Luleå University of Technology

Dept. of Computer Science, Electrical and Space Engineering

D7039E – Project in Industrial Computer Systems

Project SailorAid

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Abstract

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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

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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 choosen 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.

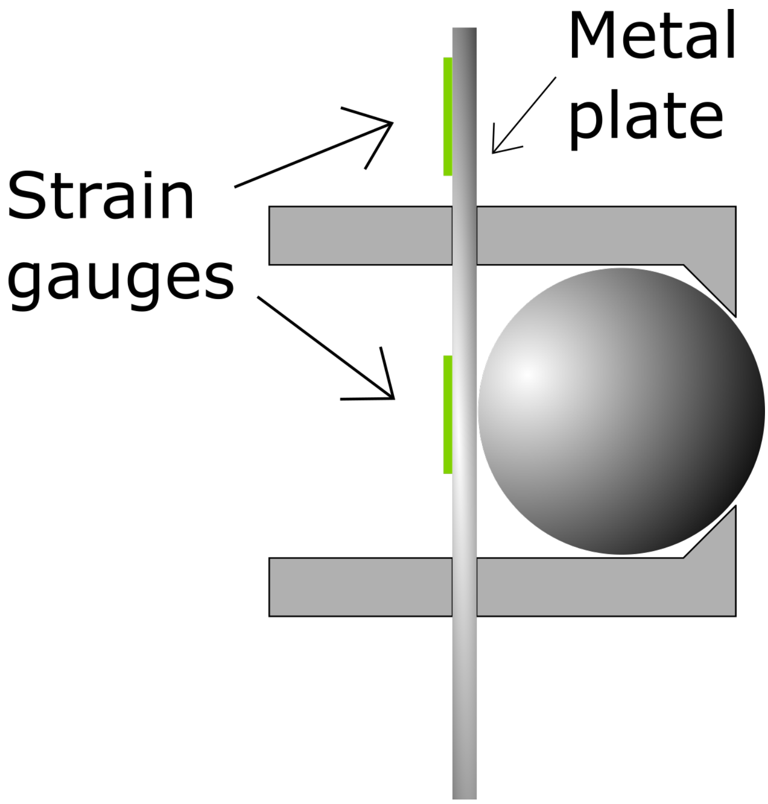

Figure 1: Function of first prototype

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.

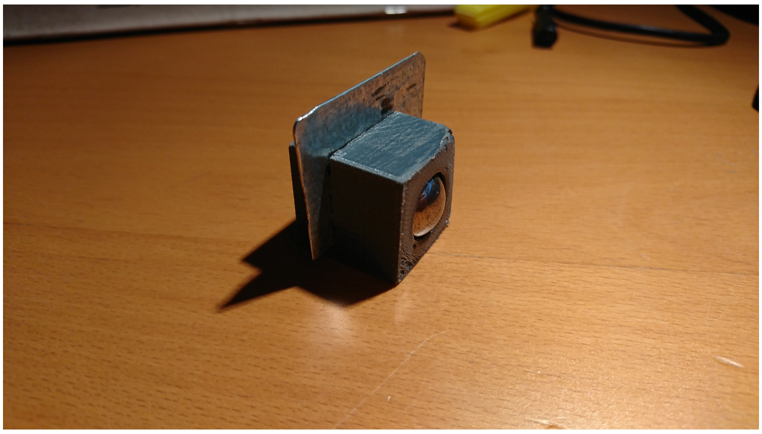

Figure 2: Function of first prototype

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.

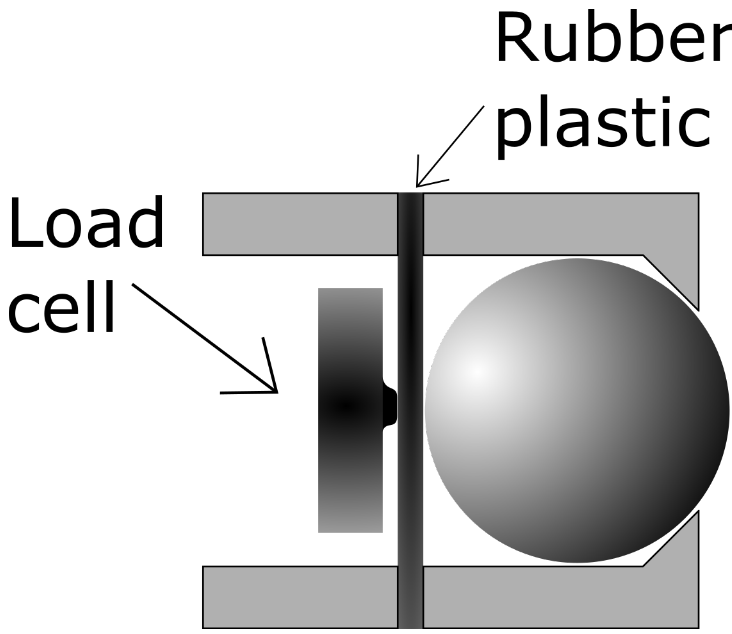

Figure 3: Function of second prototype

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 then 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 Rg.

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 STM32CubeMX[1] 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 challange 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 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

The Bluetooth firmware package called X-CUBE-BLE1[2] 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-MEMS1[3]

6.2 Android application

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[?] . Sensor fusion theory is not only found in the living species it is found in cars, planes, computers and so on ans this to enhance performance[?] . 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, atmospherics delays or clock bias errors[?] . 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[?] . Its popular to use due to its efficiency when calculating predictions.[?]

Since everything is nonlinear in the universe, many systems cannot be modeled as linear[?] 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

$$\text{State equation} \qquad x_k = F_{k-1}x_{k-1} + v_{k-1} \tag{1}$$

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

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

$$\text{Predict state estimate:} \qquad \hat{x}_{k|k-1} = F_k\hat{x}_{k|k-1} + Gv_{k-1} \tag{3}$$

$$\text{Predict covariance matrix:} \qquad P_{k|k-1} = F_kP_{k-1|k-1}F_k^T + Q_k \tag{4}$$

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

$$\text{Innovation covariance} \qquad S_k = H_kP_{k|k-1}H_k^T + R_k \tag{6}$$

$$\text{Optimal Kalman gain} \qquad K_k = P_{k|k-1}H_k^TS_k^{-1} \tag{7}$$

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

$$\text{Update covariance estimate} \qquad P_{k|k} = (I - K_kH_k)P_{k|k-1} \tag{9}$$

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

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.

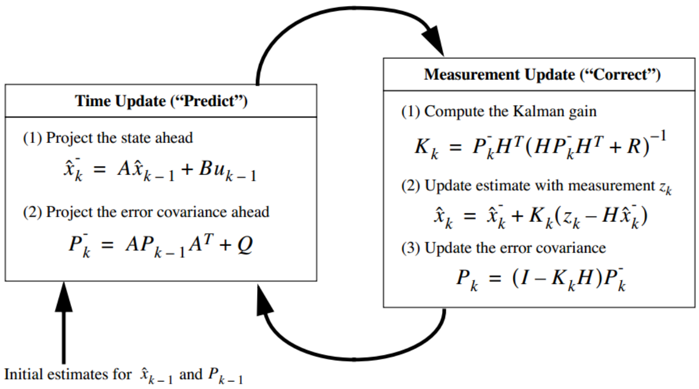

Figure 6: Kalman Filter prediction algorithm

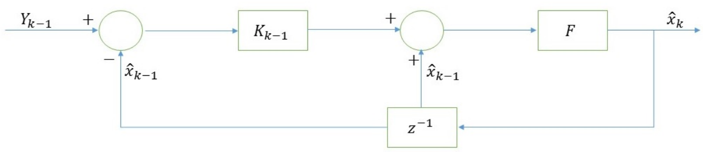

Figure 7: System diagram of Kalman prediction

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.

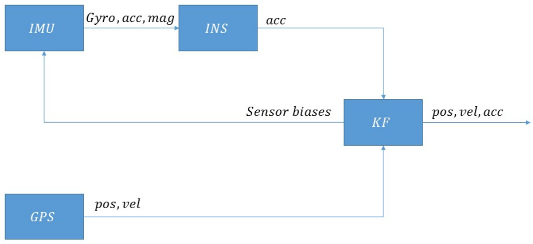

Figure 8: GPS/INS with loose integration

Kalman Filter Model

The states that we want to observe are.

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

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.

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

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

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

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

Using the above equation the state matrix is expressed as.

$$F = \begin{bmatrix} 1 & 0 & \Delta t & 0 & \frac{1}{2}\Delta t^2 & 0 \\ 0 & 1 & 0 & \Delta t & 0 & \frac{1}{2}\Delta t^2 \\ 0 & 0 & 1 & 0 & \Delta t & 0 \\ 0 & 0 & 0 & 1 & 0 & \Delta t \end{bmatrix} \qquad G = \begin{bmatrix} \Delta t^2 & 0 \\ 0 & \Delta t^2 \\ \Delta t & 0 \\ 0 & \Delta t \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{16}$$

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

$$v_k = \begin{bmatrix} \sigma^2_{IMU^x} & 0 \\ 0 & \sigma^2_{IMU^y} \end{bmatrix} \tag{17}$$

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

$$Q = \begin{bmatrix} \sigma^2_{a^x}\Delta t^4/4 & 0 & \sigma^2_{a^x}\Delta t^3/2 & 0 & \sigma^2_{a^x}\Delta t^2/2 & 0 \\ 0 & \sigma^2_{a^y}\Delta t^4/4 & 0 & \sigma^2_{a^y}\Delta t^3/2 & 0 & \sigma^2_{a^y}\Delta t^2/2 \\ \sigma^2_{a^x}\Delta t^3/2 & 0 & \sigma^2_{a^x}\Delta t^2 & 0 & \sigma^2_{a^x}\Delta t & 0 \\ 0 & \sigma^2_{a^y}\Delta t^3/2 & 0 & \sigma^2_{a^y}\Delta t^2 & 0 & \sigma^2_{a^y}\Delta t \\ \sigma^2_{a^x}\Delta t^2/2 & 0 & \sigma^2_{a^x}\Delta t & 0 & \sigma^2_{a^x} & 0 \\ 0 & \sigma^2_{a^y}\Delta t^2 & 0 & \sigma^2_{a^y}\Delta t & 0 & \sigma^2_{a^y} \end{bmatrix} \tag{18}$$

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.

$$R = \begin{bmatrix} \sigma^2_{GPS^x} & 0 & 0 & 0 & 0 & 0 \\ 0 & \sigma^2_{GPS^y} & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma^2_{GPS^{vx}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \sigma^2_{GPS^{vy}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma^2_{IMU^x} & 0 \\ 0 & 0 & 0 & 0 & 0 & \sigma^2_{IMU^y} \end{bmatrix} \tag{19}$$

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