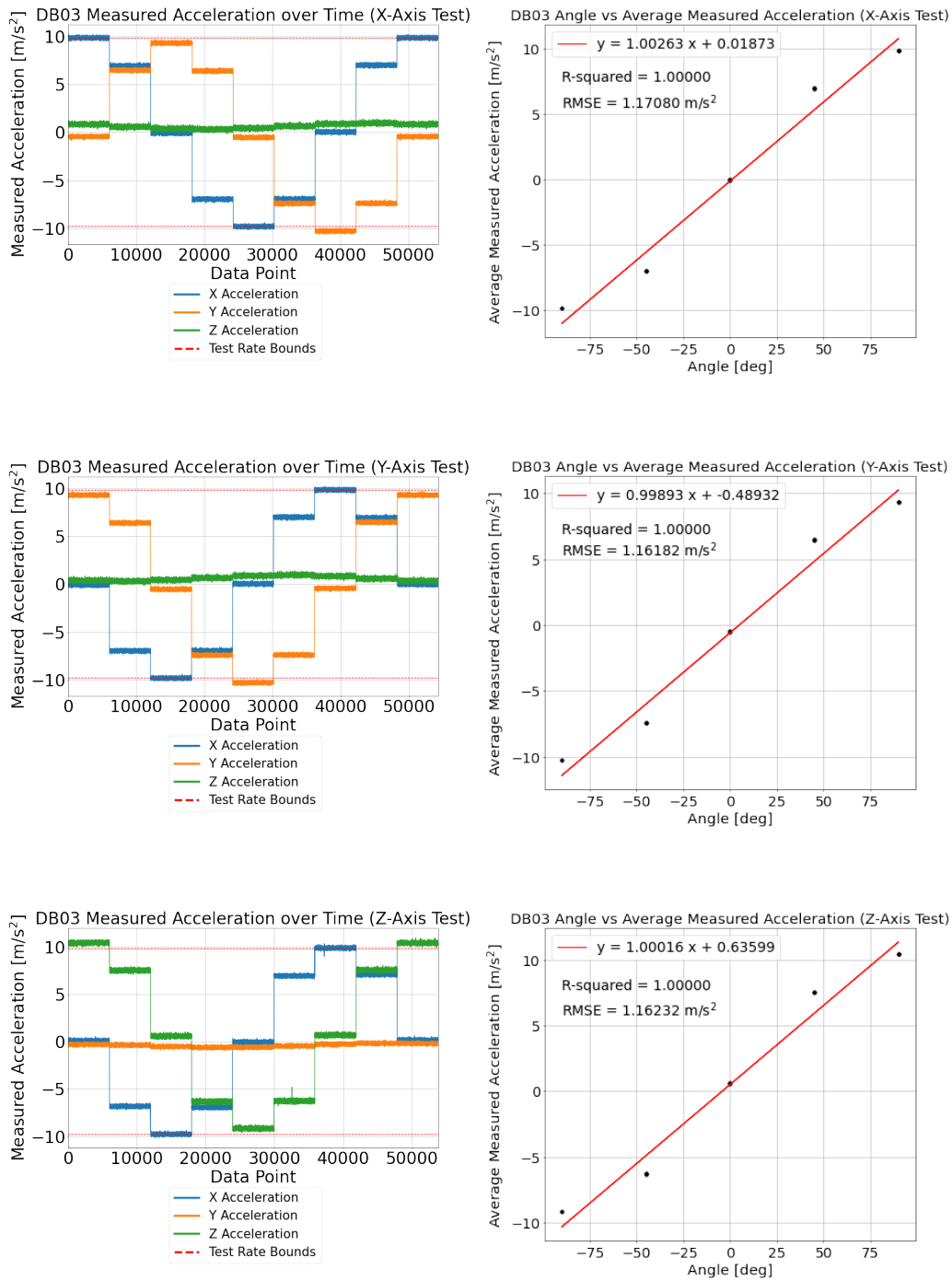


Figure 3.11: DB03 accelerometer multi-position test results: The left column plots show the full dataset for each individual axis test of revised DB03. The right column plots show the average data for each individual step of each axis test of revised DB03 along with a best fit line representing the sensor deterministic error model for fixed bias and scale factor error.

Table 3.5: Daughterboard 03 Accelerometer Multi-Position Test Results

Board #	03		
Test Axis	X	Y	Z
Accelerometer Fixed Bias [m/s ²]	0.0187	-0.489	0.636
Accelerometer Scale Factor Error [%]	0.263	-0.107	0.0161

$$M_{\text{accel, Revised DB03}} = \begin{bmatrix} 0 & 0.273 & 1.16 \\ -0.361 & 0 & -1.46 \\ 0.440 & 0.872 & 0 \end{bmatrix} \quad (3.7)$$

Table 3.6: Daughterboard 05 Accelerometer Multi-Position Test Results

Board #	05		
Test Axis	X	Y	Z
Accelerometer Fixed Bias [m/s ²]	-0.246	-0.564	0.963
Accelerometer Scale Factor Error [%]	0.241	0.191	0.0346

$$M_{\text{accel, Revised DB05}} = \begin{bmatrix} 0 & 0.186 & 0.637 \\ 0.142 & 0 & -1.36 \\ 1.08 & 0.973 & 0 \end{bmatrix} \quad (3.8)$$

Table 3.7: Daughterboard 07 Accelerometer Multi-Position Test Results

Board #	07		
Test Axis	X	Y	Z
Accelerometer Fixed Bias [m/s ²]	0.0332	-0.702	0.813
Accelerometer Scale Factor Error [%]	0.360	0.307	0.00908

$$M_{\text{accel, Revised DB07}} = \begin{bmatrix} 0 & -0.797 & 0.576 \\ 0.627 & 0 & -0.911 \\ 0.469 & 0.130 & 0 \end{bmatrix} \quad (3.9)$$

$$M_{\text{accel, Revised DB08}} = \begin{bmatrix} 0 & -0.211 & 0.731 \\ 0.0610 & 0 & -1.65 \\ 0.436 & 0.632 & 0 \end{bmatrix} \quad (3.10)$$

Table 3.8: Daughterboard 08 Accelerometer Multi-Position Test Results

Board #	08		
Test Axis	X	Y	Z
Accelerometer Fixed Bias [m/s ²]	0.0277	-0.492	0.883
Accelerometer Scale Factor Error [%]	-0.0468	-0.421	-0.107

Table 3.9: Daughterboard 10 Accelerometer Multi-Position Test Results

Board #	10		
Test Axis	X	Y	Z
Accelerometer Fixed Bias [m/s ²]	-0.102	-0.566	1.02
Accelerometer Scale Factor Error [%]	0.393	-0.176	0.449

$$M_{\text{accel, Revised DB10}} = \begin{bmatrix} 0 & -0.497 & 0.872 \\ 0.694 & 0 & -2.05 \\ 0.0230 & 0.471 & 0 \end{bmatrix} \quad (3.11)$$

Table 3.10 and Equations 3.12-3.13 present a compiled analysis of the accelerometer multi-position tests for all five revised daughterboards. Table 3.10 also makes a comparison between the deterministic error parameters of the IIS3DWB sensors across all revised daughterboards and the ranges for these same error parameters as given by the manufacturer. Like with the prototype daughterboards, the average magnitude of both the fixed bias and scale factor error across all axes is within the datasheet ranges. The highest mean magnitude of fixed bias exists in the z axis with a mean bias magnitude of 0.863 meters per second squared, or just under half of the magnitude of the datasheet range. The highest magnitude fixed bias calculated across all five revised daughterboards is the z axis of revised daughterboard 10 with a fixed bias magnitude of 1.02 meters per second squared, or approximately 57% of the datasheet value. All axes of the revised daughterboards had a mean magnitude of scale factor error less than a quarter of a percent with the highest mean magnitude existing in the x axis. The highest magnitude scale factor error across all five revised daughterboards is once again the z axis of revised daughterboard 10 with a scale factor error of 0.447%, or approximately 22% of the datasheet value.

Like with the prototype daughterboards, the misalignment matrices show some error between their calculated values and a skew symmetric matrix. This can once again be attributed to random noise in the sensors.

Table 3.10: Revised Daughterboard Accelerometer Results Statistics

Parameter	Fixed Bias [m/s²]			Scale Factor Error [%]		
Test Axis	X	Y	Z	X	Y	Z
Mean	-0.05369	-0.563	0.863	0.242	-0.0411	0.0800
Std Dev	0.108	0.0771	0.134	0.155	0.262	0.190
IIS3DWB [36]	[-1.8, +1.8]			[-2, +2]		

$$M_{\text{accel, Revised Avg}} = \begin{bmatrix} 0 & -0.209 & 0.796 \\ 0.233 & 0 & -1.49 \\ 0.490 & 0.616 & 0 \end{bmatrix} \quad (3.12)$$

$$M_{\text{accel, Revised Std Dev}} = \begin{bmatrix} 0 & 0.404 & 0.209 \\ 0.389 & 0 & 0.373 \\ 0.339 & 0.300 & 0 \end{bmatrix} \quad (3.13)$$

CHAPTER 4

GYROSCOPE RATE TESTING

This chapter covers the gyroscope rotation rate testing performed to derive the deterministic fixed bias, scale factor error, and axis misalignment of the CRM100 and CRM200 gyroscopes integrated within the DISI Kit design. Typical gyroscope rate testing is referred to as “rate table testing” as it generally involves a gyroscope sensor secured to a rate table, a piece of testing equipment consisting of a flat rotating plate to which hardware may be secured. The rate table rotates at very precise angular velocities, sometimes on the order of a small fraction of a percent of the desired angular rate [38], allowing the user to take the angular rate subjected by the rate table as ground truth and develop a model between the desired angular rate of the rate table and the output signal communicated by the gyroscope sensor. In particular, a gyroscope’s fixed bias, scale factor error, and axis misalignment are calculated by analyzing data from rate table testing. These deterministic performance parameters are then used to better calibrate the DISI Kit system.

4.1 Test Apparatus

Rather than using a rate table, this testing is instead performed using an ABB IRB 120 robotic arm, an image of which is presented in Figure 4.1. This six-axis robot is commonly used in small-parts manufacturing for its miniature stature and portability, its load capacity, and its accuracy in positional repeatability, the magnitudes of which are shown in Table 4.1.



Figure 4.1: This ABB IRB 120 robot arm is used to perform gyroscope rotation rate testing on the CRM100 and CRM200 gyroscope sensors [39].

Table 4.1: ABB IRB 120 Specifications [40]

Robot Mass	Load Capacity	Positional Repeatability
25 kg	3 kg ^[1]	0.01 mm

For a gyroscope rate test, the sensor being tested is secured and subject to a series of angular rates over a given range, the magnitude of which is generally chosen as either the measurement range of the particular gyroscope sensor model being tested or the range of angular rates that are anticipated during the application of said gyroscope sensor. Each angular rate is held for a predetermined period of time, also known as the dwell time. The dwell time consists of a stabilization time, or the period after a transition from one angular rate to the next given to allow the gyroscope signals to stabilize, and a sample time, or the period during which data are collected for post-experimental analysis. After a set dwell time for a given rate, the rate table (or in this case, the robot arm) moves on to the next desired rate. In other words, the test follows a stepwise pattern where the angular rate

¹4 kg with a vertical wrist, i.e., the fifth axis is at either +90 degrees or -90 degrees.

sequentially steps up or down as determined by the tester. The simplest version of this test steps through one cycle of rates whereas more in-depth tests may perform multiple cycles through the desired range of angular rates. An example single-cycle rate table step sequence is shown in Figure 4.2.

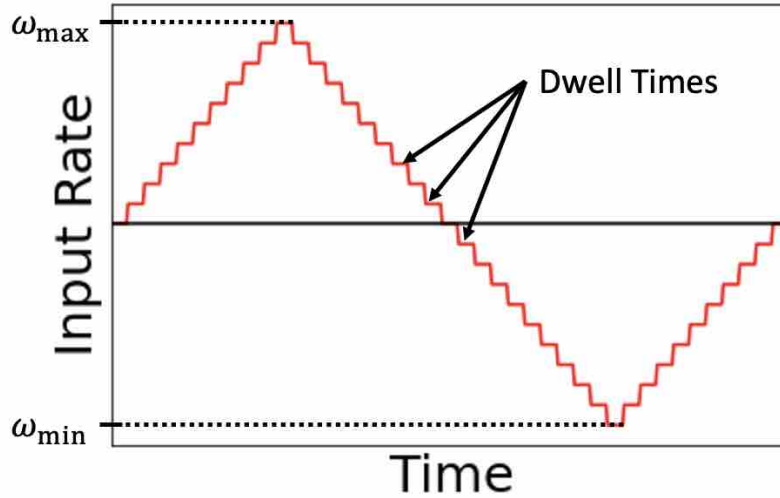


Figure 4.2: An example rate table test sequence is shown [5]. The test begins from rest, steps up to a predetermined maximum positive angular rate, steps down to a predetermined maximum negative angular rate, then steps back up to rest. The periods during which a specific input rate is held constant is known as a dwell time. These segments consist of a stabilization period and a sampling period.

As is expected, while the test apparatus steps up and down to these high angular rates, it spins in a single direction for an extended period of time. Given the fact that a robot arm is being used for this test, the performance limitations of the ABB IRB 120 must be taken into account. Each of the six axes of the robot arm has limits on how far it can rotate and how fast it can rotate before reaching a boundary limit set by the manufacturer based on the performance capabilities of the internal hardware. A summary of these joint angular limits is presented in Table 4.2.

Based on the limitations presented, the ABB IRB 120 robot arm is not capable of performing the desired gyroscope rotation rate test as the maximum angular limit is 400 degrees in the sixth axis which only slightly surpasses one full revolution. However, these limits are only applicable to the default firmware configuration and there exists a solution for the purposes of this test. ABB offers the 610-1 Independent Axis motion function software pack-

age that allows for the sixth axis of the robot arm to work independently of other axes in the robot system [41]. The angular limit can be set to extremely high magnitudes to essentially allow the end effector of the robot arm to rotate indefinitely. However, this is only true for the angular limits. The velocity limits cannot be changed from those shown in Table 4.2.

Table 4.2: ABB IRB 120 Joint Movement Limitations [40]

Joint Number	Angular Limit [deg]	Velocity Limit [deg/s]
J1	$+/-165$	$+/-250$
J2	$+/-110$	$+/-250$
J3	$+70/-110$	$+/-250$
J4	$+/-160$	$+/-320$
J5	$+/-120$	$+/-320$
J6	$+/-400$ ^[2]	$+/-420$

4.2 Test Software

ABB’s RobotStudio application [42] is used to program the ABB IRB 120 robot arm. ABB robotics use the RAPID programming language [43] to control their products. A program is written in RAPID to control the robot arm to sequence through all of the desired angular rates in order with a user-specified dwell time at each angular rate. For the prototype daughterboard testing, this was the full extent of the gyroscope rate test program. For the revised daughterboard testing, commands were added to create an input/output variable with which the system could write to a file such that the time read from the robot controller clock at the beginning of each rate step would be recorded and saved. This resulted in a list of rates and times in the following form: `CURRENT TIME is: hh:mm:ss; DESIRED RATE is: x`. In data post-processing and analysis, these logging documents are compared to the time listed in the ROS filename to better synchronize the gyroscope output data to each jump up/down in angular rate as there is some element of human error present in starting the data streaming/recording on the Teensy and starting the program on the ABB IRB 120 robot arm.

² ∞ with Option 610-1 Independent Axis software package from ABB.

4.3 Test Overview

A DISI Kit daughterboard integrated with three single-axis gyroscopes (one CRM100 for z-axis measurements and two CRM200s for x- and y-axis measurements) is secured to the robot arm via a series of user-designed and outsourced test mounts attached to the robot's sixth-joint end effector. The additional Option 610-1 motion function software package is downloaded and installed to the IRC5 robot controller to allow the sixth joint of the robot to rotate indefinitely and to allow for the robot arm to be used for rotation rate testing. A desired sequence of rotation rates and time duration is set and changed by the user between tests. The desired rotation rate of the ABB IRB 120 robot arm is taken as the ground truth in these tests to provide a benchmark rotation rate to which the raw gyroscope data are compared.

A series of step-wise rate tests is run. In the step-wise rate test, the program steps through a sequence of evenly spaced angular rates starting at zero and working its way up to the maximum rotation rate in the positive direction (i.e., counterclockwise) as defined by the measurement range of the gyroscopes being tested. Then the program steps down, continuing past zero, to the maximum rotation rate in the negative direction (i.e., clockwise). The test finishes with a stepwise series back to zero. The robot arm steps through the rates quickly, but is given enough dwell time for the rate to converge to the desired rate for a given step as well as to allow the gyroscope output signals to reach equilibrium. This test helps to show any variation between the desired rate and measured rate and it allows the user to calculate a scale factor error that is unique to the gyroscope, uncovering any hysteresis in the measurement capabilities of the gyroscope.

In testing a daughterboard with three single-axis gyroscopes, one issue that arises is the need to isolate each of the gyroscopes during a single rate test. In other words, the hardware should be mounted in such a way and the test should be designed and performed such that the rotation of the robot arm is as close to the rotation about a single measurement axis of the daughterboard as possible. A series of test mounts are designed and procured to not only allow the mounting of the entire test setup to the ABB IRB 120 robot arm, but also to allow multiple possible mounting configurations of the daughterboards, each one isolating one of the daughterboard's three measurement axes. The attitude of the robot arm is taken as ground truth

and set in such a way to better isolate the axes of the daughterboard. This isolation is also confirmed to some extent using the three-axis accelerometer on board the DISI Kit daughterboards. By taking a look at the output signal from each axis of the accelerometer, single-axis isolation can be confirmed if there is only a non-zero output signal from a single axis of the accelerometer.

4.4 Test Considerations

When designing the rate table test plan that is used to collect the data necessary to calibrate the gyroscope sensors, a number of choices are considered:

1. Test range: The maximum angular rate in each direction.
2. Step size: The interval between each desired angular rate.
3. Dwell time: The duration over which a desired rate is held to allow for stabilization of the gyroscope signal (stabilization time) as well as data collection (sample time).
4. Starting rate: The rate at which to start the stepwise rate test.

These considerations vary depending on the nature of the testing being performed as well as on the reason for the testing. For example, a test plan designed to determine the best gyroscope out of a selection varies from a test plan designed to calibrate a single gyroscope that has already been chosen for a particular use.

To develop the most thorough model of the desired angular rate and the signal produced by the gyroscope sensor, the test traverses across the entire measurement range of each particular sensor. Each of the DISI Kit daughterboards is designed to have one Silicon Sensing CRM100 [44] for z-axis angular rate measurements as well as two Silicon Sensing CRM200s [45] for x- and y- axis angular rate measurements. Images of the CRM100 and CRM200 can be seen in Figures 4.3 and 4.4, respectively. Both of these models come from the PinPoint MEMS Gyroscopes series from Silicon Sensing which is their smallest MEMS gyroscope class and has the option to be integrated in a number of different configurations. Both the CRM100 and the CRM200 measure angular rates with respect to an axis pointing outward from its front

face. Each of these products has a programmable measurement range. This is particularly useful as different measurement ranges are desired depending on the specific application for which the gyroscope sensor is used. In the case of the DISI Kit's on-orbit applications, the team expects a maximum slew rate of approximately one degree per second across the duration of the mission and a maximum hardware capability of three degrees per second if the attitude control system (ACS) is pushed to its performance limitations. That being the case, the minimum measurement range for the gyroscope is desired. For both the CRM100 and the CRM200, the minimum programmable measurement range is -75 degrees per second to $+75$ degrees per second. As a result, the gyroscope rate testing for this test includes rates from -75 degrees per second to $+75$ degrees per second.



Figure 4.3: The CRM100 is used for z-axis gyroscope measurements on the DISI Kit daughterboards [40].



Figure 4.4: Two individual CRM200s are used for x- and y-axis gyroscope measurements on the DISI Kit daughterboards [41].

The next test consideration is the step size, or the interval between each desired rate across the stepwise rate test. Ideally a test at all possible rates across the desired test range is performed. However, this is not realistic or even possible for a number of reasons. First, the time it takes to test all possible rates is superfluous. Second, the amount of data that are required to be collected to test at all of those rates is infinite. Third, the precision of the test apparatus is limited.

Prior to performing a rate test, the duration that the rate table, or in our case the ABB robot arm, needs to be held at for each rate throughout the test must be considered. This is an extremely important consideration in

order to ensure that quality data are collected. If the test apparatus steps across the test range too quickly, the gyroscope signals do not have time to stabilize between rate changes. However, there comes a point where holding at a desired rate for too long only produces redundant data.

The final consideration is the rate at which the stepwise test should begin. There are a number of potential options:

1. Start from rest (desired rate = zero degrees per second), step upward to the maximum (most positive) of the test range, step back downward to the minimum (most negative) of the test range, then finally step back upward to rest.
2. Start from the minimum (most negative) rate of the test range, step upward to the maximum (most positive) of the test range, then step back downward to the minimum rate.
3. Start from the maximum (most positive) rate of the test range, step downward to the minimum (most negative) of the test range, then step back upward to the maximum rate.

4.5 Test Plan

The gyroscope rate test using the ABB IRB 120 robot arm proceeds as follows:

1. The robot starts from rest.
2. The robot steps up every five degrees per second to a maximum counterclockwise rate of +75 degrees per second.
3. The robot steps down every five degrees per second to a maximum clockwise rate of -75 degrees per second.
4. The robot steps back up every five degrees per second to rest.

During this test, the gyroscope sensor measurements need time to stabilize at each given rate. To allow for this, the robot holds at each desired rate for 10 seconds before moving on to the next step. The sampling rate is set to 100 Hz for the duration of the test.

4.6 Test Setup

A number of issues and other considerations need to be taken into account before proceeding with the hardware test.

1. All test components, particularly the daughterboard containing the gyroscope sensors, need to be securely fastened to the robot arm. Otherwise, vibrations within the test setup while the system is rotating will introduce inaccuracies into the final calibrated system.
2. All wired connections need to be contained within the setup that is secured to the robot arm. Since the robot, and the setup as a result, is rotating for a long period of time and to very large angles, any wired connections between the test setup and any external power sources, displays such as a computer monitor for the Intel NUC, or external interfaces such as a mouse and keyboard could wind up during testing.
3. The IRC5 controller which powers, communicates with, and commands the ABB IRB 120 robot arm should be configured to a Wi-Fi network and Network Time Protocol (NTP) time server to allow for more accurate time synchronization between the robot controller and the combined Teensy/Intel NUC clock.

To resolve the first issue, a series of test mounts are machined and purchased to allow for proper mounting of the test hardware to the end effector of the ABB IRB 120 robot arm. The exact robot arm used for this series of testing can be seen in Figure 4.5.

The end effector has four simple M5 holes with a depth of 8mm. These holes are evenly distributed across the flange, spaced apart by 90 degrees from each other at 45 degrees, 135 degrees, 225 degrees, and 315 degrees from the horizontal, as seen in Figure 4.6.

A Thorlabs MB1515M solid aluminum optical breadboard is used as a plate to mount the rest of the necessary test hardware. This choice is made for its size, its ease of mounting, and its use in related hardware tests [47]. Figure 4.7 presents an image of the optical breadboard from Thorlabs. This optical breadboard is 150mm x 150mm x 12.7mm and is outfit with 36 M6x1.0-tapped holes separated by 25mm from adjacent holes and 12.5mm from the edge for edge holes. The optical breadboard also has four M6 counterbored



Figure 4.5: This robot arm located in CSL room B16 is used for the gyroscope rate testing outlined in this chapter. Here it is shown in the default or calibrated position.

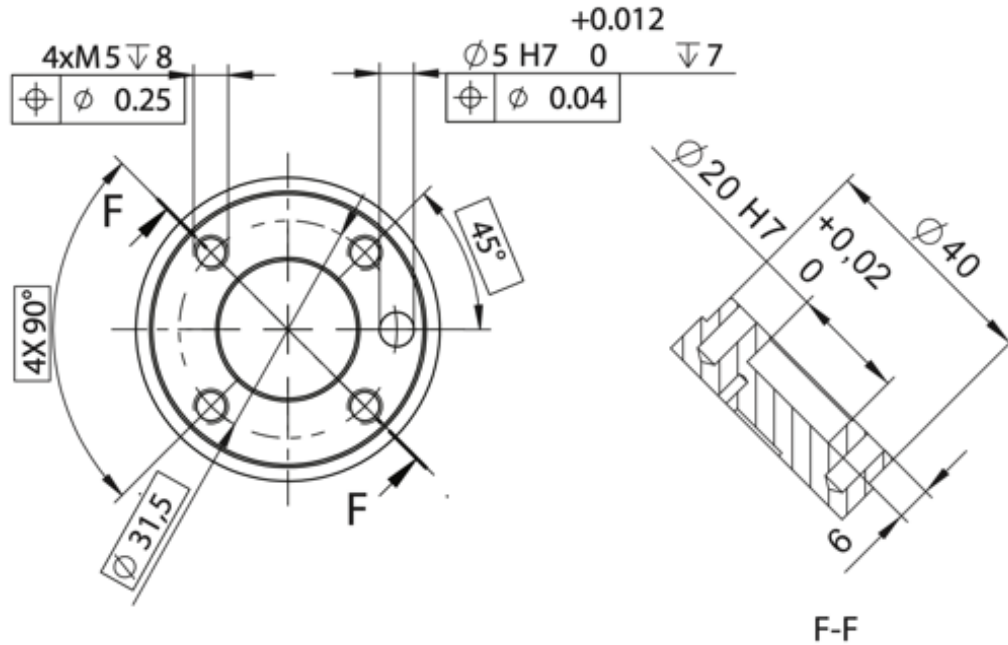


Figure 4.6: A technical schematic of the ABB IRB 120 end effector shows the mounting holes used to secure gyroscope rate test hardware [46].

holes to support M6 socket cap fasteners. These holes are separated 100mm from adjacent counterbored holes and 25mm from each of the nearest edges.

As mentioned, these holes provide numerous configurations for mounting hardware to the optical breadboard or for mounting the optical breadboard to other apparatus. However, based on the dimensions provided in Figure 4.6, one can see that the optical breadboard is not able to mount directly to the end effector of the robot arm as the adjacent holes on the end effector are approximately 22.27mm apart.



Figure 4.7: This Thorlabs optical breadboard is one of the mounts used to secure test hardware to the robot arm [48].

To allow for mounting between the end effector of the robot arm and the optical breadboard, a custom mounting adaptor is required. The adaptor is a half-inch thick circular aluminum plate with eight counterbored mounting holes evenly spaced 25mm apart from adjacent holes in a 2x4 rectangular pattern. The four inner holes are counterbored M5 through holes used for mounting the plate to the end effector of the robot arm. The four outer holes are counterbored M6 through holes used for mounting the Thorlabs optical breadboard to the aluminum plate. Based on the mounting adaptor's orientation when mounted on the robot arm, the side that shows the counterbore of the four inner holes is referred to as the front or outward facing side whereas the side which shows the counterbore of the four outer holes is referred to as the back or inward facing side of the plate. The two sides of the mounting adaptor are shown in Figures 4.8 and 4.9.

When mounting each daughterboard to the optical breadboard, the mounting orientation of the daughterboard is taken into account to confirm the isolation of the single body-frame axis of the daughterboard that is being tested in a given trial. The axes of the body frame of each daughterboard are engraved into each respective face with the z axis perpendicular to the face of the daughterboard and the x and y axes in the plane of the face of the daughterboard. To test the x and y axes of each daughterboard, the daughter-

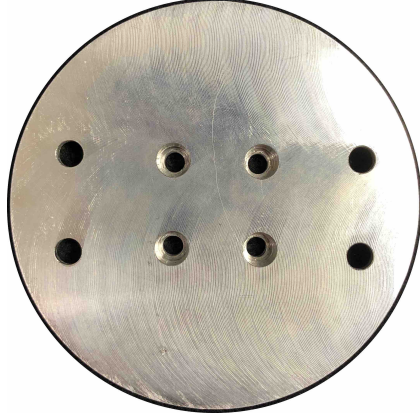


Figure 4.8: The front (outward facing) side of the aluminum mounting adaptor as seen when secured to the robot arm.

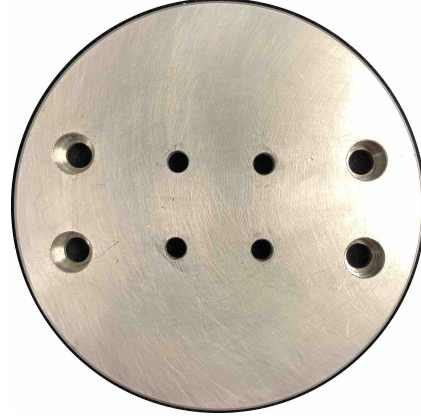


Figure 4.9: The back (inward facing) side of the aluminum mounting adaptor as seen when secured to the robot arm.

board is mounted such that the face of the daughterboard is perpendicular to the optical breadboard. To test the z axis of each daughterboard, the daughterboard is mounted such that the face of the daughterboard is parallel to the optical breadboard. Each daughterboard is mounted directly to the optical breadboard when preparing a z-axis gyroscope rate test. However, there is no way to mount each daughterboard directly to the optical breadboard to allow testing of the x and y axes. A Thorlabs AB90A/M aluminum right-angle bracket is used to allow the mounting of the daughterboard in orientations such that x- and y- axis gyroscope rate tests can be performed. This choice is made for its dimensional compatibility with the MB1515M optical breadboard as well as the DISI Kit daughterboards. Figure 4.10 presents an image of the right-angle bracket from Thorlabs.

To resolve the second issue pertaining to wired connections within the test setup, a number of hardware configuration changes are made to ensure no interfaces traverse between external components and components secured to the robot arm. For the power supply, a Turnigy 12000mAh 4-cell 14.8V 12C high discharge LiPo battery [49] along with a compatible custom-made power regulator serves as the power source for the Intel NUC. To avoid the need for external displays and interfaces for the Intel NUC, remote desktop access via NoMachine is set up on the Intel NUC. This allows users to access and operate the Intel NUC using a personal external device via a wireless connection. Upon making these changes, all necessary cabling is restricted to



Figure 4.10: This Thorlabs right-angle bracket is used to mount the DISI Kit daughterboards in an orientation that allows the gyroscope rate testing of their x and y axes [37].

those components that are secured to the robot arm: LiPo battery to voltage regulator, voltage regulator to Intel NUC, Intel NUC to Teensy, and Teensy to DISI Kit daughterboard.

The final issue pertains to time synchronization between the two clocks in the test setup: the ABB IRC5 controller clock and the Intel NUC clock as the Teensy takes the Intel NUC clock as truth when naming data recording files. This time synchronization is achieved by configuring the IRC5 controller clock to the same NTP time server as the Intel NUC. Linux devices can be setup to time synchronize with a variety of NTP servers. After the initial setup on the Intel NUC side, the IRC5 controller can be synchronized with the same NTP server via the RobotStudio application. Once both devices' clocks are configured to the same NTP server, the time is considered synchronized and both clocks are taken to be equivalent. Further details are provided in Appendix B.

Upon finalizing all decisions pertaining to test considerations, the test is set up as follows:

1. Start with the ABB IRB 120 robot arm in its default calibrated position as shown in Figure 4.5. When properly calibrated, this corresponds to all joints positioned at an angle of 0.00 degrees as shown on the ABB

FlexPendant tablet display in Figure 4.11. If the robot is not already calibrated and in this default position, then extra steps are required to manually update the robot's joint revolution counters. A series of alignment markers engraved into the body of the robot allow the robot to be calibrated [50]. Further details are provided in Appendix C.

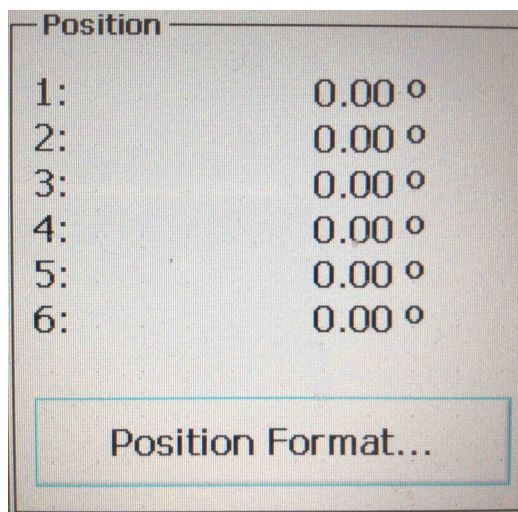


Figure 4.11: When the ABB IRB 120 robot is in the calibrated position, the positional measurements for each axis should read 0.00 degrees.

2. Using a set of four M5 socket cap bolts, the circular aluminum mounting adaptor is secured to the end effector of the robot arm via the adaptor's four inner holes. The front face as defined in Figure 4.8 faces away from the robot arm as shown in Figure 4.12.
3. Using a set of four M6 socket cap bolts, the Thorlabs optical breadboard is secured to the mounting adaptor via the adaptor's four outer holes. To keep the center of mass of the test setup as close as possible to the center axis of the end effector of the robot arm, the optical breadboard is mounted about its center as shown in Figure 4.13.
4. Using the FlexPendant Teach Pendant Unit (TPU), manually jog the robot such that the fifth joint of the robot arm is in the "wrist up" position (i.e., position 5 reads -90 degrees on the tablet display) as shown in Figure 4.14.
5. Using a set of two M6 socket cap bolts, secure the Thorlabs right-angle bracket to the optical breadboard via the bracket's front two holes. To



Figure 4.12: The circular aluminum mounting adaptor is mounted directly to the tool flange of the robot arm.

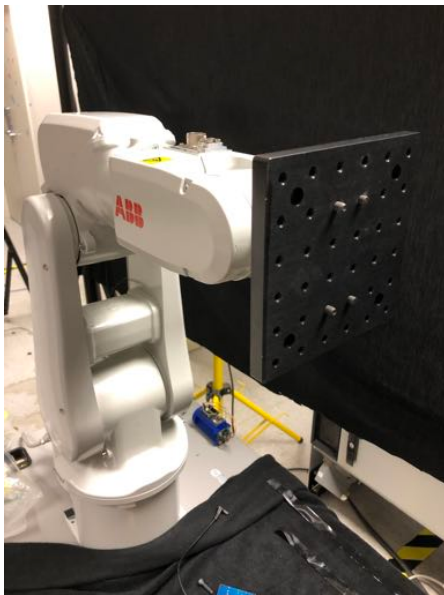


Figure 4.13: The optical breadboard is mounted to the robot arm via the aluminum mounting adaptor.

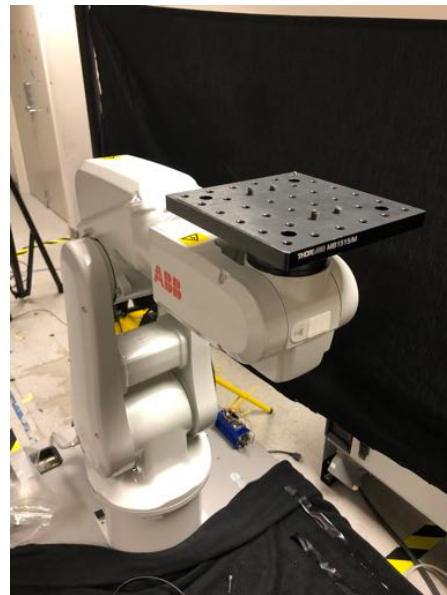


Figure 4.14: Before mounting more hardware, the robot is commanded to the “wrist up” position.

both keep the center of mass of the test setup as close as possible to the center axis of the end effector of the robot arm and to ensure that the sensors being tested are as close to the axis of rotation as possible, the right-angle bracket is mounted in the center of the optical breadboard as shown in Figure 4.15.

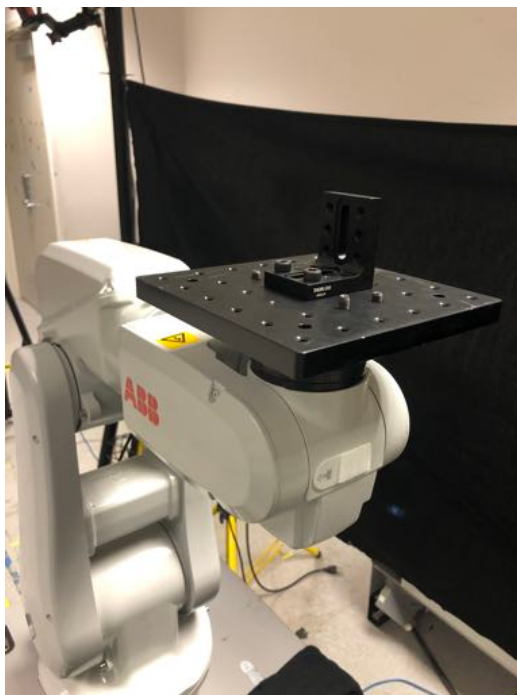


Figure 4.15: The right-angle bracket is mounted to the center of the optical breadboard.

6. Using a set of two 4/40 socket cap bolts each outfit with a 4/40-to-M6 thread adaptor and a 4/40 hex nut, secure the custom-built voltage regulator to the optical breadboard. The 4/40-to-M6 thread adaptor is necessary given the disparity between the size of the mounting holes on the voltage regulator board and the size of the mounting holes on the optical breadboard. As there is also a mismatch between the separation between adjacent holes on the voltage regulator and the separation between the holes on the optical breadboard, the voltage regulator is mounted using only two holes as shown in Figures 4.16 and 4.17. For ease of connecting the voltage regulator to the battery in a later step, it is recommended that the voltage regulator be mounted on the edge of the optical breadboard with the wires facing outward as shown in Figure 4.17.

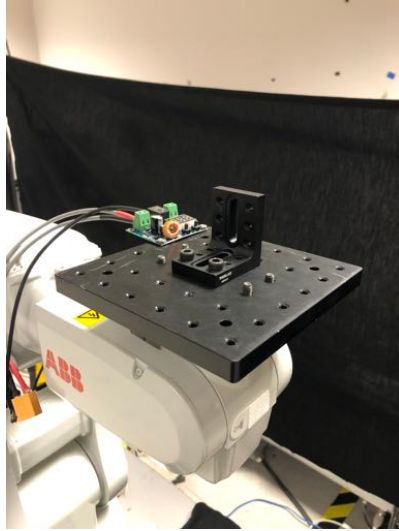


Figure 4.16: The custom-built voltage regulator is mounted to the back left corner of the optical breadboard.

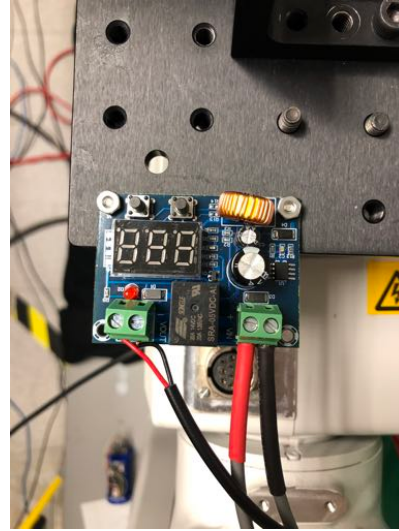


Figure 4.17: Only two mounting holes are used to mount the voltage regulator due to incompatible hole spacing.

7. Using an adhesive, secure the LiPo battery to the optical breadboard.



Figure 4.18: The LiPo battery is secured to the optical breadboard using an adhesive. Electrical tape is used for this round of rate testing.

8. Prior to securing the Intel NUC computer to the optical breadboard,

mount the red electronics breadboard with Teensy configured to the top of the Intel NUC and secure using the same adhesive used in Step 7. Then, using a USB-to-microUSB cable, connect a USB port on the Intel NUC to the microUSB port of the Teensy board as shown in Figure 4.19. After the Intel NUC has been configured with the Teensy, the setup is mounted to the optical breadboard using the same adhesive used in Step 7. An image of the final test setup prior to mounting a DISI Kit daughterboard is presented in Figure 4.20.

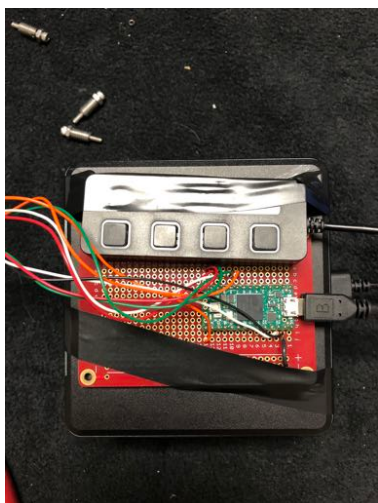


Figure 4.19: The breadboard with the Teensy circuit is secured on top of the Intel NUC using an adhesive. Electrical tape is used for this testing.



Figure 4.20: The Intel NUC and the Teensy circuit are secured to the optical breadboard using an adhesive. Electrical tape is used for this testing.

4.7 Test Procedures

1. Using a set of two 4/40 socket cap bolts each outfit with a 4/40-to-M6 thread adaptor and a 4/40 hex nut, secure a DISI Kit daughterboard to the test setup in the proper configuration (with right-angle bracket for x- or y-axis tests as shown in Figure 4.21 or directly to the optical breadboard for z-axis tests as shown in Figure 4.22 using the axis denotation engraved into the face of the board.
2. Plug the 4-pin and 5-pin DF-13 connectors from the red electronics



Figure 4.21: The daughterboard is mounted to the right-angle bracket for x- or y- axis tests.

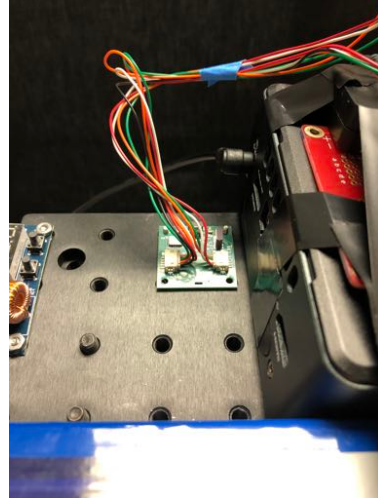


Figure 4.22: The daughterboard is mounted directly to the optical breadboard for z-axis tests.

breadboard into their respective 4-pin and 5-pin DF-13 sockets on the daughterboard as shown in Figure 4.23.



Figure 4.23: Once the daughterboard is mounted, the DF-13 connectors which interface with the Teensy are plugged into the daughterboard.

3. Plug the LiPo battery into the voltage regulator and the voltage regu-

lator into the Intel NUC.

4. Power on the Intel NUC.
5. Remote desktop into the Intel NUC using NoMachine on an external device.
6. Open a command prompt terminal. Run the appropriate ROS commands necessary to log into the ROS system, to connect the device to the Teensy interface, and to stream and record sensor data. Further details are provided in Appendix A.
7. Start the rate test on the robot arm via the FlexPendant TPU.
8. When the test has completed, stop the data recording on the Intel NUC and convert the ROS bag file (.bag) to which the data were saved into a text file (.txt) and comma-separated values file (.csv).
9. Repeat these steps for all axes of each DISI Kit daughterboard to be tested.

4.8 Prototype Hardware Test Results

Plotted gyroscope rate test data for prototype daughterboard 1 are presented in Figure 4.24. The left column of plots shows the entire dataset for each individual axis test which spans upwards of 70,000 datapoints, or approximately 700 seconds as the sampling rate during testing is set to 100 Hz. As can be seen from these images, each test shows a single axis' measured angular velocity spanning the entire test range (the test axis) whereas the other two axes only show slight increases and decreases due to axis misalignment between the three single-axis gyroscopes. The resulting numerical data presented in Table 4.3 and Equation 4.1 show a fairly significant fixed bias across all three axes with the maximum fixed bias existing in the x axis of the prototype board. On the other hand, the scale factor error is calculated to be much less severe with all three axes having a scale factor error less than half a percent, or 5000ppm. Numerical data for other prototype boards are found in Tables 4.4-4.5 and Equations 4.2-4.3. Plots for other prototype

daughterboards are left out of this chapter for conciseness. Detailed plots of other datasets are found in Appendix E.

Table 4.3: Prototype Daughterboard 1 Gyroscope Rate Test Results

Prototype Board #	1		
Test Axis	X	Y	Z
Gyroscope Fixed Bias [deg/s]	−3.10	−2.66	−0.797
Gyroscope Scale Factor Error [%]	0.286	0.459	0.133

$$M_{\text{gryo, Prototype DB1}} = \begin{bmatrix} 0 & -0.543 & -1.79 \\ -0.278 & 0 & 2.17 \\ 4.590 & -0.426 & 0 \end{bmatrix} \quad (4.1)$$

Table 4.4: Prototype Daughterboard 2 Gyroscope Rate Test Results

Prototype Board #	2		
Test Axis	X	Y	Z
Gyroscope Fixed Bias [deg/s]	−5.78	−2.21	3.66
Gyroscope Scale Factor Error [%]	0.917	0.510	0.255

$$M_{\text{gryo, Prototype DB2}} = \begin{bmatrix} 0 & -0.298 & 2.84 \\ -0.186 & 0 & 2.15 \\ 2.93 & -0.113 & 0 \end{bmatrix} \quad (4.2)$$

Table 4.5: Prototype Daughterboard 3 Gyroscope Rate Test Results

Prototype Board #	3		
Test Axis	X	Y	Z
Gyroscope Fixed Bias [deg/s]	−2.77	2.15	0.530
Gyroscope Scale Factor Error [%]	0.470	0.690	0.583

$$M_{\text{gryo, Prototype DB3}} = \begin{bmatrix} 0 & 0.0315 & -1.10 \\ -0.294 & 0 & 1.94 \\ -1.42 & -1.52 & 0 \end{bmatrix} \quad (4.3)$$

Table 4.6 and Equations 4.4-4.5 present a compiled analysis of the gyroscope rate tests for all three prototype daughterboards. Table 4.6 also makes

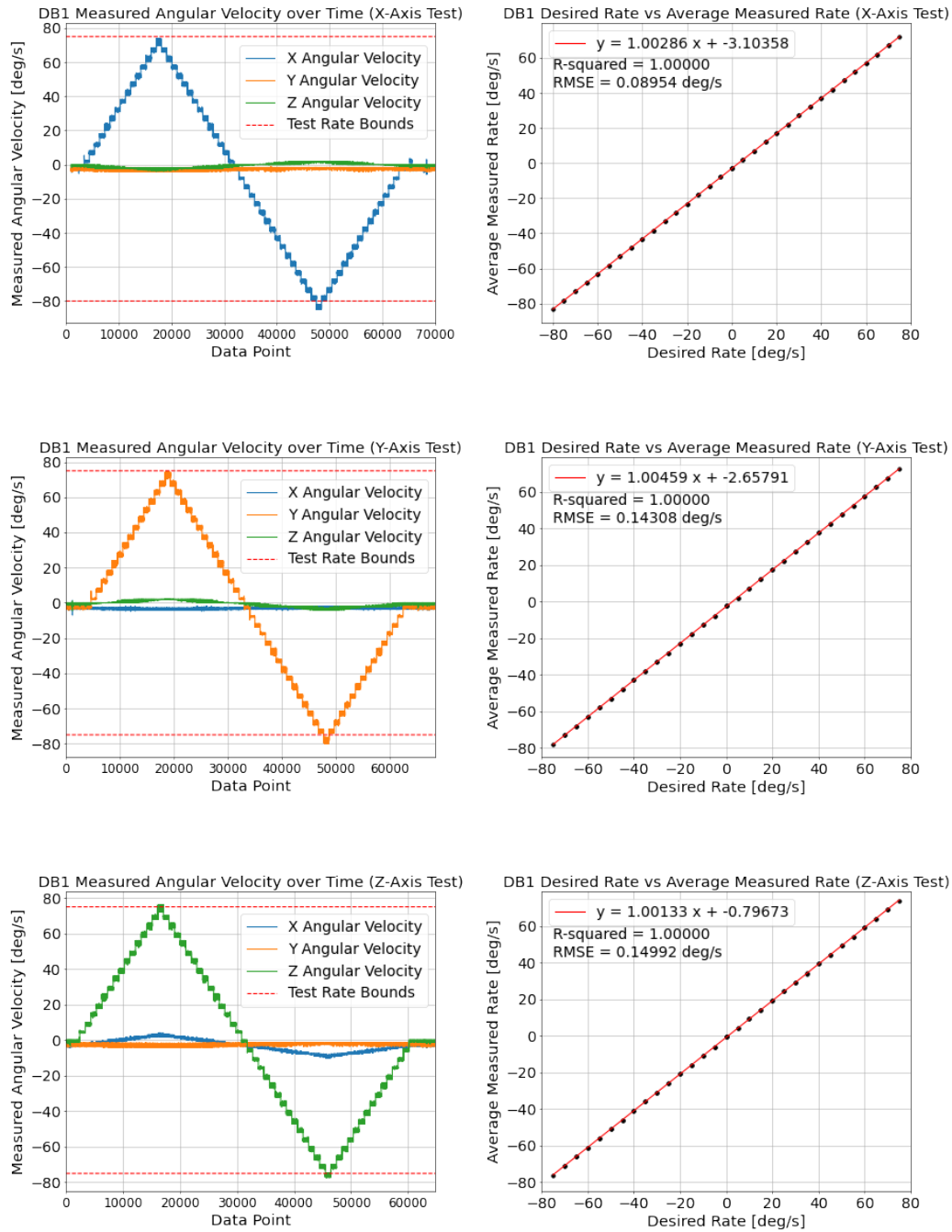


Figure 4.24: DB1 gyroscope rate test results: The left column plots show the full dataset for each individual axis test of prototype DB1. The right column plots show the average data for each individual step of each axis test of prototype DB1 along with a best fit line representing the sensor deterministic error model for fixed bias and scale factor error.

a comparison between the deterministic error parameters of the CRM100 and CRM200 gyroscope sensors across all prototype daughterboards and the ranges for these same error parameters as given by the manufacturer. The average magnitude of the x-axis fixed bias (3.82 deg/s) actually exceeds the datasheet range of $[-3, +3]$ deg/s. It is worth noting that the datasheet defines this range with respect to the value at $+25^{\circ}\text{C}$. MEMS sensors are known to be susceptible to significant performance changes over wide thermal variations. It is possible that the board, and more specifically the sensor, heated up during testing and caused greater bias within the x-axis sensor. Given that these large fixed bias magnitudes were measured while the system was at rest, it is also possible that the sensors were damaged in some way. In particular, the x-axis gyroscopes for both prototype daughterboard 1 and prototype daughterboard 2 as well as the z-axis gyroscope for prototype daughterboard 2 have fixed bias magnitudes that exceed the datasheet range, and other sensors come close to exceeding as well. The average magnitude of the y- and z-axis fixed bias are much more reasonable in magnitude at -0.908 meters per second squared and 1.13 meters per second squared which both lie well within the datasheet range. Moving onto scale factor error, all sensors have a scale factor error magnitude which lies within the datasheet range of $[-1.5, +1.5]\%$. The highest mean magnitude of scale factor error exists in the x axis with a mean scale factor error of 0.558%. The highest magnitude scale factor error across all three prototype daughterboards is the x axis of prototype daughterboard 2 with a scale factor error of 0.917%, or approximately 61% of the datasheet value.

Gyroscope cross-axis sensitivity across all prototype daughterboards has higher maximum misalignment between certain axes. The CRM100 and CRM200 are listed as having a maximum cross-axis sensitivity of $+/-11$ mrad and $+/-50$ mrad, respectively. This amounts to a maximum of 0.630 degrees of misalignment in the z axis and a maximum of 2.865 degrees of misalignment in both x and y axes. Misalignment beyond these maximums can be attributed in part to the fact that the DISI Kit daughterboards integrate three single-axis gyroscope sensors in their design rather than a single three-axis gyroscope sensor as a single three-axis sensor's misalignment does not rely as heavily on the orthogonality of the mounting as three single-axis sensors. As such, there is more room for error in misalignment given the current design. Like with the accelerometer axis misalignment, the gyroscope

axis misalignment follows the trend of straying from the skew symmetric form due to random noise in the sensors.

Table 4.6: Prototype Daughterboard Gyroscope Results Statistics

Parameter	Fixed Bias [deg/s]			Scale Factor Error [%]		
Test Axis	X	Y	Z	X	Y	Z
Mean	-3.82	-0.908	1.13	0.558	0.553	0.324
Std Dev	1.25	2.17	1.87	0.265	0.0991	0.190
CRM100 [44]		[-3, +3]			[-1.5, +1.5]	
CRM200 [45]		[-3, +3]			[-1.5, +1.5]	

$$M_{\text{gyro, Prototype Avg}} = \begin{bmatrix} 0 & -0.270 & -0.016 \\ -0.253 & 0 & 2.09 \\ 2.03 & -0.685 & 0 \end{bmatrix} \quad (4.4)$$

$$M_{\text{gyro, Prototype Std Dev}} = \begin{bmatrix} 0 & 0.236 & 2.04 \\ 0.0476 & 0 & 0.104 \\ 2.53 & 0.601 & 0 \end{bmatrix} \quad (4.5)$$

4.9 Revised Hardware Test Results

Plotted gyroscope rate test data for revised daughterboard 03 are presented in Figure 4.25. The left column of plots shows the entire dataset for each individual axis test which spans just over 60,000 datapoints, or approximately 600 seconds as the sampling rate during testing is set to 100 Hz. This decrease in the number of datapoints is attributed to the change to remote desktop into the Intel NUC as opposed to the physical interface between the Intel NUC and a monitor, mouse, and keyboard used in the first round of testing. This change decreased the amount of time taken between initiating/terminating data recording and starting/ending the RAPID program. Similar to the prototype round of testing, each test shows a single axis' measured angular velocity spanning the entire test range (the test axis) whereas the other two axes only show slight increases and decreases due to axis misalignment between the three single-axis gyroscopes. The resulting numerical data presented in Table 4.7 and Equation 4.6 also show a fairly

significant fixed bias across all three axes with the maximum fixed bias once again existing in the x axis. The scale factor error for daughterboard 03 is calculated to be more severe than the scale factor error for daughterboard 1 with two of the three axes having a scale factor error greater than half a percent. However, these error magnitudes still lie within the allowable range outlined in the CRM100 and CRM200 datasheets [44, 45]. Numerical data for other revised daughterboards are found in Tables 4.8-4.11 and Equations 4.7-4.10. Plots for other revised daughterboards are left out of this chapter for conciseness. Detailed plots of other datasets are found in Appendix E.

Table 4.7: Daughterboard 03 Gyroscope Rate Test Results

Board #	03		
Test Axis	X	Y	Z
Gyroscope Fixed Bias [deg/s]	3.69	0.861	-0.861
Gyroscope Scale Factor Error [%]	0.812	0.936	0.408

$$M_{\text{gryo, Revised DB03}} = \begin{bmatrix} 0 & -0.132 & -0.204 \\ -0.757 & 0 & 0.459 \\ -2.51 & -1.25 & 0 \end{bmatrix} \quad (4.6)$$

Table 4.8: Daughterboard 05 Gyroscope Rate Test Results

Board #	05		
Test Axis	X	Y	Z
Gyroscope Fixed Bias [deg/s]	1.20	2.98	-0.276
Gyroscope Scale Factor Error [%]	0.612	0.234	-0.263

$$M_{\text{gryo, Revised DB05}} = \begin{bmatrix} 0 & 0.0748 & 0.0538 \\ -0.489 & 0 & 0.629 \\ 0.457 & -1.51 & 0 \end{bmatrix} \quad (4.7)$$

$$M_{\text{gryo, Revised DB07}} = \begin{bmatrix} 0 & -0.227 & 0.308 \\ -0.433 & 0 & 1.17 \\ -1.54 & 0.633 & 0 \end{bmatrix} \quad (4.8)$$

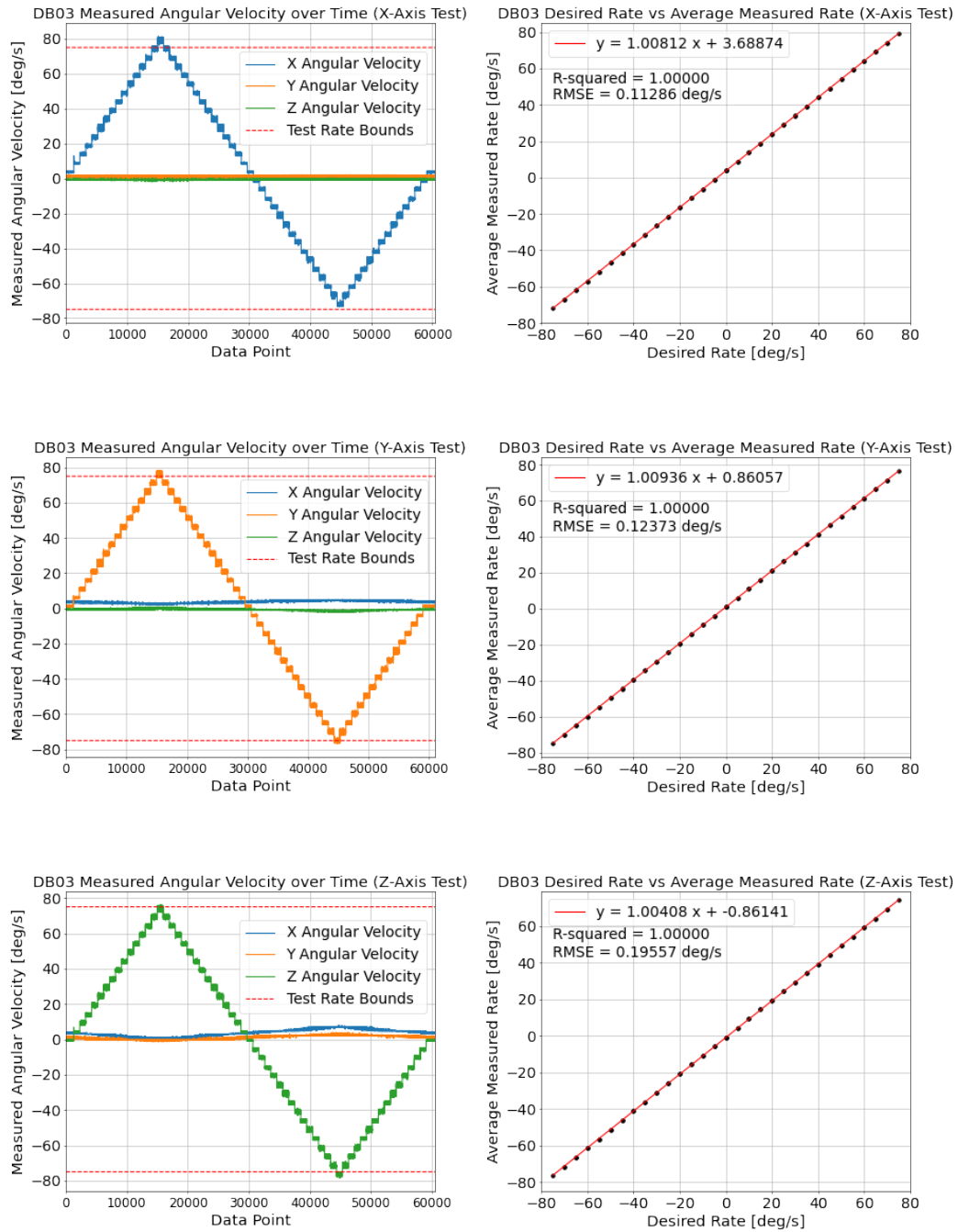


Figure 4.25: DB03 gyroscope rate test results: The left column plots show the full dataset for each individual axis test of revised DB03. The right column plots show the average data for each individual step of each axis test of revised DB03 along with a best fit line representing the sensor deterministic error model for fixed bias and scale factor error.

Table 4.9: Daughterboard 07 Gyroscope Rate Test Results

Board #	07		
Test Axis	X	Y	Z
Gyroscope Fixed Bias [deg/s]	-0.774	1.02	3.54
Gyroscope Scale Factor Error [%]	-0.00762	0.360	0.804

Table 4.10: Daughterboard 08 Gyroscope Rate Test Results

Board #	08		
Test Axis	X	Y	Z
Gyroscope Fixed Bias [deg/s]	0.862	1.51	1.27
Gyroscope Scale Factor Error [%]	0.609	1.19	0.100

$$M_{\text{gryo, Revised DB08}} = \begin{bmatrix} 0 & -0.245 & 0.217 \\ -0.0601 & 0 & 0.604 \\ 1.27 & -0.633 & 0 \end{bmatrix} \quad (4.9)$$

Table 4.11: Daughterboard 10 Gyroscope Rate Test Results

Board #	10		
Test Axis	X	Y	Z
Gyroscope Fixed Bias [deg/s]	4.02	4.19	3.28
Gyroscope Scale Factor Error [%]	0.0410	0.161	0.534

$$M_{\text{gyro, Revised DB10}} = \begin{bmatrix} 0 & 0.900 & 0.563 \\ 0.0309 & 0 & 0.0124 \\ -1.51 & -2.01 & 0 \end{bmatrix} \quad (4.10)$$

Table 4.12 and Equations 4.11-4.12 present a compiled analysis of the gyroscope rate tests for all five revised daughterboards. Table 4.12 also makes a comparison between the deterministic error parameters of the CRM100 and CRM200 gyroscope sensors across all revised daughterboards and the ranges for these same error parameters as given by the manufacturer. Unlike the prototype daughterboards, the average magnitude of the fixed bias in all axes is within the datasheet range. However, there are some individual sensors which still exceed a fixed bias magnitude of 3 degrees per second: the x

axis of daughterboard 03, the z axis of daughterboard 07, and all axes of daughterboard 10. Like the prototype daughterboards, the scale factor error calculated for all axes of all revised daughterboards is much more reasonable and does not exceed a scale factor error magnitude of 1.5%. The highest mean magnitude of scale factor error exists in the y axis with a mean scale factor error of 0.577%. The highest magnitude scale factor error across all five revised daughterboards is the y axis of revised daughterboard 08 with a scale factor error of 1.19%, or approximately 79% of the datasheet value.

Gyroscope axis misalignment across all revised daughterboards follows the trend of all other sensor axis misalignment: there exists a fair amount of deviation from the expected skew symmetric matrix.

Table 4.12: Revised Daughterboard Gyroscope Results Statistics

Parameter	Fixed Bias [deg/s]			Scale Factor Error [%]		
Test Axis	X	Y	Z	X	Y	Z
Mean	1.80	2.11	1.39	0.413	0.577	0.319
Std Dev	1.81	1.28	1.79	0.332	0.411	0.365
CRM100 [44]	[-3, +3]			[-1.5, +1.5]		
CRM200 [45]	[-3, +3]			[-1.5, +1.5]		

$$M_{\text{gyro, Revised Avg}} = \begin{bmatrix} 0 & 0.0740 & 0.188 \\ -0.342 & 0 & 0.574 \\ -0.768 & -0.952 & 0 \end{bmatrix} \quad (4.11)$$

$$M_{\text{gyro, Revised Std Dev}} = \begin{bmatrix} 0 & 0.428 & 0.256 \\ 0.290 & 0 & 0.370 \\ 1.40 & 0.908 & 0 \end{bmatrix} \quad (4.12)$$

CHAPTER 5

CONCLUSION

In this thesis, we presented a series of static and dynamic test methods that were used to calculate the deterministic performance parameters of fixed bias, scale factor error, and axis misalignment for a set of MEMS accelerometers and gyroscopes integrated within the architecture of a newly-designed distributed inertial navigation system. Although manufacturers provide a fairly accurate range of these error parameters, it is important to perform a personal assessment of individual sensors as the range of possible magnitudes is wide and an accurate model must be developed for applications with strict pose estimation requirements. Using the calculated deterministic error parameters unique to each individual DISI Kit sensor, additions are made to the DISI Kit firmware that properly correct for deterministic sensor errors as IMU data is communicated to the motherboard, prior to data being sent to the satellite bus. The sensors presented a wide range of fixed biases, scale factor errors, and cross-axis sensitivity, some even lying outside of the range of magnitudes provided by the manufacturer.

No perfect calibration methods and test procedures exist. Future work in calibrating DINS IMUs using the methods outlined in this thesis would include a number of improvements. First, test mounts would be made for all components of the test architecture such that the use of adhesives would be rendered unnecessary. This is particularly directed towards how the Intel NUC and LiPo battery were mounted during the gyroscope rotation rate tests. Although the use of electrical tape on these components does not directly impact the sensor measurements, it is beneficial to have confidence that all test components are securely fastened for the duration of the test.

Chapter 2 introduced an assumption which allowed g-dependent bias terms in the deterministic gyroscope error model to be ignored. Future work in calibrating the DINS gyroscopes would investigate g-dependent bias properly by calculating a model between the total bias magnitude and the acceleration

to which the gyroscope is being subject. This is accomplished by taking into account any offset between the sensitive axis of the gyroscope and the axis of rotation originating from the end effector of the robot arm.

Future work would also include comprehensive environmental testing. As was touched on in Chapter 2, MEMS sensor performance parameters are prone to variations in temperature, pressure, and magnetic field strength. Significant thermal, barometric, and magnetic variations experienced on orbit could cause the DISI Kit to degrade in performance, even if properly calibrated on Earth's surface. Thorough testing of the system in varying environmental conditions would only serve to improve the performance in a real-world application. This environmental testing would consist of thermal vacuum (TVAC) chamber testing in which the system is subject to a decreased pressure and is thermally cycled for a predetermined number of cycles each spanning a set thermal range and lasting a set duration. Data collected throughout the thermal cycling provide a model of the variation in temperature and pressure as compared to each of the deterministic error parameters calculated in this thesis. The environmental testing would also include Helmholtz cage testing during which the system is subject to the range of magnetic field strengths that are expected during a given mission. Data collected throughout this test once again provide a model of the variation in magnetic field strength as compared to each of the deterministic error parameters for each individual sensor.

Through continued research and improvement into the field of deterministic and stochastic sensor calibration, the industry will further increase access to and practicality of low-cost IMUs that can be integrated into systems that serve a variety of applications from robotics to space systems to autonomous vehicles and beyond.

APPENDIX A

DETAILED ROS SETUP

After connecting the Intel NUC and a DISI Kit daughterboard to the Teensy, connecting the Intel NUC to a power source and powering it on, and performing a remote desktop into the Intel NUC, the following steps are performed on the Intel NUC via the remote desktop on an external device to log into the ROS system, to connect the DISI Kit daughterboard to the Teensy interface, and to stream, record, and save sensor data for both the accelerometer multi-position test as well as the gyroscope rate test:

1. Open a terminal [Ctrl+Alt+T] and create three terminal tabs/windows using the “+” button in the upper toolbar.
2. In the first terminal window, run the following command: `roscore`.
 - (a) This logs into the ROS system on the device.
3. In the second terminal window, run the following command: `ls /dev/ttyACM*`.
 - (a) This shows the port of the Intel NUC that the Teensy is plugged into.
 - (b) Example terminal output: `/dev/ttyACM0`.
4. Once the correct port is known, run the following command: `roslaunch roserial_python serial_node.py _port:=/dev/ttyACM*` where `ttyACM*` is replaced with the port output from Step 3.
 - (a) This connects the device to the Teensy interface.
5. In the third terminal window, run the following command to stream IMU sensor data from the daughterboard: `rostopic echo /imu_raw`.

- (a) This begins a stream of output data that include orientation, linear acceleration, angular velocity, and covariance values for those three.
 - (b) To end the data stream, [Ctrl+C].
6. To record streamed data, first create a new folder in the desired directory. Follow these steps:
- (a) Go to the desired directory using the following command: `cd [PATH TO DIRECTORY]`.
 - (b) Create a new folder using the following command: `mkdir [NEW FOLDER NAME]`.
 - (c) To confirm a new folder was made in the current directory, run the `ls` command.
 - (d) Enter the new folder using the following command: `cd [NEW FOLDER NAME]`.
 - (e) Record the raw data to a file in the new folder by running the following command: `rosbag record /imu_raw`.
 - i. Note: The file name format will begin with the year, date, and time and end with suffix `.bag` (e.g. `YYYY-MM-DD-HH-mm-SS.bag`).
 - (f) To terminate the data recording, [Ctrl+C].
 - (g) To ensure a new file has been created in your current directory, run the `ls` command.
7. To get info on the new file, run the following command: `rosbag info [NEW FILE NAME]`.
8. To playback the data collected in the new file, run the following command: `rosbag play [NEW FILE NAME]`.
9. To print out the raw data in a text format within the terminal, run the following command: `rostopic echo -b [NEW FILE NAME] -p /imu_raw`.

10. To save the raw data from the .bag file to a .txt file, run the following command: `rostopic echo -b [NEW FILE NAME -p /imu_raw > [TEXT FILE NAME]`.
11. To transfer the raw data from the .txt file to a .csv file, create a duplicate copy of the .txt file and change the extension of the copy from .txt to .csv.
 - (a) This is done via the file manager application on the Intel NUC.

APPENDIX B

DETAILED ABB NETWORK AND NTP CONFIGURATION PROCEDURES

To begin, ensure a PC is connected to the IRC5 controller cabinet via the service port and power on the ABB IRB 120 robot arm and wait for the system to boot up. Then, in RobotStudio (written for 2021 version), follow these steps:

1. If prompted to login, select “Login as default user”.
2. In the upper taskbar, click on the “Controller” tab.
3. Click “Add Controller” in the “Access” section of the “Controller” tab in the taskbar.
 - (a) Clicking this button should automatically populate the “Controller” window on the left side of the application with the connected controller. This is verified by the matching the serial code that has populated the window to the serial code of the system.
 - (b) Clicking the dropdown menu will present a number of options. Selecting “One Click Connect...” will do the same as just clicking the original button. Selecting “Add Controller...” will bring up a list of all available controllers to select from. If only one controller is connected, there will only be one option.
4. Once the controller is added, click the “Request Write Access” button in the “Access” section of the “Controller” tab in the taskbar.
 - (a) The FlexPendant tablet presents a message saying that the PC is requesting write access. Click “Grant” to receive write access on the PC.

5. Once write access has been granted, click the “Properties” button in the “Configuration” section of the “Controller” tab in the taskbar. This presents a dropdown menu.
 - (a) Note: This button is at the bottom of the column of small buttons to the right of the “Configuration” button/dropdown.
6. Click on “Network Settings”→“Public Network” in the “Properties” dropdown menu. This brings up a new settings window.
7. Unless the network settings have already been prepared, the settings should default to automatically obtain the network internet protocol (IP) address and domain name system (DNS) server address. Follow these steps to manually set up the network settings:
 - (a) Open a Command Prompt.
 - (b) Type `ipconfig` in the command line.
 - i. This presents a series of IP Configuration information. The important information is in the “Wireless LAN adaptor Wi-Fi” section.
 - ii. Copy the “IPv4 Address” from the Command Prompt to the “IP Address” in the RobotStudio network settings window.
 - iii. Copy the “Subnet Mask” from the Command Prompt to the “Subnet Mask” in the RobotStudio network settings window.
 - iv. Copy the “Default Gateway” from the Command Prompt to the “Default Gateway” in the RobotStudio network settings window.
 - v. Close the Command Prompt.
 - (c) Click the Windows Start menu and select “Settings” to open up the Windows settings.
 - (d) Click “Network & Internet”.
 - (e) In the “Status” menu, find the Wi-Fi network that the PC is connect to. Click the “Properties” button corresponding to that Wi-Fi network.
 - (f) Scroll down to the “Properties” section.

- i. Copy the “IPv4 DNS servers” in the Windows settings to the “Preferred DNS server” in the RobotStudio network settings window.
- (g) Click “OK”.
- (h) The controller will need to restart to apply the changes to the settings.
 - i. Click “Restart” in the “Controller Tools” section of the “Controller” tab in the upper taskbar.
 - ii. Note: This restart will take away the PC’s write access. Once the system has been reset, repeat Step 4 to regain write access.
8. Once the network settings have been set, the system has reset, and write access has been regranted, click the “Properties” button in the “Configuration” section of the “Controller” tab in the upper taskbar. This presents a dropdown menu.
 - (a) Note: This button is at the bottom of the column of small buttons to the right of the “Configuration” button/dropdown.
9. Click on “Date and Time” in the “Properties” dropdown menu. This brings up a new settings menu.
10. Unless the date and time settings have already been prepared, the settings should default to some manually set date, time, and time zone. Follow these steps to configure the controller to an NTP time server:
 - (a) In the “Date and Time” window, ensure that the “Active Controller” listed matches the one connected to the PC.
 - (b) Choose a time server to connect to.
 - i. For the purposes of the gyroscope rate testing, select whichever time server the Intel NUC is using.
 - (c) Select the “Network Time” bubble in the “Date and Time” window.
 - (d) Type in either the uniform resource locator (URL) or the IP address of the chosen time server in the “Time server address” box.
 - (e) Select the correct time zone from the “Time zone” dropdown menu.

- (f) Click “Test time server”. The “Date and Time” window should close and a green progress bar should appear in the lower right corner of the RobotStudio application. When the progress bar fills and goes away, the test is complete.
 - i. Note: This step is optional but recommended.
 - ii. Note: This test tends to be more successful when configuring to an IP address versus a URL. Testing with the URL often causes RobotStudio to throw one of two errors:
 - A. “Time server test failed with error ‘No response from controller.’” This error is a test issue. Try moving onto Step 10.(g).
 - B. “Time server test failed with error ‘SYS_CTRL_E_FAIL.’” This error is a setup issue. Go back and ensure the network setup was successful.
- (g) After testing the time server, repeat Steps 8-9 again to reenter the “Date and Time” settings window.
 - i. If necessary, reselect the “Network Time” bubble, type in the URL or the IP address of the time server again, and reselect the correct time zone.
 - ii. Click “OK”. This should once again close the “Date and Time” window and a green progress bar should appear in the lower right corner of the RobotStudio application. When the progress bar fills and goes away, the configuration is complete.
 - iii. Note: The controller may need to be restarted to apply the changes to the settings. Follow step 7.(h) to restart the system.

APPENDIX C

DETAILED ROBOT ARM CALIBRATION PROCEDURES

On occasion, the revolution counters on the ABB IRB 120 robot arm require updating to better estimate the position and orientation of the robot itself. It is imperative that the revolution counters are updated prior to running any autonomous programs like the gyroscope rate testing performed for this thesis. There exist calibration markers for each axis of the robot which are used to position and calibrate the robot. The following steps are followed in order to update the revolution counters on the ABB IRB 120 robot arm:

1. Power on the ABB IRB 120 robot arm.
2. Once the system boots up, click the menu button in the upper left corner of the FlexPendant display.
3. Select “Jogging” from the options.
4. Using the FlexPendant tablet joystick, jog the robot to align each of the six axis markers on the robot as shown in [50].
5. On the FlexPendant tablet, click the menu button in the upper left corner of the display.
6. Select “Calibration” from the options.
7. Select the mechanical unit that requires calibration from the options presented. This brings up a calibration overview menu.
8. Click “Manual Method (Advanced)” in the lower left corner.
9. Click “Rev. Counters” from the options on the left. Then select “Update Revolution Counters...”. When asked whether to proceed, click “Yes”.

10. Once again, select the mechanical unit(s) that require calibration from the options presented. In this menu, multiple units may be selected. Once the desired units have been selected, click “OK” near the bottom right corner.
11. Select all the axes that require an update of revolution counters (or “Select All” in the bottom left corner). Then click, “Update” near the bottom right corner. When asked whether to update, click “Update”.
12. A progress window appears while the calibration is in progress. Wait until the FlexPendant states that the calibration is complete.

APPENDIX D

DETAILED ROBOT ARM SOFTWARE SETUP

D.1 Setting Robot Axis to Independent Joint

As discussed in Chapter 4, the gyroscope rate testing outlined in this thesis is only possible using the Option 610-1 Independent Axis software package from ABB. This software add-on allows the sixth axis of the ABB IRB 120 to be commanded to rotate indefinitely rather than being constrained to the joint movement limitations outlined in Table 4.2. After installing the software package, a few more steps are followed in order to activate the new capabilities in autonomous RAPID programs:

1. Power on the ABB IRB 120 robot arm.
2. Once the system boots up, click the menu button in the upper left corner of the FlexPendant display.
3. Select “Control Panel” from the options.
4. Select “Configuration” from the options.
5. Change the topic to “Motion” by clicking the “Topics” button in the bottom menu bar and selecting “Motion” from the options.
6. Select “Arm” from the options and click the “Show All” button in the bottom menu bar.
7. Select which axis is to be set to Independent Joint.
 - (a) Note: The ABB IRB 120 robot can only set the sixth axis to be independent.
8. Click the “Edit” button in the bottom menu bar.

9. Click the row with “Independent Joint” listed as the parameter name.
10. Select “On” from the dropdown menu.
11. Select “OK” and restart the robot to allow the changes to take effect.

D.2 Editing Independent Joint Bounds

After setting the sixth axis of the ABB IRB 120 to an independent joint, the new rotational bounds of the axis must be set.

1. Follow steps 1-7 of Appendix D.1.
2. Click the row with “Independent Upper Joint Bound” or “Independent Lower Joint Bound” listed as the parameter name.
3. Type in a new upper/lower bound for the selected axis. For the purpose of the gyroscope rate testing outlined in this thesis, the bounds upper and lower bounds can be set to something extreme such as +1000000 and -1000000 , respectively.
 - (a) Note: Units are in radians and default values are set to 0.
4. Select “OK” and restart the robot to allow the changes to take effect.

D.3 Sending RAPID Program from RobotStudio to IRC5 Controller

Autonomous programs for the ABB IRB 120 robot are written in the RobotStudio application on an external device prior to uploading to the robot itself. Once the desired RAPID program is complete, the following steps are performed to transfer the program to the robot controller:

1. Save the desired program to the external device and take note of the save location.
2. In RobotStudio, click on the “Controller” tab in the upper toolbar.
3. In the “Controller Tools” section of the toolbar, click “File Transfer”.

4. In the “PC Explorer” side of the “File Transfer” window, navigate to the save location of the desired program in the PC.
5. In the “Controller Explorer” side of the “File Transfer” window, navigate to the location in the robot controller where the program is to be saved.
6. Select the program file to transfer.
7. Click the rightward-pointing arrow to send the program file to the controller.
8. Close the “File Transfer” window.
9. To re-edit a program saved to the controller, open the program in RobotStudio, make desired edits, perform Steps 1-8 for transferring the file, and overwrite the file.

D.4 Running Autonomous Programs

Once the RAPID program is written and uploaded to the robot controller, the following steps allow the running of the program on the ABB IRB 120 robot arm:

1. On the FlexPendant tablet, enter the “Production Window” by clicking on the menu at the upper left corner of the screen and selecting “Production Window” at the bottom left of the menu.
2. To load an autonomous program to the robot, select “Load Program...” near the lower left corner of the Production Window. Then select which program to load and run.
 - (a) Confirm that the correct program is loaded by selecting the desired robot on the left portion of the screen and checking that the code for the program you selected has been loaded.
3. On the IRC5 controller cabinet, set the system to autonomous mode by turning the key to the left (i.e., counterclockwise).
4. On the FlexPendant tablet, confirm that the system has been turned to autonomous mode.

5. Turn the motors on by pressing the white light-emitting diode (LED) on the IRC5 controller cabinet. A click should sound and the light should go solid which signifies the motors are turned on.
6. On the FlexPendant Production Window, select “PP to Main” to reset the program. This is a good habit prior to every run in the off chance the program pointer is not already at the beginning of the program.
7. To run the program, click the play button among the set of white buttons to the right of the FlexPendant tablet screen. The program should begin and the pointer should work its way through the program as it progresses.

Autonomous programs have the option to run a single time or cyclically (repeat over and over until stopped). This option is changed by clicking the gears button at the bottom right corner of the Production Window (when in manual mode, this button is instead a circle with a “...” inside and also lists the robot and what axes are currently set to be jogged by the joystick) and then clicking the button that looks like blocks with a play button next to it (third option from the top).

Autonomous programs also have the option to run at fractional speeds (50%, 25%, custom speeds). This option is changed by clicking the gears button (or the “...” button if in manual mode) and then clicking the button that looks like a speedometer (second option from the bottom).

APPENDIX E

DETAILED RESULTS

This appendix includes full sets of plotted sensor data as well as linear interpolations of the data from the accelerometer multi-position testing and gyroscope rate testing outlined in this thesis. It begins with accelerometer multi-position test plots for prototype daughterboards 2 and 3 in Figures E.1 and E.2, respectively, then continues onto accelerometer test plots for revised daughterboards 05, 07, 08 and 10 in Figures E.3, E.4, E.5, and E.6, respectively. The gyroscope rate test plots follow the accelerometer test data starting with gyroscope data from prototype daughterboards 2 and 3 in Figures E.7 and E.8, respectively, then continuing onto gyroscope data from revised daughterboards 05, 07, 08, and 10 in Figures E.9, E.10, E.11, and E.12, respectively.

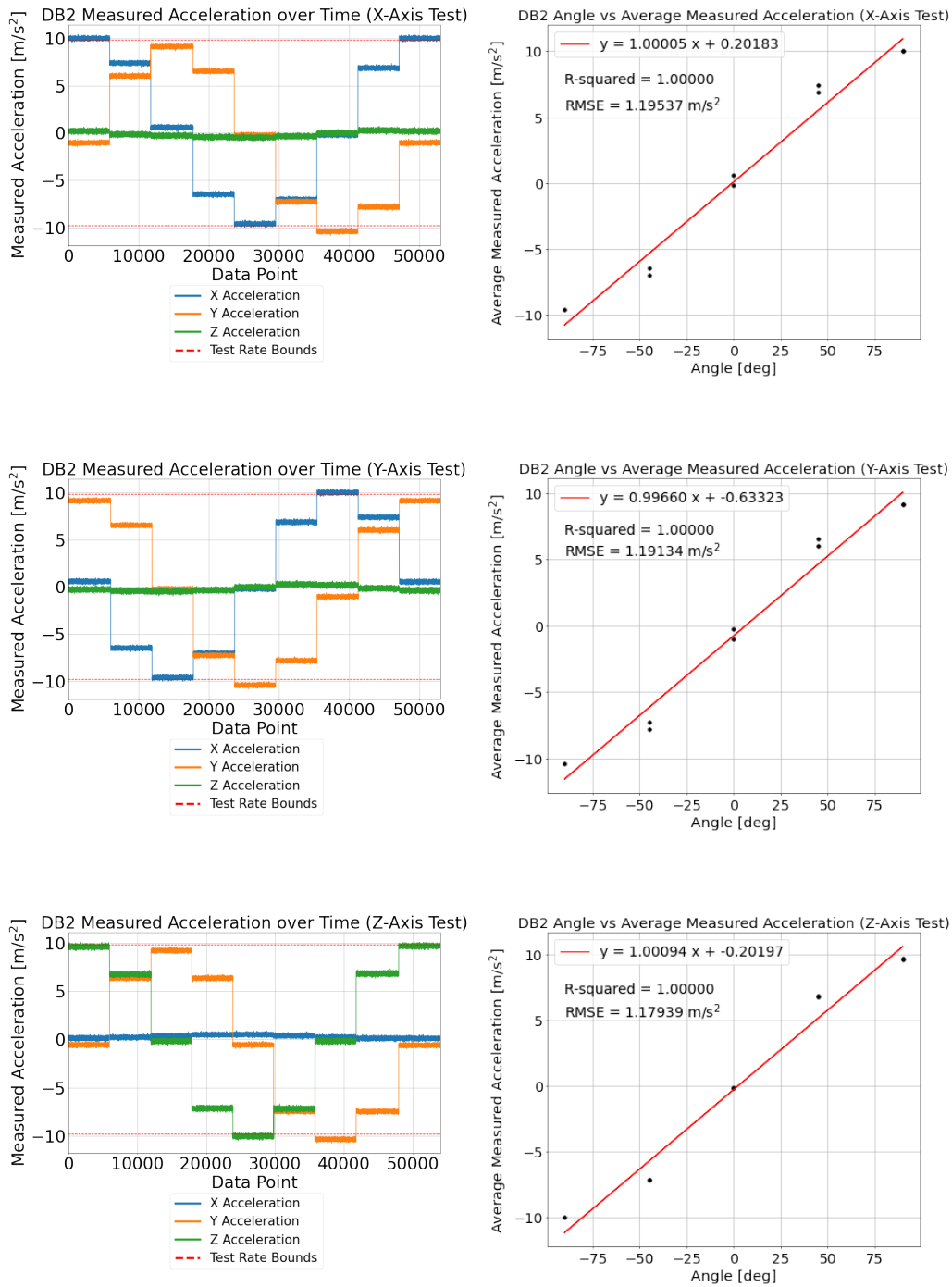


Figure E.1: DB2 accelerometer multi-position test results: The left column plots show the full dataset for each individual axis test of prototype DB2. The right column plots show the average data for each individual step of each axis test of prototype DB2 along with a best fit line representing the sensor deterministic error model for fixed bias and scale factor error.

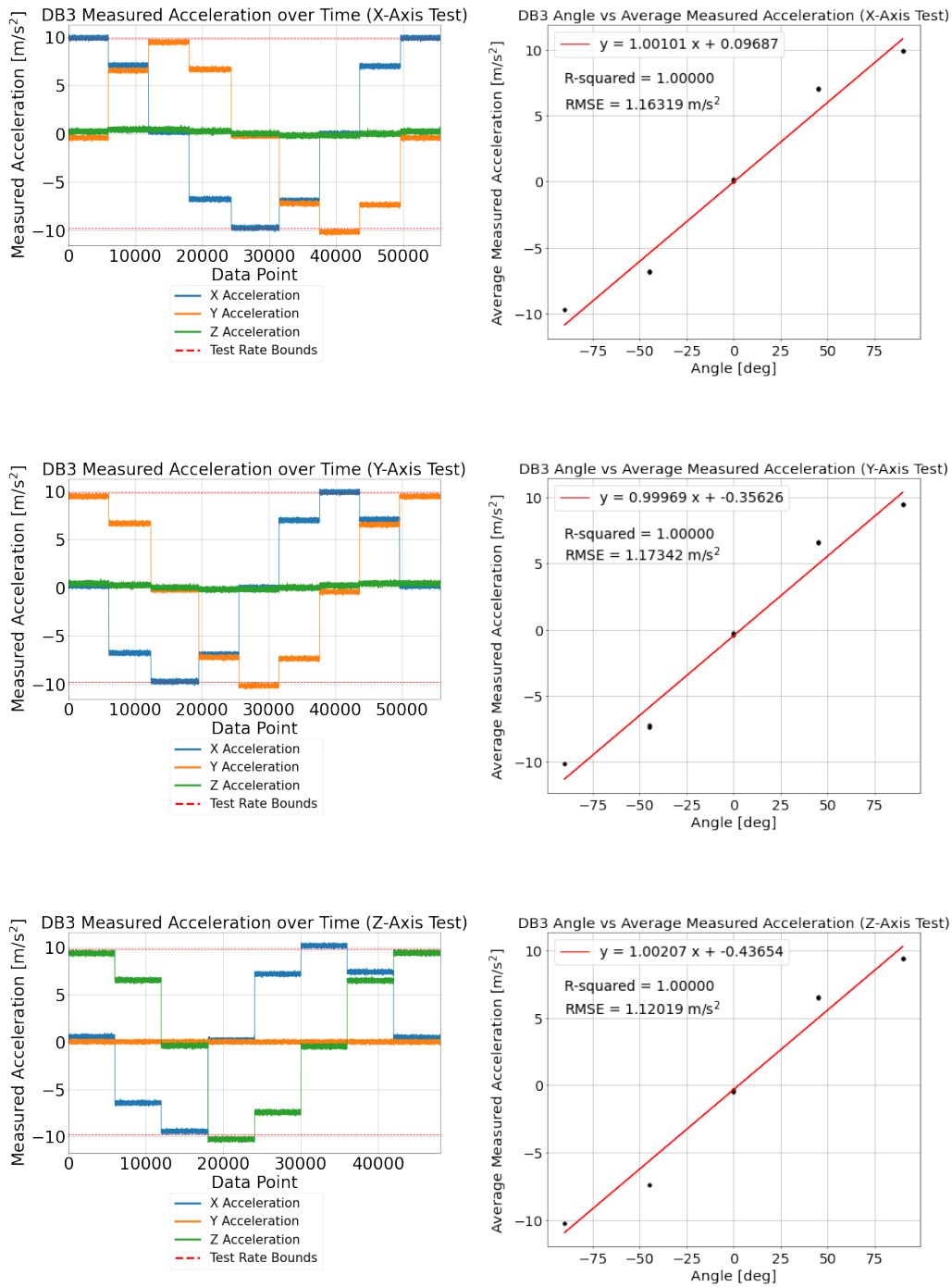


Figure E.2: DB3 accelerometer multi-position test results: The left column plots show the full dataset for each individual axis test of prototype DB3. The right column plots show the average data for each individual step of each axis test of prototype DB3 along with a best fit line representing the sensor deterministic error model for fixed bias and scale factor error.

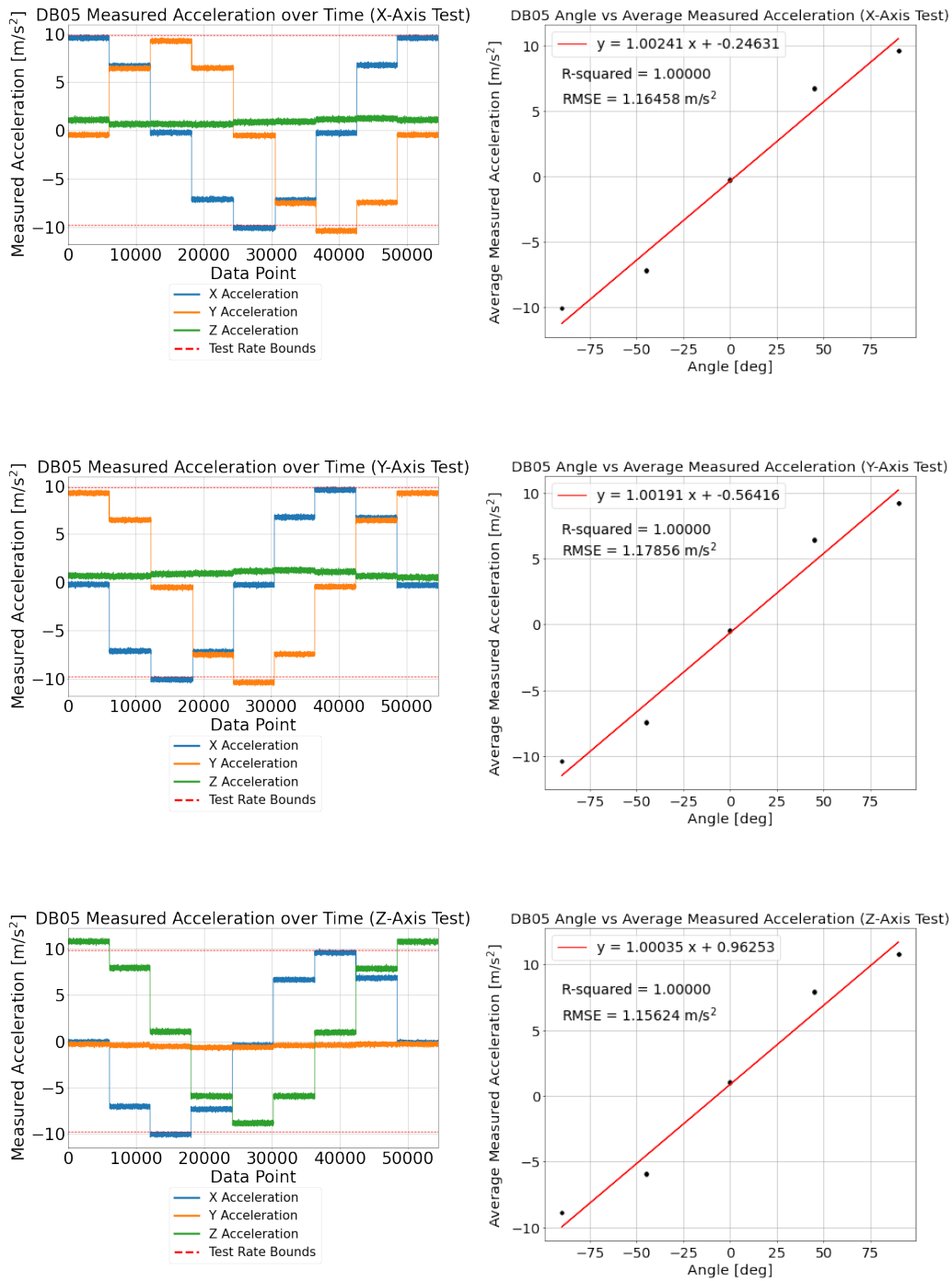


Figure E.3: DB05 accelerometer multi-position test results: The left column plots show the full dataset for each individual axis test of revised DB05. The right column plots show the average data for each individual step of each axis test of revised DB05 along with a best fit line representing the sensor deterministic error model for fixed bias and scale factor error.

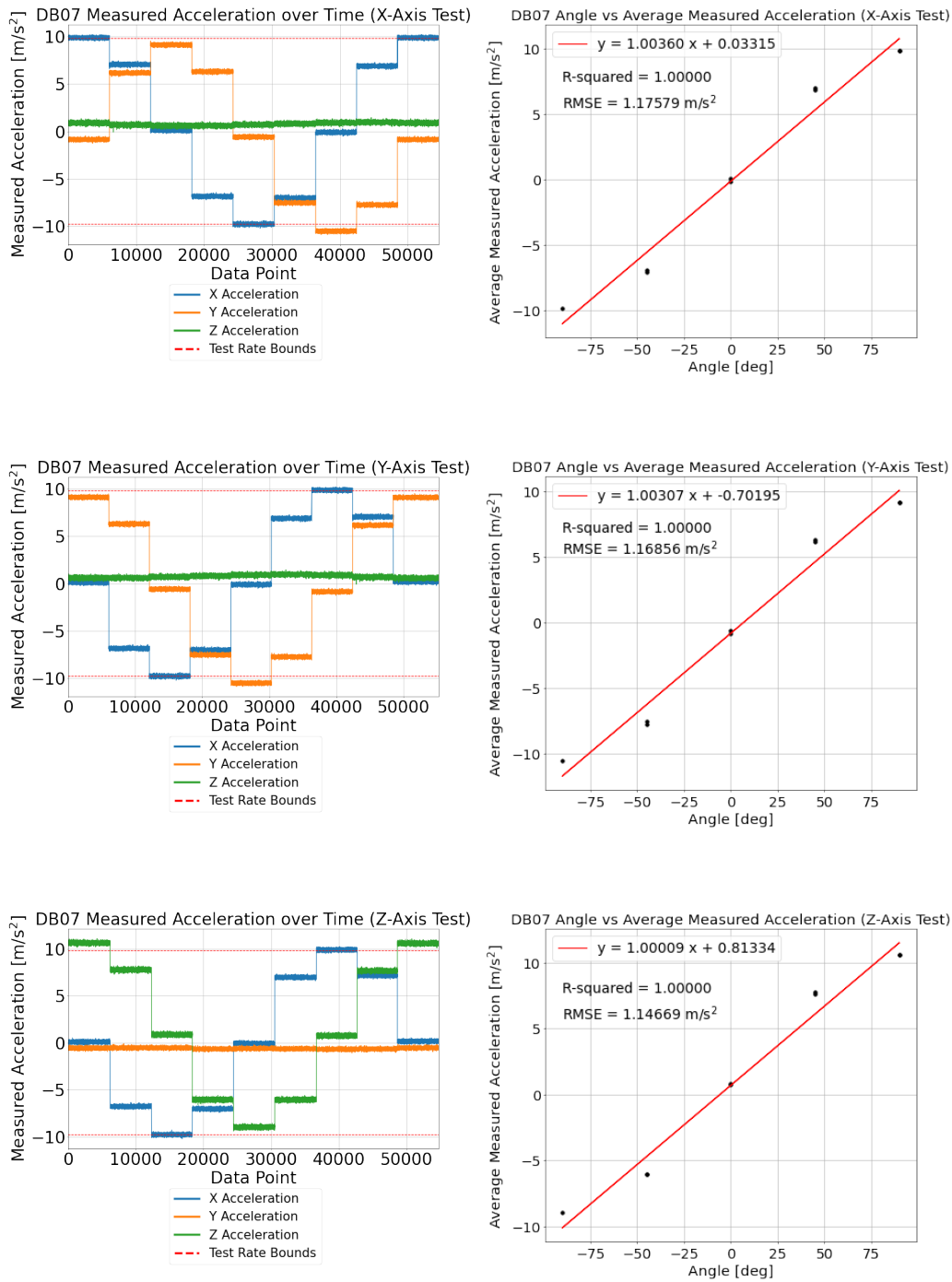


Figure E.4: DB07 accelerometer multi-position test results: The left column plots show the full dataset for each individual axis test of revised DB07. The right column plots show the average data for each individual step of each axis test of revised DB07 along with a best fit line representing the sensor deterministic error model for fixed bias and scale factor error.

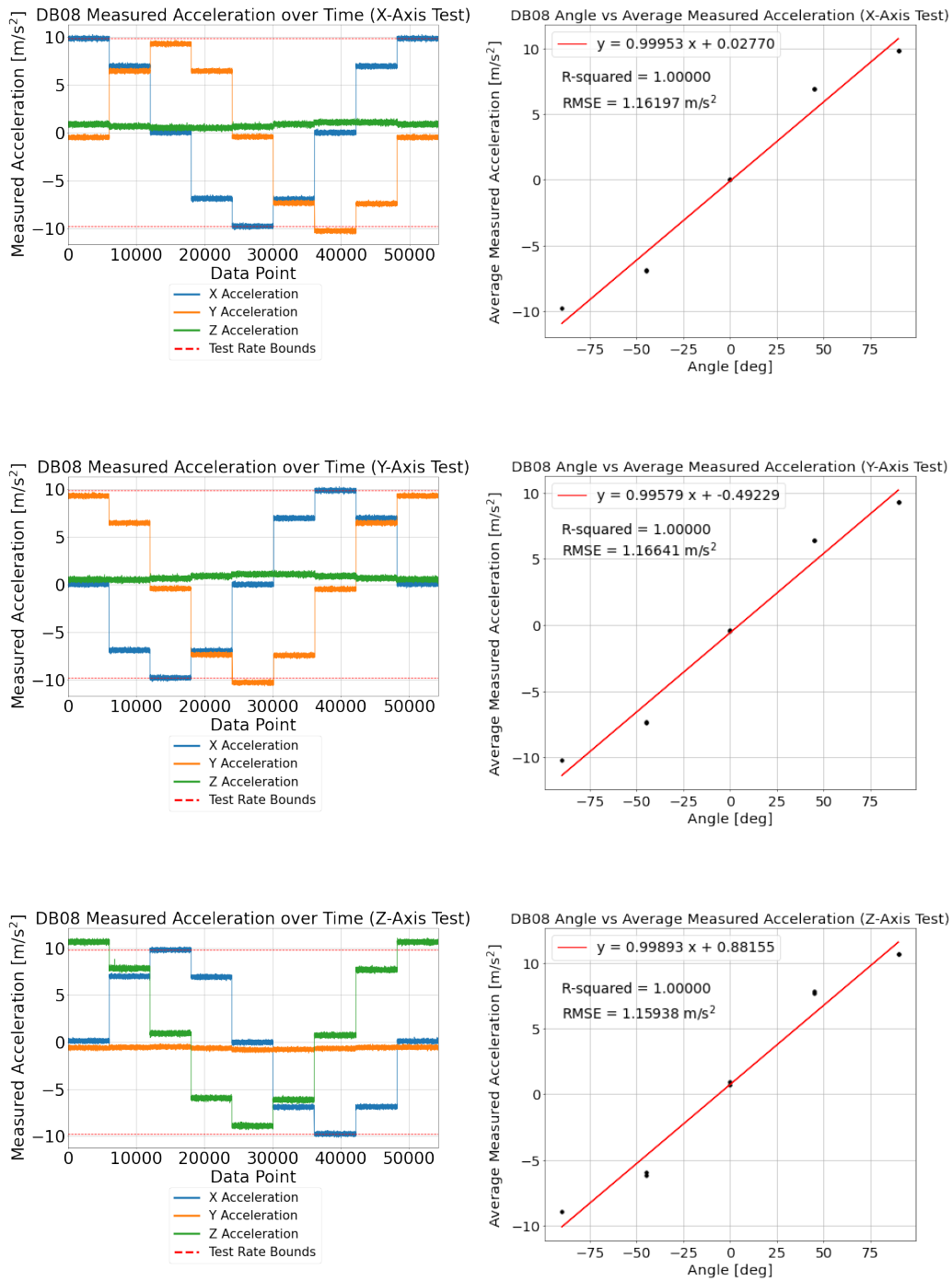


Figure E.5: DB08 accelerometer multi-position test results: The left column plots show the full dataset for each individual axis test of revised DB08. The right column plots show the average data for each individual step of each axis test of revised DB08 along with a best fit line representing the sensor deterministic error model for fixed bias and scale factor error.

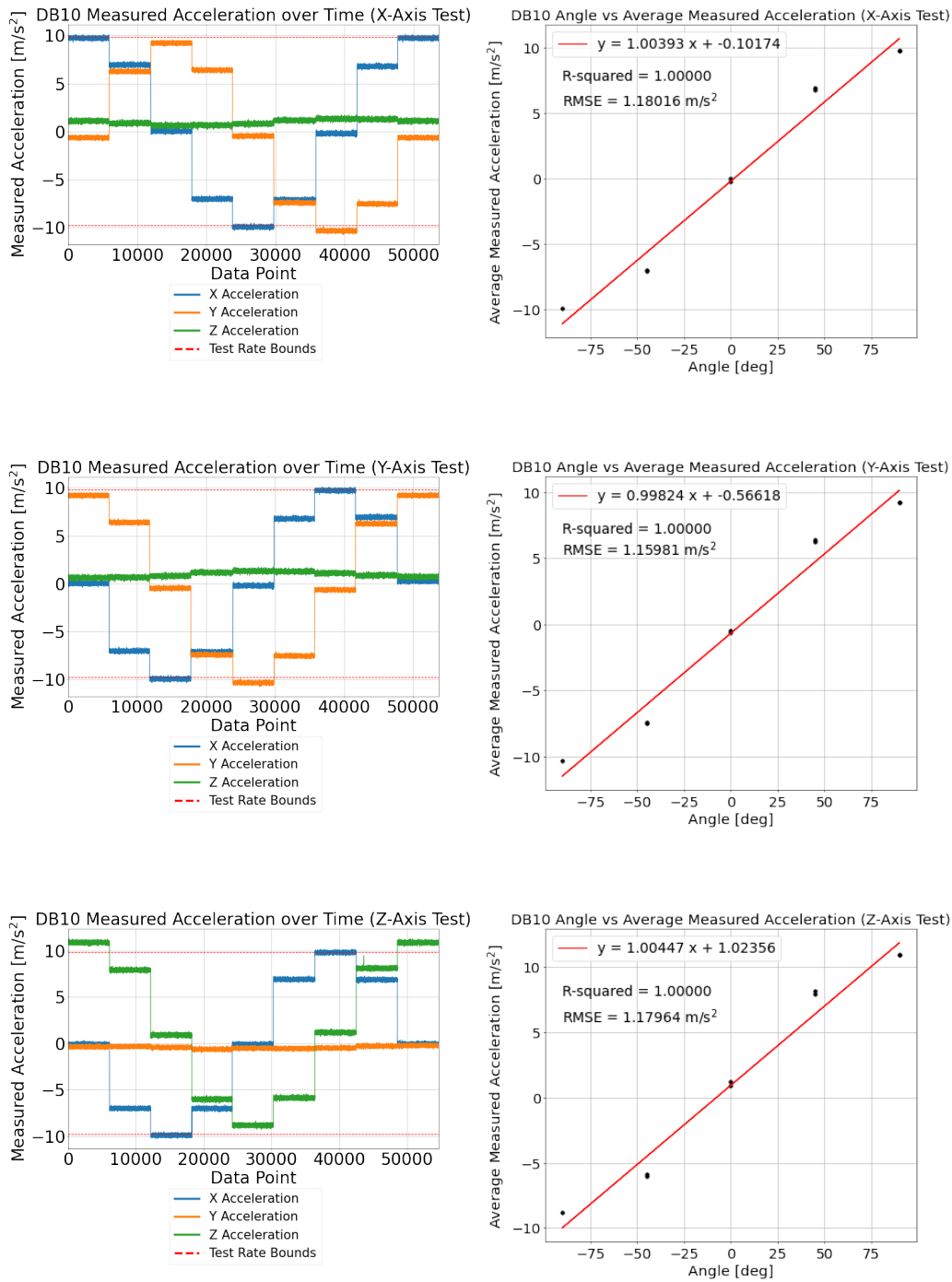


Figure E.6: DB10 accelerometer multi-position test results: The left column plots show the full dataset for each individual axis test of revised DB10. The right column plots show the average data for each individual step of each axis test of revised DB10 along with a best fit line representing the sensor deterministic error model for fixed bias and scale factor error.

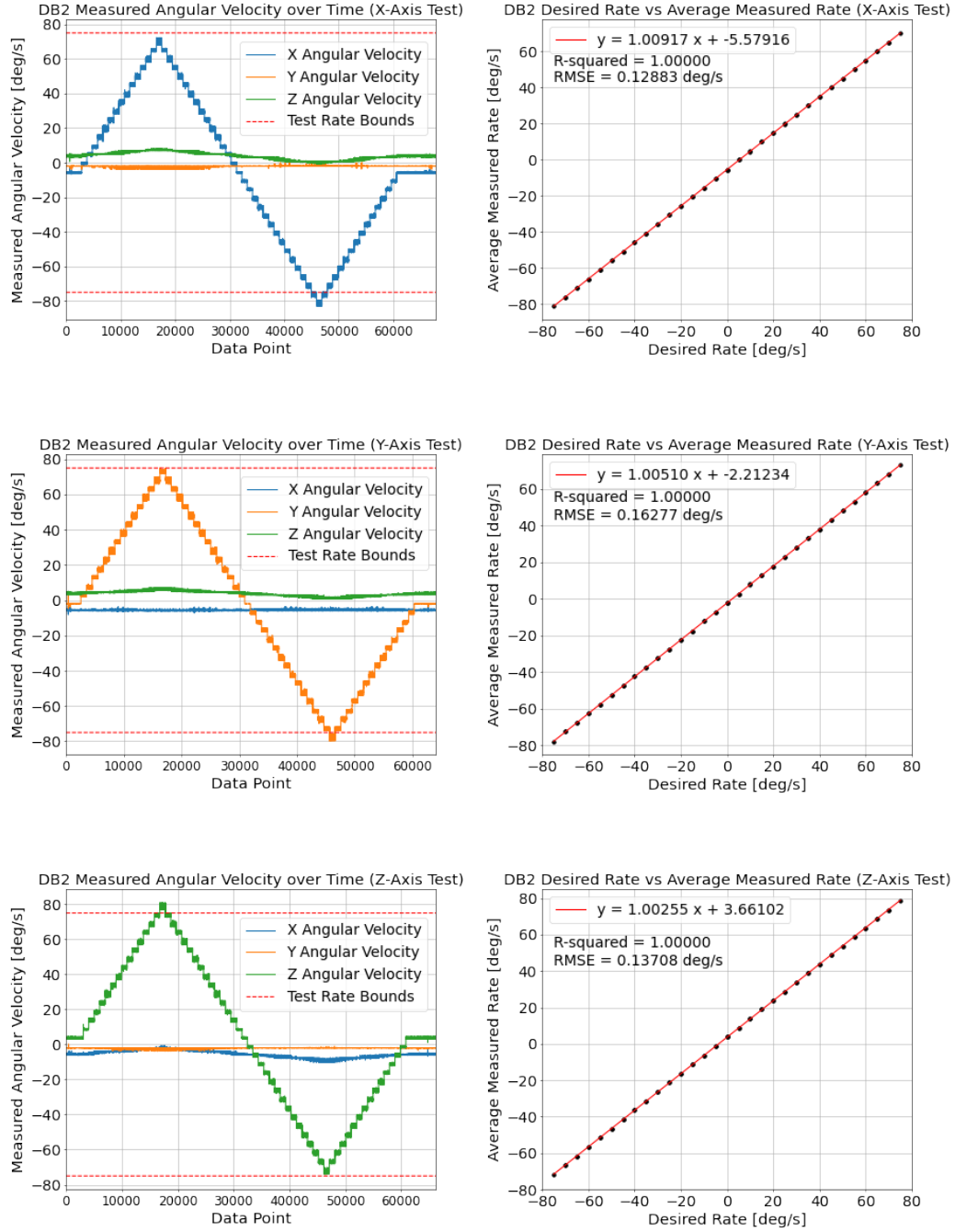


Figure E.7: DB2 gyroscope rate test results: The left column plots show the full dataset for each individual axis test of prototype DB2. The right column plots show the average data for each individual step of each axis test of prototype DB2 along with a best fit line representing the sensor deterministic error model for fixed bias and scale factor error.

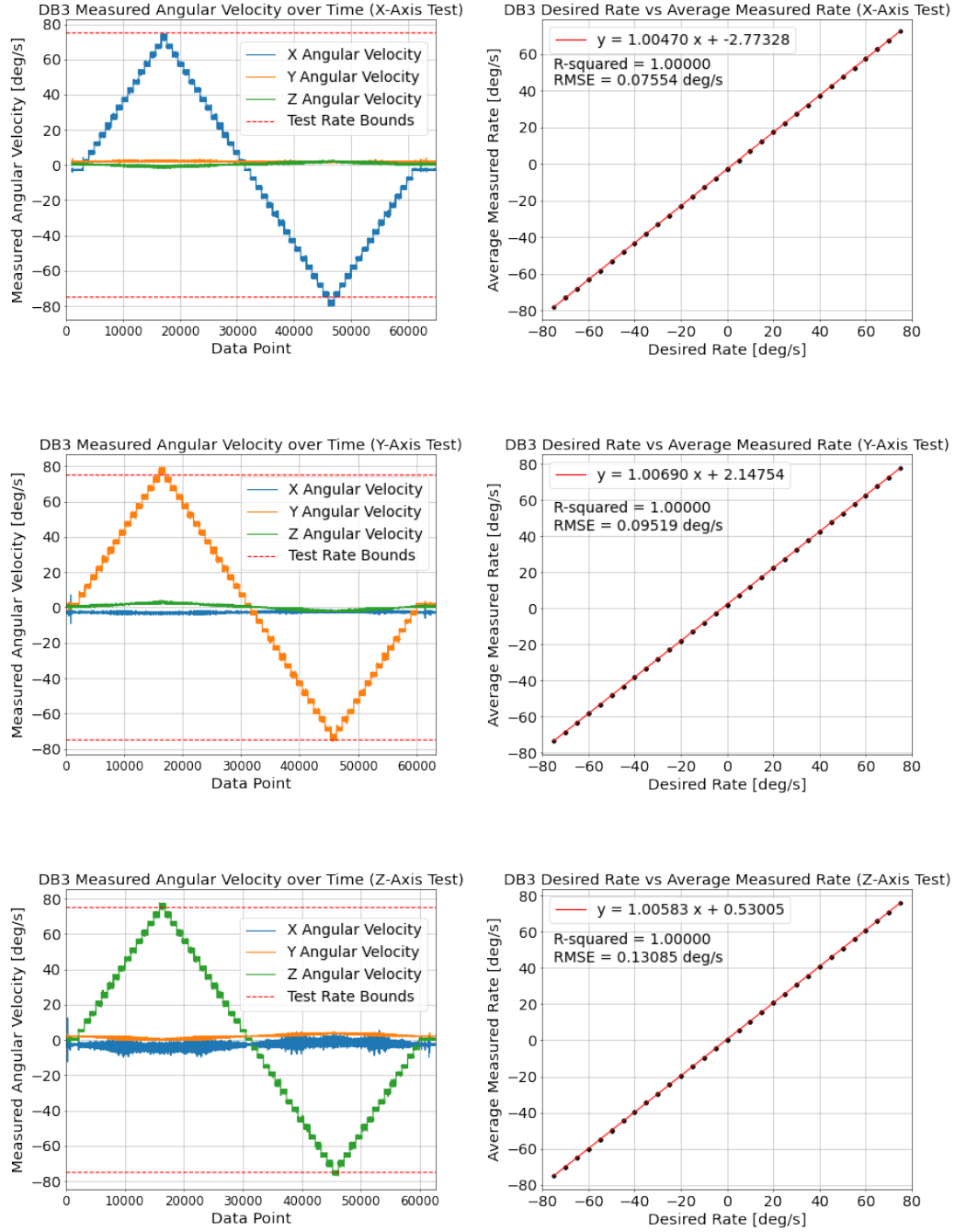


Figure E.8: DB3 gyroscope rate test results: The left column plots show the full dataset for each individual axis test of prototype DB3. The right column plots show the average data for each individual step of each axis test of prototype DB3 along with a best fit line representing the sensor deterministic error model for fixed bias and scale factor error.

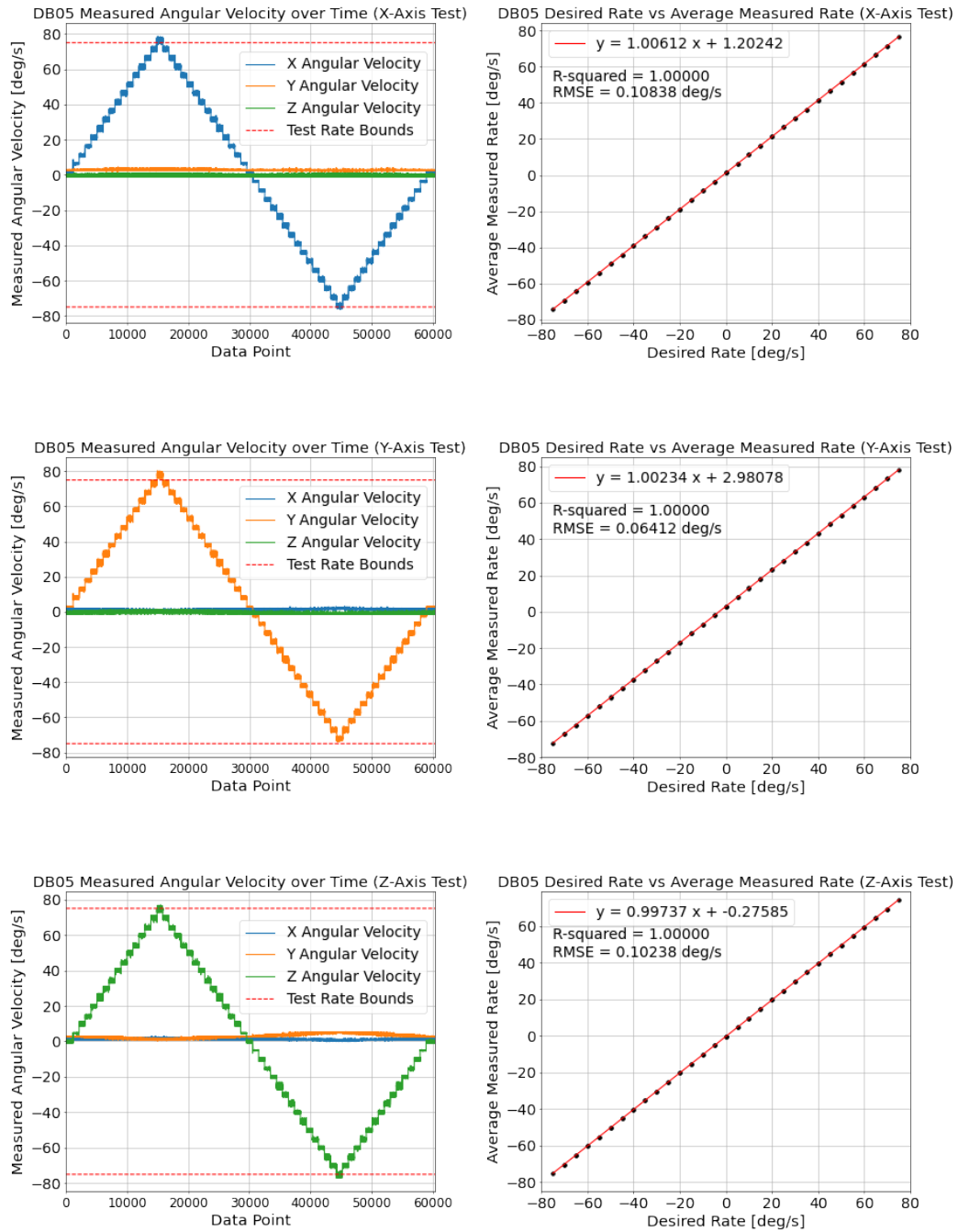


Figure E.9: DB05 gyroscope rate test results: The left column plots show the full dataset for each individual axis test of revised DB05. The right column plots show the average data for each individual step of each axis test of revised DB05 along with a best fit line representing the sensor deterministic error model for fixed bias and scale factor error.

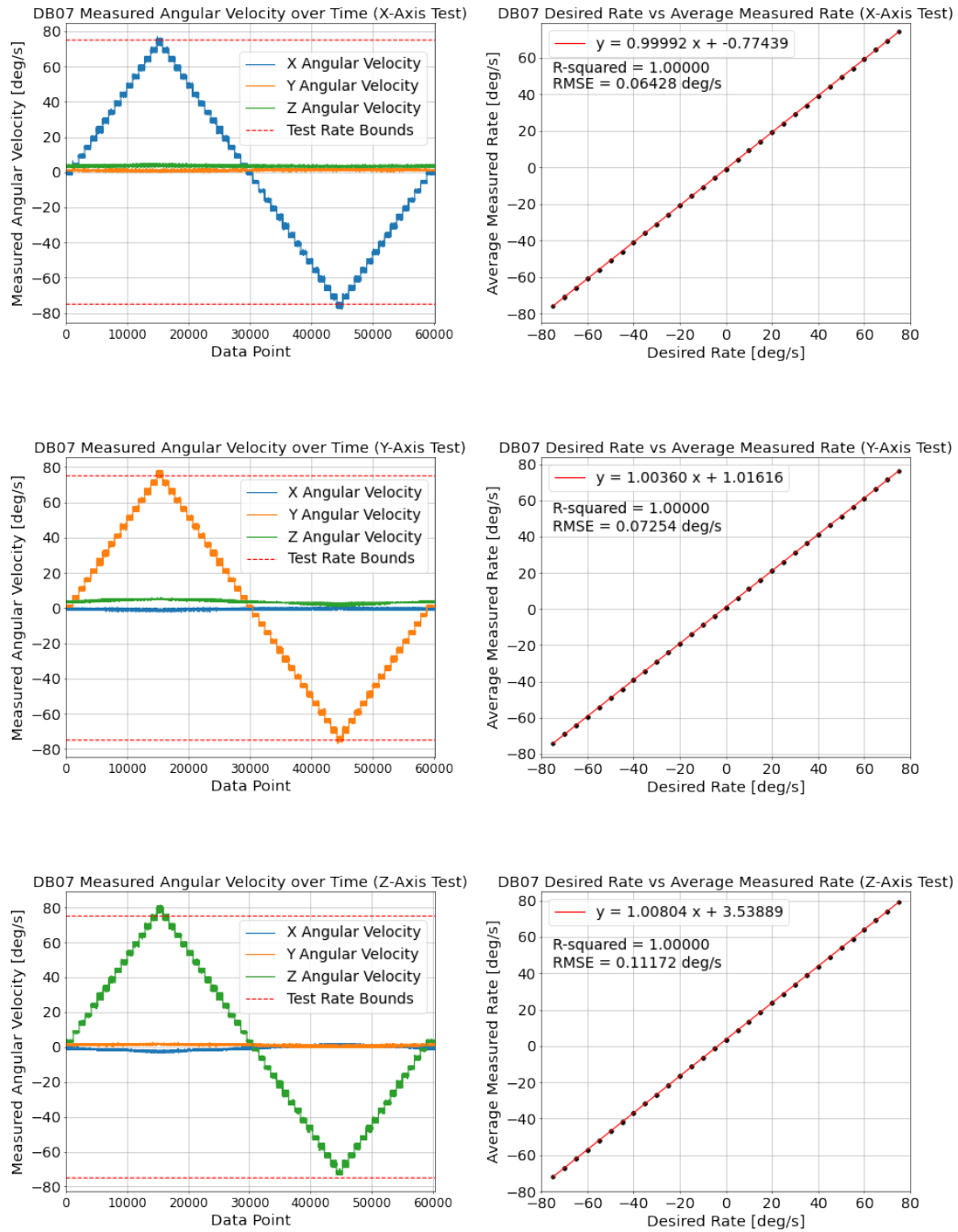


Figure E.10: DB07 gyroscope rate test results: The left column plots show the full dataset for each individual axis test of revised DB07. The right column plots show the average data for each individual step of each axis test of revised DB07 along with a best fit line representing the sensor deterministic error model for fixed bias and scale factor error.

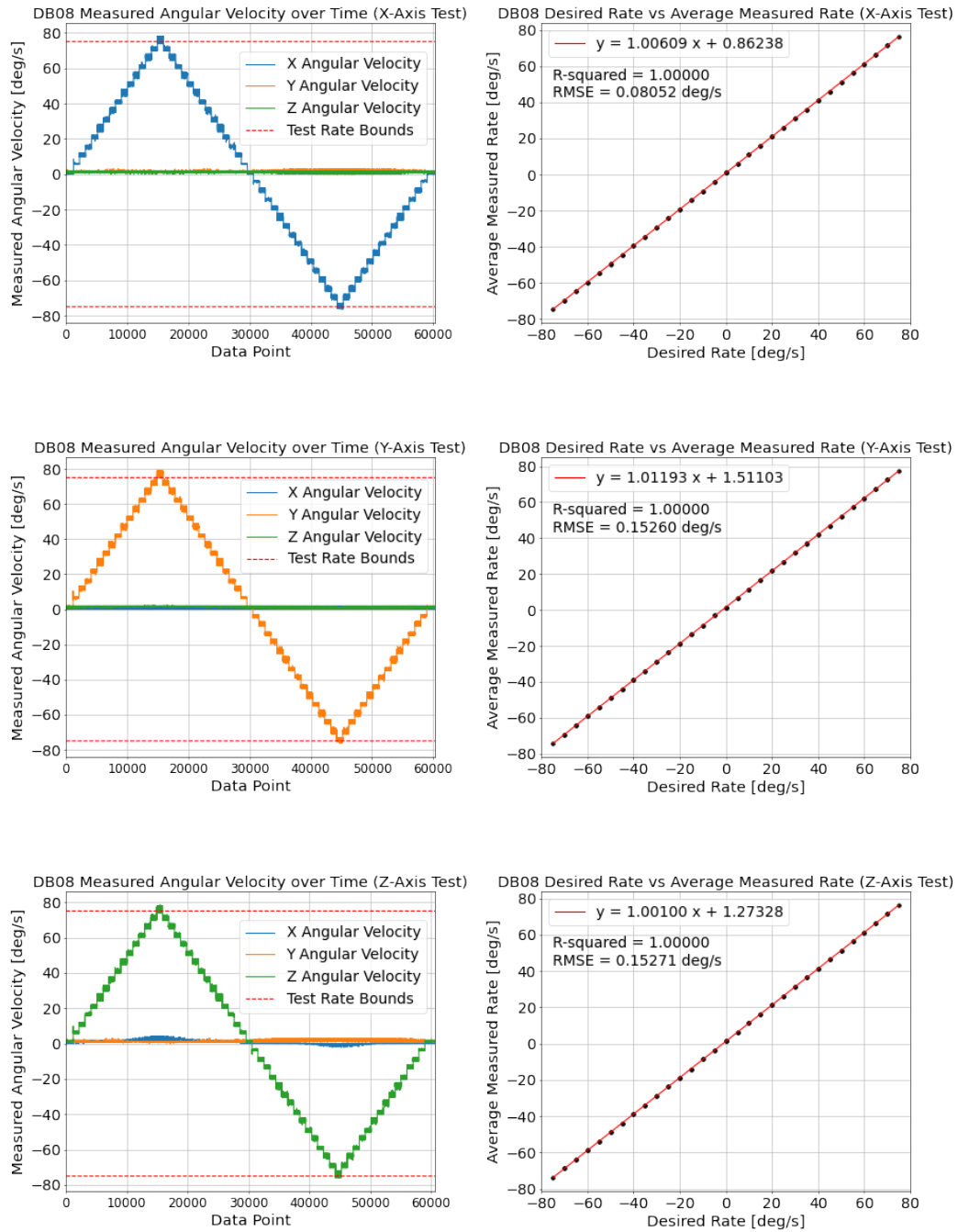


Figure E.11: DB08 gyroscope rate test results: The left column plots show the full dataset for each individual axis test of revised DB08. The right column plots show the average data for each individual step of each axis test of revised DB08 along with a best fit line representing the sensor deterministic error model for fixed bias and scale factor error.

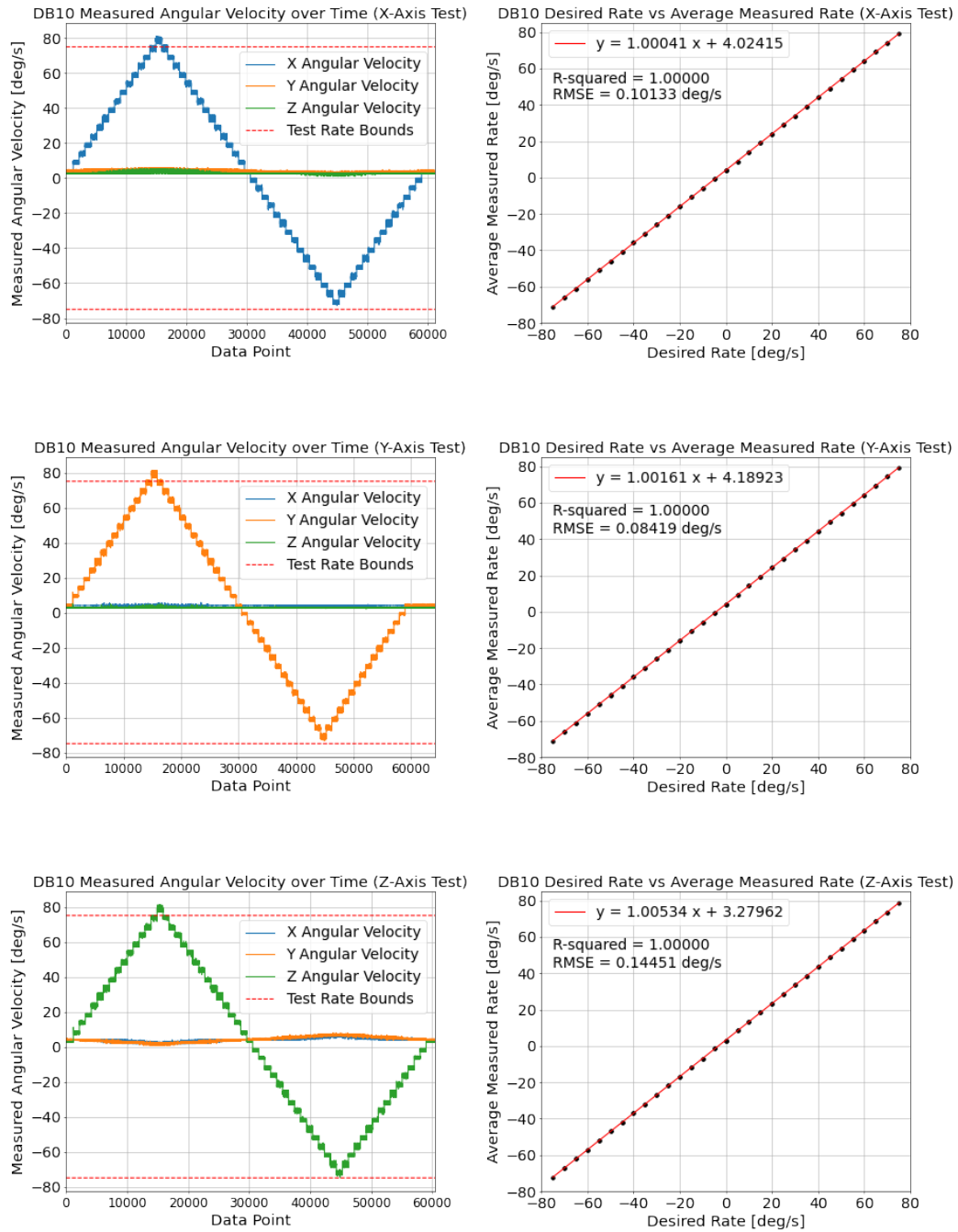


Figure E.12: DB10 gyroscope rate test results: The left column plots show the full dataset for each individual axis test of revised DB10. The right column plots show the average data for each individual step of each axis test of revised DB10 along with a best fit line representing the sensor deterministic error model for fixed bias and scale factor error.

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