

LULEÅ UNIVERSITY OF TECHNOLOGY

DEPT. OF COMPUTER SCIENCE, ELECTRICAL AND
SPACE ENGINEERING

D7039E – PROJECT IN INDUSTRIAL COMPUTER SYSTEMS

Project SailorAid

Authors

Axelsson Oskar,
Brolin, Daniel,
Eriksson, Kenny
Lundberg, Josef,
Grape, Elias
Sjölund, Johannes
Theolin, Henrik

Supervisor
van Deventer, Jan

September 27, 2017



Abstract

Some abstract description of the project... Quisque ullamcorper placat ipsum. Cras nibh. Morbi vel justo vitae lacus tincidunt ultrices. Lorem ipsum dolor sit amet, consectetur adipiscing elit. In hac habitasse platea dictumst. Integer tempus convallis augue. Etiam facilisis. Nunc elementum fermentum wisi. Aenean placerat. Ut imperdiet, enim sed gravida sollicitudin, felis odio placerat quam, ac pulvinar elit purus eget enim. Nunc vitae tortor. Proin tempus nibh sit amet nisl. Vivamus quis tortor vitae risus porta vehicula.

Fusce mauris. Vestibulum luctus nibh at lectus. Sed bibendum, nulla a faucibus semper, leo velit ultricies tellus, ac venenatis arcu wisi vel nisl. Vestibulum diam. Aliquam pellentesque, augue quis sagittis posuere, turpis lacus congue quam, in hendrerit risus eros eget felis. Maecenas eget erat in sapien mattis porttitor. Vestibulum porttitor. Nulla facilisi. Sed a turpis eu lacus commodo facilisis. Morbi fringilla, wisi in dignissim interdum, justo lectus sagittis dui, et vehicula libero dui cursus dui. Mauris tempor ligula sed lacus. Duis cursus enim ut augue. Cras ac magna. Cras nulla. Nulla egestas. Curabitur a leo. Quisque egestas wisi eget nunc. Nam feugiat lacus vel est. Curabitur consectetur.

testing...

Contents

1	Introduction	2
SJÖLUND, JOHANNES (THEOLIN, HENRIK)		
1.1	Goals	2
2	The Physics of Sailing	2
3	Product Application	4
3.1	Navigation and Tracking	4
SJÖLUND, JOHANNES (THEOLIN, HENRIK)		
3.2	Speed optimization	4
SJÖLUND, JOHANNES (THEOLIN, HENRIK)		
4	Hardware Design	5
5	Sensors	6
LUNDBERG, JOSEF (NO ONE)		
5.1	Force sensors	6
5.2	The prototype	6
5.3	Choice of component	9
5.4	Amplifier	9
6	Software Design	11
SJÖLUND, JOHANNES (NO ONE)		
6.1	ARM firmware	11
6.2	Android application	11
7	Kalman filter	12
AXELSSON, OSKAR (NO ONE)		
7.1	Kalman Filter	12
References		16

1 Introduction

SJÖLUND, JOHANNES (THEOLIN, HENRIK)

The art of sailing has been around for millenia. For much of human history it has been an absolutely vital part of civilization, providing efficient means of transporting goods all around the world. Today sailing has become a leisure activity enjoyed by millions of people around the world. Modern sailboats come in a large span of sizes, from large ships with crews of dozens down to small single-man dinghies. While slipping across the waves out at sea with only the wind to drive you is a calming experience, it is not a simple thing to do. When you are alone on the water, you have to be in control of the tension of the sail, the attitude of the boat, the forces on the centerboard and more while deciding how to respond to all of these. The goal of Project SailorAid is to offload the decision-making from the sailor onto a compact, portable and simple system that will analyze these parameters and provide clear directions to the sailor.

1.1 Goals

The primary functional goals are as follows:

- . Boat attitude
 - Implementing an appropriate sensor array:
 - * Accelerometer
 - * Gyroscope
 - * Magnetometer
 - Fusing the sensor output to get an accurate estimate of boat attitude
- . Position tracking and velocity
 - Implementing a GPS system
 - Fusing the GPS output with the accelerometer output for more accurate positioning and velocity
- . Design a force measurement circuit for the centerboard
 - Design an appropriate sensor mount off the centerboard
 - Implement an appropriate sensor
 - Implement a centerboard-depth sensor

2 The Physics of Sailing

Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetuer id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium

quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

Nam dui ligula, fringilla a, euismod sodales, sollicitudin vel, wisi. Morbi auctor lorem non justo. Nam lacus libero, pretium at, lobortis vitae, ultricies et, tellus. Donec aliquet, tortor sed accumsan bibendum, erat ligula aliquet magna, vitae ornare odio metus a mi. Morbi ac orci et nisl hendrerit mollis. Suspendisse ut massa. Cras nec ante. Pellentesque a nulla. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Aliquam tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque cursus luctus mauris.

3 Product Application

Morbi luctus, wisi viverra faucibus pretium, nibh est placerat odio, nec commodo wisi enim eget quam. Quisque libero justo, consectetur a, feugiat vitae, porttitor eu, libero. Suspendisse sed mauris vitae elit sollicitudin malesuada. Maecenas ultricies eros sit amet ante. Ut venenatis velit. Maecenas sed mi eget dui varius euismod. Phasellus aliquet volutpat odio. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Pellentesque sit amet pede ac sem eleifend consectetur. Nullam elementum, urna vel imperdiet sodales, elit ipsum pharetra ligula, ac pretium ante justo a nulla. Curabitur tristique arcu eu metus. Vestibulum lectus. Proin mauris. Proin eu nunc eu urna hendrerit faucibus. Aliquam auctor, pede consequat laoreet varius, eros tellus scelerisque quam, pellentesque hendrerit ipsum dolor sed augue. Nulla nec lacus.

3.1 Navigation and Tracking

SJÖLUND, JOHANNES (THEOLIN, HENRIK)

Suspendisse vitae elit. Aliquam arcu neque, ornare in, ullamcorper quis, commodo eu, libero. Fusce sagittis erat at erat tristique mollis. Maecenas sapien libero, molestie et, lobortis in, sodales eget, dui. Morbi ultrices rutrum lorem. Nam elementum ullamcorper leo. Morbi dui. Aliquam sagittis. Nunc placerat. Pellentesque tristique sodales est. Maecenas imperdiet lacinia velit. Cras non urna. Morbi eros pede, suscipit ac, varius vel, egestas non, eros. Praesent malesuada, diam id pretium elementum, eros sem dictum tortor, vel consectetur odio sem sed wisi.

3.2 Speed optimization

SJÖLUND, JOHANNES (THEOLIN, HENRIK)

Sed feugiat. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Ut pellentesque augue sed urna. Vestibulum diam eros, fringilla et, consectetur eu, nonummy id, sapien. Nullam at lectus. In sagittis ultrices mauris. Curabitur malesuada erat sit amet massa. Fusce blandit. Aliquam erat volutpat. Aliquam euismod. Aenean vel lectus. Nunc imperdiet justo nec dolor.

4 Hardware Design

5 Sensors

LUNDBERG, JOSEF (NO ONE)

In order to sail properly and make the most out of the wind that's is supplied by the nature itself some data acquisition is needed. The sailing is all about this harnessing all the forces of the nature and the wind that it pushing towards you. Since there has not been any other extensive projects and measurements in this particular area the measurements have to be done in new ways.

5.1 Force sensors

The goal here is to have a system that can measure the forces that pushes on the centerboard by the water it goes through. The implementation: By looking at some different solutions there is not any other solutions that might be as clean looking and prominent as this approach. Important to know is that every solution is mandatory to be waterproof and sealed properly from the harsh environment that this system has as its home turf. The solutions that required the sensors to be mounted on the outside or in parts that would be in danger if a crash might occur was scratched. The board itself will not be disassembled in any major part of way. Meaning that this approach doesn't need any modifications to the board itself. This has been the goal and the chosen approach. Modifications in the mounting plate is the way to go, the other solutions is either way more difficult to apply and mount or more complex.

5.2 The prototype

To implement the gauges, a prototype is designed to show how the measurements will be made. The prototype is a bit bigger than the intended solution for this project but it's good to see how it would be constructed. The function is easy to understand. The board goes on the outside and can easily slide up and down past this ball. The ball itself is kept inside this small area where it can move in and out. The force is then measured at the back where there will be a plate. The deflection of this plate which will be the origin to the strain will be measured through strain gauges. The gauge itself will measure a small difference in resistance. This small difference is most likely going to be difficult to measure without any amplifying circuit connected. With a such small signal the system might have issues with noise. Another problem is that the signal might drift, and therefore make different measurements as the circuit is running. And finally, with the measured values getting amplified with a big amount the resulting signal may be off by a large amount.

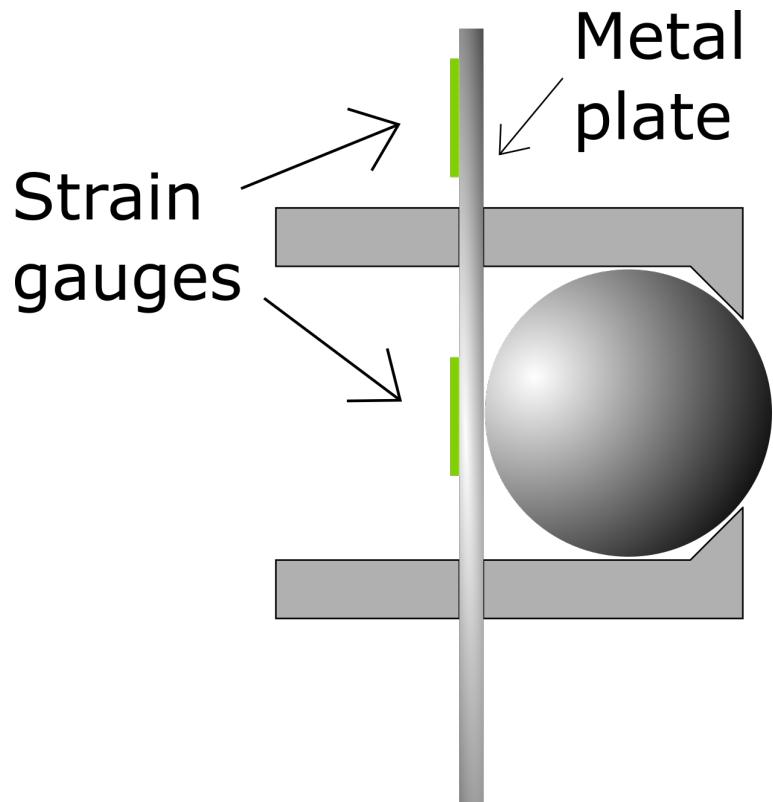


Figure 1: Function of first prototype

This way of implementing strain gauges was the first idea. The main case for this strategy was that in the start of this project these gauges were supplied to us, as a leftover from the last group. With this implementation, we could already start working on a prototype and get a small head start in to the project. But as some research shows, it is a more difficult way to solve this problem and it would take bit more work and some sensitive circuits to measure the force. The gauges also need to be stuck in place using some specific glue and can easily be done incorrectly and therefore prevent good measurements.

A model of the pressure sensor was constructed in the CAD program fusion 3D. This model was created in order to clearly show the function of this sensor and to help the thought process involved in the improving of this design.

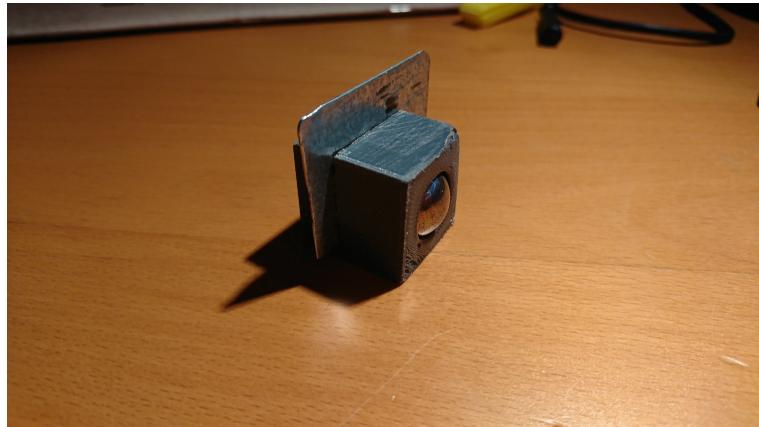


Figure 2: Function of first prototype

New idea: A better solution is to make some research into load cells, which is a sensor which also utilizes strain gauges to measuring forces. The difference is that the gauges are already implemented in the sensor. The difference in the prototype is instead of having a metal plate, it can be built with a piece of plastic or rubber which can deform so the force is distributed directly to the sensor. By implementing this sensor, a lot of time was saved in troubleshooting. And by having a sensor unit, the modified mounting plate will be easier to produce.

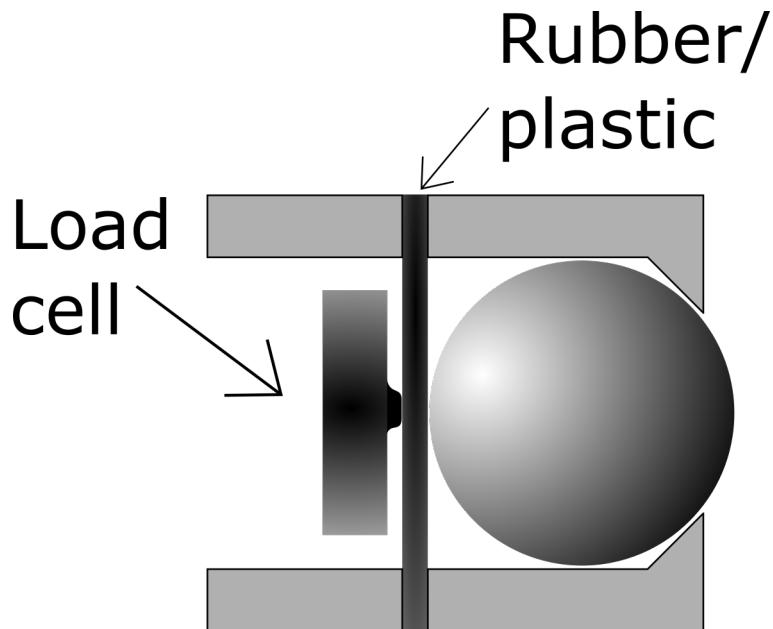


Figure 3: Function of second prototype

5.3 Choice of component

The force from the board onto the mounting plate will be a considerable amount. The actual force is something that's not known for sure. The initial assumption was that the decision of buying the right sensor we think that a sensor with a 90.75 kg force range should be enough. In the case that we max out the sensor and overload the cell it's rated for a 150% overload without causing some damage to the sensor. The sensor for this application is selected to be this part, the compression load cell called FX1901. From the datasheet the voltage readings of this piece could be calculated. With a maximum voltage reading of around $36mV/V$



Figure 4: Load cell, FX1901

5.4 Amplifier

That's a small signal and needs to be amplified to get some good measurements. A good measurement signal to the MCU should be in the order of in between 0 - 5 volts.

This is achieved by an amplification gain of around 20.

To find some inspiration and insight about amplifiers some different applications and projects were viewed and analysed.

In the world of amplifiers they come in almost any shape and functions, it's almost like when you are going to choose a particular transistor for a project.

By taking some inspiration from other projects a suitable amplifier was at last chosen from the vast ocean of different amplifiers.

The choice fell on this little fellow, the INA126.



Figure 5: Amplifier for the load cell signal

Which not look so interesting but has the benefit of having a smaller power consumption than many others by being a bit simpler than many others. But sufficient for our purpose.

It seems like a smart choice because when the system is battery operated, like in this case, every watt counts.

The gain on this piece is easily calculated with this function. Gain is $5 + \frac{80k}{R_g}$ ohm divided by our chosen resistor R_g .

If our desired 20 gain might not work or the voltages calculated is off, the gain is easily redone with this expression.

Now that we know how to get the force measurements, we are going to talk about how to measure the frequency of waves at sea.

6 Software Design

SJÖLUND, JOHANNES (NO ONE)

The software has been divided into two parts, the firmware for the ARM MCU with associated sensors, and an Android application which can display sensor data. These two parts utilize a Bluetooth connection to communicate their current states. For example, when the IMU calculates a new orientation, this data should be processed by the firmware, and the resulting calculations sent to the Android application over Bluetooth to be displayed to the user.

6.1 ARM firmware

In order to speed up firmware development, the STM32CubeMX¹ initialization code generator was used to set up a basic working system. This application, developed by ST, can generate C language code for setting up MCU clocks, peripherals, interrupts and similar. It is controlled by a graphical interface for setting MCU options and controlling the previously mentioned code generation.

The main challenge in working with this type of code generation is integrating it with software libraries not built for it. If the library interferes with generated code by overriding functions and register values, the software may enter an undefined state and stop working. Care therefore had to be taken to only use the parts of the libraries which did not interfere. Frequent testing of any newly added functionality had to be done in order to find interfering parts.

Two libraries produced by ST were used, one for the Bluetooth module, and one for the IMU.

6.1.1 Bluetooth

The Bluetooth firmware package called X-CUBE-BLE1² developed by ST consists of several parts, MCU and Bluetooth evaluation board device definitions such as named pins and ports, functions for manipulating them, a Bluetooth GATT server implementation, as well as several demo applications which could communicate with Android devices. Additionally a Android demo application for displaying sensor data from Bluetooth was included.

These parts were integrated into the code generated by STM32CubeMX

6.1.2 IMU

X-CUBE-MEMS1³

6.2 Android application

The main reason for this project is to give a sailor qualitative feedback and help in clearing the mind of the techniques required to achieve a smooth sailing experience so that the sailor can focus on the joy of sailing. It is therefore crucial that the data is displayed in a manner that is easy to interpret and provide the help that is called for. To increase the flexibility of the design it was decided to implement several different user interfaces that the user could switch between while running the application. This was determined to be a good way of increasing the chances that the user would find a interface to its liking.

7 Kalman filter

AXELSSON, OSKAR (NO ONE)

Sensor theory

Sensor fusion can be observed everywhere e.g., living animals uses all of its senses to survive daily, an animal cannot hunt using its eyes only, it has to combine its sense of smell, eyes and hearing to hunt the pray⁴. Sensor fusion theory is not only found in the living species it is found in cars, planes, computers and so on and this to enhance performance⁴. In this project sensor fusion will be used to enhance the accuracy of the dinghy's position and velocity. The fusion will be between a GPS and the IMU.

The GPS's accuracy is not uniform since it might be buildings reflections, atmospheric delays or clock bias errors⁵. Using only information provided by a IMU is not sufficient either since the sensors will drift after time, using the sensors only for short time will give accurate readings.

7.1 Kalman Filter

A popular filter to use when doing sensor fusion is to use a Kalman filter, (KF). The Kalman Filter is a recursive filtering method for discrete data, the algorithm was developed by an Hungarian mathematician Rudolf (Rudi) Emil Kalman in 1960⁵. Its popular to use due to its efficiency when calculating predictions.⁷

Since everything is nonlinear in the universe, many systems cannot be modeled as linear⁶ and therefore Extended Kalman, (EKF) Filter has to be applied when this cases arises. The EKF linearizes the system around its working points. When deriving the dynamics of the system the decision can be made which type of filter will be used. The model is given as a linear equation

$$\text{State equation} \quad x_k = F_{k-1}x_{k-1} + v_{k-1} \quad (1)$$

$$\text{Observation equation} \quad z_k = H(x_k) + w_k \quad (2)$$

where v_k and w_k is the process noise and measurement noise, respectively both assumed to be zero mean Gaussian noise with covariance matrices Q_k and R_k , i.e. $v_k \in \mathcal{N}(0, Q_{k-1})$ and $w_k \in \mathcal{N}(0, R_k)$.

$$\text{Predict state estimate:} \quad \hat{x}_{k|k-1} = F_k \hat{x}_{k|k-1} + G v_{k-1} \quad (3)$$

$$\text{Predict covariance matrix:} \quad P_{k|k-1} = F_k P_{k-1|k-1} F_k^T + Q_k \quad (4)$$

$$\text{measurement residual} \quad \tilde{y}_k = z_k - H_k \hat{x}_{k|k-1} \quad (5)$$

$$\text{Innovation covariance} \quad S_k = H_k P_{k|k-1} H_k^T + R_k \quad (6)$$

$$\text{Optimal Kalman gain} \quad K_k = P_{k|k-1} H_k^T S_k^{-1} \quad (7)$$

$$\text{Update state estimate} \quad \hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k \tilde{y}_k \quad (8)$$

$$\text{Update covariance estimate} \quad P_{k|k} = (I - K_k H_k) P_{k|k-1} \quad (9)$$

$$\text{Measurement post-fit residual} \quad \tilde{y}_{k|k} = z_k - H_k \hat{x}_{k|k} \quad (10)$$

If Eq.(5) and Eq.(8) is analyzed we see that depending on how much we believe in the observations that are observed will affect the gain matrix. Consider Fig.

6 as a map of how the algorithm works and Fig. 8 as a description on how the system works.

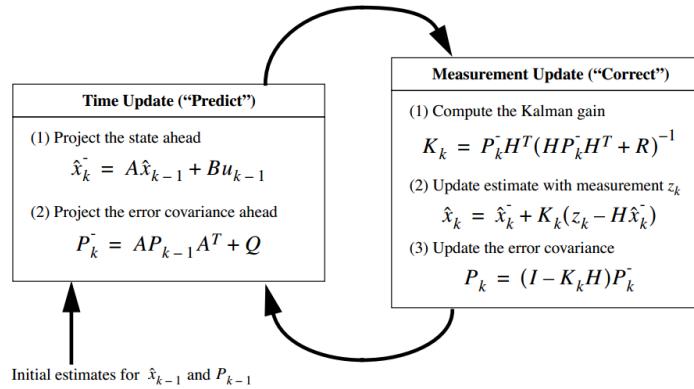


Figure 6: Kalman Filter prediction algorithm

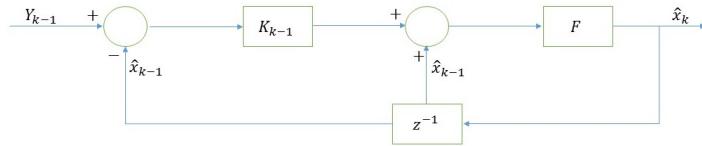


Figure 7: System diagram of Kalman prediction

Integration GPS/INS

It exist different types of integration levels most common are loosely, tightly and ultra-tightly coupled. The two last types are used when the output from the GPS receiver is its pseudo-range and carrier-range. Since the GPS receiver that is used in this project uses NMEA standard, the output from the GPS will be the calculated position, velocity and heading. Then using a loosely coupled integration is preferred, profits using loose coupled are that its easiest way of fusion sensors together. Consider Fig. as how the system works between the different sensors.

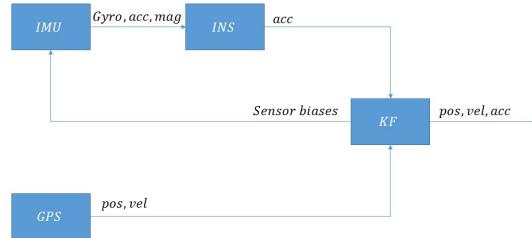


Figure 8: GPS/INS with loose integration

Kalman Filter Model

The states that we want to observe are.

$$\bar{x} = \begin{bmatrix} x^{pos} & [m] \\ y^{pos} & [m] \\ v^x & [m/s] \\ v^y & [m/s] \end{bmatrix} \quad (11)$$

x_{pos} and y_{pos} is the position in x and y direction, respectively, velocity, v , acceleration, a . The coordinate system that is used for calculations are the WGS-84. See Fig. ?? for a geometrical perspective.

The Kalman filter calculates estimates of the true values of states recursively over time using incoming measurements and a mathematical process model, i.e. it uses x_{k-1} to calculate x_k . Hence a mathematical model has to be derived describing the process, the GPS will provide heading position and velocity, the IMU will provide acceleration in xy -direction.

The model will not make an assumption that the acceleration is constant under the sampling times, this since the sampling period is 1Hz. The process model is derived using kinematics using only xy -directions.

$$x_k^{pos} = x_{k-1}^{pos} + \Delta t v_{k-1}^x + \frac{1}{2} \Delta t^2 a_{k-1}^x \quad (12)$$

$$y_k^{pos} = y_{k-1}^{pos} + \Delta t v_{k-1}^y + \frac{1}{2} \Delta t^2 a_{k-1}^y \quad (13)$$

$$v_k^x = v_{k-1}^x + \Delta t a_{k-1}^x \quad (14)$$

$$v_k^y = v_{k-1}^y + \Delta t a_{k-1}^y \quad (15)$$

Using the above equation the state matrix is expressed as.

$$F = \begin{bmatrix} 1 & 0 & \Delta t & 0 & \frac{1}{2}\Delta t^2 & 0 \\ 0 & 1 & 0 & \Delta t & 0 & \frac{1}{2}\Delta t^2 \\ 0 & 0 & 1 & 0 & \Delta t & 0 \\ 0 & 0 & 0 & 1 & 0 & \Delta t \end{bmatrix} \quad G = \begin{bmatrix} \Delta t^2 & 0 \\ 0 & \Delta t^2 \\ \Delta t & 0 \\ 0 & \Delta t \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (16)$$

In The constant acceleration model the acceleration increments are assumed to have zero-mean, thus the covariance matrix is.

$$v_k = \begin{bmatrix} \sigma_{IMU^x}^2 & 0 \\ 0 & \sigma_{IMU^y}^2 \end{bmatrix} \quad (17)$$

Where $\sigma_{IMU^x}^2$ and $\sigma_{IMU^y}^2$ is the standard deviation squared in x and y direction respectively. Then the covariance matrix, (the measurement noise) is derived $Q = GwG^T$.

$$Q = \begin{bmatrix} \sigma_{a^x}^2 \Delta t^4 / 4 & 0 & \sigma_{a^x}^2 \Delta t^3 / 2 & 0 & \sigma_{a^x}^2 \Delta t^2 / 2 & 0 \\ 0 & \sigma_{a^y}^2 \Delta t^4 / 4 & 0 & \sigma_{a^y}^2 \Delta t^3 / 2 & 0 & \sigma_{a^y}^2 \Delta t^2 / 2 \\ \sigma_{a^x}^2 \Delta t^3 / 2 & 0 & \sigma_{a^x}^2 \Delta t^2 & 0 & \sigma_{a^x}^2 \Delta t & 0 \\ 0 & \sigma_{a^y}^2 \Delta t^3 / 2 & 0 & \sigma_{a^y}^2 \Delta t^2 & 0 & \sigma_{a^y}^2 \Delta t \\ \sigma_{a^x}^2 \Delta t^2 / 2 & 0 & \sigma_{a^x}^2 \Delta t & 0 & \sigma_{a^x}^2 & 0 \\ 0 & \sigma_{a^y}^2 \Delta t^2 & 0 & \sigma_{a^y}^2 \Delta t & 0 & \sigma_{a^y}^2 \end{bmatrix} \quad (18)$$

Consider (16) and (18) we can see that the matrices are linear, this implies that a linear model approach is sufficient to use, hence a linear Kalman Filter is used. The measurement variance is user determined, more specific, it depends on the hardware and given by.

$$R = \begin{bmatrix} \sigma_{GPS^x}^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & \sigma_{GPS^y}^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma_{GPS^{vx}}^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & \sigma_{GPS^{vy}}^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma_{IMU^x}^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & \sigma_{IMU^y}^2 \end{bmatrix} \quad (19)$$

The output from the GPS follows WGS-84 standard this means that the GPS will provide information in global frame, i.e longitude and latitude in degrees. This has to be convert into a navigation frame.

References

- [1] <http://www.st.com/en/development-tools/stm32cubemx.html>
- [2] <http://www.st.com/en/embedded-software/x-cube-ble1.html>
- [3] <http://www.st.com/en/embedded-software/x-cube-mems1.html>
- [4] D.L. Hall and J. Llinas. An introduction to multisensor data fusion. *Proceedings of the*. IEEE, 85(1):6 –23, jan 1997
- [5] BOKEN *BOKEN*.
- [6] Dr. Oliver Nelles
nonlinear system identification.
- [7] Duygun, M., Kutlu, L. & Sickles, R.C. J Prod Anal (2016) 46: 155. <https://doi.org/10.1007/s11123-016-0477-z>