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Development of cost effective IMU calibration procedures

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Relatório submetido à Universidade Federal de Santa Catarina como requisito para a aprovação na disciplina **DAS 5511: Projeto de Fim de Curso** do curso de Graduação em Engenharia de Controle e Automação.
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Esta monografia foi julgada no contexto da disciplina DAS5511: Projeto de Fim de Curso e aprovada na sua forma final pelo Curso de Engenharia de Controle e Automação.

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Hugo Pereira Fagundes.

RESUMO

A empresa Hexagon Agriculture está trabalhando na digitalização da agricultura. Entre as soluções oferecidas pela Hexagon Agriculture está o Piloto Automático, que utiliza um módulo GNSS em conjunto com sensores inerciais microeletromecânicos para estimar a posição do veículo. Os sensores inerciais são afetados por diversas fontes de erro e vários desses erros são sistemáticos. Os erros sistemáticos influenciam significamente na acurácia dos sensores inerciais. Neste trabalho é apresentado primeiramente um estudo sobre as características dos sensores inerciais montados em uma das placas da Hexagon Agriculture. A partir das conclusões retiradas do estudo inicial são propostos métodos de calibração para os sensores inerciais. As propostas de calibração foram então testadas e a partir do resultado destes testes, foram classificadas em viáveis ou não. O conclusão deste trabalho é que existem métodos de calibração que podem ser aplicados nos sensores inerciais resultando em melhoria significativa na acurácia dos sensores inerciais, apesar de que ainda não foi possível de se obter resultados conclusivos sobre a durabilidade dessa calibração, que depende da estabilidade dos erros sistemáticos com o tempo. Além da melhoria na acurácia dos sensores inerciais, também haverá um ganho muito significativo na confiabilidade nos sensores e na padronização da performance dos sensores inerciais. É importante também ressaltar que em algumas aplicações do piloto automático da Hexagon Agriculture é requisitada alta acurácia, que para isso são usados módulos GNSS de alta performance, acurácia de centímetros, mas caso o terreno no qual o piloto automático seja utilizado for muito acidentado, os sensores inerciais se tornam fundamentais para manter a acurácia da estimação de posição, situação na qual a calibração se torna ainda mais significante.

Palavras-chave: Calibração. Sensores. Inerciais. Navegação.

ABSTRACT

Hexagon Agriculture is working on digitizing agriculture. Among the solutions offered by Hexagon Agriculture there is an Auto Steering System which uses a GNSS module working with a MEMS IMU to estimate the vehicle's position, attitude and speed. An IMU is affected by a wide range of errors, some of those errors are systematic and those systematic errors are very relevant to the IMU accuracy. This work starts with a preliminary study on IMU parts mounted in one of Hexagon Agriculture's board. Using the conclusion of the preliminary studies, solutions are proposed, intending to calibrate the IMU. The proposed solutions, calibration procedures, were tested and classified as feasible or not. The achieved conclusion is that there are calibration methods which may be applied on the studied IMU and promote a relevant improvement on the IMU accuracy, although it has not been possible to conclude about how long will the calibration last, which depends on the systematic errors stability with time. Alongside with the accuracy improvement there is also a significant improvement on the reliability of the IMU as their performance will be more uniform. It is also important to emphasize that some applications of the Auto Steering System requires high accuracy, so high tech GNSS modules are used with centimeter level accuracy, but if the Auto Steering System is used in rough terrain, the IMU becomes fundamental to keep the accuracy on the position estimation. On higher level accuracy application e.g., five centimeter requirement, calibrating the IMU becomes even more relevant.

Key-words: INS, IMU, Gyroscope, Accelerometer, Bias, Calibration, Low-Cost, Misalignment, Sensitivity

FIGURES LIST

ACRONYMS AND ABBREVIATIONS LIST

UFSC - Universidade Federal de Santa Catarina

DAS - Departamento de Automação e Sistemas

IMU - Inertial Measurement Unit

INS - Inertial Navigation System

MEMS - Microelectromechanical Systems

CS - Chip Select

GNSS - Global Navigation Satellite Systems

SPI - Serial Peripheral Interface Bus

RTK - Real Time Kinematic

FFT - Fast Fourier Transform

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1 INTRODUCTION

This project was developed aiming to improve the performance of some Hexagon Agriculture solutions. This introduction will contains a brief description of the company, the project and its goals.

1.1 The company

Hexagon Agriculture is committed on developing information technology solutions for the agro industry. Hexagon Agriculture works on smart planning, efficient field execution, precise machine controls and automated workflows that optimise operations and increase profits.

Hexagon Agriculture is part of Hexagon, a leading global provider of information technology solutions that drive productivity and quality across geospatial and industrial landscapes

Hexagon's solutions integrate sensors, software, domain knowledge and customer workflows into intelligent information ecosystems that deliver actionable information. They are used in a broad range of vital industries.

Hexagon Agriculture works with Precision Agriculture, which includes an Auto Steering system, developed to improve performance and operation precision, aids navigation and can be fully integrated with other functions of Hexagon's precision agriculture equipment.

Available in Electric and Hydraulic models, Auto Steering provides a big advantage minimising overlap during planting, the application of product resources and cultivation practices.

The option of following predefined lines allows the route to be planned directly from your office or a control room. As a result, users can maximise field resources and the repetitiveness of the trajectory, as well as significantly reduce soil compaction.

On average, if operated appropriately, Auto Steering system is expected to provide 5% gain in savings for product resources and up to 3% in gain of the cultivation area..

This information was retrieved from Hexagon Agriculture website, where it is possible to obtain further information about the company.

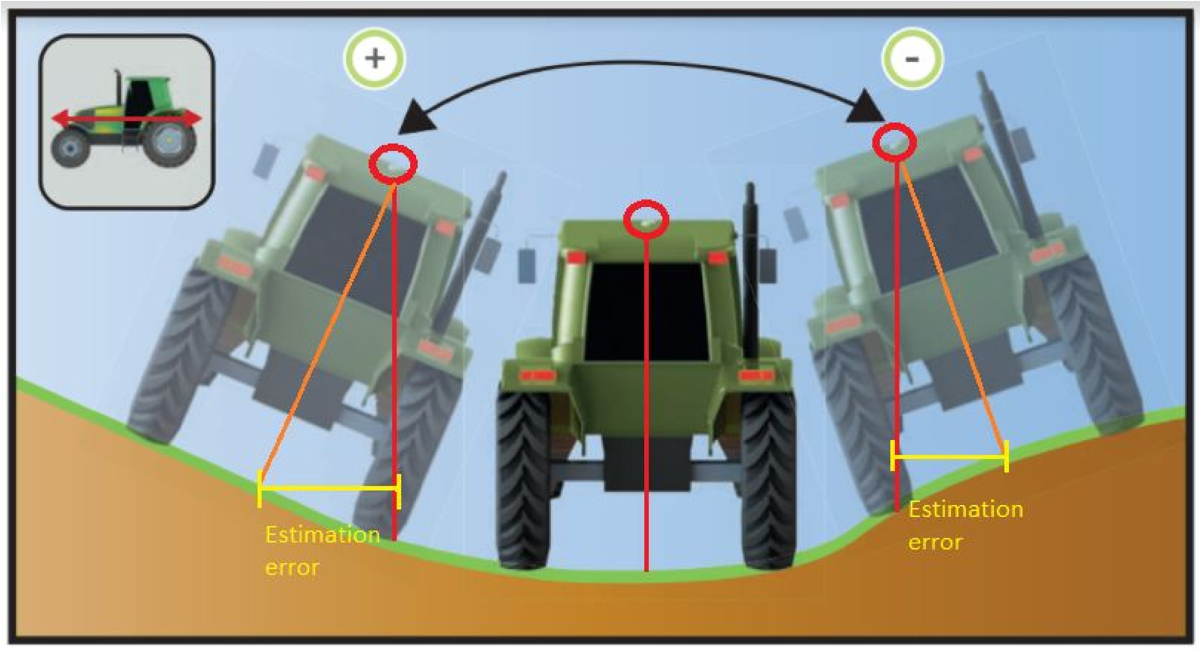
1.2 Introduction to the project

Hexagon Agriculture's Auto Steering system has to know it's position, attitude and speed in order to be able to steer the vehicle, for this task a Global Navigation Satellite System (GNSS) module and an Inertial Measurement Unit (IMU) are used.

Hexagon's IMU uses motion sensors (accelerometers) and rotation sensors (gyroscope). Both accelerometer and gyroscope are microelectromechanical systems (MEMS). MEMS IMU can be found on the market already calibrated and uncalibrated and this calibration represents a huge difference on the parts price. Non calibrated IMU have reduced accuracy as pointed out in [1] “low cost IMUs are affected by systematic error given by imprecise scaling factors and axes misalignments that decrease accuracy in the position and attitudes estimation.”

The GNSS module provides the vehicle position, more accurately, it provides the position of the GNSS antenna installed on the vehicle. If the vehicle is tilted, the GNSS antenna relative position to the vehicle center will vary and there will be an error at the position estimation as shown at Figure 1.

Figure 1: Position estimation error due to vehicle tilt.



Source: *Adapted from* Ti7 User Manual V100R003.E01-A [B.3]

Hexagon Agriculture uses the IMU mostly for tilt compensation. The vehicle's attitude is estimated with the IMU and then it is possible to perform tilt compensation. Calibrating the IMU would improve the attitude estimation accuracy, resulting in an improvement on Hexagon's Auto Steering systems with improved accuracy and more important consistent performance.

1.3 Project goals

The goal of this project is to develop cost effective IMU calibration procedures, including an analysis on the accuracy improvements achieved by those calibration procedures.

Improving the IMU data accuracy is a non-trivial task and has many ways to be achieved as mentioned in [4]. Therefore, the first step was studying an actual IMU used by Hexagon Agriculture, understand its characteristics and then study calibration procedures which would represent relevant improvement and are not too sophisticated or use very expensive equipments.

It is important to explain that there are factory calibrated IMU on the market, with much higher accuracy but their cost is over ten times higher, which would make

Hexagon Agriculture Auto Steering more expensive and less competitive, therefore, it is important to reinforce, this project goal is improving the IMU accuracy without significantly increasing the cost.

Based on the preliminary studies, discussed in Chapter 2, the following sections describe the techniques chosen to improve the accuracy:

1.3.1 Replace the used gyroscope

Hexagon Agriculture's engineers realized the gyroscope mounted in one of their boards was possibly causing some undesirable behaviour on the Auto Steering system. Then, it was decided to evaluate other gyroscopes.

Different gyroscope's brands have diverged information on their datasheet, check [B.1], [B.2] and [B.4]. The datasheet's performance characteristics section provides only typical expected performance, there is no guarantee that the IMU will perform within those limits, there is not even information about what is the expected population of parts which will meet those performance characteristics.

Considering the inconsistency and missing information of the gyroscope's datasheets, Hexagon's engineers decided to order gyroscope's samples from different manufacturers and execute some performance tests on them and potentially choose a new gyroscope for some of the Auto Steering system boards.

1.3.2 Compensate the gyroscope's bias over temperature

In section 2.1 it is explained that on the gyroscopes the author studied, bias over temperature is one of the most relevant sources of systematic errors.

While the gyroscope is in use, compensating the bias which is caused by temperature variations would represent a relevant improvement on the gyrocope's performance.

1.3.3 Improve the communication between the microcontroller and the IMU parts

While the author was studying the gyroscopes used in some of Hexagon Agriculture's boards it was noticed that there were some nonsense data received from the gyroscope. After discussing it with Hexagon's engineers, it was reported as a known characteristic and it was concluded that these nonsense data were very likely caused by communication issues.

Improving the communication between the microcontroller and the gyroscope would not necessarily provoke a relevant performance improvement but understanding what caused this issues or treating those communication problems when this errors happened would mean a more trustworthy system and all following calibration techniques would have a higher chance of success.

1.3.4 Calibrate the accelerometer and gyroscope bias, scale, misalignment, cross axis sensitivity

Bias, scale, misalignment and cross axis sensitivity are very relevant systematic errors, as described in [1]. Specially on IMU which uses components mounted in different spots on the board, there will be a misalignment between the components, depending on the positions the components were soldered on the board. This misalignment can be measured and compensated.

There is a calibration procedure proposed in [1] which uses no external equipment and may present very significant improvement. This calibration procedure has already been discussed and studied by Hexagon Agriculture engineers but has not being fully implemented yet.

1.4 Document outline

This document contains discussions on the full process, from motivation to results.

Chapter 2 discusses the preliminary studies which motivated and defined the requirement of the project.

Chapter 3 describes the proposed solution based on the preliminary studies.

Chapter 4 describes tests which were performed aiming to validate the effectiveness of the proposed solutions.

Chapter 5 describes the implementation, used tools, classes diagrams and other details which made it possible.

Chapter 6 discusses the results achieved with the implemented calibration procedures.

Chapter 7 concludes the importance of this project and the potential of future works within the context.

2 PRELIMINARY STUDIES

Hexagon Agriculture produces an Auto Steering system which is planned to be used in a wide range of applications, as Mowing vehicles, Snow clearing vehicles, Planting and many others. In all those applications, an IMU is used to assist providing the vehicle's position. Each of those applications have specific accuracy requirements.

The IMU on Hexagon Agriculture's Auto Steering system is responsible for estimating the vehicle's roll, pitch and assisting on the heading estimation. Depending on the application it might be required a higher accuracy or even the ability of navigating without the GNSS position input for some time, which requires high stability and accuracy. In order to explain how higher accuracy may be accomplished it is interesting to explain the IMU characteristics.

Hexagon Agriculture IMU is composed by the STMicroelectronics gyroscope A3G4250 and NXP Semiconductors accelerometer MMA8451Q. Which are low costs MEMS sensors.

The characteristic mentioned in Section 2.1 are related to MEMS sensors, specifically the accelerometer and gyroscope used by Hexagon Agriculture.

2.1 IMU characteristics

Usual IMUs get a triaxial accelerometer and a triaxial gyroscope. Those sensors can be in the same package or mounted in different spots at the same board.

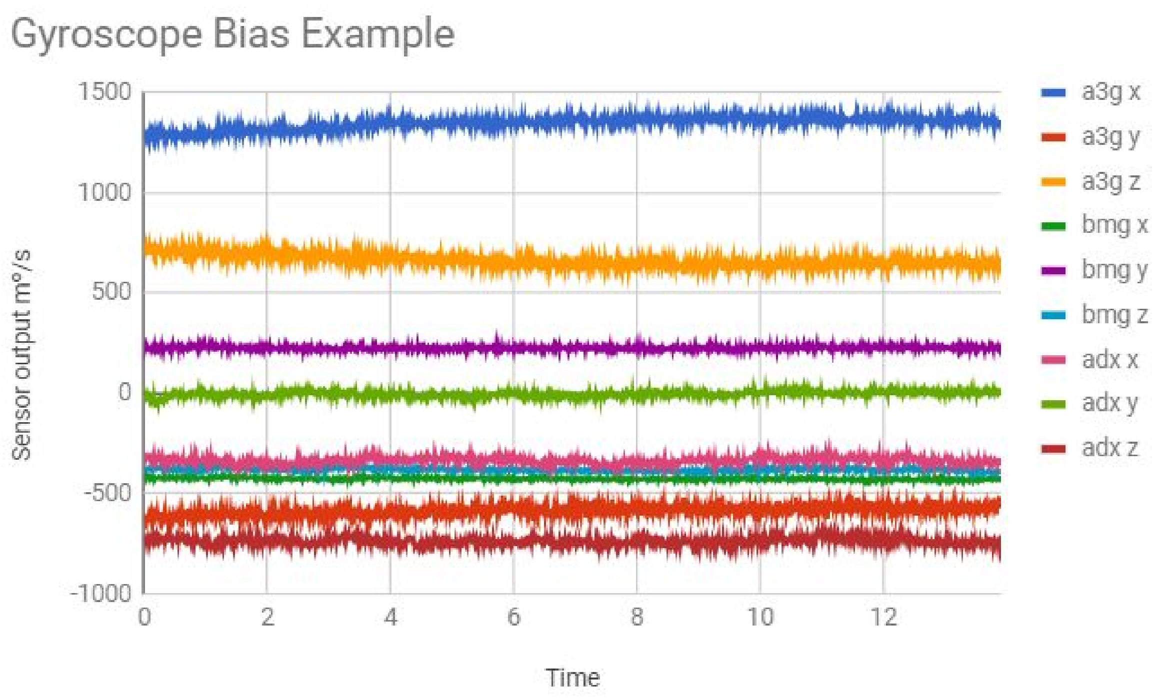
Hexagon Agriculture's studied IMU is composed of a triaxial accelerometer and a triaxial gyroscope, mounted in different spots at the same board. According to

[5] and Hexagon Agriculture's experts, it is possible to point out the most relevant performance characteristics:

2.1.1 Bias

Bias is defined in [5]: “For a given physical input, the sensor outputs a measurement, offset by the bias .For example, if the IMU is stationary and level, the vertical axis measures the effect of gravitational acceleration. Gravity has a nominal acceleration of 9.81 m/s^2 , but if the measurement is biased, the IMU may report 9.75 m/s^2 . The difference between the real value and the output is the bias.” Figure 2 shows an example of measured gyroscope bias.

Figure 2: Bias example

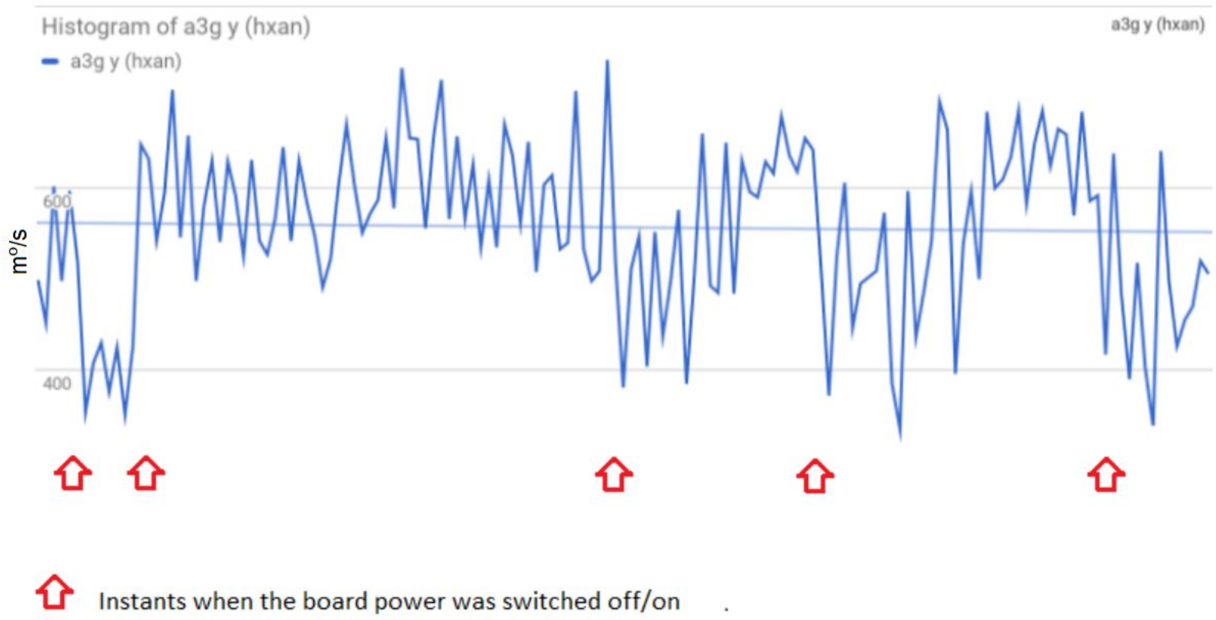


Source: Gyroscope test report [A.1]

As described in [A.1], bias is the most relevant source of errors. It is possible to divide it in categories:

- Turn on to turn on bias stability
  When the sensors, gyroscope and accelerometer are turned on, they might have a different output bias. This characteristic is described as turn-on to turn-on bias or Bias repeatability in [5], and it is a non systematic error. Figure 3 shows an example of turn on to turn on bias.

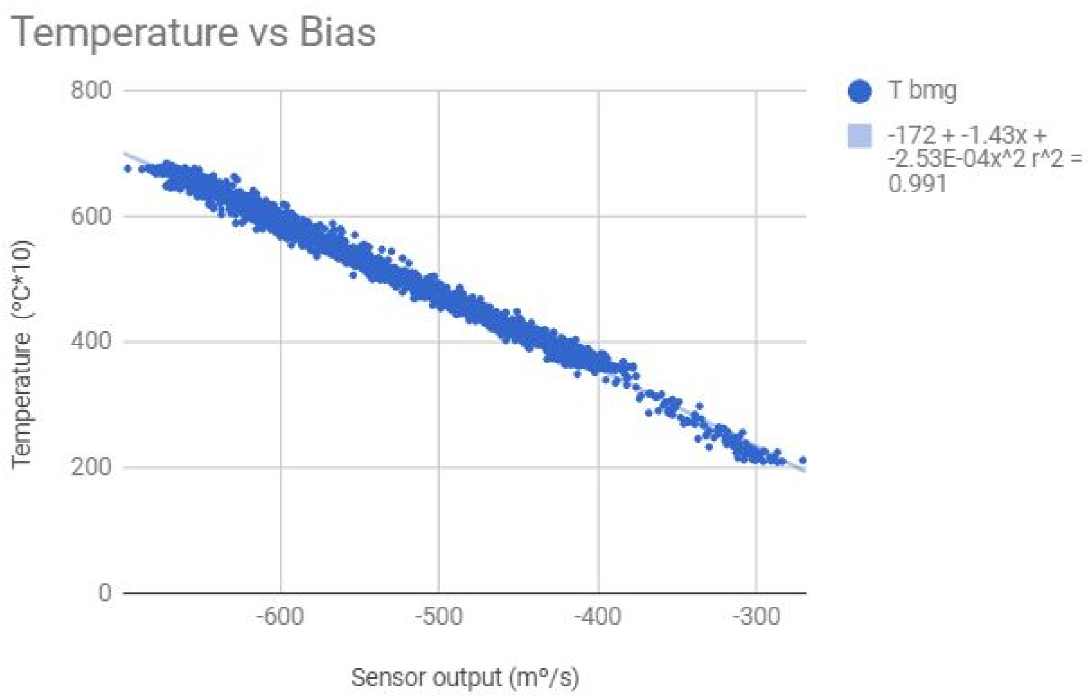
Figure 3: Turn on to turn on bias example



Source: Gyroscope test report [A.1]

- Bias over temperature
  Temperature variations may cause bias variations, usually the relation between temperature variations and bias is nonlinear. It is included in Bias Stability (In-run bias) category in [5]. Figure 3 shows an example of bias caused by temperature variation.

Figure 4: Bias over temperature example



Source: Gyroscope test report [A.1]

- Random Bias

  The measured bias has also a component of unknown sources, which can be considered as random. It is probably influenced by moisture, mechanical abuse, exposure to high temperatures and other effects.

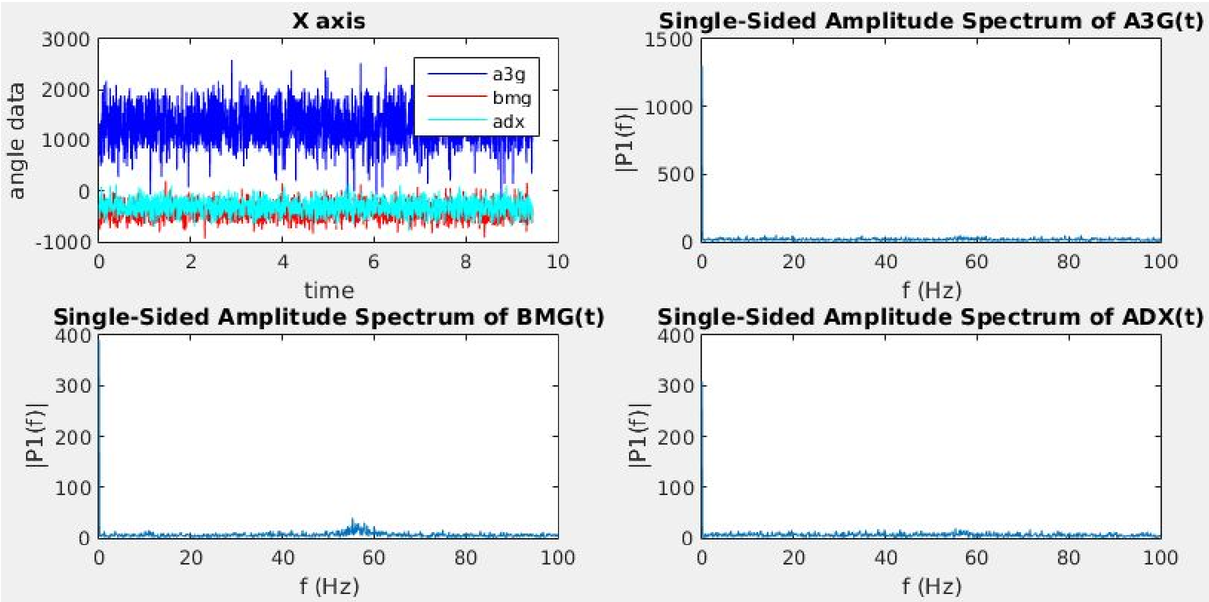
  This bias is included on the bias stability analysis made by most of IMU's manufacturers, as described in [5].

2.1.2 Noise

Noise is a very relevant source of error on both gyroscope and accelerometer.

The noise is usually much lower than the bias, and is a very relevant characteristic, usually IMU components with lower noise are more expensive and achieve higher overall performance. This is further described in [5] as Random Walk (Sensor Noise). Figure 5 shows noise example on gyroscope data.

Figure 5: Noise example



Source: Gyroscope test report [A.1]

2.1.3 Sensitivity

The sensitivity is the relation between the sensor input and output. Every inertial MEMs sensor has it's own nominal sensitivity, but the actual sensitivity will fluctuate around it within a certain tolerance. This characteristic is described in [5] as Scale Factor.

Temperature is a known factor which influences the sensitivity as shown at Figure 6.

Figure 6: Sensitivity over temperature example

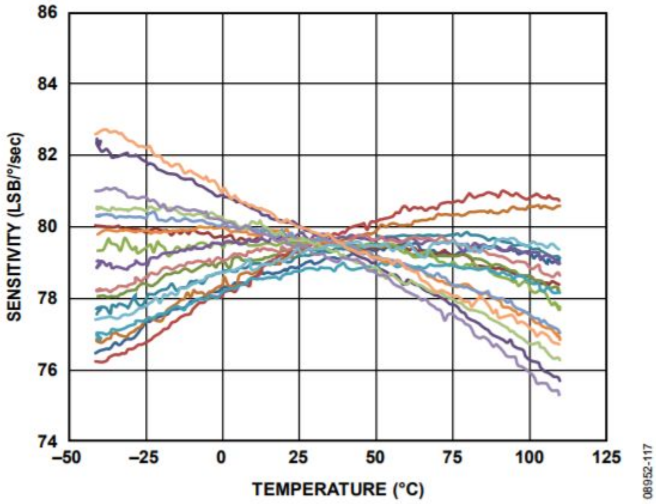


Figure 15. Sensitivity over Temperature

Source:ADXRS450 datasheet [B.1]

2.1.4 Cross axis sensitivity and misalignment

Both gyroscope and accelerometer will have a expected misalignment between its axes. It is a mechanical characteristic of the sensor. This characteristic is described as Sensor Non-orthogonality (Misalignment) in [5].

The misalignment will affect the readings. It implicates in undesirable output at not incited axes. This characteristic is also described as cross axis sensitivity, which is more generic and includes the misalignment effect. IMU manufacturers usually include the cross axis sensitivity tolerance at the datasheet.

It is very important to mention that in situations where the accelerometer and gyroscope are not on the same package, but mounted at the same board, they will also have a misalignment between the sensors, which will influence at the sensor fusion. The misalignment between sensor is further explained in [1].

2.1.5 Gyroscope G sensitivity

Gyroscopes are designed to measure angular speed. But even though, they are also influenced by linear acceleration. This undesirable characteristic is also known as g sensitivity or G Dependency (Acceleration Effect), it is further discussed in [5].

G sensitivity is very relevant in environments with high level of vibration. In some of the vehicles which Hexagon Agriculture has it's IMU installed the vibration is as high as 5g. In [3] there is an example on the g sensitivity effect.

2.2 Improvement potential

To estimate the improvement potential, it is possible to compare the uncalibrated IMU typical performance, according to its datasheet, and compare it to a factory calibrated IMU, which can be considered as the best possible outcome achieved by the cost-effective procedures proposed at this document.

All errors at the IMU output are used as input to the INS, which uses a Kalman filter. There is no simple way to estimate the relation between the input errors from the IMU and the INS output: attitude estimation. For those reasons this Chapter will approach the potential improvement on the IMU only and ignore the IMU data treatment made by the INS. To check the actual improvement on the Automatic Steering system, tests on working conditions were performed and are discussed in Chapter 5.

The author studied a Hexagon Agriculture's board with a IMU composed by STMicroelectronics gyroscope: A3G4250 and NXP Semiconductors accelerometer MMA8451Q. Those sensors performance will be used for the improvement potential discussion.

In order to estimate the effects of the IMU performance characteristics, let's suppose this IMU is installed on a vehicle which the GNSS antenna is located 2.5 meters away from the ground, for simplicity this vehicle will be called as Hexagon's tractor from now on.

A tilted vehicles will misplace the antenna, the conversion from vehicle roll to antenna misplacement is modelled by this formula:

$$Antenna\_misplacement = sin(roll) * H_{antenna}$$

The error estimation presented in Section 2.2.1 and Section 2.2.2 used the formula above.

2.2.1 Gyroscope errors estimation

According to STMicroelectronics gyroscope A3G4250 datasheet [B.1]:

- Sensitivity vary up to 15% from the nominal sensitivity;
- Bias is up to 25 º/s;
- Rate noise density is up to 0.15 $º/s/\sqrt{Hz}$;
- There is no information relative to its cross axis sensitivity.

To estimate the effect of 15% sensitivity error, let's consider Hexagon's tractor moves to a inclined terrain, suppose 20º, disconsidering the bias, this sensitivity error would estimate the vehicle attitude with a 3º error. Considering Hexagon's tractor, 3º roll means an antenna misplacement of 0.13m.

This gyroscope bias could potentially indicate a 25º/s angular speed, which would be integrated over time, to estimate the vehicle's attitude. A vehicle roll of 25º, would place the antenna of Hexagon's tractor 1.06m dislocated from the center, similar effect caused by the gyroscope bias.

There is also the noise which is harder to estimate its effect, but the peak to peak noise is around 0.6 º/s, which would be integrated over time and possibly compensated itself, since the average noise is null.

2.2.2 Accelerometer errors estimation

According to NXP Semiconductors accelerometer MMA8451Q datasheet [B.5]:

- Sensitivity typically vary 2.64% from the nominal;
- Bias is typically up to 20 mg;
- Rate noise density is typically 126 $\mu g/\sqrt{Hz}$;
- There is no information relative to its cross axis sensitivity.

It is important to notice that these values are all typical, there is no guarantee that there might be a part with worse performance than the specified on the datasheet.

To estimate the influence of the sensitivity error, it is calculated the attitude using accelerometer data as described in [6]. Let's suppose Hexagon's tractor moves to a inclined terrain, suppose 20º. The roll estimation formula uses two axes data and with this sensitivity error, it could imply in 3.62º error on the vehicle position estimation.

To estimate the bias influence on the roll estimation, considering it adds 0.20mg on y axis and subtract 0.20mg on the z axis, it would imply 3.62º error on the vehicle position estimation.

The noise on this accelerometer will be filtered and leveraged at the INS's kalman filter, and do not represent relevant errors.

2.2.3 Factory calibrated IMU comparison

Hexagon Agriculture has arranged a meeting with Analog Devices engineers. Analog Devices Engineers indicated a factory calibrated IMU for Hexagon Agriculture application, and this indicated IMU is not yet official, but Analog Devices Inc. sent the preliminary documents with these specified performance characteristics:

- Gyroscope sensitivity error is typically up to 0.25%;
- Gyroscope bias is typically up to 0.2 º/s;
- Gyroscope rate noise density is typically up to 0.008 $°/s/\sqrt{Hz}$;
- Gyroscope misalignment is typically up to 0.1 %;
- Accelerometer sensitivity error is typically up to 0.1%;
- Accelerometer bias is typically up to 4 mg;
- Accelerometer rate noise density is typically up to 87 $\mu g\sqrt{Hz}$.

These IMU calibration procedures uses highly sophisticated calibration procedures and equipments. Therefore, it is reasonable to consider that these specifications are the best possible results to be achieved with MEMS IMU calibration procedures.

It is important to note that this performance characteristics are guaranteed throughout all working temperature range, which in this IMU is from -40ºC to +105ºC.

2.3 Actual calibration procedures

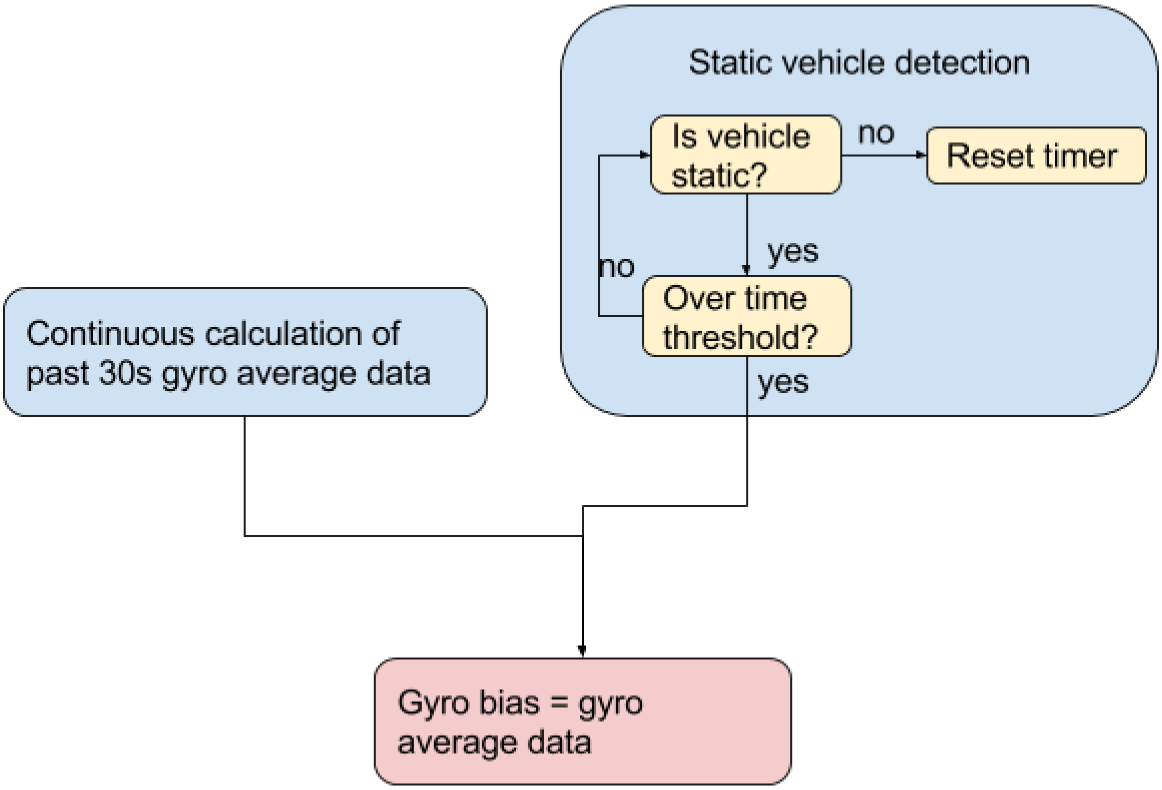
Hexagon Agriculture, until November 2017 uses the following strategies to improve the IMU performance.

2.3.1 Gyroscope bias compensation

There is an algorithm which identifies when the vehicle is not moving, once the vehicle has stayed stationary for over 30s, it calculates the average data of the gyroscope, which is a fine estimation for the bias at this point of time. The estimated bias is then subtracted from the raw gyroscope data. Figure 7 illustrates the operation of this calibration algorithm.

This calibration procedure is very effective and represents great improvement. But it is usual that Hexagon Agriculture`s IMU is used in some application e.g. spraying plantation, application which may imply on a vehicle not stopping for long periods of time, including large temperature variations during this time, e.g. when the vehicle starts working at a cold early morning until a hot midday. In those conditions, the gyroscope bias compensation will not be performed throughout this whole period while the vehicle is moving and the gyroscope error will increase due to bias variation.

Figure 7: Hexagon Agriculture`s bias compensation



Source: Author's creation

2.3.2 Accelerometer mounting position compensation

Hexagon Agriculture's IMU is mounted on boards, called drivers which are installed at fixed positions on vehicles. As it is close to impossible installing those boards on a perfect plane with the ground in every single vehicle, Hexagon Agriculture uses the following calibration procedure.

After Hexagon Agriculture's drivers are mounted on a vehicle, it is instructed that the user calibrates the accelerometer, indicating the user to waits for 20s with the vehicle stationary and afterwards move the vehicle and stop it at the same position but facing the opposite direction. Figure 8 shows the onboard controller screen which helps the user perform this calibration procedure.

Figure 8: Accelerometer calibration screen

Source: Ti7 User Manual V100R003.E01-A [B.3]

Stopping at the same place but facing the opposite direction makes it possible to isolate the ground inclination from the mounting position inclination. Them the mounting position attitude will be compensated on the accelerometer data.

It is important to notice that an eventual bias on the accelerometer data will be interpreted as mounting position attitude and will also be compensated with this procedure.

2.3.1 Gyroscope pass band filter

It is possible to set a high pass filter on the gyroscope, when this high pass filter is configured, the gyroscope's output data will already be filtered.

A3G4250 gyroscope can be configured with a low pass filter and a high pass filter. To configure those filters it is needed to write on specific configurations registers.

Hexagon Agriculture configures the A3G4250 with an output data rate of 800Hz, a low pass filter with cutoff frequency at 30Hz and a high pass filter with a cutoff frequency at 0.1Hz.

There is no specification on the attenuation caused by those filters at A3G4250 datasheet.

3 SOLUTION PROPOSALS

After carefully analysing the preliminary studies discussed in Chapter 2, there were six groups of proposals to improve Hexagon Agriculture's IMU performance which will be discussed in this Chapter.

3.1 Gyroscope bias over temperature corrections

As explained in 2.1.1, the IMU bias is a very relevant source of error. Specifically on the studied gyroscopes the bias variations with temperature were very relevant and systematic. Therefore ,compensating the bias over temperature became a clear potential improvement.

In order to compensate the gyroscope bias influenced by temperature variations, two different strategies were proposed. Those strategies are described in Section 3.1.1 and 3.1.2.

3.1.1 Use a lookup table with bias values on temperature range

The author's first idea was to store the gyroscope bias with respective temperature in a table. This table would be stored in a non volatile memory at the board where the gyroscope is mounted.

This table would have to contain all temperature range in which the gyroscope is expected to be used. It would be necessary to vary the gyroscope temperature throughout the desired range in order to obtain the respective bias.

This strategy presents two major disadvantages:

- Submit the gyroscope throughout the whole expected temperature in working conditions means that first it is necessary to define what is this temperature range and afterwards put the gyroscope in a controlled temperature environment which would have to achieve all this temperature range.

  Hexagon Agriculture owns machines called Burn In, which are used to test equipments increasing the temperature. But Hexagon Agriculture does not own machines which are able to decrease the temperature.

Some Hexagon Agriculture Auto Steering systems might be used in freezing environments, which means the bias over temperature table should have freezing temperatures and its correspondent bias. A machine which achieve freezing temperatures would have to be acquired.

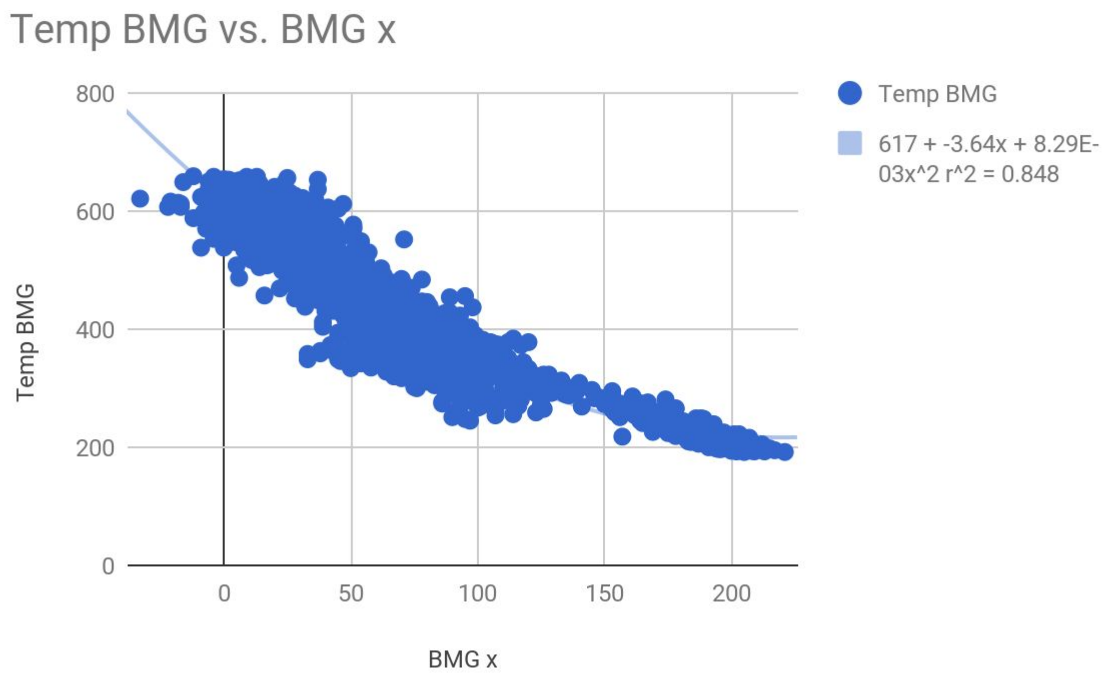
- This table might be large, depending on the temperature range and chosen temperature resolution. The board non volatile memory is limited, and using a large part of it is highly discouraged.

3.1.2 Find a curve that represent the bias variations due to temperature

After the preliminary studies, the author realized it was possible to use linear regression to represent the bias over temperature curve. The author tested using linear regression and using its coefficient to compensate bias, achieving great results. The author proposed using a linear regression to Hexagon Agriculture experts, who explained that it would be a more generic approach, with higher chances of working to use polynomial regression, because some bias over temperature curves from other sensors could not be linear.

As seen in Figure 9, Hexagon Agriculture's experts were right, there were curves which would not be well fit with linear regression.

Figure 9: Polynomial approximation to bias over temperature curve



Source: Gyroscope test report [A.1]

In order to implement this strategy, it is needed to put the board with the mounted gyroscope in a controlled temperature environment. After the temperature varies over a certain range, it is necessary to use a curve fitting algorithm which approximates it to a polynomial function and then use this function to compensate the bias influenced by the temperature.

The main advantages of this strategy are that it is possible to estimate the bias influenced by the temperature on temperature ranges which were not achieved during the calibration procedure and there is need to store just the polynomial coefficients at the board`s non volatile memory.

It is important to check the estimated polynomial function correlation to the bias over temperature, because if the correlation is too short, it means it was a poor approach and when trying to compensate the bias with this polynomial function that does not represent the curve well, the output could be worse than without the compensation.

How does the polynomial function is used to improve the gyroscope performance will be explained in Chapter 5.

3.2 Vibration rejection

Hexagon Agriculture install its IMUs on vehicles, usually tractors with have pretty high level of vibration. This vibration produces undesirable output at the inertial sensors. The accelerometer will measures vibration, as it involves acceleration, and disturbing the tilt estimation, as for the gyroscope, it should not be influenced by vibration, but it is, as explained in Section 2.1.5.

3.2.1 Project a dynamic stop band filter

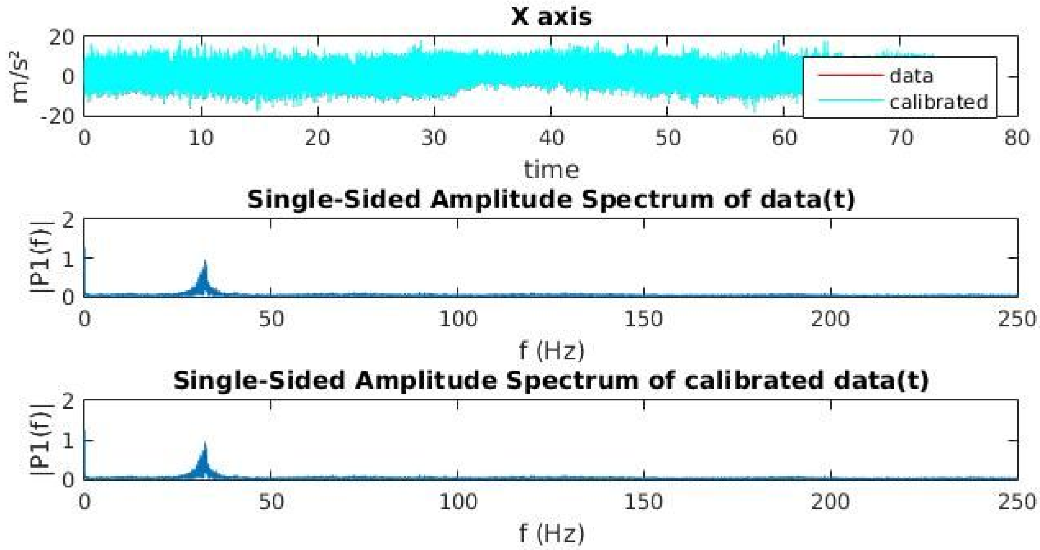
On Hexagon Agriculture's applications, the highest source of vibration is the vehicle's motor. Therefore, It would be possible to project a stop band filter to filter out this highest source of vibration, improving the IMU's performance.

To implement the stop band filter, it is needed to define the desired filtered frequency range, since the vehicle's motor may operate in a wide frequency range it would not be a feasible solution filter out all possible working frequencies because it would filter out too much gyroscope data which is not related to vibration.

In order to minimize the filtered range and still filter most of the vibration influence the author proposed a method to estimate the motor's frequency. There could be used a Fourier Transform algorithm on the accelerometer data which would detect the frequency range which is highest source of vibration and then adjust the cutoff frequencies of the stop band filter to this frequency range.

Figure 10 shows graphs using FFT to detect the motor's frequency. X axis is the accelerometer raw data in one of its axis.

Figure 10: Detection of highest vibration source



Source: IMU Calibration report [A.2]

3.2.2 Use the accelerometer data to correct the gyroscope linear g sensitivity

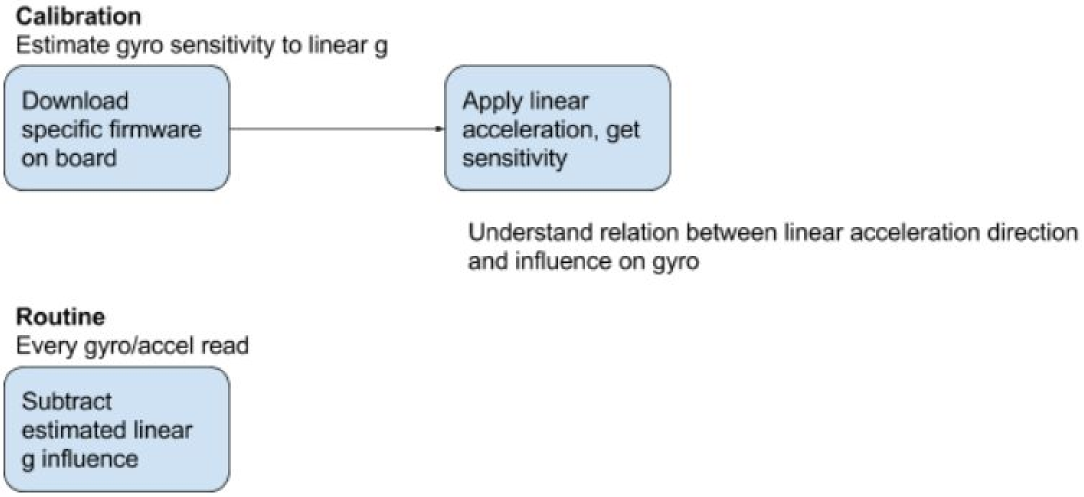
Another strategy to compensate vibration would be compensating gyroscope linear g sensitivity, which includes vibration. Gyroscope's linear g sensitivity is usually ignored, but might be a very relevant source of error, as explained in [2].

The author proposed compensating linear g sensitivity measuring linear g with the accelerometer, estimate the effect it would make at the gyroscope and then compensate it. While studying the datasheet of a factory calibrated Analog Devices IMU, the author learned that Analog Devices uses a similar strategy. Analog Devices multiplies the accelerometer data to a 3x3 matrix and subtract the result from the gyroscope data in order to compensate linear g. This 3x3 matrix represents the effect of linear g and the matrix values varies with temperature, as the gyroscope linear g sensitivity also varies with temperature.

The hard part of this strategy is determining the gyroscope linear g sensitivity. As the gyroscope has many errors on its data it is very difficult to isolate the linear g sensitivity error. Analog Devices uses very sophisticated machines for this task.

Figure 11 illustrate how linear g calibration procedure proposed by the author would work.

Figure 11: Linear g calibration proposal



Source: Gyro Accuracy improvement algorithm design [A.3]

3.3 Communication errors treatment

As explained in Section 1.3.3, the communication between the Microcontroller and the gyroscope had some issues. Those communication errors source was unknown and extinguishing those errors would raise the IMU reliability considerably.

3.3.1 Understanding what is causing the errors

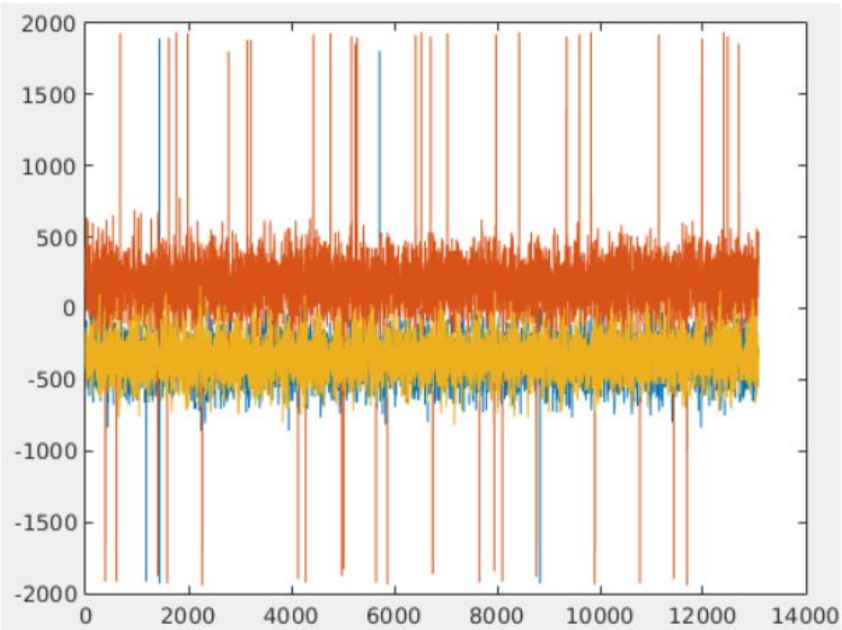
The best way to minimize the communication errors effects at the IMU output is to extinguish the communication errors. To extinguish the communication errors it is necessary to understand what is causing them, some hypotheses were raised during discussions between the author and Hexagon's engineers:

- The SPI clock frequency was too high
  The communication with the gyroscope is made via SPI, according to the the gyroscope's datasheet the clock frequency was already within the accepted limits, but Hexagon Agriculture experts defended that testing lower frequencies was important.
- The SPI clock polarity was inverted
- The period between the registers access was too low
- There were interference
- The period between the CS and clock first pulse was too low

Study and test those hypotheses could potentially determine the errors source and them a strategy to fix them could be developed.

The communication errors were evident when plotting the raw data from the gyroscope, like shown in Figure 12.

Figure 12: Gyroscope communication error



Source: IMU calibration report [A.2]

3.3.2 Detect the errors occur and treat them

It is also possible to develop an algorithm to detect when those communication errors occur and use some strategy to minimize the influence of those errors.

The challenge is not to create an algorithm which would not demand relevant extra computing or delay to detect those errors, this overhead/delay could potentially represent a worse effect than the communication errors.

Detecting communication errors advantage is that it could also be useful to detect a wide range of communication errors, e.g., when the sensor stops working completely.

3.4 Substitute the gyroscope

Hexagon Agriculture studied board used STMicroelectronics gyroscope A3G4250. In the first semester of 2017 it was decided to evaluate other gyroscope, Bosch's BMG250, which is also a low cost MEMS gyroscope.

On the preliminary tests, it was detected very undesirable behaviour from A3G4250 when compared to BMG250, therefore, Hexagon Agriculture's engineers decided to start using Bosch's gyroscope.

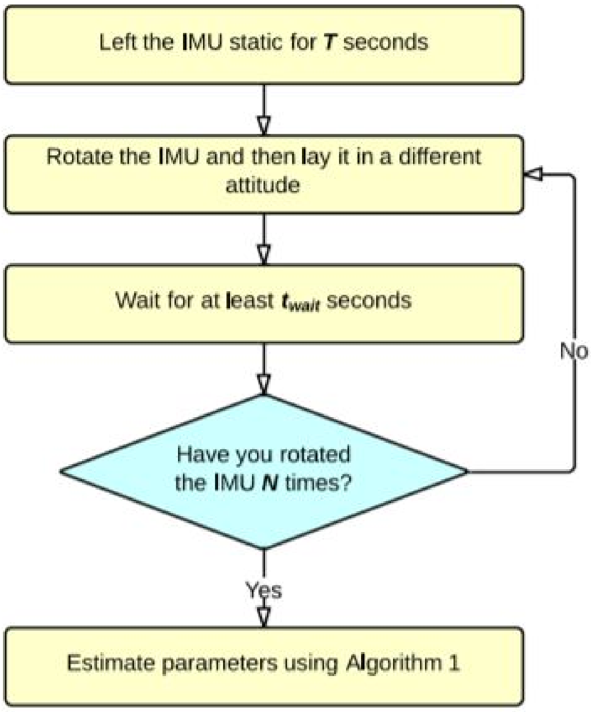
The challenge is testing and measuring the actual improvement caused by substituting the gyroscope, more information about those tests are in Chapter 4.

3.5 Multiple position systematic errors calibration

Calibrating the IMU has been one of Hexagon Agriculture's goals for years. In those years some studies were made, the most promising study was based on [1], a calibration method which uses no external equipments and is potentially able to calibrate accelerometer's bias, sensitivity, misalignment, gyroscope's bias, sensitivity and misalignment.

This procedure consists in positioning the IMU in multiple positions, wait for a fixed time in each position and then use an error model and minimization algorithms to determine bias, misalignment and cross axis sensitivity. This calibration procedure is illustrated in Figure 13.

Figure 13: Multiple position calibration



Source: Calibration and performance evaluation of low-cost IMUs [1]

In order to explain this calibration procedure a bit further it can be split into accelerometer calibration, Section 3.5.1 and gyroscope calibration, Section 3.5.2.

3.5.1 Accelerometer

The accelerometer is put in multiple stationary positions, it is extracted the accelerometer mean data at those stationary positions. The mean data at each stationary position is used to calculate the local gravity. The nominal local gravity is used as an input to the calibration algorithm. A minimization algorithm is used, to estimate the parameters of error model.

The error model of the accelerometer is composed by a bias vector, a sensitivity vector and a misalignment matrix. For more information, read [1].

3.5.2 Gyroscope

The gyroscope calibration starts with a starting stationary period, the mean gyroscope data during the initial period is approximated to the gyroscope bias, part of the gyroscope error model.

The gyroscope's data is integrated and then the board's attitude is estimated on every static interval, this attitude is compared to the attitude calculated by the calibrated accelerometer data. The attitude calculated using the accelerometer data is used as the reference and afterwards a minimization algorithm estimates the gyroscope sensitivity vector and misalignment from the gyroscope to the accelerometer and between the gyroscope's own axes. For more information, read [1].

3.6 Include a magnetometer

The studied Hexagon Agriculture's IMU is used to compensate the GNSS antenna mislocation by inclined terrains, as explained in Section 1.2, but it is possible that some application may require the IMU to estimate the vehicle's position for short periods of time when there is no GNSS signal.

In order to estimate the vehicle's position is is essential to estimate the vehicle's heading. The vehicle's heading is not observable by the accelerometer, therefore, in a IMU with an accelerometer and gyroscope, only the gyroscope's data can be used to estimate the vehicle's heading.

In order to use a gyroscope to estimate a vehicle's heading, it is needed to integrate the gyroscope data with time. Integrating the gyroscope's data means the gyroscope's will also be integrated and the estimation error will increase with time. Therefore, estimating heading with a decent accuracy requires a super accurate gyroscope, very well calibrated and the heading estimation will still be valid only through short periods of time.

The author researches pointed out that many IMUs also include magnetometers. The main advantage of magnetometers is that it's data does not need to be integrated through time, then it is possible to have a much more stable heading estimation.

Including a magnetometer in Hexagon Agriculture's IMU could enable using the Auto Steering system in a new range of applications where the GNSS signal may not always be strong enough.

4 TESTS ON PROPOSALS

This Chapter will describe tests which were performed aiming to validate the effectiveness of the proposed solutions.

Executing tests on the proposed solution was an essential part of this project, considering that most of the proposed calibration procedure involve an extra step on every board production, meaning extra time and money invested.

The objective of this tests were:

1. Confirm that the proposed calibration procedures actually improve the IMU performance.
2. Estimate the proposed calibration procedures final effect on Hexagon Agriculture's Auto Steering system.
3. Confirm that the proposed calibration procedures are feasible, considering the restricted computational power and memory of the microcontroller.
4. Confirm the IMU performance improvement are worth the extra time and money invested on the calibration procedure.

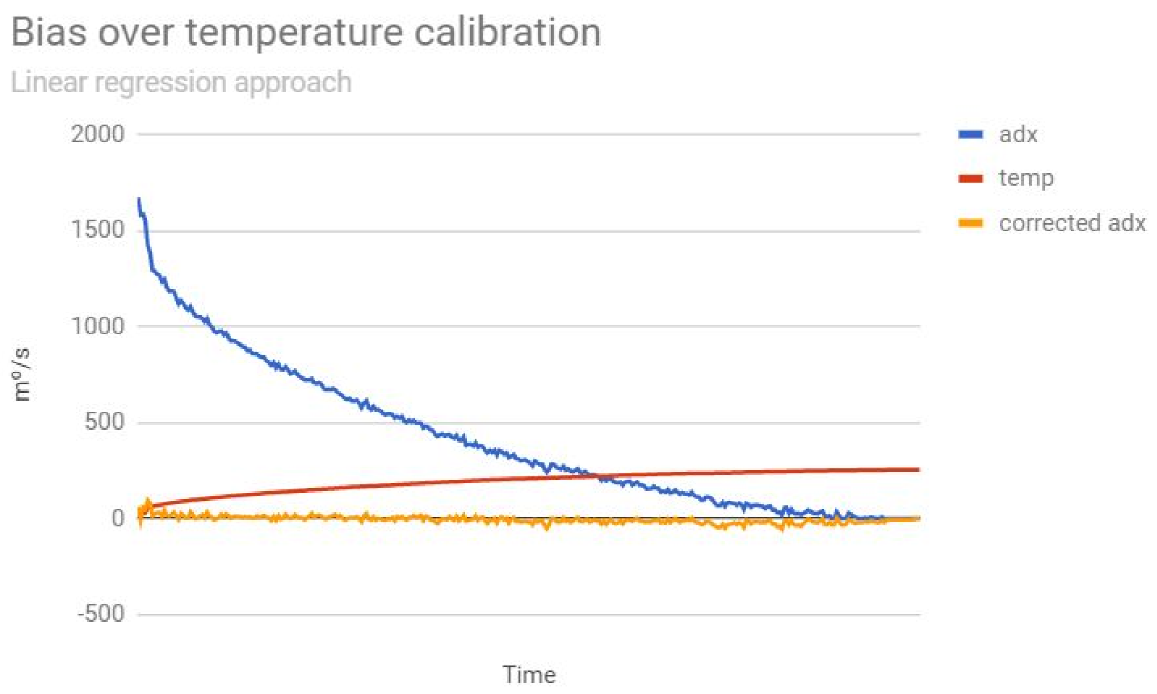
The next Section describes the tests executed by the author aiming to validate the calibration procedures proposals.

4.1 Gyroscope bias over temperature

The author's first executed test on gyroscope bias over temperature calibration was using linear regression, as explained in Section 3.1.2. After performing the linear regression, the linear coefficient was used to compensate the bias, reading the temperature of the sensor periodically and when there is temperature variations, compensate the estimated bias.

Figure 14 shows an example of a bias over temperature calibration using linear regression approach. Figure 14: ADX refers to a gyroscope used during this test.

Figure 14: Linear compensation bias over temperature



Source: Gyroscope Tests report [A.1]

Although the linear regression approach seemed very effective, some gyroscopes data curves did fit considerably better on a second order polynomial regression instead.

The main difference on the polynomial regression to the linear regression is the curve fitting algorithm which is more complex. The extra non volatile memory used will not be relevant and the compensation algorithm does not require much extra computational time.

The author studied polynomial curve fitting algorithms which could run on the board microcontroller and Hexagon Agriculture engineers considered it feasible. A requirement of the curve fitting algorithm is a correlation between the estimated algorithm and the bias over temperature points. If the correlation is shorter than a threshold, this calibration would be aborted on the respective board.

An important point to note is that the shorter is the temperature variation that will be used as input to the polynomial regression the higher are the chances of the outputted polynome not representing bias over temperature well. The duration of the calibration is also important, the longer it takes, the higher will be influence of the bias over time instability, which is undesirable.

4.2 Vibration rejection

The author performed tests on using the accelerometer data to compensate linear g sensitivity, consisting of applying 1 g in each axis of the gyroscope, one by one, using the earth gravity.

This test was performed on 3 different gyroscopes and it was not possible to identify any linear g sensitivity. There is noise, multiple source bias and many other errors which also influence at the result, filtering it to isolate the linear g sensitivity proved to be a tough task.

The author concluded that in order to detect the linear g sensitivity on the available sensors it will be necessary to either perform effective calibration procedures on the gyroscope before trying to detect linear g sensitivity or to apply higher linear acceleration, using external equipments.

This calibration procedure was evaluated as not a priority, considering it was not possible to identify linear g sensitivity on the studied gyroscopes, it meant linear g sensitivity is not very relevant on the studied gyroscopes. Using external equipments for this calibration would mean high costs, sophisticated procedures and it is still potentially not going to represent relevant improvements.

There were no tests executed on the dynamic stop band filter, due to lack of time.

4.3 Communication errors treatment

In order to test the potential improvement on treating the communication errors, the author collected the raw data from the gyroscope, removing data which represented communication errors and then plotting the trapezoidal integral of the gyroscope data with and without the communication errors data.

There were no relevant difference caused by removing the communication errors. But the communication errors were still a very undesirable characteristic, specially by not knowing what causes it and not knowing if the amount of errors are the same in every sensor.

There was a meeting with Hexagon Agriculture's engineers and it was decided to refactor the whole code related to reading the data available from the IMU. With a better code, it would be easier to treat the communication errors.

4.4 Substitute the gyroscope

Measuring the improvement caused by substituting the gyroscope is a non trivial task. In order to determine which gyroscope is more accurate, a reference is required.

The preliminary studies described in Chapter 2 consisted on performing tests with Bosch's gyroscope BMG250, STMicroelectronics gyroscope A3G4250 and Analog Devices gyroscope ADXRS450 characteristics. ADXRS450 is a more expensive gyroscope and it was expected to be more accurate. In all executed tests BMG250 and ADXRS450 data were always similar, indicating their sensitivity was closer to the nominal sensitivity. The sensor noise was much higher in A3G4250 than BMG250 as well.

Analog Device’s ADXRS450 is built with a fully differential architecture as explained in [B.1] and it was possible to measure a approximately ten times lower vibration rectification in ADXRS450 when compared to BMG250 or A3G4250.

Considering the preliminary studies, Hexagon Agriculture decided to substitute the A3G4250 by BMG250, similar cost gyroscopes and apparently, from the preliminary studies, BMG250 performs much better.

There were further tests on the improvement achieved by substituting A3G4250 for BMG250, the results of those tests are available on Section 6.1.

4.5 Multiple position systematic errors calibration

In order to validate this calibration method proposed in [1], it was necessary to apply that calibration method on Hexagon Agriculture's studied IMU.

Developing this algorithm is no easy task, there are many details to be aware and the development itself would take a very long time. The objective was validating this calibration procedure first. With further researches online, the author found an open source repository from Alberto Pretto, author of [1]. Which contained the algorithm used on his paper. This algorithm was studied and parameterized to Hexagon Agriculture's studied IMU.

The first results were discouraging, the minimization algorithm did not converge, indicating the calibration procedure did not work, but after some more adjustments, the accelerometer calibration eventually converged. The second step was checking if the values which minimization converged were good, meaning the error parameters estimation was accurate.

To check if the calibration procedure worked, it was available the calibrated accelerometer data and uncalibrated accelerometer data. But there were no reference to check which data was more accurate.

To check if there were actual improvement with the calibration, the author's mentor at the company indicated using fifteen boards, calibrate them all and then log the accelerometer data during very similar set of movements with these boards. Compare the uncalibrated accelerometer and calibrated accelerometer data from all of them, checking if the calibrated accelerometers data converge, which would mean the calibration was actually working.

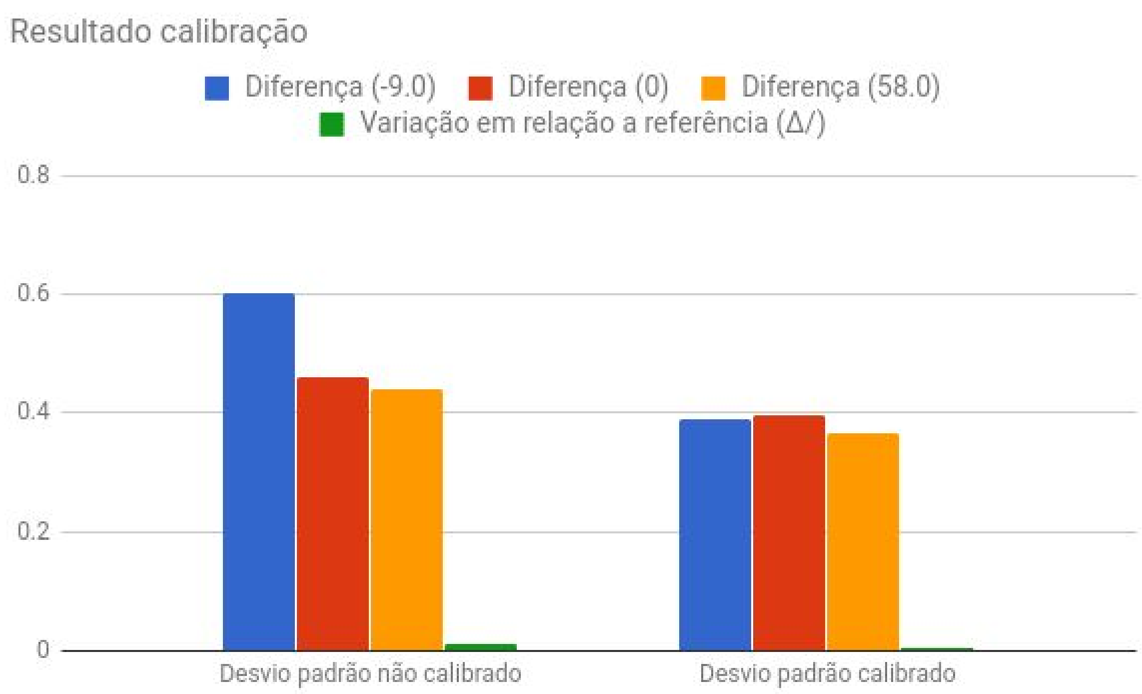
To repeat the same set of movement on the boards, a rotating platform was built, shown at Figure 15.

Figure 15: Rotation board

Source: Author's personal archive

In order to estimate the improvement achieved by the calibration, the author attached an encoder to the rotating board and positioned all 15 boards where the encoder indicated -9.0º, 0.0º and 58.0º. The roll of every board on those positions was calculated, using the uncalibrated accelerometer and calibrated accelerometer data. Then compared the standard deviation of the calculated roll with the uncalibrated accelerometer data and calibrated accelerometer data. When lower standard deviation between the data, means the results are converging and probably to the *real* value. The result is presented in Figure 16.

Figure 16: Accelerometer multiple positions calibration results

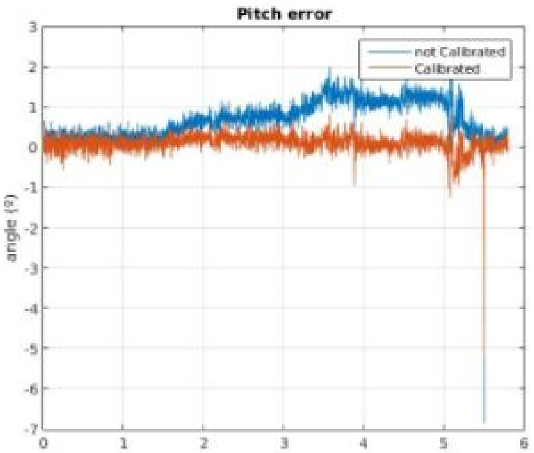


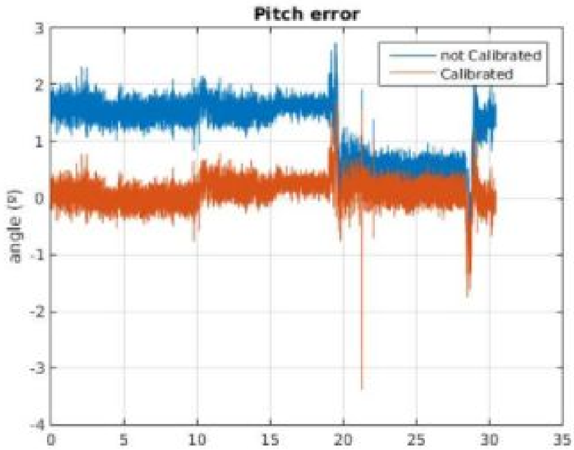
Source: IMU Calibration Report [A.2]

Figure 17 shows an example of the calibration improvement. It is plotted the error on the pitch estimation using the accelerometer data. The encoder data was used as reference to calculate the error. The important characteristic to notice is that the not calibrated data varies significantly from the reference, there is no guarantee the reference is accurate but the pitch output should always have the exactly same offset to the reference form the encoder.

It is possible to see in Figure 17 that the calibrated accelerometer data variation to the reference is much lower than the uncalibrated accelerometer data, which is a very strong indicator that the calibration procedure worked indeed.

Figure 17 (a): Accelerometer calibration output 1 (b): Accelerometer calibration output 2





Source: IMU Calibration Report [A.2]

The gyroscope calibration procedure, in the other hand, did not appear to improve the gyroscope data. The minimization algorithm did not converge after many attempts and sometimes it converged to totally non sense values. For those reasons it was possible to conclude that the proposed gyroscope calibration in [1] is not robust enough.

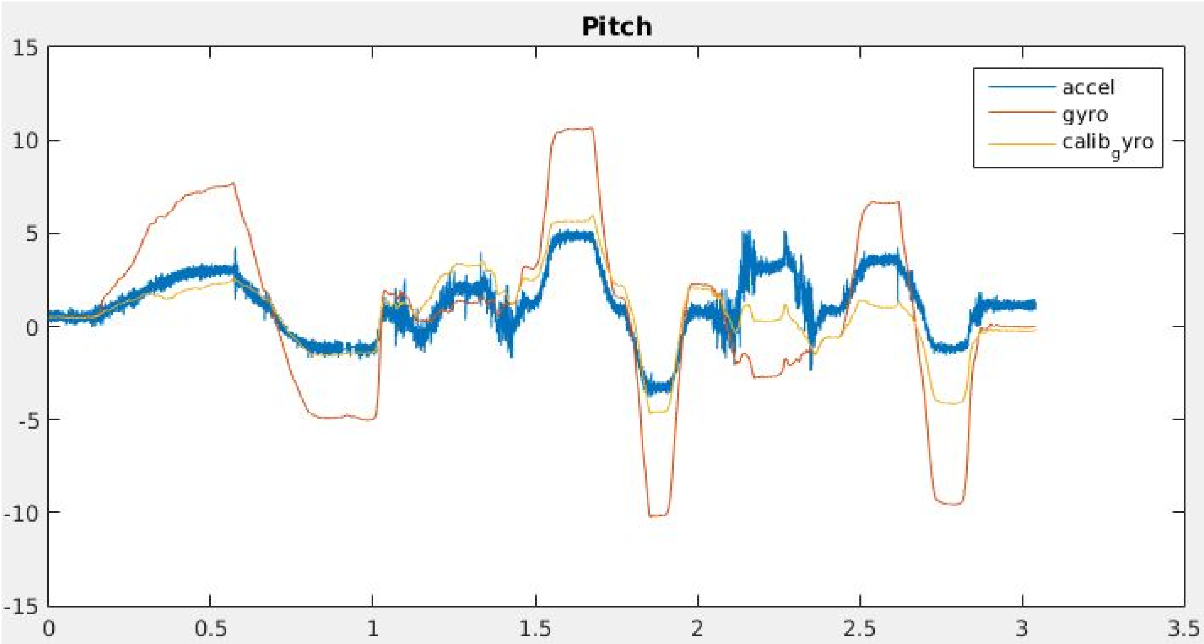
There were many attempts made by the author to make the gyroscope calibration proposed in [1], including improving the rotating platform, changing the set of calibration movements and even contacting the author, Alberto Pretto, via email and checking if he could understand why it was not converging. But there were no encouraging result.

The gyroscope calibration proposed in [1] was eventually evaluated as not feasible with the proposed algorithm as it is.

A very interesting test was forcing a misalignment on the gyroscope raw data and then using this data with the forced misalignment as input for the calibration method. If the calibration method actually worked, it should identify this misalignment and the resulting calibration matrix would fix it.

Figure 18 shows the data with the estimated pitch from the gyroscope with forced misalignment (*legend: gyro)*, the reference was the estimated pitch with the accelerometer (*legend: accel*). After applying the calibration method on the gyroscope data with forced misalignment the pitch was plotted (*legend calib gyro)*.

Figure 18: Forced misalignment



Source: IMU Calibration report [A.2]

Due to time constraints, the implementation the gyroscope multiple positions calibration was left as future work.

4.6 Include a magnetometer

When the author proposed the idea of including a magnetometer, Hexagon Agriculture's engineers explained that including a magnetometer has already being considered and discussed, and eventually the idea was rejected.

Hexagon Agriculture engineers explained Magnetometers are very susceptible to interference. This interference can be demonstrated by moving one smartphone close to another with a compass application running then it will be possible to realize that the compass is drastically affected by the other smartphone magnetic field.

Considering how susceptible to interference magnetometers are, it would be very risky to use magnetometers at the wide range of Hexagon Agriculture's Auto Steering system working conditions.

5 IMPLEMENTATION

There were many tools used during this project development, they are discussed at this Chapter.

5.1 Development Methodology

To implement the proposed calibration procedures, the author used Hexagon Agriculture's development methodology.

Hexagon Agriculture uses Agile Methodology with two weeks sprints. Every cycle starts with a sprint planning, where the team decide which tasks are going to be performed throughout the spring, vote on the task's complexity and discuss their requirements. On the end of every sprint there is a sprint review meeting.

Agile Methodology was very suitable to this project, since the project scope was constantly changing according to the tests results and the agile method short cycles made it possible to analyse the results, adapt the planning and decide new strategies methodically.

5.2 Used Softwares

Hexagon Agriculture uses the software Jira [7] for issue tracking, project planning and documentation. Jira is integrated with a version control software: Git [8], which is managed by Bitbucket [9].

Jira keeps all documentation of the project, description and motivations It is a very useful tool to keep track of the project development.

Git and Bitbucket were essential in every phase of the project. Git enables keeping every version making it possible to go back whenever necessary and it is vital when multiple people work at the same project. While bitbucket is a really good tool to visualize how the different branches are progressing, learning and reviewing other team members code.

To develop the firmwares for the microcontroller which communicates with the IMU the author used Kinetis Design Studio Integrated Development Environment [11]. It enables editing, compiling and debugging, it is based on free, open-source software including Eclipse [12], GNU Compiler Collection (GCC) [13], GNU Debugger (GDB) [14] and others.

In order to download the developed firmwares to the board it was necessary to use P&E's Micro plugins and drivers.

Most of the development tools were available at Hexagon Agriculture webpage devtools, including instructions on how to develop code using Hexagon Agriculture standards, code style and more. A very important aspect on Hexagon Agriculture software development procedures is writing unit tests, which is a vital way to minimize bugs and developing new features without breaking previous versions.

In order to analyze the data collected from the IMU, the author used Google Sheets [14] and Matlab [15]. All the reports were written using Google Docs [16]. The documents and tests results were stored and shared with Google Drive [17].

5.3 Used Hardware

The Microcontroller used was 120 MHz Arm Cortex-M4-based Microcontroller with FPU.

To download the firmware into the microcontroller Hexagon Agriculture uses P&E's Micro USB Multilink Debug probe.

The author used two Hexagon Agriculture's boards with mounted IMU, Hexagon Agriculture's driver ATCD and Hexagon Agriculture's driver HXAN. Those boards communicate with Hexagon Agriculture's onboard controllers Ti5 and Ti7.

The IMU components tested by the author were gyroscopes: Bosch's gyroscope BMG250, STMicroelectronics gyroscope A3G4250 and Analog Devices gyroscope ADXRS450, and accelerometer: NXP Semiconductors accelerometer MMA8451Q.

There were also used soldering tools, oscilloscopes, multimeters and other equipments.

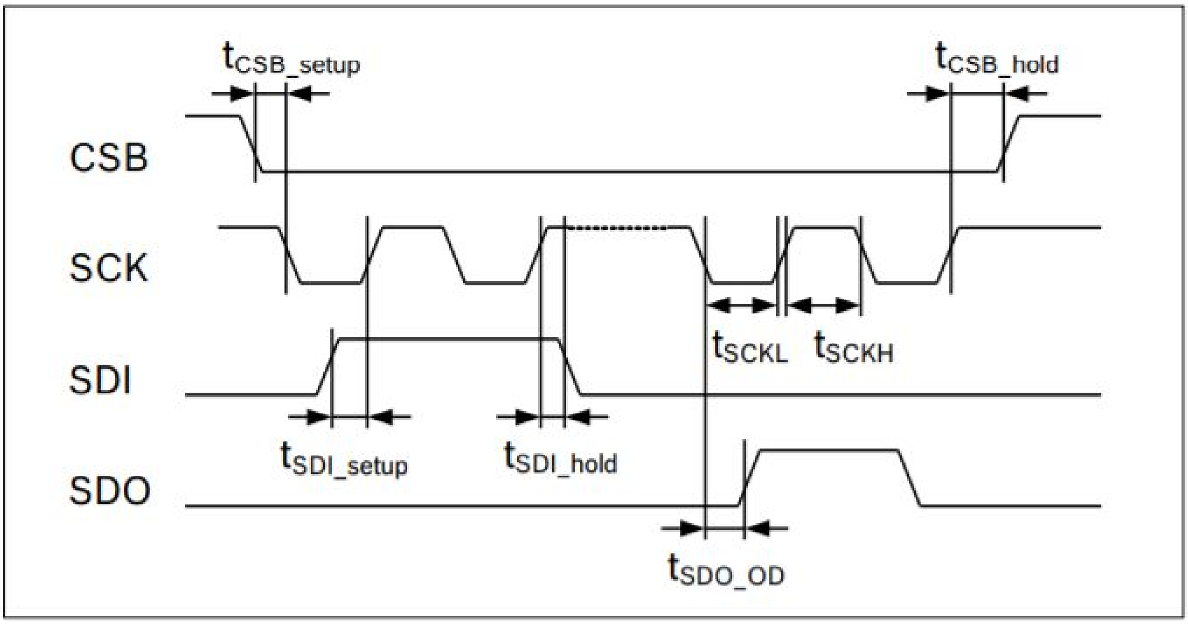
5.4 Implemented calibration procedures

Most of the proposed calibration procedures were not implemented during the timespan of this project. The implemented or partially implemented procedures are discussed in this Section.

5.4.1 Minimizing communication errors

In order to minimize the communications errors between the microcontroller and the IMU, the author studied SPI characteristics and tried manipulating it's possible configurations.

Figure 19: BMG250 SPI timing diagrams



Source: BMG250 datasheet [B.4]

The first attempt was slowing down the SPI clock, even though it was working on lower frequencies than the sensors limit, according to their datasheet. It did not work, actually some sensors had actually more communication errors with lower SPI clock frequencies.

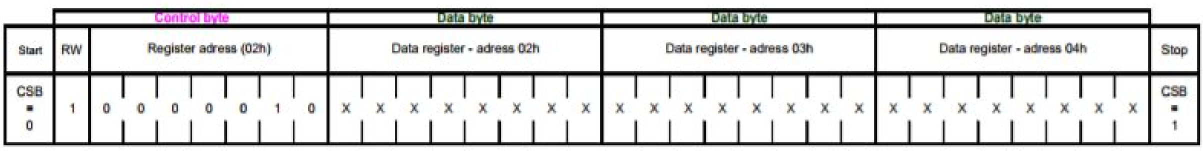
The SPI clock has a default value, it is described as clock polarity, Bosch's gyroscope BMG250 can work with the clock default as high or low. The author tried both set ups, but the communication errors did not cease.

On SPI communications it is necessary to use a Chip Select signal to start transmitting. There is minimum delay between the Chip Select and the clock first pulse. The author tried raising the delay between the Chip Select and the clock first pulse, but that did not achieve any improvement as well.

An important timing characteristic is the minimum delay between read access. The author did try raising the delay between messages when without success and eventually realized that there were always three consecutive read access, one for each accelerometer axis which did not have delay between them.

There is a multiple read access mode on both Bosch's BMG250 and STMicroelectronics A3G4250, which sets the Chip Select once and read multiple registers in sequence as shown at Figure 20.

Figure 20: SPI multiple read principles

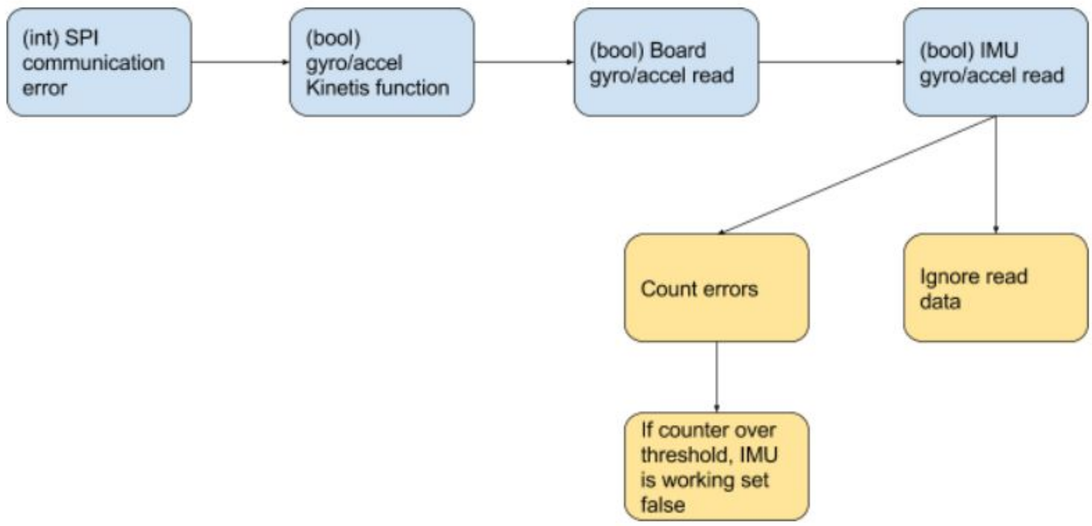


Source: BMG250 datasheet [B.4]

The author configured multiple registers read mode and the result was great, on BMG250 there were no more apparent communication errors and on A3G4250 it were drastically reduced.

There were also a simple detecting errors algorithm implemented, using the the data flow illustrated in Figure 17. This error detection algorithm detects a few timing related errors but does not detect non sense data as the communication errors which were described previously.

Figure 21: IMU errors detection data flow



Source: IMU calibration report [B.2]

5.4.2 Bias over temperature

The bias over temperature calibration is made in two steps:

1. Find Polynom

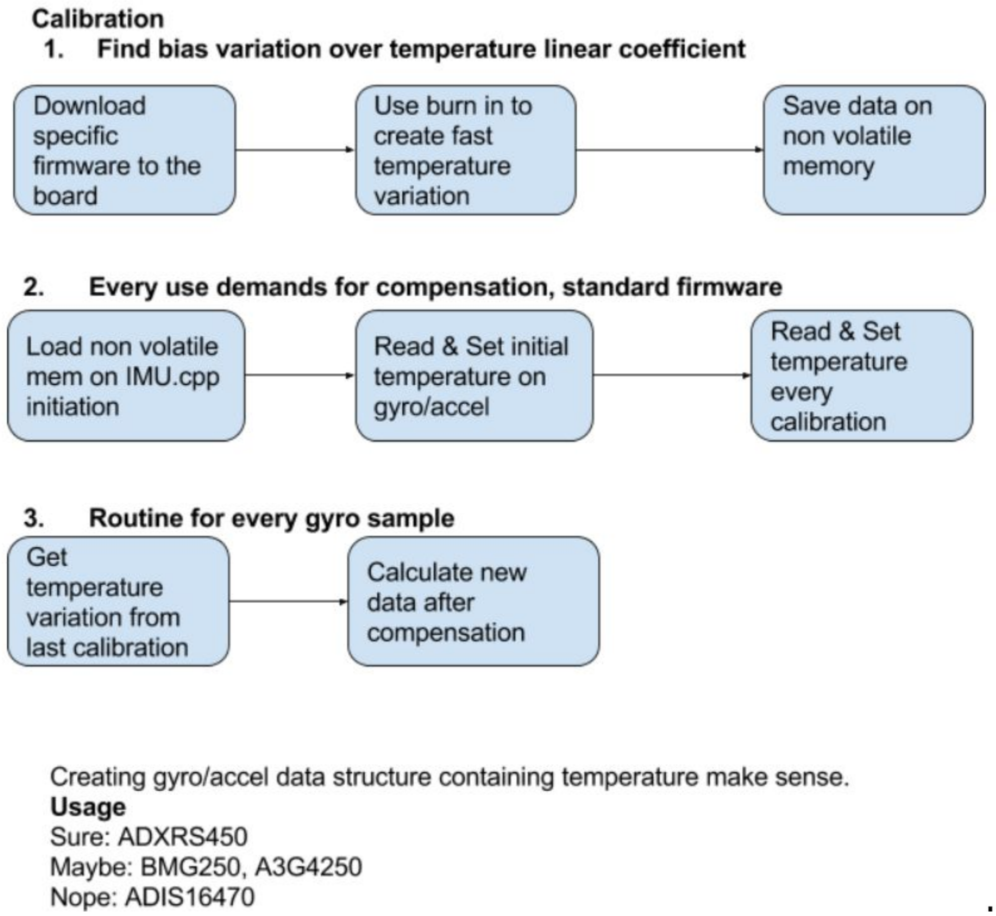
   This step consists in downloading a specific calibration firmware to the board, this firmware will contain a polynomial regression algorithm. The board will be put inside a Burn In and powered on, the firmware then will start logging the gyroscope data during a specific time with varying temperature. When this time is done, the linear regression algorithm will run and if the approximation is good enough, the polynomial coefficients will be written at the board's non-volatile memory.

2. During operation

   During operation, the sensor temperature will be read every couple seconds and every time there are temperature variations, the bias estimation according to the polynomial regression will subtracted from the gyroscope raw data.

This procedure is illustrated in Figure 22.

Figure 22: Bias over temperature calibration scheme



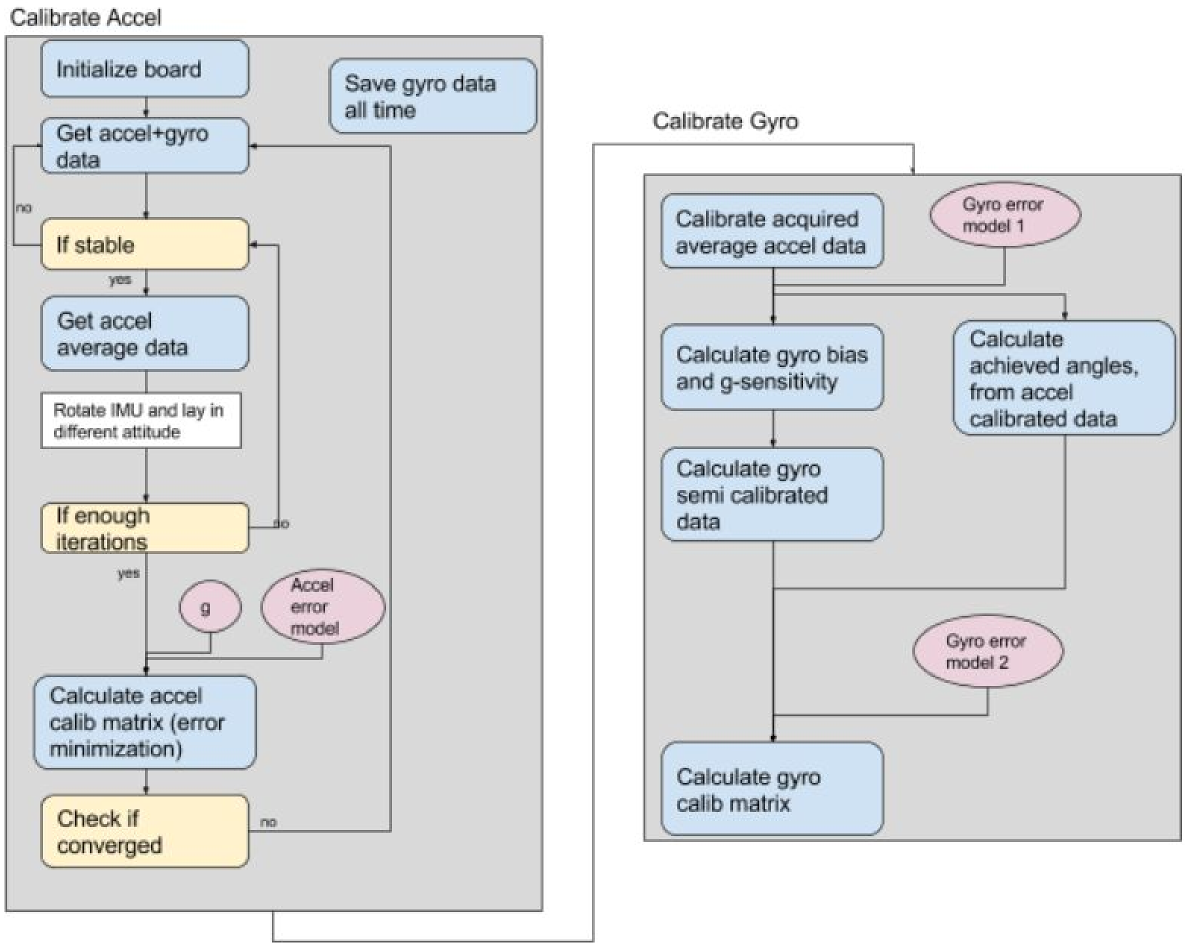
Source: Gyro Accuracy improvement algorithm design [A.3]

5.4.3 Multiple positions calibration

As explained in Chapter 4, the multiple positions calibration described in [1] was considered feasible, the accelerometer calibration did present relevant results.

On [1], it is explained that the aimed results are misalignment calibration matrices, sensitivity and bias vectors. In order to obtain these matrices and vectors it is necessary to perform the procedure illustrated at Figure 23.

Figure 23: Multiple position calibration scheme

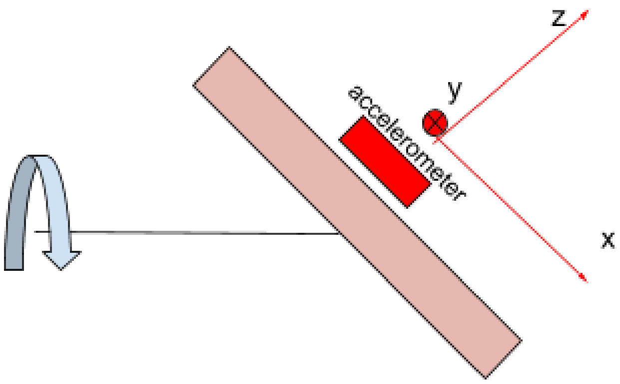


Source: Gyro Accuracy improvement algorithm design [A.3]

The algorithm which performs this calibration may require a significant amount of memory and computation time, therefore, a specific firmware designed to perform this calibration should be developed.

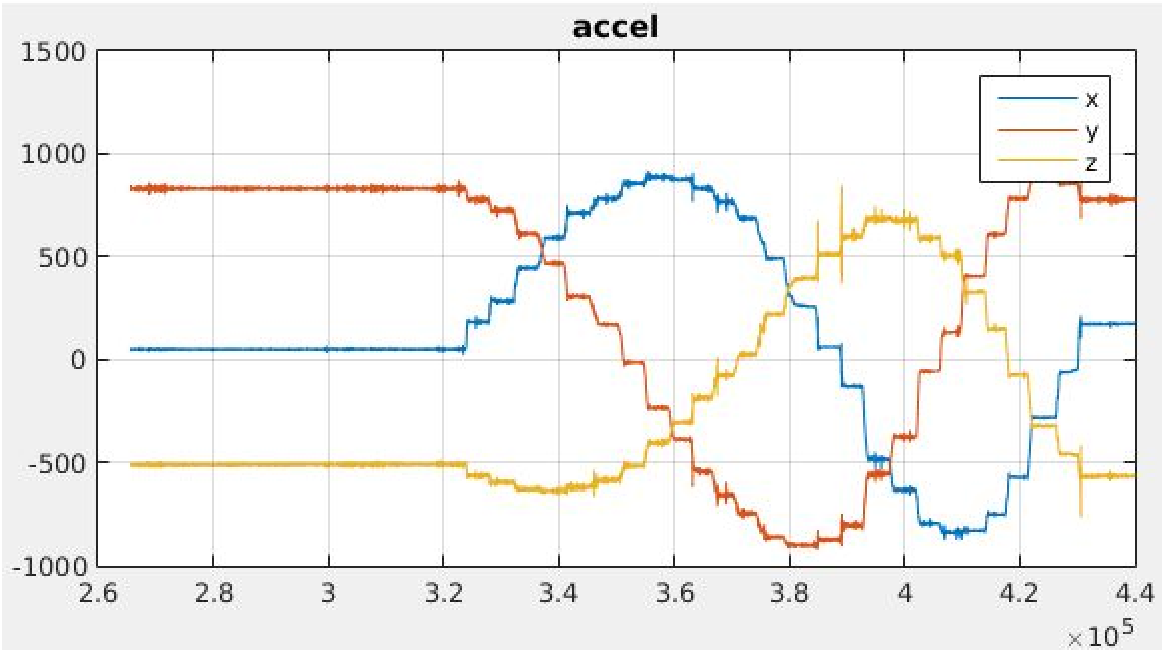
During the tests, the author realized a very interesting possibility, rotating the board using a single axis rotation on a dislocated platform as shown in Figure 24 could accomplish enough observability to the accelerometer calibration, as shown in Figure 25.

Figure 24: Dislocated rotating platform



Source: Author's creation

Figure 25: Single axis rotation accelerometer data



Source: IMU Calibration report [A.2]

The estimated time for the complete calibration of each board would be downloading the calibration firmware, placing the board at the rotating platform and performing the expected set of movements. Which all together may take approximately 2 minutes per board.

The rotating platform can be created using available materials at Hexagon Agriculture's headquarters, with no extra costs.

While the IMU is on use, the achieved calibration matrixes would be multiplied to the accelerometer raw data, this is explained in [1].

6 RESULTS

This project was mostly consisted on studies and validation tests. The actual implementation within the time constraints was only possible on reducing the communication errors and substituting the gyroscope.

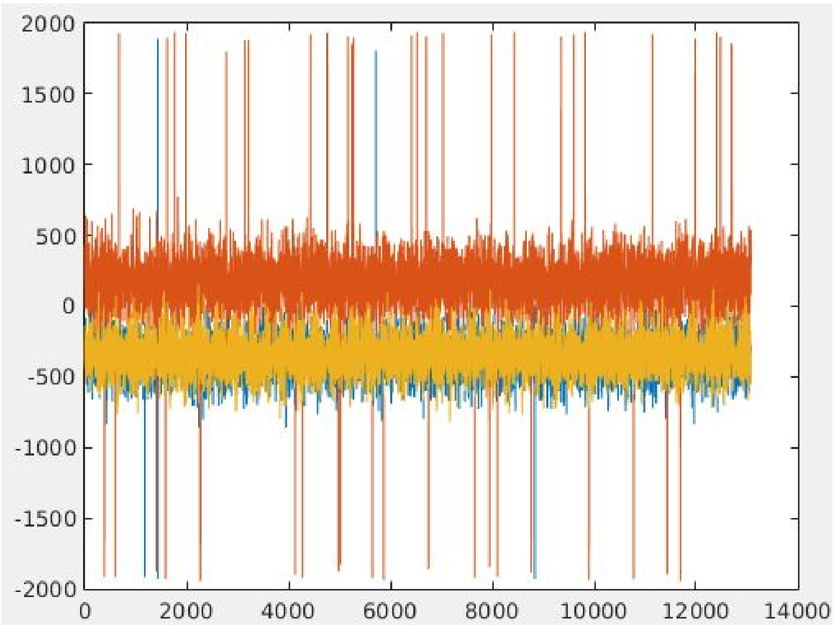
6.1 Reducing communication errors

As explained in Chapter 4, reducing the communication errors did not have any apparent improvement on the IMU performance, it was a measurement to improve the system's reliability.

The result of the IMU communication errors study was changing the how the gyroscope rate registers are read, using multiple registers read mode which successfully reduced the communication errors.

Figure 26 shows how did the gyroscope raw data looked before using multiple registers read mode.

Figure 26: Communication errors prior to fix



Source: Imu Calibration Report [A.2]

6.2 Replacing the gyroscope

On replacing the gyroscope, the strategy defined to test the improvement achieved by substituting STMicroelectronics gyroscope A3G4250 by Bosch gyroscope BMG250 was mounting both sensors on the same board and put this board on a vehicle, use the Auto Steering system on this vehicle at rough terrain conditions and measure the achieved improved.

To estimate the improvement achieved by this substitution it was necessary to compare the estimated data by the INS to a reference as close as possible to the actual vehicle's attitude. It was used Novatel Align firmware, which is a composed by two GNSS antennas, that comparing their relative position, it provided the vehicle's heading and roll with great accuracy.

The tests consisted of comparing the roll provided by Novatel Align to the roll provided by Hexagon Agriculture's INS with gyroscope A3G4250 and gyroscope BMG250.

When considering the cost, Bosch’s BMG250 has a very similar cost to STMicroelectronics A3G4250, therefore the decision to replace the gyroscope did not increase the IMU cost.

7 CONCLUSIONS AND FUTURE WORKS

The author expects this project to generate a very positive impact in Hexagon Agriculture. This project was not only developed for Hexagon Agriculture but it was also of great importance for the author's education. The impacts in both company and author's education are discussed in this Chapter.

7.1 Author's background

The author learned a lot while developing this project, specially adapting to Hexagon Agriculture's development tools and methodology. UFSC's Automation & Control Engineering bachelor does have a course where systems development methodologies are addressed, but object-oriented software engineering was not studied as deep as required for this project. The author had not properly used version control softwares until the beginning of this project, which would have been a great tool to improve the author's teamwork skills.

DAS successfully taught the author on thinking methodically, analysing problems and proposed solutions. Instrumentation and Electronic were highly needed throughout the whole project, the author had a solid base at these areas. Many other areas covered by UFSC's Automation & Control Engineering bachelor were used, it can be mentioned: Signal processing, Numerical analysis, Microcontrollers architecture and programming and Real time systems.

It was clear that the wide range of areas covered by UFSC's Automation & Control Engineering bachelor enabled the author to rapidly learn the specific areas required for developing this project.

7.2 Project impact

The most valuable conclusion of this work is that it is possible to develop cost effective calibration procedures for MEMS IMU and there is a great improvement potential on the studied IMUs.

Even though most of the proposed calibration procedures were not fully implemented, the executed tests results were very encouraging and the improvement potential is very clear. The most important unanswered question is how long are those calibration procedures expected to last.

It is very difficult to be sure how long the sensor characteristics described in 2.1 will remain, possibly throughout the sensor lifecycle it's characteristics will change, but when and how significantly it will be it is not known. The author even contacted the manufacturers, inquiring about the sensor performance throughout its lifespan, but they had no data about it.

The calibration will last just as long as the sensors characteristics remains. As the stability of the sensors characteristics is unknown, the calibration timespan is also unknown.

Besides the calibration timespan uncertainty, there are some encouraging results presented in Chapter 6.

Analysing the proposed calibration which have not been implemented yet, bias over temperature can definitely be considered as the best cost benefit proposal. Considering it is relatively easily to implement and it correct bias, which is the most relevant studied error on the gyroscope.

The multiple position calibration proved promising for the accelerometer as shown at section 4.5. In order to implement this procedure during the board production, it was planned to use a motor for the one axis turning table, diminishing the chances of mistakes by manually rotating the board. As for the gyroscope, more studies have to be done, the results were not as expected from [1].

Vibration compensation potential has not been proved yet, the first set of tests using FFT were executed after data was retrieved from the IMU log. In order to implement such solution, the FFT algorithm must run in real time at the microcontroller, which has limited power and it would definitely be challenging, demanding a significant amount of effort to develop and test this solution, therefore it was not prioritized by Hexagon experts.

Hexagon Agriculture may be highly benefited with this project, especially when considering applications which demand very high accuracy. In applications which demands high accuracy, Hexagon Agriculture provides highly sophisticated

GNSS modules which supports RTK with centimeter accuracy level. If those applications which demand very high accuracy are on rough, inclined terrains, the IMU is necessary for the tilt correction explained in Section 1.2. Non calibrated IMUs may not be as accurate as it is required for those applications.

Perhaps the most important advantage of this project is the certainty that every calibrated IMU will perform alike. Without the calibration there is the possibility of using a specific part with much lower performance, as most of the performance specifications on the IMU components datasheet are just typical.

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APPENDIX A

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