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2016•2017
Faculteit Industriële ingenieurswetenschappen
master in de industriële wetenschappen: elektronica-ICT

Masterthesis

Human equilibrium augmentation in an exoskeleton using IMUs

PROMOTOR :
Prof. dr. ir. Nele MENTENS

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dr. Ludo CUYPERS

COPROMOTOR :
Dhr. Michel D'HAVE

Bram Willekens
Scriptie ingediend tot het behalen van de graad van master in de industriële wetenschappen: elektronica-ICT

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Preface

Enhancing the human body has intrigued me for many years now. Building something which helps people do things they never could or cannot do anymore, fits my interests completely. Since AXOSUIT focuses on the elderly, working on improving their full-body personal mobility, reaching and grasping abilities, this project suits me entirely. Aware of the fact that the life expectancy of people generally rises, the need for these kinds of applications will grow accordingly. Contributing to the quality of many lives, including those of my friends, my family - and maybe myself - makes me feel worthwhile.

Therefore, this master's thesis has been an enjoyable project despite the long hours and hard work. I frequently stayed up late working, just being absorbed by the project and completely losing all sense of time.

I would like to thank my external promotor Dr Ludo Cuypers for giving me the opportunity to be part of his research team. But also for his perceptive comments and questions that guided me to accomplish this master's thesis.

I also owe much gratitude to my internal promotor Prof. Dr. Nele Mentens for her valuable feedback, which provided me with more insight into how this thesis could be improved.

I would like to extend this gratitude to all the members of COMmeto, functioning as part of this team, motivates me to contribute my part the best I can.

I also owe much appreciation to mother Ingrid, my brother Toon and the rest of my family, for trusting and believing in me.

To my partner Yana and my friends, for encouraging me and supporting me from the sidelines. Their love and friendship made the path less troublesome and more fun.

And finally, to all my fellow students who created an enjoyable but also a motivational atmosphere.

Table of Contents

List of Tables

List of Figures

Glossary of Terms

ADL	Activities of Daily Living: Basic self-care activities, usually learned in early childhood. A few examples are eating, toileting, dressing, taking a bath and walking.
AXO-SUIT [1]	AXO-SUIT is the project in which COMmeto is involved, the exoskeleton mentioned in this thesis is its product.
DoF	Degrees of Freedom: In mechanical devices, DoF is the number of independent parameters that define the state of a physical system. In an IMU with 9 DoF, for instance, the position, orientation, and magnetic orientation are each defined by 3 components of translation, rotation and magnetic field.
iADL	Instrumental Activities of Daily Living: More advanced skills necessary to live independently. Examples of this are cooking, shopping, housekeeping, managing finances and driving.
IMU	Inertial Measurement Unit: An electronic device which measures the linear accelerations, angular rate and in some cases the surrounding magnetic field vector.
MCU	Microcontroller Unit: A small, chip-sized and self-contained computer system usually on a single integrated circuit.

Abstract (Nederlands)

COMmeto BVBA is betrokken bij diverse R&D-projecten, waaronder AXO-SUIT, een project dat drie jaar gefinancierd is in het kader van het AAL-Joint Programme. Het project onderzoekt de persoonlijke behoeften van ouderen, zodat die hun dagelijkse activiteiten (ADL, iADL) ongestoord kunnen voortzetten.

Het AXO-SUIT exoskelet biedt geen ondersteuning aan het evenwicht van de persoon die het draagt. Wanneer er evenwichtsproblemen optreden, moeten de gebruikers hun evenwicht zelfstandig behouden. Het doel van deze masterproef is om te onderzoeken in welke mate Inertial Measurement Units (IMU) kunnen bijdragen tot het detecteren van evenwichtsproblemen en welke algoritmen er nodig zijn om de informatie te leveren over hoe de bewegingen van het exoskelet bijgesteld moeten worden zodat het exoskelet geautomatiseerde hulp geeft bij het behouden van het evenwicht.

Omwille van de complexiteit van het menselijk lichaam, de kosten en het energieverbruik, is er een literatuurstudie uitgevoerd om de vereisten van de IMU's en de communicatieprotocollen te bepalen. Na deze selectie is er een model gebouwd om de data-acquisitie van de IMU's te testen. Door deze data te interpreteren, zijn de relatieve posities van de IMU's berekend en de hoek tussen de twee scharnierende delen bepaald. Ten slotte, om de resultaten te valideren, zijn de berekeningen vergeleken met andere sensoren en zijn de vastgelegde gegevens weergegeven in datastructuren die relevant zijn in de context van de andere datastructuren van het exoskelet.

Abstract (English)

COMmeto BVBA is involved in several R&D projects, one being AXO-SUIT, a three-year project funded under the AAL Joint Programme. The project specifies full-body personal requirements of elderly persons, allowing them to continue their daily activities (ADL, iADL).

The AXO-SUIT exoskeleton does not provide any support to the equilibrium of the person wearing it. So, when equilibrium issues occur, the persons wearing the exoskeleton must keep equilibrium on their own. The purpose of this master's thesis is to research how Inertial Measurement Units (IMU) can contribute to detecting the equilibrium problems and which algorithms are needed to provide information on how to adjust the movements of the exoskeleton so that the exoskeleton gives automated assistance to improve the equilibrium of the exoskeleton and its user.

A literary study on the requirements for the IMUs and the communication protocols was conducted taking into account the human body's complexity, cost and power consumption. After making a selection, a model was built to test the data capturing of the IMUs. These data are interpreted to calculate the relative positions of the IMUs and to determine the angle between the two hinging parts. Lastly, to validate the results, the calculations are compared with other sensors and the captured data are represented in data structures that are relevant in the context of the other exoskeleton data structures.

1 Introduction

COMmeto BVBA [2] is involved in several research and development (R&D) projects. One of them is AXO-SUIT [1]. AXO-SUIT is a three-year project which started on October 1st 2014 and is funded under the Active and Assisted Living (AAL) Joint Programme, Call 6. The project brings together 3 universities and 5 companies active and experienced in R&D of assistive devices. The goal is to specify the full-body personal mobility, reaching, and grasping requirements of elderly persons, allowing them to continue managing their daily activities. This involves voluntary occupation (maintaining gardens, carrying groceries, shopping, cooking and activities of daily living (ADL, iADL)) as well as participating in local social activities while preserving their health and providing motivation to remain active and independent.

1.1 Problem Definition

Currently the AXO-SUIT exoskeleton does not provide any support to the equilibrium of the person wearing it. So, when equilibrium issues occur, the persons wearing the exoskeleton must keep equilibrium on their own. It is desirable that the exoskeleton gives automated assistance to improve the equilibrium of the exoskeleton and its user.

1.2 Question

The purpose of this master's thesis is to research how IMUs can contribute to detecting the equilibrium problems. Another goal is to investigate which algorithms are needed to provide information on how to adjust the movements of the exoskeleton so that the exoskeleton gives automated assistance to improve the equilibrium of the exoskeleton and its user.

1.3 Objective

By September 4, 2017 the data from each 9-DoF IMUs are captured correctly. These data are represented in an algorithmic structure that corresponds to the real-life posture of the exoskeleton. The data representation is converted to the corrective data sent to the actuators on the exoskeleton.

1.4 Materials and Methods

1.4.1 Literature Study

For the exoskeleton to be able to measure any possible equilibrium issues, IMUs will be placed on the exoskeleton's limbs and body. The first task is to determine the requirements (sampling frequency, accuracy…) on the IMUs. Therefore, research on the equilibrium of the human body is required. After a study on the possible IMU candidates, the most cost-effective IMU is selected amongst these candidates. Secondly, the amount of IMUs necessary and their locations are determined and the protocols for the communication between the IMUs and the microprocessor unit are defined. Finally, the most appropriate representation of the data captured by the IMUs is selected.

1.4.2 Test Setups

After the components and communication protocols have been selected, a test setup will be built to set up the IMUs and start capturing data. Initially, the model used will be a single joint model with only one degree of freedom, like a knee or an elbow. Once the IMUs are correctly installed on the model and data can be captured, the data should be interpreted to calculate the relative positions of the IMUs and determine the angle between the two hinging parts. To validate the results, the calculations will be compared with other sensors. The captured data should be represented in data structures that are relevant in the context of the other exoskeleton data structures.

Possible future expansions consist of the modelling of a human leg and to use the developed data representation to keep this model upright. Therefore, an algorithm should be built which will take the received data as input and calculates the corrective data to be sent to the actuators.

A final model could be a mechanical lower body, with the purpose to keep the model's equilibrium while disruptions occur. The origin of the disruptions are external forces or movements on the upper body.

1.5 Outline

This master's thesis is written as a single document, all chapters are related to the same objectives and results. In chapter 1, a quick "Introduction" summarizes the overall objective of the master's thesis and describes how the different chapters are organized. To continue, the next chapter, chapter 2, contains the necessary information regarding the complications following the use of "Inertial Measurement Units as Wearable Orientation Sensors". Chapter 3 states the different "Objectives" of this master's thesis together with the questions they pose. Chapter 4 contains the "Materials and Methods" and describes how the IMUs and communication protocols were selected and how the data are handled. A quick explanation of the "Problems" that occurred during the project and how they were dealt with is described in chapter 5. Finally, a "Conclusion" is drawn in chapter 6, summarizing concisely the results and gives a viewpoint toward future work.

2 Inertial Measurement Units as Wearable Orientation Sensors

2.1 Common Problems of IMUs when assessing orientations

Measuring with inertial-based sensors presents some degree of challenge. In theory, the position and the orientation of an IMU can be estimated precisely. However, in practice, errors easily build up due to drift, particularly on the long run. The same can be said for magnetic-based sensors, in which nearby ferromagnetic objects alter the measured magnetic field and distort the estimation of the magnetic field of the earth.

Solutions to these drift errors and magnetic field errors have been proposed in related work. The drift that gyroscopes build up over the course of longer periods can almost completely be reduced by using a filter such as a Kalman Filter. There are other possibilities to remove drift, like resetting when at the sensor is at rest, combining sensors, using constraints based on the joints and adding a magnetometer. But, as mentioned above, the magnetometer has magnetic distortions and will need corrections as well. This can be realised by implementing heading correction algorithms or by adjusting the Kalman filter to employ both inertial- and magnetic-based sensor data.

2.2 Necessity of Calibration

When dealing with sensors, especially inertial sensors, proper bias calibration is detrimental. Measuring linear accelerations and angular rotations while in motion only gives differential information. While this is useful to calculate the difference between the current and the previous state, it is vulnerable to sensor biases. These can be reduced by performing a substantial amount of measurement readings with the body at rest and preferably in a known posture. When the body is in this state, gravity is the only acceleration, there are no angular velocities and the magnetic field is static.

As with all wearable sensors, the placement of the IMUs on the body segments deviates due to irregularities in the different body types of individuals. Because of this, the relative position between IMUs deviates and depends on how they are positioned compared to the body joints. To provide this information, the person wearing the exoskeleton must perform certain positions in a calibration stage. The measurement data gathered during this stage will provide the information needed to create a biomechanical model which contains all necessary relations between each IMU.

2.3 Human Body Joint Angles

The human body is far from rigid, its biological limbs can be stretched in more ways than a single rotation. However, these rotations can be separated into rotations around 3 mutually perpendicular axes because of the conventional definition of Euler.

In the clinical reference system [3], shown in Figure 1, these rotations are divided into Flexion/Extension, Abduction/Adduction and Internal/External rotational motion. The Flexion/Extension angle of a human body joint is defined as the angle between both connecting limbs along the main axis of relative motion. Flexion defines the movement in which the angle between two body parts decreases, while extension is the opposite movement in which that angle increases. Abduction and adduction describe the angle with the midline of the upper body part, and defines the movement in which that angle increases and decreases, respectively. The internal and external rotation (medial and lateral rotation) involve the movement of the limbs along their long axis and define the movement towards and away from the body midline, respectively.

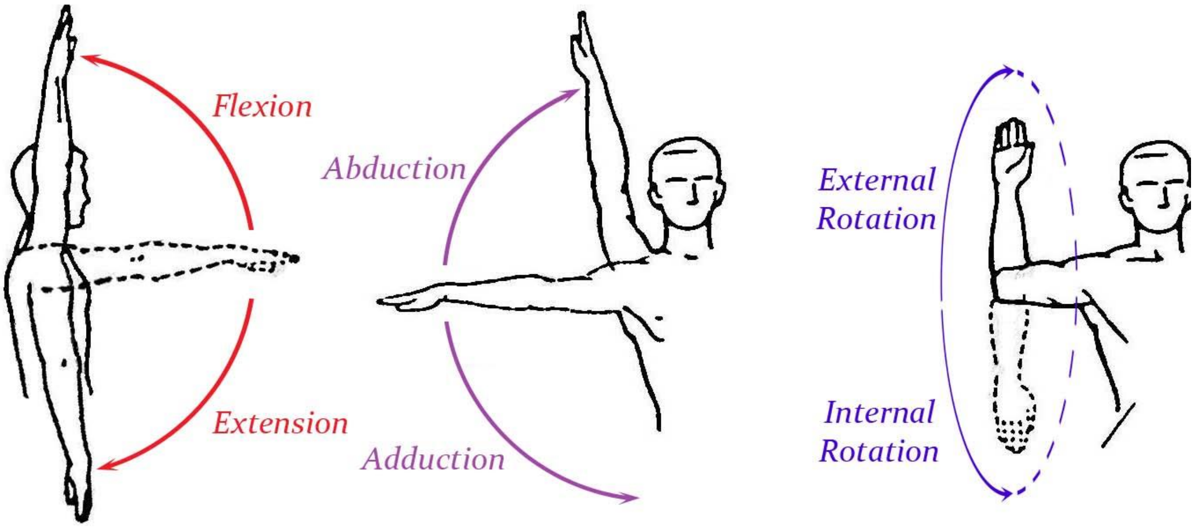

Figure 1: Clinical Reference System of the shoulder [4]

In contrary to mechanical rigid hinge joints, biological hinge joints, such as a knee or an elbow, are not constrained to rotating around a single axis. Abduction and adduction are relatively impossible to perform and internal or external rotations are relative small. Apart from the forearm, those angles almost never exceed a range of ±10°. Regarding this, together with the mechanical limitations of the exoskeleton, these additional DoFs are left out of consideration in those cases.

2.4 Defining the Orientation of an IMU

2.4.1 Measuring the Orientation at rest

To provide proper calibration and to calculate the exact locations on the body segments, the individual orientation of each IMU proves to be very useful. When the body is at rest, an accelerometer provides enough information to calculate the orientation relative to gravity, while the magnetometer gives an estimation of the magnetic field of the earth based on the locally measured one. Both vectors, gravity and magnetic field, are necessary to accurately estimate the orientation of the IMU.

The accelerometer measures three Cartesian components on its three axes of sensitivity. These represent the total of all accelerations in those three theoretically independent directions. Even though there usually is some degree of cross-axis sensitivity in practice, in the case of the MPU-9250 this is maximum 2% and relatively small. In Figure 2, the three separate axes of the accelerometer are shown. When the body is at rest there is no other acceleration except for gravity, meaning that the Cartesian components of the gravity vector are directly measured by the accelerometer as shown in Figure 3.

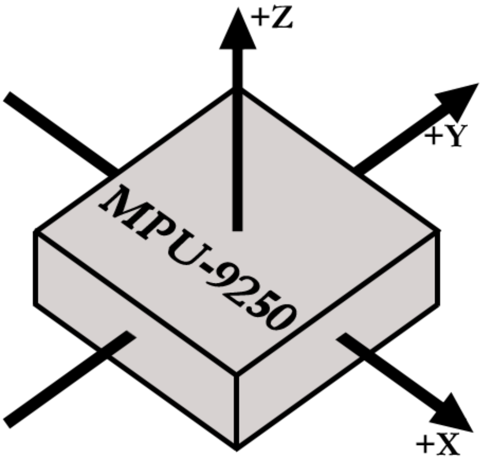

Figure 2: Accelerometer axes

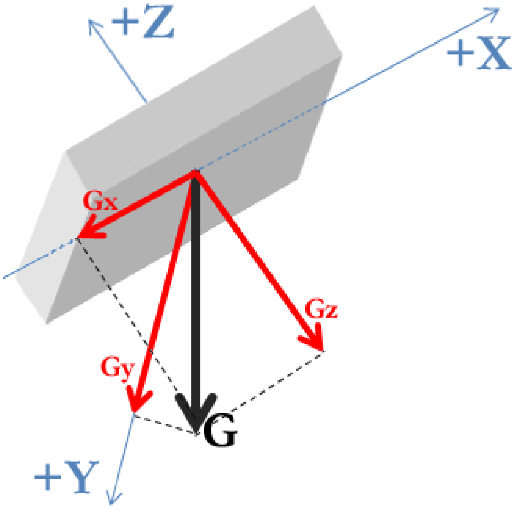

Figure 3: Gravity vector split into the accelerometer's Cartesian components

Since the force of gravity always acts perpendicular to the surface of the earth, by performing trigonometric functions, it is possible to calculate two out of the three Cartesian angles. In flight dynamics (see Figure 4), where the z-component of gravity is usually the largest, these would be called roll and pitch. Roll and pitch are defined as clockwise rotations around the x-axis and y-axis, respectively.

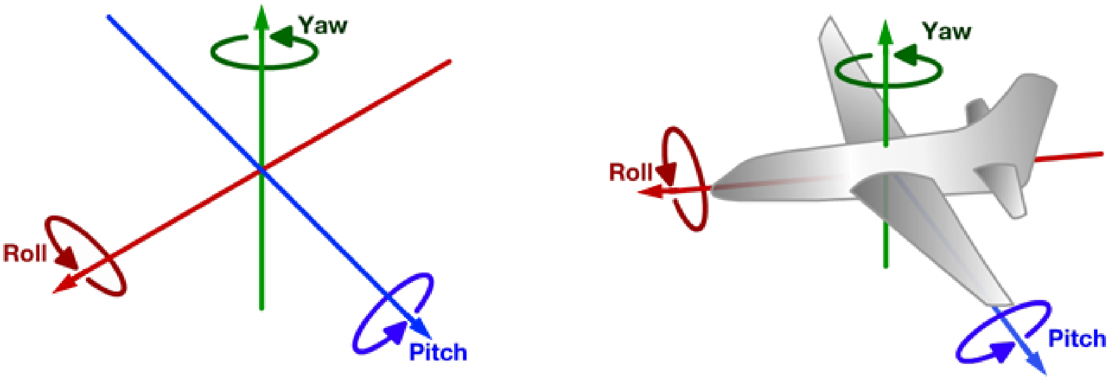

Figure 4: Flight dynamics: Roll, Pitch and Yaw [5]

Considering that an orientation requires at least 2 vectors with different directions to be unique, in addition to the gravity vector, the magnetic field vector can be used. This vector depends greatly on the sensor's location on earth, but unless traveling massive distances without recalibrating, it will be nearly static. However, nearby ferromagnetic objects will distort the measured magnetic field and can prove to be problematic when the distortion becomes proportionally big.

With that in mind, we can calculate the orientation during periods where there is little to no movement. Examples of these are the calibration stage where the positioning of the sensors on the body segments is determined, and the biomechanical model containing that information is created.

2.4.2 Calculating the Orientation during Movement

Since accelerometers measure the total acceleration and not just gravity, with the body accelerating in any other direction, the total acceleration vector can hardly be used to calculate the angle with the earth's surface. Therefore, the only vector left is the earth's magnetic field vector and although this vector can be used to restrain the possibilities, it is not sufficient to accurately estimate the orientation.

Another way to calculate the orientation is to use the gyroscope to calculate the rotations that occurred since a previously known state. The gyroscope measures the angular velocity, which can then be integrated with the time passed. Doing this provides the angle that the IMU has rotated during that period, after which the new orientation is calculated by rotating the previous orientation over these angles.

Using the gyroscope to estimate is much more accurate in short timespans compared to the accelerometer and the magnetometer, but in the long run it causes drift. The first cause of this drift is the gyroscope's sensor bias. The physical properties of an inertial sensor change slightly over time and use, which results in a small offset on the measured values. Over larger periods of time, this small offset will accumulate quickly, resulting in sufficiently larger errors. The second cause of gyroscope drifting are the errors accumulated during integration. Although small in one calculation, when repeated over larger timespans, these errors will accumulate as well.

In conclusion, estimating the orientation with the gyroscope is the most accurate method, but when used over relatively longer timespans, a correction of the gyroscope's bias is mandatory.

2.4.3 Estimating with the Kalman Filter

Neither the accelerometer and magnetometer, nor the gyroscope provide a stable and accurate method of calculating the orientation during movement. The accelerometer can only be used when the body is at rest and the gyro will need bias-correction when used for longer periods. A solution to this problem is the Kalman filter, which provides bias-correction of the gyroscope by using the accelerometer and magnetometer estimations.

The Kalman Filter estimates unknown variables, such as the orientation, based on the measurements observed over time. It is a recursive algorithm meaning that it only needs the previously estimated state and the current measurements. To understand how the Kalman filter works, it is often split into two separate stages: a prediction stage in which the previously estimated state is used to predict the current state, which is called the predicted or **a priori** state; an update stage, in which the a priori state is combined with the information gained from the actual measurements, resulting in a refined state, which is called the updated or **a posteriori** state.

The Kalman filter in the Figure 5 is used to calculate the orientation of a single IMU. The gyroscope measurements together with the previously estimated state are used to predict the a priori state. This is justified by the accuracy of the gyroscope when there is sufficient bias-correction. The a priori state is then compared to the estimated orientation based on the magnetometer's and the accelerometer's measurements. These last ones, however, are left out of consideration when the body is in an accelerating state. Based on this comparison, the a priori state is adjusted and updated to get the a posteriori state.

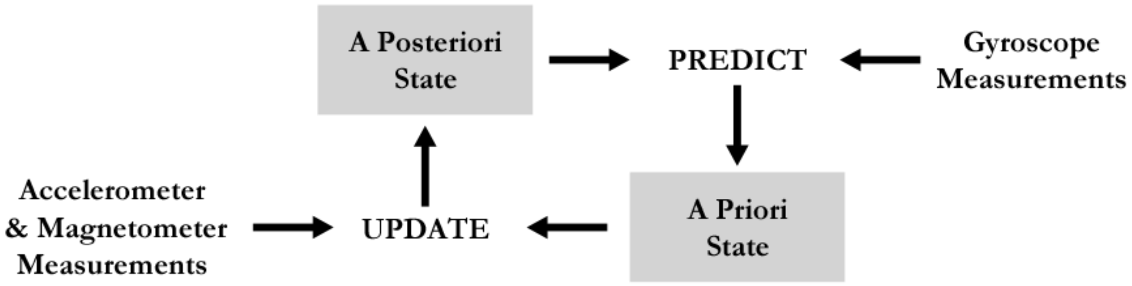

Figure 5: Kalman filter stages for estimating the orientation

The state of the system in a Kalman Filter is represented by two variables: the **a posteriori state estimate $\hat{\mathbf{x}}_{\mathbf{k|k}}$**, which includes the orientation of the sensors and the biases of their gyroscope, and the **a posteriori error covariance matrix $\mathbf{P}_{\mathbf{k|k}}$**, which reflects how accurate the state is estimated. As used above, the notation $\hat{x}_{k|i}$represents the estimation of *x* at time *k* while using the measurements at time *i* and before, where *i* is always a time prior to *k*.

Analysing the Kalman filter used the first stage predicts the a priori state of both the system state $\hat{\mathbf{x}}_{\mathbf{k|k-1}}$ and the error covariance matrix $\mathbf{P}_{\mathbf{k|k-1}}$. At first, applying a state transition matrix F_k to the previous state estimate $\hat{\mathbf{x}}_{\mathbf{k-1|k-1}}$ will correct the orientation based on the previously estimated biases. After that, the input vector u_k, which is chosen to be the gyroscope measurement, is added after transition by its transition matrix G_k. The process noise is left out but will be taken into account using its covariance matrix Q_k. Because F_k, G_k and Q_k do not change over time in this design, they are chosen to be constant.

$$\boldsymbol{\hat{x}_{k|k-1}} = \boldsymbol{F \cdot \hat{x}_{k-1|k-1} + G \cdot u_k} \tag{1}$$

$$\boldsymbol{P_{k|k-1}} = \boldsymbol{F \cdot P_{k-1|k-1} \cdot F^T + Q} \tag{2}$$

To begin the second stage, we will calculate the innovation y_k, and the innovation covariance S_k. The innovation y_k is the residual when comparing the a priori state estimate calculated above with the estimated state based on the measurements. This last one can be gained by applying a transition matrix H to the measured values z_k. Measurement noise is compensated in the innovation covariance S_k, where the measurement noise covariance R_k is included.

$$y_k = z_k - H \cdot \boldsymbol{\hat{x}_{k|k-1}} \tag{3}$$

$$S_k = R + H \cdot P_{k|k-1} \cdot H^T \tag{4}$$

Based on the innovation covariance and the a priori error covariance we can then calculate the optimal Kalman gain matrix K_k:

$$K_k = P_{k|k-1} \cdot H^T \cdot S \tag{5}$$

After all these calculations, the system state and error covariance can be updated accordingly:

$$\boldsymbol{\hat{x}_{k|k}} \;=\; \boldsymbol{\hat{x}_{k|k-1}} + \boldsymbol{K_k} \cdot \boldsymbol{y_k} \tag{6}$$

$$\boldsymbol{P_{k|k}} \;=\; (\boldsymbol{I} - \boldsymbol{K_k} \cdot \boldsymbol{H})\boldsymbol{P_{k|k-1}} \tag{7}$$

The most difficult part in implementing this filter is the estimation of the process and measurement noise covariance matrices Q_k and R_k. These noise sources are assumed to be zero mean Gaussian white noise and their covariances are chosen to be constant to simplify the implementation.

3 Objectives

As already mentioned in the introduction, the overall objective of the project is that the exoskeleton gives automated assistance to improve the equilibrium of the exoskeleton and its user. To achieve this, the movement data sent to the actuators should be adjusted by an algorithm, which takes incoming equilibrium information and calculates which corrections are to be made. The sensors used to provide this information were chosen to be IMUs.

To be able to work towards this main objective in a step-by-step method, it can be partitioned into smaller objectives as summarized below:

3.1 Objective 1

Decide which IMU will be used to measure the position, speed and acceleration of the human body and which communication protocol is most effective to communicate with the MCU.

Questions:

- What are the requirements of the IMUs to be able to measure human body movements accurately in the most cost-efficient manner?
- Which communication protocols are available and which is the most effective one for this setup?

3.2 Objective 2

- Enable self-tests, calibrations and set up the IMUs such that the data from each IMU are captured correctly.
- Create a model setup with only one DoF and represent the captured data in an algorithmic structure that corresponds to that model.
- Determine the location of the joint in respect to the IMUs and calculate the angle between the two segments.

3.3 Objective 3

- Expand the model step by step to achieve a mechanical model of a human lower body.
- Convert the data representation to the corrective data sent to the actuators on that model.
- With those corrections, keep the model's equilibrium while disruptions are occurring. These disruptions can be caused by external forces or movements on the upper body.

3.4 Objective 4

Integrate the algorithms used into the AXO-SUIT exoskeleton.

4 Materials and Methods

4.1 Setup and environment

4.1.1 IMU

Deciding on which IMU to choose depends on multiple factors.

In the first place, the specifications of the IMU must be at least high enough to measure the human body kinematics accurately. This includes a sampling speed that is high enough to be able to notice equilibrium problems quickly and react accordingly, but also means the accuracy of the sensors should be adequate.

Next in order is the price or cost-effectiveness together with availability. It should be noted that at the current MCU there was a single IMU available, which, considering that, could be a possible candidate.

A last factor taken into consideration is the power consumption of the sensor. However, relative to the actuators and other mechanical parts on the exoskeleton, the IMUs, even in larger quantities, will not make a noticeable difference regarding the total power consumption.

In Table 1, the selected IMU, the MPU-9250 [5], is compared to its predecessor, the MPU-9150 [6], and its future successor, the ICM-20948 [7]. Most others like the BMI055 and the BMI160 were disregarded because they did not have an on-chip magnetometer, were less accurate or unavailable.

Table 1: Differences between the MPU-9250 and its predecessor and successor

	MPU-9150	**MPU-9250**	**ICM-20948**
Gyro Rate Noise (dps/$\sqrt{Hz}$)	0,005	0,01	N/A
Magnetometer sensitivity (LSB/g)	±1200	±4800	2048 - 16384
Communication protocols available	I²C	I²C or SPI	I²C or SPI
Size (mm³)	4x4x1	3x3x1	3x3x1
Logic Supply Voltage	1.8V or VDD	1.7V to VDD or VDD	VDD
Operating Voltage	2.4V-3.46V	2.4V-3.6V	1.71V-3.6V
Power Usage	Higher	Lower	Lowest

4.1.2 Communication Protocol

There are a variety of busses used to communicate between multiple hardware chips including I^2C and SPI. However, before starting to weigh the pros and cons of each type of bus, after looking at which busses are compatible with the chosen IMUs, only those mentioned before are remaining. Deciding between those two options is mainly done based on data transferring speed, implementation and reliability. A few differences are listed in Table 2.

Table 2: Comparison table of I^2C versus SPI

Protocol	I^2C	SPI
Wires	Always 2 wires: • Clock • Data	Minimal 4 wires: • Clock • Data In • Data Out • Clock Select line(s)
Addressing	Software coded	Hardware (CS lines)
Data rate	Standard mode 100 kHz to fast mode 400 kHz communication	About 1 MHz Communication Up to 20 MHz when reading sensor/interrupt registers
Power Consumption	A little more due to pull-ups	Pull-ups are optimal
Others	• Cheaper implementation • Data acknowledgment • Less susceptible to noise • Can be used over greater distances	• Has no formal standard

For communication with the MCU, the CAN bus was already present and provided a communication that was acceptable.

4.1.3 Development environment

Software development environment choices were limited to the ones available at COMmeto.

4.2 Data processing

Data processing, as defined here, will start with the raw data gathered from the IMUs and end with the estimated values for the orientation and position relative to a predefined state. This includes bias-correction, scaling of the data, calculating and estimating angles.

At first, most of the data processing is done by the processor of the developer's computer. The MCU gathers the data received from the sensors and pushes them on the CAN bus. On the other end of the CAN bus, a Beagle Bone Black retrieves the data and communicates them to the computer through Ethernet or USB. Where, finally, the data are analysed and the resulting information visualized for easy human interpretation.

Later, the MCU will pre-process the raw sensor data to lower the workload higher up the chain. Then, the remaining data processing, previously done on the computer, shifts step by step towards the Beagle Bone Black.

4.3 Data Analysis

Using the information calculated during data processing, the future state and the equilibrium problems that state may be in are roughly predicted. These equilibrium problems are then reduced by adjusting the movements of the person wearing the exoskeleton.

Similar to the data processing, the data analysis is executed on the computer first and later shifts to the Beagle Bone Black.

5 Problems

As with most projects, performing the necessary steps to complete this master's thesis did not go without any problems appearing. These problems usually arose at unexpected times and every now and then hindered the project's progress. This chapter summarizes the problems that occurred and how those problems were dealt with.

5.1 IMU shipment delay

One of the most annoying problems when ordering components is delay. Because the IMUs took a long time to arrive, building the model got delayed. Luckily there was a IMU present on the available MCU circuit board and even though this IMU was not the one that was decided on (but its predecessor), it provided a learning experience on how to communicate with an IMU and gave the option to start building the basic software. There was less similarity than expected between the actual chosen IMUs and the previously mentioned predecessor, which caused a lot of rewriting of previously written code.

5.2 Framework errors

The Atmel Software Framework (ASF) is far from perfect. It provides the most basic functionality and due to its sheer size, finding which parts are lacking is never an easy task. However, finding a better alternative is not always a viable option. On top of that, the MCU board used in this project is manufactured by Atmel.

5.2.1 Multiple I^{2}C slaves

Since the MCU needs to communicate with multiple IMUs, taking advantage of multiple slaves is the easiest solution to implement. However, the ASF does not support sending packets with different destination addresses. This means part of the ASF code for I^{2}C needs to be layered into the software written for the project itself.

5.2.2 Multiple I^{2}C busses

As mentioned before, each MCU gathers data from multiple IMUs. However, the I^{2}C addresses of the IMUs, that were decided on for this project, are hardware-coded. This means that, unlike with software-coded addresses, the addresses are limited to those available by connecting certain pins to certain voltages. In this case, there were only two options to choose from which means that there can only be two IMUs in each I^{2}C bus. This leaves two main options for setups with more than two IMUs: a cascade method or a parallel method. The layout for both these methods can be seen in Figure 6 and 7, respectively.

In a cascade layout, each upper-level IMU (on the left side Figure 6) connects with a lower-level one (right) through its auxiliary I²C bus. This is the I²C bus used for external sensors and the same one the internal magnetometer is connected to. In this way, the upper-level IMU can load the lower-level IMU's sensor data in its external sensor register in the same way it loads in its own magnetometer. And the MCU can read both the data from the upper-level and lower-level IMU in their respective registers at the same time.

But this creates yet another problem, as there are only 24 registers available for storing external sensor data. Of these 24 registers, the IMU's own magnetometer already reserves 8, leaving only 16 registers to hold the second IMU's raw sensor data. Considering that both the gyroscope and accelerometer use 6 registers, the temperature meter uses 2 and the magnetometer of the lower-level IMU also uses 8 registers, there are not enough registers to hold all data. There are solutions for this problem but those are not specified here.

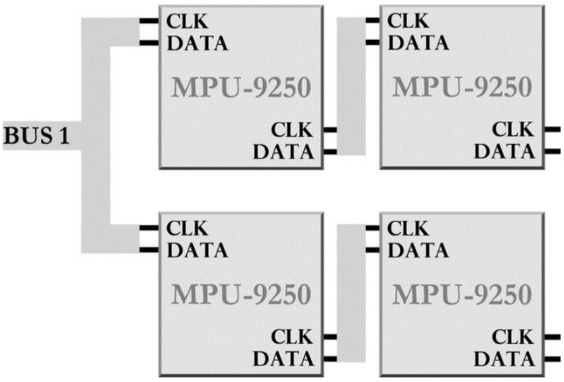

Figure 6: Cascade layout using a single I²C-bus

A parallel layout, on the other side, has no such problems as all IMUs are directly connected to the MCU in this layout. As shown in Figure 7, one major difference is the implementation of a second I²C-bus on the MCU board. This was already implemented on the present MCU and would pose no problem to implement in future boards as well.

This would also be the faster one if communication with the I²C bus would become a problem.

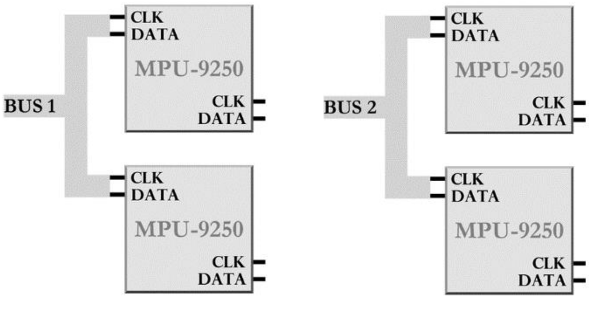

Figure 7: Parallel layout using two I²C-busses

After deciding to use the parallel layout and trying to access both I^2C busses from the software, another problem with the ASF presented itself. Even though the framework could access both busses individually, accessing both at the same time seemed impossible. However, an acceptable workaround for this problem has not been found so far.

5.3 Communication Jitter

While evaluating the periods in between the timestamps of several datasets on the computer, most of them are 4 to 5 milliseconds later than the previous one. However, every so often these periods extend significantly, this phenomenon is called jitter.

The most practical way to notice the jitter is on the computer, where the data is visualized. Because this is at the end of the communication chain, there are many possible sources of this jitter, maybe even more than one. Locating the sources is a matter of checking each possible cause starting with the most obvious one, the communication.

Starting at the end of the communication, the Beagle Bone Black transfers the data it retrieves on the CAN-bus over an Ethernet-connection to the computer. After replacing the Ethernet-connection with a USB-connection, no changes were noticeable.

Going further along the chain, the Beagle Bone Black program, which retrieves the data from the CAN-bus might pause at certain times to garbage collect for example. However, even when using the timestamps the Beagle Bone Black creates when it retrieves a packet from the CAN-bus, the jitter remains. The frequency it occurs did however reduce, making this one of the problem’s sources.

The overall problem doesn’t come from the Beagle Bone Black however which means that the jitters is caused by the communication on the CAN-bus or it is already present on the MCU. To solve this the MCU is set up to run an asynchronous timer with a 1 MHz frequency. Using this timer to create timestamps and send these along with the data, allows calculating the time in between two datasets to a precision of a microsecond. But, even with this new information, there is still a significant gap in between two sets of data, moreover these gaps seem to be repeating in a periodical way.

Extensive searching and experimenting revealed that the gaps were caused by packets of data disappearing when communicated over the CAN-bus. The exact cause of this has not yet been revealed and will require more research. However, it possibly lies too at the receiving end of the CAN-bus, the Beagle Bone Black.

5.4 Communication Delay

Communication delay has been present during the entire length of the project. The visualized data seems to be approximately three seconds too late. For now, as there is still no feedback given to the actuators, this delay isn’t that significant. Because of that this problem has not been inspected thoroughly.

6 Conclusion

Although this master's thesis aimed to improve the equilibrium of the exoskeleton and its user, it resulted in the estimation of the orientation of each sensor separately. The MCU can gather data from two maximum IMUs at a time, due to the aforementioned ASF problem. When this is solved and both I^2C busses can be accessed at the same time, all four IMUs are available. There is still a little jitter and an approximately three-second delay present which distorts the estimation and makes it harder to visually confirm the measurements.

However, a cost effective IMU is selected, one able to accurately measure human body movements, together with a matching communication protocol. The IMUs can self-test, calibrate themselves and perform a setup stage at start up. Afterwards, they begin gathering sensor data such that the MCU can start collecting these correctly and send them towards the Beagle Bone Black. Here the data are represented in an algorithmic structure and send them to the computer to visualize them in a humanly understandable way.

Future work could expand the model to a mechanical human leg and to use the developed data representation to keep this model upright. And finally, modelling a mechanical lower body, with the purpose to keep the model's equilibrium while disruptions occur.

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