

LULEÅ UNIVERSITY OF TECHNOLOGY

DEPT. OF COMPUTER SCIENCE, ELECTRICAL AND  
SPACE ENGINEERING

D7039E – PROJECT IN INDUSTRIAL COMPUTER SYSTEMS

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## Project SailorAid

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*Authors*

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

*Supervisor*  
van Deventer, Jan

October 20, 2017



**Abstract**

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testing...

## Contents

## 1 Introduction

WHO??? (NO ONE)

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

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### 3 Product Application

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#### 3.1 Navigation and Tracking

SJÖLUND, JOHANNES (THEOLIN, HENRIK)

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#### 3.2 Speed optimization

SJÖLUND, JOHANNES (THEOLIN, HENRIK)

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## 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.

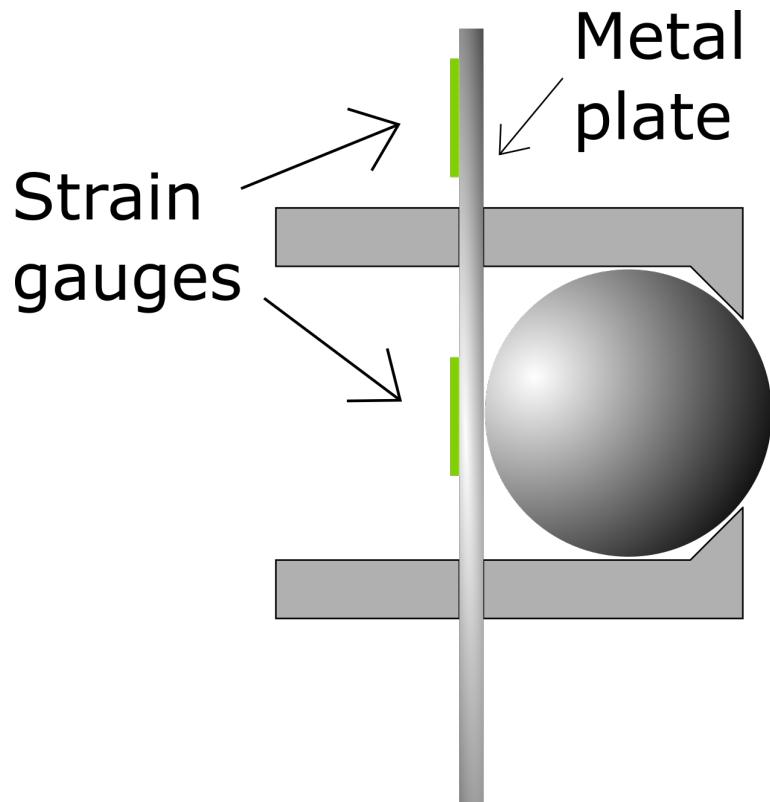


Figure 1: Function of first prototype

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.

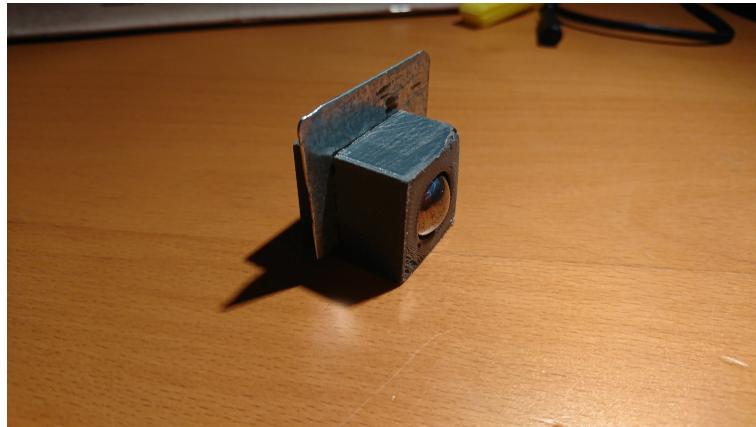


Figure 2: Function of first prototype

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 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 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.

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.

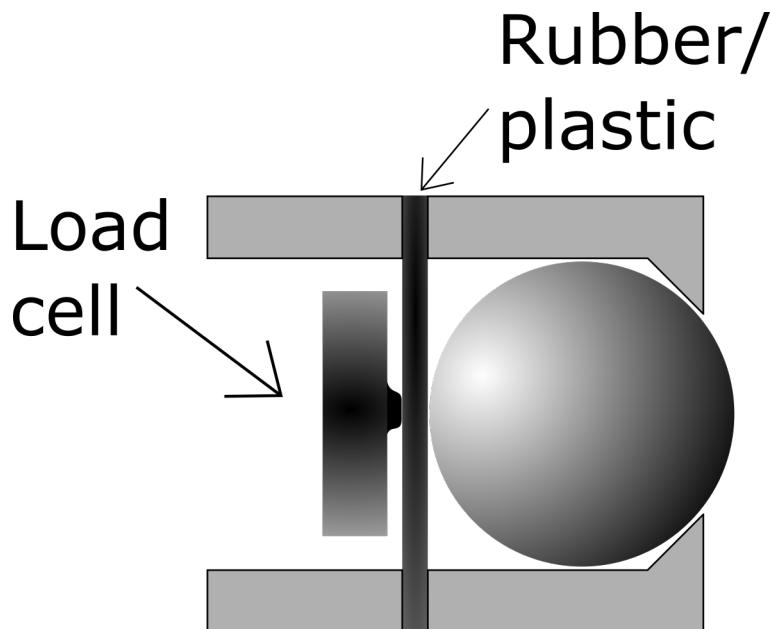


Figure 3: Function of second prototype

### 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 a load cell with a 90.75 kg force range should be enough. In the case the sensor will be maxed out the cell it's rated for a 150% overload without causing some damage to the sensor. The chosen sensor for this application is selected to 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

In order for the microcontroller to make some good measurements from the load cell an amplification for the 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.

A suitable amplifier needs to be choosen from the vast ocean of different models. Inspiration is taken from The university of Chicago?? in an experiment where they uses this exact load cell togheter with an instrumental amplifier called INA125. This amplifier is somewhat more complicated and have some more feautures that other amplifiers. In the same family of instrument amplifiers a model called INA126 is selectet as a less complicated and more power efficiant solution.

The choice fell on this little fellow, the INA126.

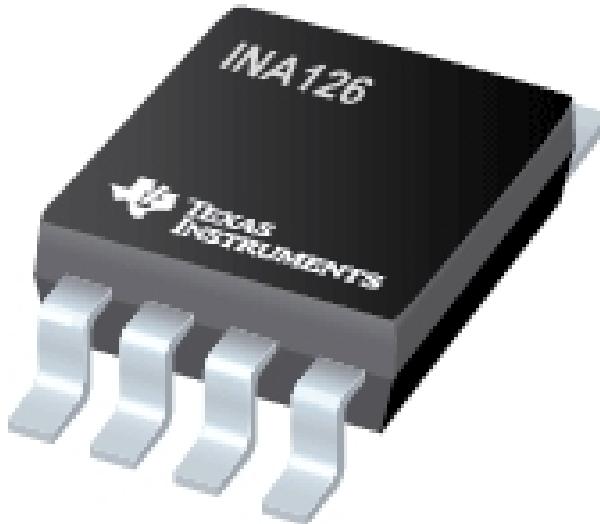


Figure 5: Amplifier for the load cell signal

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 plus 80k 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.

$$Gain = 5 + \frac{80k\Omega}{R_G} \quad (1)$$

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.

### 5.5 Height of daggerboard sensor

The main issues might be that the Height of daggerboard: One of the best implementations of a height sensor would be the use of a linear wire distance sensor. This particular sensor measures how far a wire is pulled, which gives a very accurate measurement. This solution can be totally watertight and concealed in the main centerplate.



Figure 6: Linear draw wire sensor, Micro epsilon MK30

We have found some sensors that might work for us, this is the smallest we found. It's 3 cm wide and about 5 cm high. As we have some tight space constraints this can probably fit inside or just stick out a little bit. This particular sensor is in the range of 2000 kr, which feel like a lot. But if no other solution works this might be considered again.

We have also looked into some light sensors. This is implemented with the use of a plate placed ion top of the dagger-board and with the light being sent up to this panel, the height can be calculated. First we looked into some ir-sensors. They will probably send the signal in a wide spread which will make the distance measurement troublesome as this signal has just a small plate to bounce off.

But with the use of a LIDAR system, we can point our light signal at an exact spot and then get an exact measurement of the height. Many of the lidar systems we found was too big for our project and also very expensive. A suitable sensor that we found was a small "micro lidar" circuit from adafruit:

### 5.5.1 Component

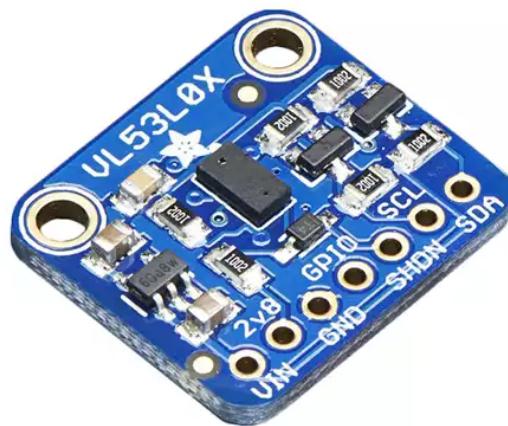


Figure 7: Time of flight distance sensor, Adafruit VL53L0X

#### Problems:

As there will always be water around and on the centerplate the light that is sent might get directed "wrong" if there is only some small water droplets in between the sensor and the panel that we want to reflect our light on.

By the fact that the sensor have to be water proof the signal has to go through a medium. The medium can be some type of plastic or even glass. If the signal can be read correctly through this medium or if the signal will get corrupted, we don't know yet. That is something that we need to test later when our parts has come in.

## 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

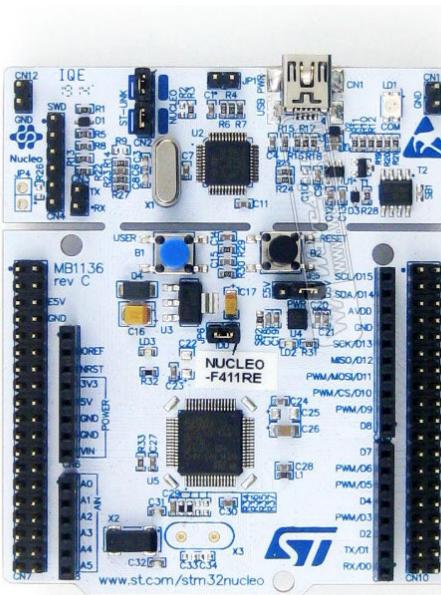


Figure 8

For rapid prototyping and firmware development purposes, the NUCLEO-F411RE development board seen in figure 8 was used. This board contains break-out pins for the ARM Cortex-M microcontroller STM32F411RE, a UART to USB bridging circuit and general purpose LEDs and buttons. It is compatible with various Arduino shields as well as expansion boards developed by ST.

In order to speed up firmware development, the STM32CubeMX<sup>?</sup> 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 external software libraries directly not built for it. If the library interferes with generated code by overriding settings and register values, the software may enter an undefined state and stop working. Care therefor 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



Figure 9

For prototyping, the Bluetooth evaluation board X-NUCLEO-IDB05A1<sup>?</sup> seen in figure 9 was used, which could be stacked on top of the Nucleo board. The pins on the evaluation board connected it to an SPI port on the MCU.

To avoid having to implement the Bluetooth stack from scratch, the firmware package called X-CUBE-BLE1<sup>?</sup> developed by ST was used. It consisted 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 showing usage examples. Additionally an Android demo application for displaying sensor data from Bluetooth was available from the Google Play platform, called BlueNRG<sup>?</sup>. The library code was integrated into the code generated by STM32CubeMX, added as an external library and statically linked.

While ST included example code for communicating with the Bluetooth module over SPI through interrupt based DMA transfer, this code was quite difficult to get working. Instead it was decided that blocking SPI communication were to be used, since this was much simpler to get working. The reasoning was that since the module supported a baud rate of up to 10 Mbit/s, this would be fast enough to cause minimal interference with other parts of the firmware code.

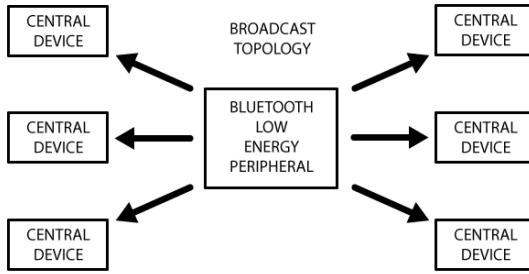


Figure 10: Bluetooth GAP topology.

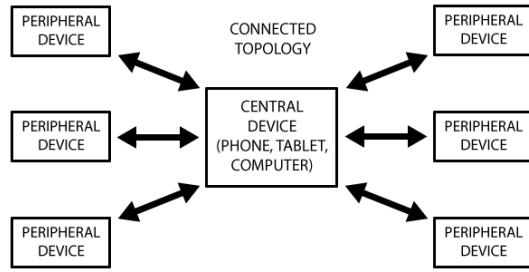


Figure 11: Bluetooth GATT topology.

As mentioned previously, the library implemented the Bluetooth GATT protocol. This protocol supports bidirectional communication from a single central device, in this case an Android cell phone, to several peripheral devices, such as the embedded system in this project. The library also supported the Bluetooth GAP protocol, which is a unidirectional communication protocol allowing one peripheral device to broadcast to multiple central devices. Figures 11 and 10 illustrates the topological differences between these protocols.

For this project, the GATT protocol was chosen. The reasoning was that enabling the Android app to send commands to the embedded system could be useful for controlling functionality. This meant that only a single phone could be connected to the system at any time, as opposed to the GAP protocol, which would allow multiple phones to listen to the Bluetooth broadcasts. Since the embedded system is designed to be used on a small dinghy with space for a maximum of two people, this seemed like a reasonable trade-off. If the system was to be used on a larger sail boat, the GAP protocol might be more useful, since it would allow multiple passengers to listen to broadcasted sensor data.

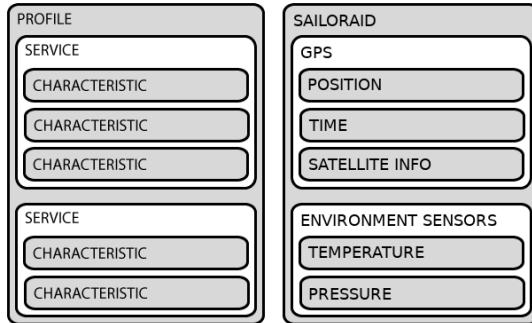


Figure 12: Bluetooth GATT transaction profile with usage example.

The GATT protocol performs transactions by nested structures called Profiles, Services and Characteristics. An example of this structure can be seen in figure 12. These structures were already implemented in the X-CUBE-BLE1 and updated by simple function calls. When new sensor data was received from e.g. the GPS or IMU devices, these functions were called at regular intervals which pushed the data to the Android app. Each profile were given a unique identifier which allowed the app to recognize which type of data was received.

#### 6.1.2 IMU

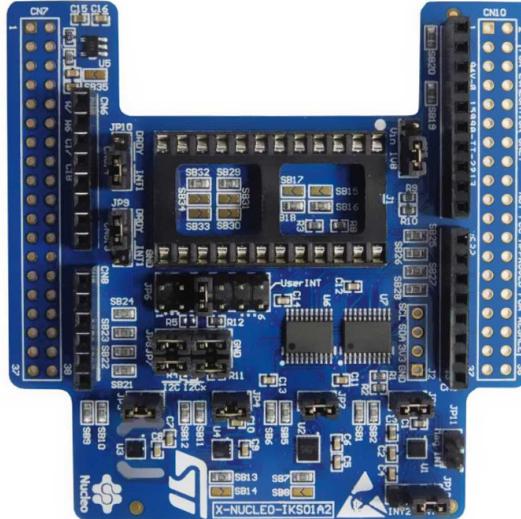


Figure 13

In order to measure the various time dependent spatial features such as orientation, acceleration and velocity, an IMU device was used. More specifically, the X-NUCLEO-IKS01A2<sup>7</sup> evaluation board (figure 13) developed by ST was chosen for rapid prototyping purposes. This board included the LSM6DSL 3D accelerometer/gyroscope, the LSM303AGR 3D accelerometer/magnetometer,

the HTS221 humidity and temperature sensor as well as the LPS22HB pressure sensor.

To interface the firmware with the board, the X-CUBE-MEMS1<sup>7</sup> library developed by ST was used. This library implemented the I<sup>2</sup>C communication protocol used by the previously mentioned IMU devices in the form of simple function calls, which saved a lot of development time. It was quite simple to integrate with the code generation from STM32CubeMX, only a few source definitions had to be modified. Like with the Bluetooth library (section 6.1.1) blocking communication was chosen to simplify the code, even though the MCU supported interrupt based DMA transfers. The I<sup>2</sup>C operated in fast mode at 400 kHz which was thought to cause minimal interference with the rest of the system in blocking transfer mode.

An important use case for the IMU was to determine the current orientation of the dinghy. To accomplish this, a type of sensor fusion algorithm called Madgwick AHRS (section ??) was used.

#### 6.1.3 Madgwick AHRS

Madgwick AHRS<sup>7</sup> is a type of sensor fusion algorithm which calculates the current orientation in space from three dimensional vectors of acceleration, angular velocity and magnetic field strength. It was developed in 2010 by Sebastian O.H. Madgwick as a more performant alternative to the Kalman filter approach. It basically integrates the angular velocity from the gyroscope, while using the accelerometer and magnetometer to create a reference to the horizontal plane. Earth's magnetic poles provides a horizontal vector which lies on the plane, while the gravitational acceleration is the plane's normal vector. This is then used by the algorithm to compensate for drift in gyro integration. The algorithm stores orientation in quaternions (rotation vectors with four elements), but can convert it to Euler angles, which can be more easily used.

The mathematical background of this algorithm is quite complicated and outside the scope of this report, see the official report<sup>7</sup> for more details.

#### 6.1.4 USB UART

Since this project involved analyzing sensor data for developing sensor fusion algorithms, for example combining GPS and accelerometer for accurate positioning (section ??) and measuring water wave properties, it was important to be able to log data at a reasonably high frequency. To this end, a hardware UART-over-USB chip was used, the ST-LINK/V2-1 on the Nucleo board, and FTDI FT232R on the custom project board.

MATLAB  
serial read

#### 6.1.5 GPS

#### 6.1.6 Range sensor

### 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 it's 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 pray<sup>?</sup>. 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 performance<sup>?</sup>. 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 errors<sup>?</sup>. 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 1960<sup>?</sup>. Its popular to use due to its efficiency when calculating predictions.<sup>?</sup>

Since everything is nonlinear in the universe, many systems cannot be modeled as linear<sup>?</sup> 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

$$\text{State equation} \quad x_k = F_{k-1}x_{k-1} + v_{k-1} \quad (2)$$

$$\text{Observation equation} \quad z_k = H(x_k) + w_k \quad (3)$$

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  $w_k \in \mathcal{N}(0, R_k)$ .

$$\text{Predict state estimate:} \quad \hat{x}_{k|k-1} = F_k \hat{x}_{k|k-1} + G v_{k-1} \quad (4)$$

$$\text{Predict covariance matrix:} \quad P_{k|k-1} = F_k P_{k-1|k-1} F_k^T + Q_k \quad (5)$$

$$\text{measurement residual} \quad \tilde{y}_k = z_k - H_k \hat{x}_{k|k-1} \quad (6)$$

$$\text{Innovation covariance} \quad S_k = H_k P_{k|k-1} H_k^T + R_k \quad (7)$$

$$\text{Optimal Kalman gain} \quad K_k = P_{k|k-1} H_k^T S_k^{-1} \quad (8)$$

$$\text{Update state estimate} \quad \hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k \tilde{y}_k \quad (9)$$

$$\text{Update covariance estimate} \quad P_{k|k} = (I - K_k H_k) P_{k|k-1} \quad (10)$$

$$\text{Measurement post-fit residual} \quad \tilde{y}_{k|k} = z_k - H_k \hat{x}_{k|k} \quad (11)$$

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

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

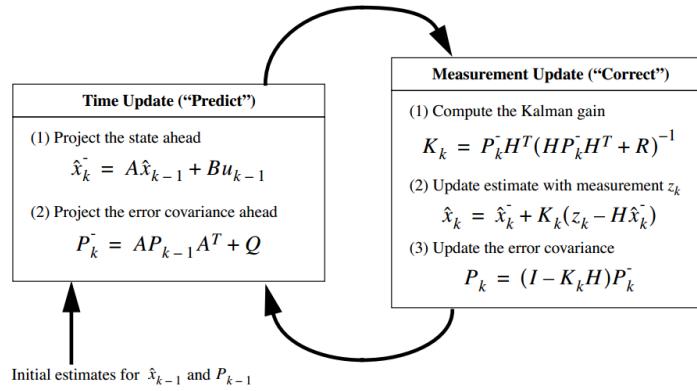


Figure 14: Kalman Filter prediction algorithm

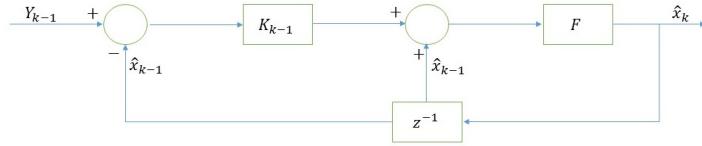


Figure 15: System diagram of Kalman prediction

## 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.

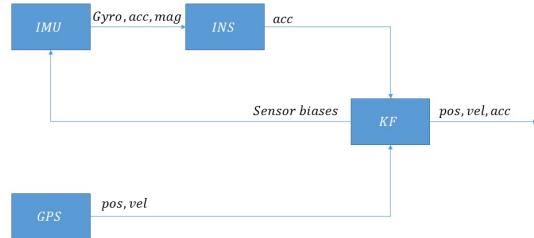


Figure 16: GPS/INS with loose integration

## Kalman Filter Model

The states that we want to observe are.

$$\bar{x} = \begin{bmatrix} x^{pos} & [m] \\ y^{pos} & [m] \\ v^x & [m/s] \\ v^y & [m/s] \end{bmatrix} \quad (12)$$

$x_{pos}$  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.

$$x_k^{pos} = x_{k-1}^{pos} + \Delta t v_{k-1}^x + \frac{1}{2} \Delta t^2 a_{k-1}^x \quad (13)$$

$$y_k^{pos} = y_{k-1}^{pos} + \Delta t v_{k-1}^y + \frac{1}{2} \Delta t^2 a_{k-1}^y \quad (14)$$

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

$$v_k^y = v_{k-1}^y + \Delta t a_{k-1}^y \quad (16)$$

Using the above equation the state matrix is expressed as.

$$F = \begin{bmatrix} 1 & 0 & \Delta t & 0 & \frac{1}{2}\Delta t^2 & 0 \\ 0 & 1 & 0 & \Delta t & 0 & \frac{1}{2}\Delta t^2 \\ 0 & 0 & 1 & 0 & \Delta t & 0 \\ 0 & 0 & 0 & 1 & 0 & \Delta t \end{bmatrix} \quad G = \begin{bmatrix} \Delta t^2 & 0 \\ 0 & \Delta t^2 \\ \Delta t & 0 \\ 0 & \Delta t \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (17)$$

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

$$v_k = \begin{bmatrix} \sigma_{IMU^x}^2 & 0 \\ 0 & \sigma_{IMU^y}^2 \end{bmatrix} \quad (18)$$

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  $Q = GwG^T$ .

$$Q = \begin{bmatrix} \sigma_{a^x}^2 \Delta t^4 / 4 & 0 & \sigma_{a^x}^2 \Delta t^3 / 2 & 0 & \sigma_{a^x}^2 \Delta t^2 / 2 & 0 \\ 0 & \sigma_{a^y}^2 \Delta t^4 / 4 & 0 & \sigma_{a^y}^2 \Delta t^3 / 2 & 0 & \sigma_{a^y}^2 \Delta t^2 / 2 \\ \sigma_{a^x}^2 \Delta t^3 / 2 & 0 & \sigma_{a^x}^2 \Delta t^2 & 0 & \sigma_{a^x}^2 \Delta t & 0 \\ 0 & \sigma_{a^y}^2 \Delta t^3 / 2 & 0 & \sigma_{a^y}^2 \Delta t^2 & 0 & \sigma_{a^y}^2 \Delta t \\ \sigma_{a^x}^2 \Delta t^2 / 2 & 0 & \sigma_{a^x}^2 \Delta t & 0 & \sigma_{a^x}^2 & 0 \\ 0 & \sigma_{a^y}^2 \Delta t^2 & 0 & \sigma_{a^y}^2 \Delta t & 0 & \sigma_{a^y}^2 \end{bmatrix} \quad (19)$$

Consider (??) and (??) 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.

$$R = \begin{bmatrix} \sigma_{GPS^x}^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & \sigma_{GPS^y}^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma_{GPS^{vx}}^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & \sigma_{GPS^{vy}}^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma_{IMU^x}^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & \sigma_{IMU^y}^2 \end{bmatrix} \quad (20)$$

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.

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