Test Bench for Monitoring and Control of Linear Axis Degradation Using Sensor-based Metrology

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Abstract

Machine tool linear axes are widely used in the industry for positioning the workpiece or tool. During usage the guideways will degrade and this will lead to inaccuracies in positioning. The current procedures to diagnose the magnitude of these inaccuracies and calibrate the systems are expensive and time consuming. This report presents a preliminary study of geometric error inducement in feed drive systems and presents concepts of how to induce these errors, it also investigates the possibility of error detection for stacked errors through an inertial measurement unit.

Preface

We want to thank Gregory Vogl and Andreas Archenti for enlightening discussions and for laying the foundation for this project.

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Team I am μ

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Nomenclature

Abbreviations

Abbreviation	**Description**
AC	Alternating Current
CCC	Cross Coupling Controller
CNC	Computer Numerical Control
CMM	Coordinate Measuring Machine
DC	Direct Current
DOF	Degrees of Freedom
EDM	Electrical Discharge Machining
FLC	Fuzzy Logic Controller
IDS	Inertial Displacement Sensors
IMU	Inertial Measurement Unit
ISO	International Organization for Standardization
MEMS	Micro Electronic Mechanical Systems
NC	Numerical Control
RPM	Revolutions Per Minute
TCM	Tool Condition Monitoring
TUR	Test Uncertainty Ratio
ZPETC	Zero Phase Error Tracking Controller

1 Introduction

Machine tools that depend on multi-axial feed drive systems are often used with high loads and frequent usage during their functional lifespan. Material fatigue, abrasion or adhesion will eventually cause degradation and this will affect the precision of the tool [Li et al., 2014]. To counteract the degradation of the CNC-machines visual inspection and preventive maintenance like calibration are done [Uhlmann et al., 2008].

In order to recalibrate the feed drive system today ball bars, cross grid encoders, and laser interferometers are used to measure the geometric errors [Xu et al., 2016]. This is often not cost effective since the machine must be taken of the production line during the calibration. Instead, if these errors would be measured and corrected autonomously it would lower production costs and prolong the life of the machine.

1.1 Background and Objective

This report is done as part of the Mechatronics Advanced Course, a project course given in the spring of 2016 and continuing in autumn. The project is done in collaboration with Royal Institute of Technology (KTH) and National Institute of Standards and Technology (NIST) and is a continuation of a study by Vogl et al.. The study investigates the error detection for one axial feed drive system using an IMU [Vogl et al., 2015].

The project is divided into three phases: (1) Building a two axis test bench with the possibility to introduce errors, (2) Development of a sensor-based measurement instrument, (3) Conducting uncertainty analysis and construct error budgets of measurements. The test bench should meet the requirements in Appendix A.

The project's primarily focus is building the test bench, i.e. the first two phases. The problem can be condensed to, (1), how to introduce geometric and repeatable errors in a two axis feed drive system? And (2), how to measure these errors?

The objective of this report is to do preliminary research of how to induce repeatable stacked errors in the biaxial feed drive system and if they are possible to detect using an IMU and present the error inducing concepts.

1.2 Scope

The long term vision of the project is to develop a self-diagnostic and calibrating system for machine tools. This report is aimed to make the preliminary research on the subject and is limited to the construction of a two axis feed drive system, construction of an IMU, inducing artificial errors to the feed drive system and detecting these errors through an IMU. The actual correction and recalibration of the specific hardware will be excluded in this report.

2 Theory

In building a test rig a lot of components are needed, these components are often used in multiaxial machines such as CNC machines, 3D printers or CMM. This section introduces the necessary theory and components needed to build a test bench, as well as the basic concepts behind machine tool errors and how they affect the machined parts geometric and dimensional accuracy. The choice of components will affect the options of error inducement.

2.1 Test Bench

2.1.1 Guideways

Linear Rolling Guideways

To achieve a linear moving motion between the carriage and the guideway, rolling elements such as balls or rollers can be placed in either the carriage or the guideway. With this setup, high positional accuracy can be achieved with minimum driving force required since the contact between carriage and guideway is a rolling contact which reduces friction [HIWIN, 2013]. By applying an appropriate preload to the system the space between the rolling elements can be reduced which increases the stiffness and rigidity of the system [Shaw and Su, 2011].

Ball bearing elements are more applicable in high velocity applications due to their lower frictional resistance. However the load distribution on roller bearings is a line rather than a point as with ball bearings, which means that the roller bearing elements have a higher load capacity [NTN Corporation, 2001].

Different configurations of the rolling elements can be used to further enhance the characteristics of the rolling elements in linear motion guideways. For example, recirculating units can be used to increase the stroke length of the carriage and achieve further travel lengths. The bearing elements are placed in the carriage rather on the guideway, so a limited number of bearing elements can achieve a longer travel length of the machine tool.

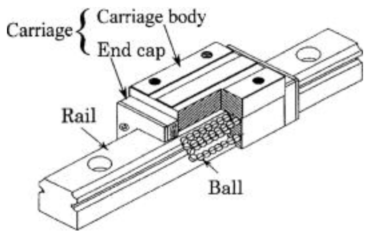

Figure 2.1. Recirculating ball bearings in a carriage.

The recirculating motion is achieved when the bearing elements that temporarily rolls on guideway come in contact with an endcap placed in the carriage, were the bearing elements circulating direction is forced to reversed and fed back into the carriage (see Fig. 2.1). With recirculation the rolling elements have constant lubrication as they are fed back into the carriage and thus increase the service life of the feed drive system. The rolling elements are contained and sealed within the carriage which reduces the chance of dust entering the rolling elements which eventually lowers the systems accuracy [Schaeffler Group, 2007].

With crossed roller bearings in the guideway, the rollers are placed in a crisscross pattern in the guideway to ensure a long contact length between the rollers and the carriage which gives a high rigidity in the system and less elastic deformation in the bearing element. Since the rollers are placed in the guideways itself, the stroke lengths of the carriage is limited by the lengths of the guideway [THK, 2007].

Hydrostatic Guideways

In the hydrostatic guideways the surface of the platform and rails are separated by cells that are pressurized with thin oil. Since there is no direct contact between the platform and rail the stick slip and static friction is eliminated. The guides have several cells that usually have different pressure in them to be able to handle varying operating conditions. To pressurize the cells one pump is used in combination with restrictors to give the cells different pressure. The hydrostatic guideways used to be expensive and hard to install but recently manufacturers have developed a new kind that is based on the standardized dimensions of the rolling guideways. This new version offer high precision, better damping for high dynamic rigidity and is more cost-effective than its predecessor [Altintas et al., 2011]. This new kind has a chamber system inside the platform that is charged with hydraulic oil. The oil is fed to the pressure sider under continuous pressure filling the pressure cells. Integrated chokes are set so the pressure in the cells is uniformly distributed. The unpressurised oil is extracted from the chamber system and is fed back to the oil circuit (see Fig. 2.2, [Schaeffler Technologies, 2015]).

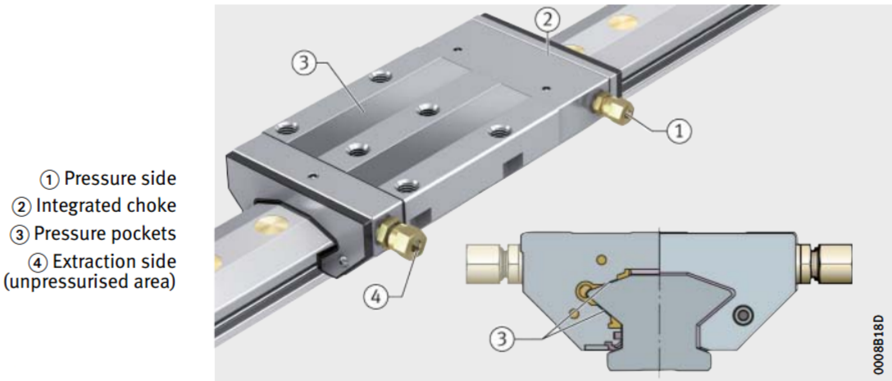

Figure 2.2. Functional parts of the compact hydrostatic guideway

2.1.2 Motors

Electrical motors can run either on AC or DC power and translates alternate or direct current into rotational or linear motion. They come in a number of various designs, to cover all would be beyond the scope of this report but there are three main categories. Brushless DC, brushed DC and induction, or asynchronous, AC motor. They all rely on forces produced by a magnetic field between the stators and a rotor, and the means of producing this magnetic field is what makes them differ from each other.

Brushed DC

The brushed DC motor is usually designed with permanent magnets in the stator and with windings in the rotor that change polarity as it turns using a mechanical commutator. The brushes of the commutator is subject to wear and require periodic replacement and the thermal efficiency is typically around 75%. The cost of a brushed DC motor is low and it is relatively easy to model for control purposes as it displays a linear relation between torque and current as well as voltage and RPM which makes the controller inexpensive as well [Gamazo-Real and Gómez-Gil, 2010]. However the windings in the rotor makes heat removal difficult and commutator arcing is a problem at high voltages, this limits the applications and it is therefore most commonly used in smaller low power and low end products [Krishnan, 2009].

Brushless DC

The brushless DC motor commonly uses permanent magnets in the rotor and change the polarity in the stator by running a current in the windings. This eliminates the need for a mechanical commutator and the motor is thus less susceptible to wear. Changing the current in the stator to produce forces betweeen the rotor and the stator at the correct time requires more complex control. This can be done with analog hardware or digitally with software and a microcontroller in combination with encoders to read rotor position. This improves commutation efficiency as well control performance. The brushless motor have several advantages over the brushed DC, including higher torque per watt as well as torque to weight ratio leading to higher efficiency, typically around 90% [Krishnan, 2009]. Increased reliability, reduced noise, longer lifetime, less electromagnetic interference and easier heat reduction due to the heat generating parts being located on the outside of the motor. This comes at a substantial cost increase as well as a more complex control implementation.

Induction AC

An induction or asynchronous AC motor is run by alternating current. The rotor usually consists of windings in which a current is induced by the stator. The stator consists of windings in which the alternating current creates a rotating magnetic field, which creates forces to drive the rotor. They can come in both three phase as well as single phase configuration with the single phase typically being used for smaller loads and may have a fixed rotation direction. Although traditionally used in fixed speed applications, thanks to the advancement of control theory and variable frequency drives they are increasingly used in varible speed service. The efficiency is around 85% up to 97% and it has low wear as a result of the lack of mechanical commutators. The motor itself is relatively cheap but the need of inverters to handle the AC current adds some cost. The heat removal is relatively easy as most heat will be generated in the stator windings located on the outer part of the motor, but due to the induced currents in the rotor it may be required to cool it in high power applications. Modeling for control purposes is complex, and the control can consist of changing the frequency to control the speed as well as regulating the voltage or current of the supplied AC to control the torque. Varying the frequency is the most common way to control the motor and can be done to a high precision [Cheng et al., 2011].

Linear Motors

Linear motors have a lot of advantages, they have high precision, high speed and high acceleration, because of this they are becoming more prevalent in the industry, especially when high accuracy and precision is needed [Wang and Xi, 2008].

The principle of a linear motor is the same as an AC or DC motor but the motor is unfolded. It is possible to reach sub-micron precision with linear motion [Brandenburg et al., 2000]. Since there is no need to convert rotary motion to linear motion the friction is reduced, which reduces noise and increases the precision. Because of the lack of centrifugal force the speed is in theory unlimited and greater than in rotary motors [Hu et al., 2013]. Some disadvantages is the cost associated with linear motors, compared to rotary motors and ball screws it is more expensive [Olarra et al., 2009].

2.1.3 Rotary Encoders

A rotary encoder, or shaft encoder, is an electro-mechanical device that converts the angular position or motion of a shaft or axle to an analog or digital code. The most common type are optical encoders, which consist of a light source and a sensor that are placed on opposing sides of a disc with sectors that are either transparent or opaque. These will produce pulses of light when the disc is spinning which are measurable. In incremental encoders the pulses of lights are counted and by knowing the amount of pulses per revolution the rotational velocity is derived. In absolute encoders the disc have specific pulse patters depending on which rotation the disc currently has [Wilson, 2005].

2.1.4 Software

In feed drive machines today many different types of control algorithms are used. The choice of which algorithm used are based on how fast your system should be and how accurate the modeling of the system is. Errors that will occur through software is position errors along the axis and contour errors. Where the latter is the error perpendicular to the reference trajectory toward the actual position. In order to minimize the errors in the system, feedback control is used. For low speed and low friction feed drive systems a proportional controller could be enough. Often a more advanced PID or state space controller is used in the industry. In this report the feedback control theory will not be explained further and will be assumed as previous knowledge. For feed drive systems that require more accuracy or have a higher complexity, control algorithms like different feedforward or cross-coupling controllers can be used. It should be acknowledged that there are multiple types of control algorithms that are used in this field that are not mentioned in this report, such as optimal control, adaptive control and robust control. These are more rarely used in industry and are considered to be less likely to be used in the project.

Feedforward Controllers

A feedforward controller is a controller that predicts the system or subsystem response in order to calculate the input for a desired output. This can often make the system faster but will require low model errors. There will always be model errors and to reduce them a feedback controller must also be implemented in conjunction with the feedforward controller. In general there are two different types of models for feedforward controllers [Koren and Lo, 1992].

- Trajectory control, where a feedforward part is the inverse of the plant and the control input is the sum of the output from the feedback controller and the feedforward controller. This will then make the feedforward controller only dependant on the plant thus making the design of the two controllers seperate to each other.

- Feedforward controller where the controller is the inverse of the total open loop system making the controller dependant on the feedback controller.

There are many examples of how to design the latter for feed drive systems. Zero Phase Error Tracking controller (ZPETC) is a methodology to control non-minimal phase systems [Tomizuka, 1987].

Cross Coupling Controller

Cross coupling controllers (CCC) is a method specific for biaxial systems and was first proposed by [Koren, 1980]. This method is a way to minimize the contour error for nonlinear and corner paths by taking the error for each axis to alternate the control signal. For usual feedback systems the computer predefines a path for each axis and does not take the the position error for the other axis in consideration. By using the cross coupling controller the input signal of each axis will also be affected by the contour error with a weighting factor W,

$$U_i(n) = E_i(n) + WE(n). \tag{2.1}$$

Where $U_i(n)$, in is the control signal at instance (n) for the ith axis, $E_i(n)$ is the position error for the ith axis at instance n and $E(n)$ is proportional to the contour error at instance (n). This example envolves a simple proportional controller with gain factor 1 for the position errors but can of course be combined with a more complex PID controller.

This system requires no extra hardware compared to regular feedback systems and improves the performance by controlling the system as a single unit rather then separate control loops in conjunction [Shih et al., 2002].

Fuzzy Logic Controller

FLC is a more robust way of generating the output and might be better for feed drive systems that have large friction disturbances than feed forward systems or the more traditional feedback systems. This controller have been suggested to be used in conjunction with the cross coupling controller with some success [Yeh et al., 1997].

The main advantage with fuzzy logic is that it can be used for very complex systems where a precise model cant be achieved. FLC has been used in CNC-machines mostly to adjust the feed rate in the cutting process where there is degeneration of the cutting tool [Kim and Jeon, 2011].

The basic principle of fuzzy logic is to derive the controller input through probability analysis of the sensor data. This can than make complex systems have a less deterministic output given a specific control system.

2.2 Geometric Errors in Linear Axes

Geometric errors in machine tools lead to performance degradation, which affects the final geometric and dimensional accuracy of machined workpieces negatively. These faults account for economic losses up to tens of billions of US dollars per year [Vogl et al., 2015]. Thus, this is an area that has been widely researched.

In a three-axial CNC–machine there are 21 geometric error sources in every direction that directly affect the accuracy performance [Caballero-Ruiz et al., 2007]. Errors can be classified into three levels: volumetric errors, axis motion errors and geometric errors, where volumetric and axis errors are the source of geometric errors.

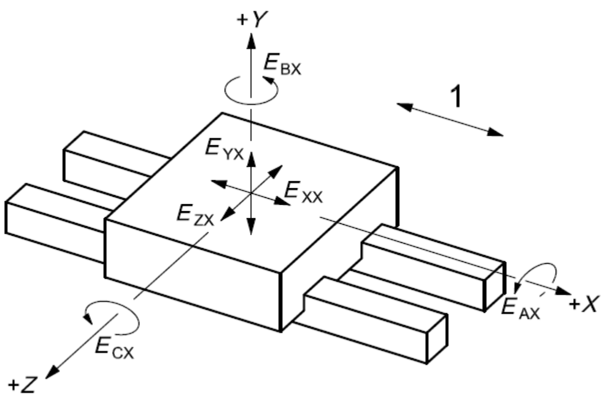

Figure 2.3. Angular and linear error motions of a component commanded to move along a (nominal) straight-line trajectory parallel to the X-axis.

The different errors shown in Fig. 2.3 are due to many error sources. Among others, the most important causes of errors are: of kinematic errors, thermo-mechanical errors, loads, dynamic forces and motion control and control software [Schwenke et al., 2008].

One of the objectives of this project is to develop a sensor-based measurement instrument in order to monitor linear axis degradation in feed drive systems. This knowledge could be very useful for the industry since more automated and efficient methods are needed to self-diagnose the condition of a machine as well as to plan its calibration.

Axis degradation leads to translational (straightness) and angular errors (see Fig. 2.4), so the measurement instrument is expected to identify these deviations. According to the ISO 10791-2 standard the acceptable straightness error is limited to 20 μm and the angular error is limited to 60 μrad (for linear axis of vertical machining centers).

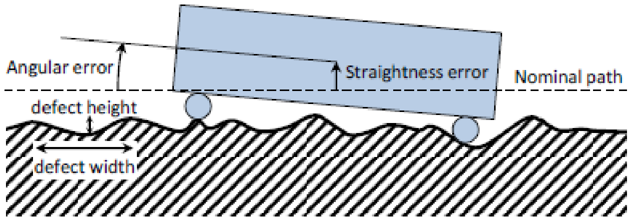

Figure 2.4. Schematic of effect of linear axis degradation on axis motion (courtesy: Gregory W. Vogl, NIST).

In order to measure these errors, the measurement uncertainties must be less than the specified tolerances. Vogl et al. recommends a TUR of at least 4:1 (5 μm of straightness error uncertainty and 15 μrad of angular error uncertainty) but a TUR of 10:1 or 100:1 would be desired (Table 2.1).

TUR	Straightness Error Uncertainty	Angular Error Uncertainty
4:1	5 μm	15 μrad
10:1	2 μm	6 μrad
100:1	0.2 μm	0.6 μrad

Table 2.1. Measurement uncertainties for straightness and angular errors based on TUR values.

3 State of the Art

This chapter discusses the state of the art of what is considered the key problems in this project. This is determined to be how to create repeatable and controllable errors in feed drive systems and how to identify them with an IMU. Then, this is followed by a short discussion on how to compensate for these errors.

3.1 Geometric Error Generation

Vogl et al. introduced errors in three different ways. The first way was to raise the rail using shims; this error will simulate the low spatial frequency degradation of a machine tool [Vogl, 2016].

To simulate the high frequency errors Vogl et al. took out the balls from one of the trucks and introduced errors to them by removing material from them [Vogl, 2016]. Vogl used the same technique to introduce the error on all of the balls so the size of the errors where roughly the same. Between the tests he took out all the balls again adding one additional error on all of the balls in a random location. The reason for this is to simulate how the errors increase over time. An other way that Vogl introduced errors was by deforming the rails using a punch to add small dents that the trucks would roll over to create high frequency errors.

It is possible to simulate degradation in the physical machine tool testing system by inducing geometric errors in the feed-drive system. This can be accomplished by changing the geometric characteristics of the system by grinding away small parts of the carriage itself. A method to analyse this is by examining the vibration and acoustic emissions while running multiple carriages with different sized artificially made defects on a linear guideway with recirculating ball bearings [Ohta et al., 2010]. Research has been conducted regarding this subject by comparing six carriages with different defects with a reference carriage with no defects. The carriages run over a guideway at constant linear velocity of 1 m/s and the vibrations and acoustic emissions were analysed by an accelerometer and acoustic emission sensor. The defects in the carriages showed an increase of vibrations and acoustic emissions.

This was not caused by the depth or the length of the defects, but the defect angle [Ohta et al., 2010].

In a study by Verl et al. a test bench with an error was needed, they introduced the errors by using at least one worn out part. To introduce an error that is similar to the real ones that occur over time in a reasonable time they accelerated the wear progress by adding abrasive material to the lubrication [Verl et al., 2009].

3.2 Geometric Error Detection

As discussed previously, a measurement instrument and a sensor based method is needed in order to study the degradations phenomena in linear axes of machine tools and to be able to help manufacturers to plan maintenance, production and improve part quality in an automated way.

Several attempts have been made using different sensors and methods but their success has been limited. One suggestion utilizes a sensorless method to monitor mechanical degradation by executing predefined excitation cycles in order to identify typical disturbances, such as pittings and backlash on the guideways [Plapper and Weck, 2001]. Another makes use of a motor torque sensor to monitor the status of the translational axes [Li et al., 2014]. Feng and Pan have studied the relation between ball screw preload variations and vibrations in the machine parts, which are identified by some accelerometers [Feng and Pan, 2012]. Another attempt has been made by Garinei and Marsili to detect defects in ball screw actuators through a Hall effect sensor [Garinei and Marsili, 2012]. And Biehl et al. have also tried to measure the preload in ball screw drives but with a piezoresistive thin film sensor [Biehl et al., 2012].

TCM systems are systems that monitor the condition of the machine tool. They do not determine the exact position, instead they work by monitoring the wear and tear in order to avoid tool breakdown [Rehorn et al., 2005]. A variety of sensors have been used in research some of which could be could be used in error detection. Acoustic emission sensors have been used to measure the contact between the work piece and the tool [Kumar et al., 2010]. In one study, capacitance sensors were used to measure geometric errors in a miniaturized machine tool [Lee and Yang, 2005]. Capacitive sensors in combination with laser interferometry have also been used to measure all the geometric errors in a three-axis machine tool [Lee et al., 2016].

The characteristics of the sensors used limited the success of these experiments. On one hand, built-in sensors usually have a high accuracy but it is difficult to place them close to the tracked mechanical components. On the other hand, external sensors, such as laser interferometers, give very good results but they are very expensive and the cost associated with does not make it worthwhile.

In conclusion, a cost-effective and flexible tool that can diagnose the state of a machine tool in a short period of time is needed. For all these reasons, an IMU is proposed as the measurement instrument. Even if it may not have seemed possible to use an IMU for this application in the past, the development of these sensors under the last years have made them viable for high accuracy and low noise purposes.

3.2.1 Inertial Measurement Unit

An IMU is a device for measuring three axis acceleration, angular turning rate and sometimes magnetic field around its body. Its construction consist of a combination of accelerometers, gyroscopes and occasionally magnetometers, in a single package. The data gather ed from these sensors can be used, after fusing the different measurements, to estimate velocity, position and orientation.

IMUs have traditionally mainly been used in inertial navigation systems of aircrafts, spacecrafts, missiles and drones. However, the development of MEMS under the last years have made it possible to use these sensors in many other different areas, such as, manufacturing, robotics, sports, medical rehabilitation or augmented reality [Ahmad et al., 2013].

For example, Godha and Cannon propose to integrate a GPS with a low cost IMU for land vehicle navigation with the aim to reduce GPS constraints and improve positional accuracy [Godha and Cannon, 2005]. Another application is suggested by Won et al. who use an IMU to keep track of a fastening tool and to identify fastened bolts [Won et al., 2009]. Ciuti et al. took advantage of different MEMS to monitor, sense and give feedback to users about their health status, as well as information during physical activities [Ciuti et al., 2015].

Regarding the objective of the project, IMUs have also been used in feed drive systems of machining tools. Vogl et al. have developed an instrument (formed by individual accelerometers, gyroscopes and inclinometers) and a sensor-method to estimate the condition of a linear axis with the aim to identify linear axis degradation [Vogl et al., 2015]. Liao and Lee (2009) have also studied machine performance degradation in a chiller system with the aid of 6 accelerometers and a fixed cycle test procedure [Liao and Lee, 2009].

As discussed before, it is essential to select an appropriate IMU to meet the high-end requirements of this project and to be able to identify geometric errors in the scale of micrometers. Due to this it is necessary to further investigate the possible IMU errors, their effects and how to minimize them.

The market of inertial measurement sensors is very wide both in terms of performance and price. Depending on similar performance classes they can be classified in different grades: Navigation or Marine grade, Tactical grade, Industrial grade and Automotive or Consumer grade. Table 3.1 gathers typical performance parameters for different IMU grades.

IMU Grade	Accel Bias (mg)	Accel noise ($mg/\sqrt{Hz}$)	Gyro Bias ($°/h$)	Gyro Noise ($°/h/\sqrt{Hz}$)
Navigation	0.01-0.1	0.005-0.01	0.001-0.01	0.002-0.005
Tactical	0.1-1	0.2-0.4	0.01-1	0.2-0.5
Industrial	1-10	N/A	1-100	N/A
Automotive	>10	N/A	>100	N/A

Table 3.1. Typical Accelerometer and Gyros Bias and Noise for Different IMU Grades. Table modified from previous works [Groves, 2013, Gebre-Egziabher, 2004].

In most of the low cost IMUs, the accelerometers and gyroscopes are manufactured as MEMS. These are made of relatively small structures, which are manufactured using silicon or quartz. They have many advantages, such as; small size, low power consumption, low weight, robust construction, short start-up time, high reliability and are appropriate to operate in hostile environments.

Liu et al. discuss that it is complicated to make MEMS-based accelerometers based on common technologies (piezoresistive, piezoelectric and capacitive) with enough sensitivity and resolution for applications that require accuracies below the micro-g. Instead they suggest a micro-machined accelerometer which takes advantage of a tunneling transducer to feature micro-g resolution [Liu et al., 1998].

However, MEMS sensors can still be used in applications where accuracy in the range of micrometers is needed for short periods of time, as it can be seen in the works of Spiewak et al., who have conducted several experiments to characterize, identify and attenuate errors for different accelerometers [Spiewak, 2005, Spiewak et al., 2013].

3.2.2 Methodology

The biggest problem associated with accelerometers and gyros is their big drift, this becomes even more significant if the position is estimated by integrating the acceleration twice or estimating the angular position by integrating the angular speed due to a non zero mean getting amplified, this might result in an increasingly bad measurement with time. Spiewak (2005), argues that they are not suitable for static or quasi-static measurements, so it results complicated to use them as the only measuring system [Spiewak, 2005].

There are two main approaches to deal with this problem, one consist of using one or several secondary sensors to overcome the disadvantages of the IMU by fusioning the different sensors data with the aim of having a combined final measurement that is better than each individual sensor reading. The second approach consist of using the IMU for short periods of time in order to limit the sensor drift.

A lot of research has been done regarding the first method and it has been proven to give satisfactory results for many applications. The idea behind it is to collect data from multiple sensors and to execute an algorithm, such as a Kalman filter or an extended Kalman filter, to fuse the data. For example, Godha and Cannon, (2005) propose the use of a Kalman filter to fuse the data of an IMU with a GPS [Godha and Cannon, 2005]. This method allows to improve the GPS accuracy while the IMU drift problem is reduced because the Kalman filter is used to estimate its bias. So it boosts the advantages and lowers the disadvantages of both sensors allowing the final setup to achieve an accuracy in the range of centimeters.

However, when it is not possible to utilize a secondary sensor or a higher accuracy is desired, others methods might be used. As discussed before, Vogl et al. developed a sensor based method to estimate the state of linear axes machine tool degradation by collecting data from three accelerometers, a tri-axial gyroscope and two inclinometers [Vogl et al., 2015]. Vogl et al. use the gyro signal to get angular errors by integrating them once and accelerometers to get translational errors by integrating them twice. In addition, inclinometers were used to get low frequency angular errors.

Vogl et al. performed several fixed-cycle tests where one axis is moved its entire travel length at different constant speeds (0.02 m/s for slow speed, 0.1 m/s for moderate speed and 1 m/s for fast speed). This is done to compensate for the different bandwith and noise properties of the sensors used and to be able to identify different spatial frequencies. In addition, this method takes advantage of the enhanced signal-to-noise and lower sensor drift at faster speeds, while taking advantage of the detection of higher spatial frequencies at slower speeds. After this data is collected, it is filtered, combined together and averaged to get the original geometric errors. The whole procedure can be seen in Fig. 3.1.

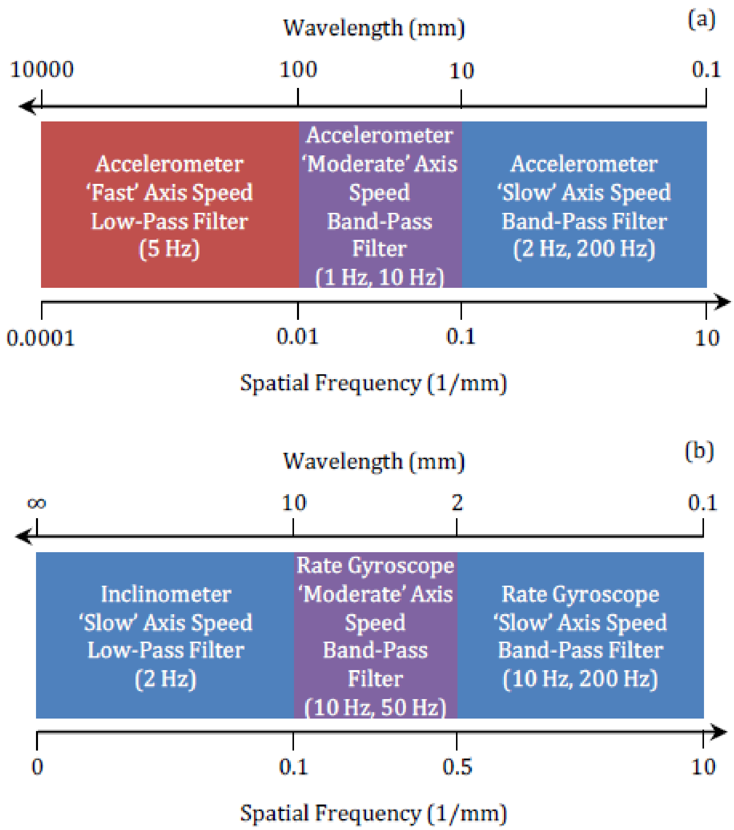

Figure 3.1. Fixed-cycle test data analysis for (a) straightness errors and (b) angular errors ([Vogl et al., 2015]).

The results from Vogl et al. show that the method is acceptable as it can achieve TURs of the given constraint of 4:1. However, the methodology is limited, the uncertainties of the errors are both due to the methodology proposed and the sensors noise. It is concluded that the limited bandwidth of the accelerometers (at low frequencies) lead to uncertainties for the straightness errors whereas the gyros noise is responsible of the angular error uncertainties.

Another approach is discussed by Spiewak, who argues that micrometer accuracy of IDS is possible during short periods of time (less than 1 second) employing commercially available accelerometers [Spiewak, 2005]. Spiewak, studied the impact of static phenomena and he considers that because of measuring by IMUs involves integration, the accuracy depends heavily on the low frequency distortions. In order to compensate for it, the static sensor noise error has been approximated by the following equation:

$$\epsilon = a_0 + a_1 t^2 + a_2 sin(2\pi t/T_m + a_3) \tag{3.1}$$

where $a_i, i = 1, 2, 3$ and Tm are empirical constants and the noise is almost sinusoidal.

In addition to this, the dynamic phenomena constitutes another important source of errors, which is mainly caused by non-linearities of the transducer and imperfections in the manufacturing. To deal with this, Spiewak, (2005) suggest to use multiple sensors and to average their output signals, attenuate distortions through different models, isolate sensors from non-essential vibrations and to use an optimal sensor design procedure. This paper also proposes a method that involves minimization of a target function which is the difference between the signals sampled and predicted by an appropriate model.

Finally, other research show that introducing sensor redundancy in the system can improve the overall accuracy since sensor failure can be identified and multiple data collection can allow to provide enough valuable information. The results obtained from Clausen et al., (2015) show that multiple low-grade IMUs can achieve a better performance than a single IMU [Clausen et al., 2015].

3.3 Geometric Error Compensation

In a three-axial CNC–machine there are 21 geometric error sources in every direction that directly affect the accuracy performance [Caballero-Ruiz et al., 2007]. The geometric errors are mostly derived from wear in the machine tools but also from built in inaccuracies and kinematic errors [Ramesh et al., 2000]. From interferometer measurements a mathematical model of the errors can be designed to act as a compensation model for these geometrical errors. The resulting error estimation can be achieved by back-propagation [Rumelhart et al., 1988]. Research regarding this subject has been conducted and an error compensation model has been successfully been implemented into a CNC-machine. The model modified the output position command of the CNC-machine by calculating the difference between the nominal position and the predicted error. The CNC-machine was run in a backward and forward direction with a error compensation model, which was later compared to an uncompensated model. The results showed a decrease in positional geometric error by 40 µm [Raksiri and Parnichkun, 2004].

The time delay introduced to the system by using error compensation has proved to be an issue. The overall volumetric accuracy is reduced if the correction signal is not updated fast enough. To work around this problem a real time computation of the compensation algorithms with a neglectible time delay is required. [Longstaff et al., 2005] used a Siemens 840D controller [Siemens, 2015] to basically run the compensation algorithms in real time by applying the compensated output during the spare cycle time from the NC processor. This compensated controller was compared to an uncompensated in a CNC-machine where the input the system was the geometric errors collected by an laser interferometer, the results showed a 97% reduction in geometric errors [Longstaff et al., 2005].

4 Proposed Solutions

This chapter describes the planned solution to the discussed problem.

4.1 Construction of Test Bench

A two axis feed drive system with multiple ways of inducing different artificial repeatable errors will be constructed. The requirements for the test bench can be seen in Appendix A. The parts used for the construction can be seen in Table B. Motors will be controlled by a PID controller with a trajectory planner. The controller shall receive a two-dimensional position command, calculate an optimal trajectory path and execute it.

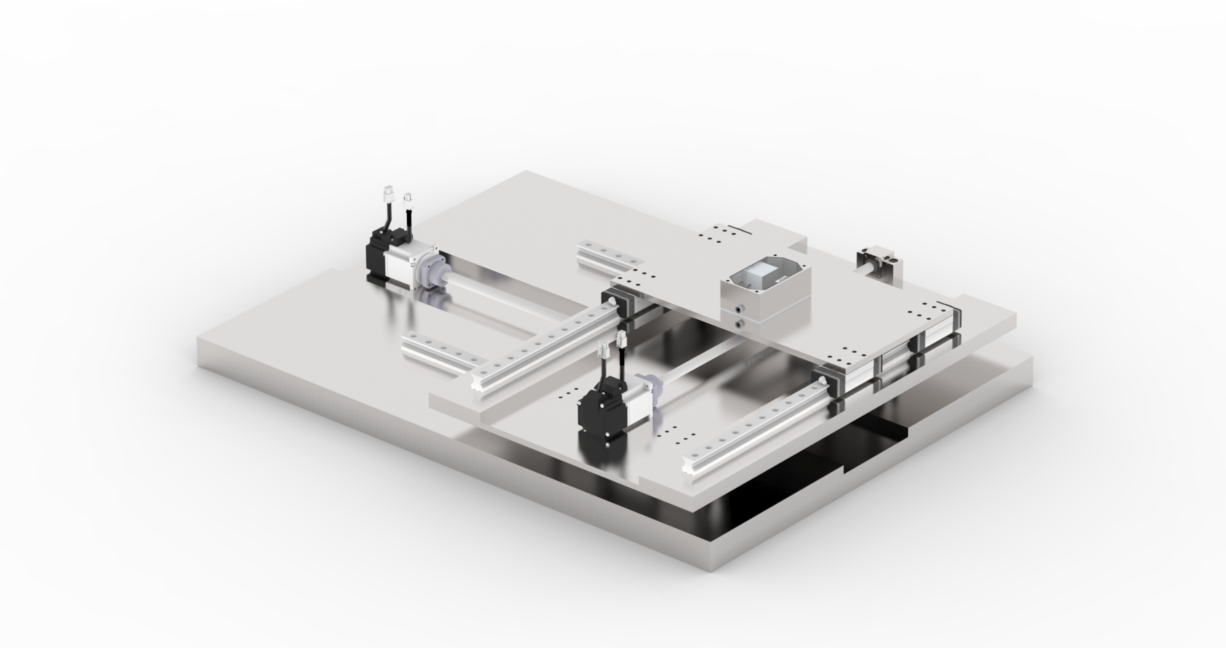

Figure 4.1. Test bench

4.1.1 Verification Tests

The test bench must be constructed with minimal misalignment. A laser measurement system will be used to verify this. A reference will be placed upon the test bench carriage, one axis will be locked and the other will be moved with small incremental steps from one end of its path to the other. In every stop the reference position will be measured. The optical laser can determine position for three axis as well as the pitch and jaw during the measurement. Feedback regarding the straightness of the measurement will be used to calibrate and rearrange the guide rails to be within specifications from Appendix A. The locked axis will be moved 0.5 cm and the test will be repeated until the whole 2D-plane has been covered. The test bench must fulfill the requirement of accuracy to be able to validate the measured results. This test will be done one axis at a time. The controller is given a known position command and shall execute it. The test bench carriage reference shall position itself with the accuracy specified in the requirements. The actual position will be measured with a laser system.

4.2 Construction of IMU

An IMU will be constructed from a triaxial gyroscope, a triaxial accelerometer and a diaxial inclinometer as specified in Table B. The components will be mounted in a custom made box that in turn will be mounted onto the test bench carriage (see Fig. 4.2). The signals will be sent to the controller and a monitoring computer and interpreted there.

4.2.1 Specifications

The IMU's requires very low bias noise but only a small operating range. Recommended components [Vogl, 2016]:

Gyroscope

- Range of $\pm 100°/sec$.
- Bias stability $4°/hour\ 1\sigma$.
- Bias due to temperature $< 0.05°/sec\ 1\sigma$.

Accelerometer

- Range of $\pm 2g$.
- Sensor resolution $0.001°/sec$.
- Frequency response 0-400 Hz $\pm 1dB$.

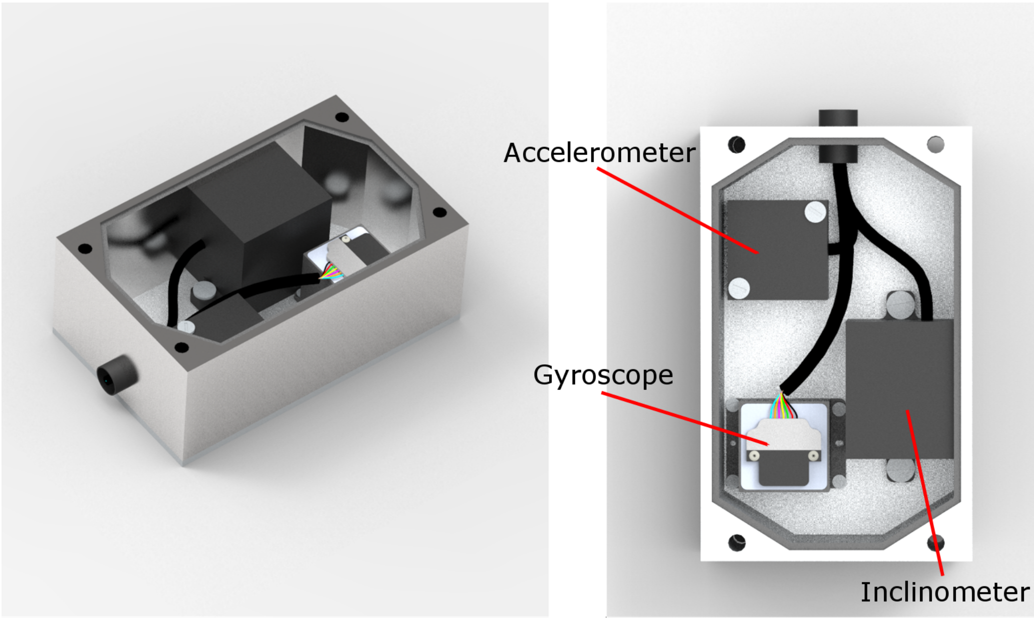

Figure 4.2. The IMU

4.2.2 Verification Tests

Accuracy

The IMU must be able to measure deviations as specified by the requirements. This test assumed the existence of a reference measurement done by with a laser measurement system which will be done prior. The mounted IMU will perform the same movement as the reference measurement and shall report a similar enough result.

4.3 Error Inducement Concepts

Real world errors can be anything from microscopic chipping creating high frequency errors to the entire guideway being bent from for example overload creating low frequency errors. It will be necessary to attempt to simulate the full range of these errors as realistically as possible. A number of possible concepts have been developed for the chosen test bed configuration. Some of these concepts could be combined with each other whereas others will require a separate test bed set up, the important part is to have both high, medium and low frequencies represented.

4.3.1 Concept #1 - Indenting the Rail

By indenting or scratching the surface of the guideway where the rollers travel it's possible to simulate errors. Depending on the size of these indentations, medium-high frequency to very high frequency errors could be generated. Since the guideways would be physically damaged, the errors would be similar to the real errors that occur in machine tools due to wear on the guideways. The indentations would be made by creating around ten slits with the same width in an array with an EDM. By dividing the guideway in to multiple sections and have a different error array in every section it is possible to test multiple errors in one run.

Figure 4.3. Guideway with a slit array

Advantages:

- Realistic simulation errors.
- Can simulate a range of errors in a single run.
- Can simulate high frequency errors.
- The position and the size of the errors can be specifically chosen.

Disadvantages:

- Would require an extra rail with the slit arrays.
- Changing between the modified and an original rail is necessary to try different errors and could lead to non-repeatable behaviours.

4.3.2 Concept #2 - Deforming the Rollers

In order for the trucks to easily travel along the guideway they have rollers to lower the friction. By deforming these rollers it's possible to induce errors, this would be done by either removing material from the rollers in an abrasive way or use and EDM to cut slits in rollers. The abrasive method would result in an errors that's close to real wear but it would be hard to know exactly the size of the errors. By choosing to deform combinations of several rollers and alternating the size of the deformation different amount of wear could be simulated. The downside is that it would be very difficult to exchange the rollers in a manner that still provides repeatability.

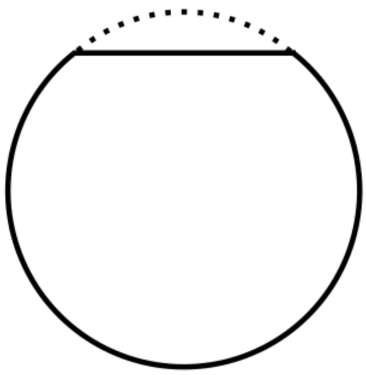

Figure 4.4. How the rollers could be deformed

Advantages:

- Able to induce high frequency errors.
- Can be used on the same guideway as several other error inducement concepts.

Disadvantages:

- May be a tedious and time consuming process of removing and deforming rollers as well as difficult to replace the rollers.
- Errors might appear seemingly at random and won't be the same from run to run.
- Removing the ball slide to replace rollers will change the preload of the entire system, making comparisons to previous runs harder.

4.3.3 Concept #3 - Linear Push

By replacing some of the screws that are securing the guideway to the base plate with piezo actuators, or find other ways to enable a linear force to push various parts of the guideway, small deformations will appear in the rail. By varying the pressure and the position of the actuators different low frequency errors can be induced. As long as the rail does not plastically deform the errors could quickly be changed and the set up could be used in combination with other error inducement concepts. Securing the actuators to the guideway and base plate will however introduce some design problems.

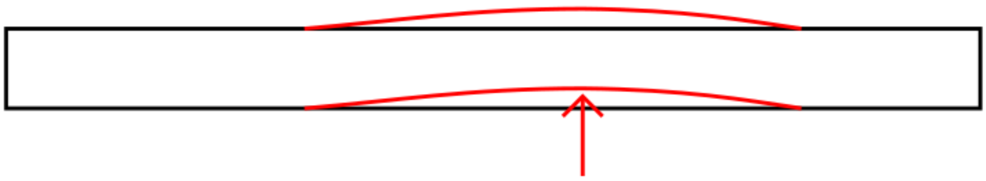

Figure 4.5. Bending of the guideway

Advantages:

- Very controllable and errors are easily repeated.
- The induced errors can be manipulated between runs with little effort.

Disadvantages:

- Extra steps must be taken during the design phase to allow for these linear forces.
- Constructing this will be time consuming.
- The forces needed to bend the rail may be too large to realistically handle.

4.3.4 Concept #4 - Software

By making small changes to the signals that is sent from the controller to the motors it's possible to generate errors by moving the platform in the Y-axis while measuring the straightens along X-axis. The errors simulated could be in any frequency region, even the high frequency region depending on the control and motor performance. This method would require fast and precise control in order to simulate the exact same errors over several runs.

Advantages:

- No additional hardware required, easy and cheap to implement.
- Could induce both high frequency and low frequency errors.
- Quite controllable and can easily be adjusted between runs without affecting preloads or other parts of the system.

Disadvantages:

- Requires a precise and fast control system.
- It may be hard to validate it as a realistic error.

4.3.5 Concept #5 - Linear Force Pulses

If the actuators from concept #3 is used it is possible to induce low frequency errors by bending the rail. However if the actuators are activated in pulses it is possible to induce higher frequency errors due to the vibrations in the guideway.

Advantages:

- Able to induce high frequency errors without having to damage any parts.
- Is easy to alter the frequency to get other types of error
- Can be combined with other types of error inducements.
- Comes as a bonus to the concept #3.

Disadvantages:

- Hard to measure a reference signal without the aid of dynamic measuring methods.
- It will be difficult to sync the phase of the pulses with the trajectory of the ball slide between repeated runs.

5 Conclusions and Status Report

The preliminary research in the field of error inducement and error detection through the use of a sensor-based method concludes that the project description is reasonable and does not need any large alterations. All requirements stated in Appendix A are possible to fulfill. Multiple realistic concepts on how to induce the errors have been derived in Chapter 4.

Discussions with the Swedish supplier Acumo have been held, and the company will provide the guideways, ball screws and motor. By choosing one supplier for the test bench components, the quality can be assured, compatibility guaranteed and the costs kept down. The IMU components have been recommended by G. Vogl. A more complete parts list for both the test bed and the IMU that will fulfill the requirements can be seen in Appendix B. Most of the components will be ordered before summer, and assembly will start in beginning of September, the installation of the IMU will be done in parallel.

6 Future Research

The future usage of the test bench will be in research. Some points may be:

- Developing and calibrating new sensors in a controlled environment.
- Developing and calibrating self-diagnosis techniques.
- Measuring the component and location errors of each axis with different types of instruments and building a geometric model from the results.
- Thorough study of the interpolation errors when using different methodologies.
- Building a model which connects direct and indirect measurements.
- Study the errors in position control loops.
- Perform uncertainty analysis of muli-axes feed drive systems.
- Analyze the energy consumption of feed drive systems.
- Study the effect of different system preloads.
- Study the thermal behaviour of the feed drive system.

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A Requirements

The following requirements are set requirements from the stakeholder in order to validate the functionality of the test bench and the IMU that have been investigate during the research phase of the project. The choice of components and design of the system was made from this premise.

Test Bench and Electrical System Requirements

- The minimal stiffness of each axis will be more or equal to 400 $[\frac{N}{\mu m}]$ in the axis direction.
- The axial positioning accuracy shall be $\pm$ 5 μm.
- The test bench shall be able to induce controlled errors in position and straightness on the controlled axis of a magnitude of at least 20 μm.

IMU Requirements

- The IMU shall measure the position error with an accuracy of ± 5 μm.
- The IMU shall detect a straightness error of at least 20 μm with a test uncertainty level more than 4:1.
- The IMU should not average more than 10 measurements to be within $\pm$ 5 μm of the interferometer measurement.

Software Requirements

- The positioning accuracy shall be $\pm$ 5 μm.
- The software should have a user friendly GUI for advanced users. The GUI should have modifiable control parameters in the interface.
- The system should have trajectory controlled tool paths.

Overall System Requirements

- The system shall have a safety distance from where no human can be harmed from the workpiece.

Soft Requirements

These are listed as "soft requirements" since they does not need to be met in order to fulfill the functionality of the system, but serve as an indicator of the construction design.

- The tabletop of the bench will be 250x250 $[mm]$.
- The maximum stroke will be 300x300 $[mm]$.
- The maximum feed force on the workpiece will be 2000 $[N]$.
- The maximum speed of the workpiece will be 30 $[\frac{m}{s}]$.
- The maximum mass of the workpiece will be 100 $[kg]$.

B Parts List

Not all parts are ordered at the time of writing and it might be subject to changes.

Component	Amount	Comments
Servodriver 400W LIQI	2	One received free as a gift from Acumo.
Servomotor 400W keyshaft LIQI	2	One received free as a gift from Acumo.
Sensor Cable Panasonic, 2m, 50-750W.	2	One received free as a gift from Acumo.
Motorcable LIQI, 2m, 50-750W	2	One received free as a gift from Acumo.
Ball screw lead 5mm length 400mm C5	2	
NSK fixed side support unit	2	
NSK fixed side support unit	2	
Carriage 25m	8	
Bellows Couplings G6	2	

Table B.1. Estimated parts list for the test bench

Component	Amount	Comments
Accelerometer 4630A-002-XXX	1	
Gyro G200D-100-300	1	
Inclinometer SX46125	1	

Table B.2. Estimated parts list for the IMU