Faculty of Science
Science and Engineering

Graduate and Post Graduate
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Control of Autonomous sailboats

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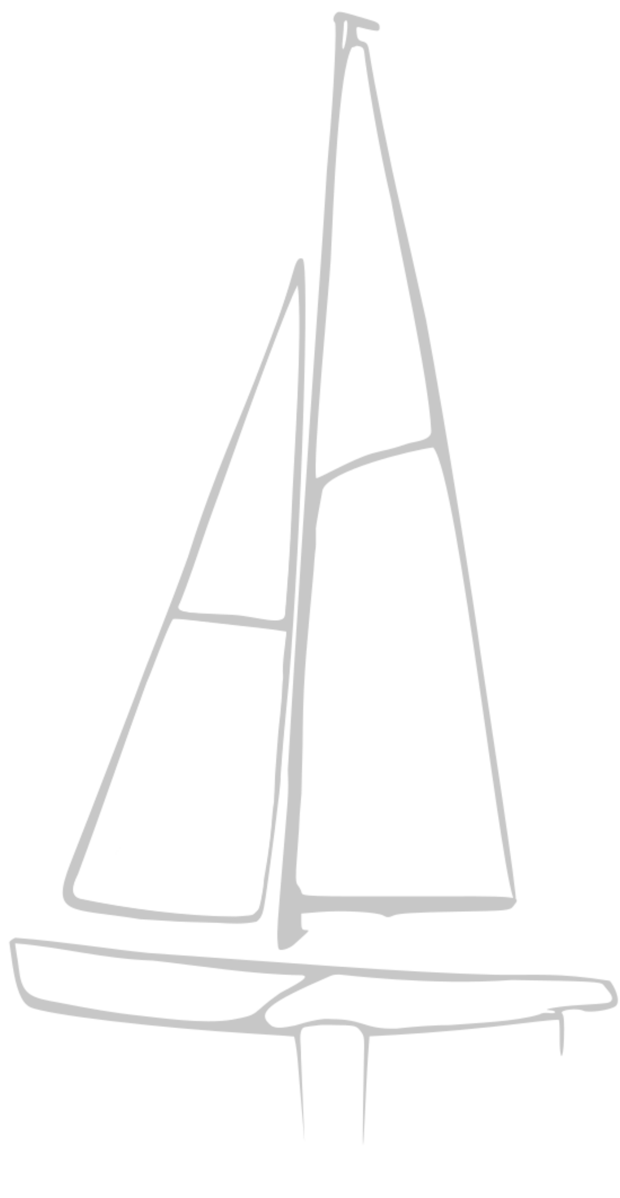

Acknowledgement

I would like to thank my internship tutor, Dr Jian Wan, lecturer in Control Systems Engineering in the University of Plymouth. I had a warm welcome in the university and Mr Wan was reactive to answer my questions and to bring me new components I needed.

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Thanks to Luc Jaulin, my teacher in robotics, which proposed me this internship and guided me to develop the Kalman Filter I needed.

Résumé

Ce document présente le travail que j'ai effectué au cours de mon stage de trois mois à l'Université de Plymouth. Le sujet était le suivant *Contrôle de voiliers autonomes*. Pour de nombreuses applications telles que la collecte d'échantillons, l'exploration des fonds marins ou la navigation dans les océans, les voiliers autonomes constituent un domaine de recherche en plein essor. C'est pourquoi j'ai décidé de travailler sur ce domaine pour mon stage dans le cadre de la fin de ma deuxième année d'école d'ingénieur à l'ENSTA Bretagne.

Après avoir acquis les données des capteurs du bateau, ma mission était de filtrer les valeurs d'entrée pour pouvoir les utiliser dans un contrôleur. Ensuite, je devais construire le contrôleur, le tester en simulation et en situation réelle. L'essentiel était de créer un système robuste et générique pouvant être cloné sur de nombreux autres bateaux.

Plusieurs tests ont été effectués dans la baie de Plymouth et le comportement de chaque contrôleur a été validé. Comme test final, la participation à la WRSC en Chine a prouvé que le système fonctionnait, même dans des conditions défavorables.

Abstract

This document reports the work I did during my three month internship at the University of Plymouth. The subject was *Control of autonomous sailboats.* Autonomous sailboats are an active field of research due to many applications such as collecting samples, exploring seabed or travelling ocean. That is why I decided to work on this domain for my internship of secondary year student from ENSTA Bretagne.

After acquiring data from sensors, my mission was to filter the input values to be able to use them in a controller. Then I had to build the controller, to test it in simulation and in real situation. The main point was to design a robust and generic system that can be cloned on other boats.

Many tests have been done in the Plymouth bay, and the behaviour of each controllers have been validated. The participation to the WRSC in China was the final test, and it was proven during this competition that the system works, even in unfavorable conditions.

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Introduction

After the golden age of internet, autonomous robots are an uncontested new trend in technology. Whether in the air with drones, on land with autonomous cars or under the see with AUVs (Autonomous Underwater Vehicles), autonomy touches more and more applications. The multiplication of autonomous robots creates a virtuous circle for the economy and the research on this domain.

The University of Plymouth is known for its department Autonomous Marine Systems Research. Many projects on boats, sailboats and underwater vehicles exists, led by researchers, PhD students or students. The Plymouth bay and the large tank test in the university allows workers to work on a pleasant and convenient place.

My internship was focused on *Control of autonomous sailboats*. Jian Wan (internship tutor), wanted a robust system to reuse it for research and teaching. During these three months, I chose to focus my work on designing filters for raw data and creating controllers.

1 Sailboat

1.1 How does it work ?

The following description of a sailboat is made on a robotic point of view. The purpose of this paragraph is to describe the actuators and the environment of a sailboat, without deep knowledge on sailing and naval architecture.

A sailboat can be separated in three main parts : the hull, the sail and the rudder.

- The hull is the fix part of a sailboat that generate the buoyancy. Three general types can be found. As it is named, a trimaran has three hulls, two on sides and one on the center of the boat. A catamaran has two hulls on its sides and joining part to fix them and to create the body. A mono hull is only composed by one hull. The issue with this architecture is about stability. That is why a mono hull is mainly coupled with a fin and keel to create a counterweight.

- The element which moves the boat is the sail. The sail is a stretched canvas that capture the wind. On contact to the sail, the wind force is transferred to the sail. Hung on the mast, the sail gives this force to the boat, creating/generating a thrust. Generally there are two sails : a little front one, named the jib, and a big one, named the main sail on the back.

- The rudder is most of the time fixed on the back of the boat. It can be assimilated to a plate that changes the flow around itself, resulting in a force and moment on the water. Orienting the rudder made the boat rotating. The orientation of the rudder is between $-\pi/2$ and $\pi/2$, on a local basis. It is relevant to notice that it is mechanically allowed to go below $-\pi/4$ and above $\pi/4$ but this will slow the boat. That is why the angle of the rudder is controlled between $-\pi/4$ and $\pi/4$.

To sum up, the sail is the actuator used to control the speed, the rudder is the one to control the orientation and the hull is the mechanics that determine the behaviour of the boat.

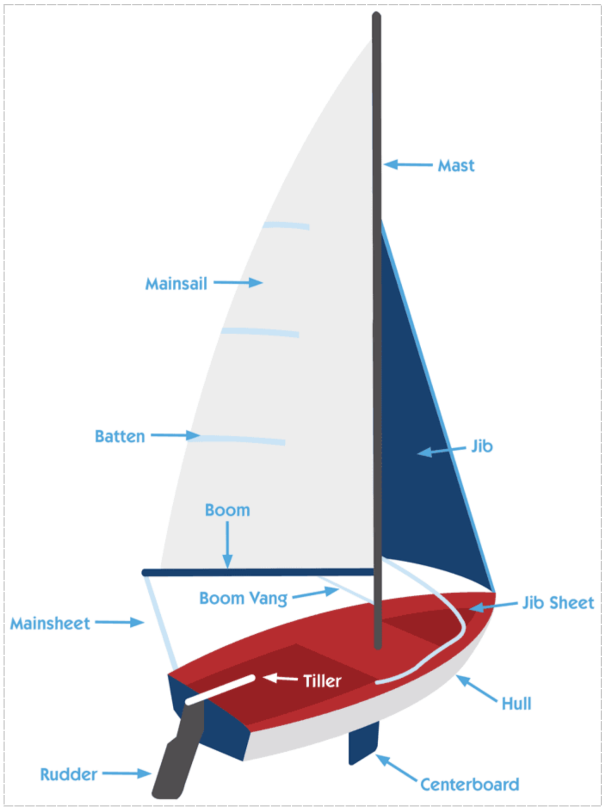

Figure 1: Sailboat parts

1.2 Ragazza : main information

The Ragazza sailboat (from ProBoat) was chosen by my mentor. It is relatively cheap, 100% waterproof and robust.

Beam	247.65mm
Boat Type	Sailboat
Completion Level	Ready-To-Run
Hull Material	Fiberglass
Mast Height	1.55m
Sail Area (Jib)	0.24 m^2
Sail Area (Main)	0.18 m^2
Sail Area (Overall)	0.42 m^2
Steering	Rudder

Figure 2: Ragazza sailboat

There is only one access to enter the boat. From this access you can see the two servo motors, one for the rudder and the other for the sails. Due to this architecture, the jib and the main sail are commanded simultaneously : it is not possible to turn the main sail while the jib stay on its initial position.

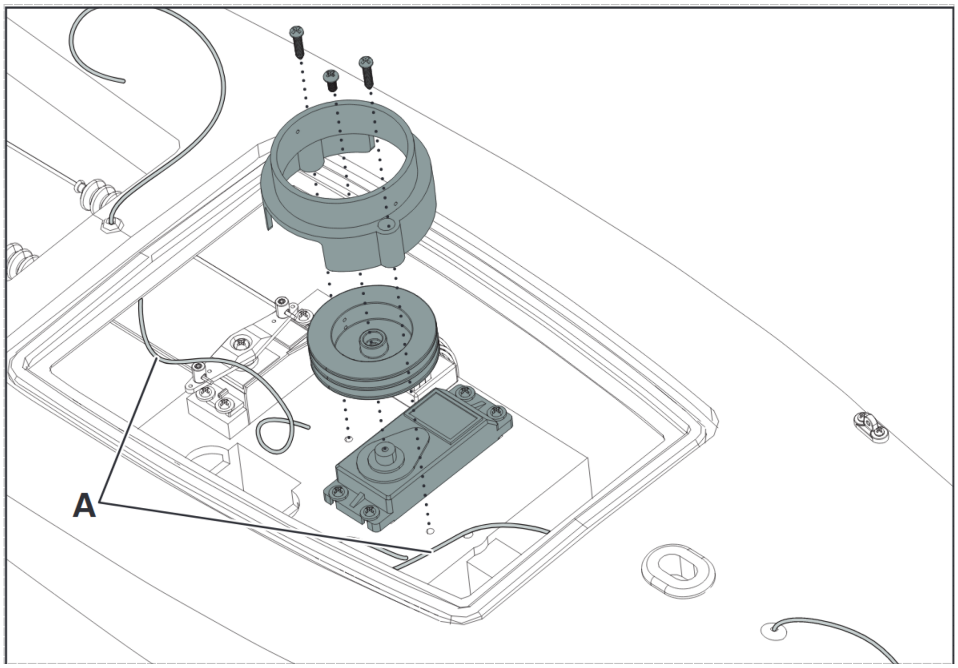

Figure 3: Motors

It can be seen in the previous figure that there is a box where the two motors are fixed. This box takes a large space inside the boat, that is why the remaining space for integration of electronics was the main constraint. As a second constraint, it was not allowed to drill any holes. Other options had to be found to fix external sensors, ad 3D-printed parts and suction pads.

2 Sensor integration and electronic cards

2.1 Requirements and data flow

To control the boat autonomously, few parameters must be known. First of all, the position of the sailboat is needed. It will give information about the precise location of the boat on earth and to position itself compared to a target. In most cases, GPS (Global Positioning System) sensors are implemented to complete this task. Once it knows its position, the second step is to look for the attitude, i.e. the orientation of the boat in a three dimensions space. Euler angles, are often used to describe the attitude of an object, and this choice has been taken in this project. To obtain Euler angle, an algorithm (described in 3.1) is applied to an IMU (Inertial Measurement Unit). Nevertheless, this is not enough to sail the boat properly. The wind is a crucial factor that cannot be forgotten. The relative orientation of the wind is acquired too to know where does it come from. This is relevant to avoid the "No go zone" or "No sail zone". The No go zone is a configuration where the boat has front wind and is not able to use it to move.

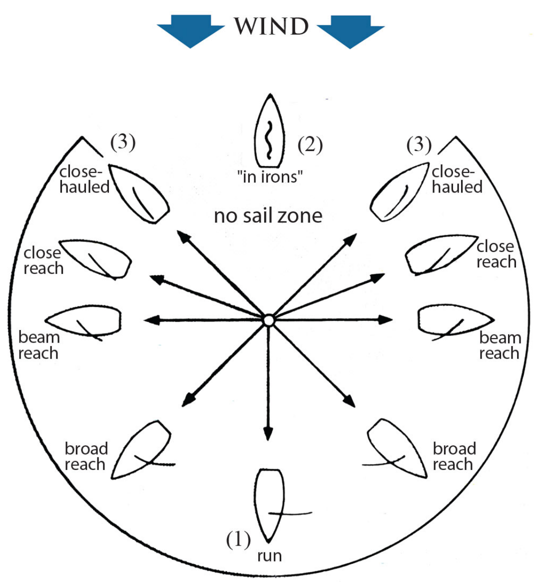

Figure 4: No sail zone

In this situation, the boat is uncontrollable and starts to drift. Waiting a change of wind direction or a rotation of a boat is not an option if the controller must be efficient in any cases. Finally, a couple of variable is significant to keep this idea of efficiency : the wind speed and the speed of the boat. The wind speed got by the boat is called the apparent wind. It is known that when a boat goes to a high speed you can feel induced wind due to the movement of the boat, even if there were no wind without speed. The following figure shows how to compute the general wind, called the true wind

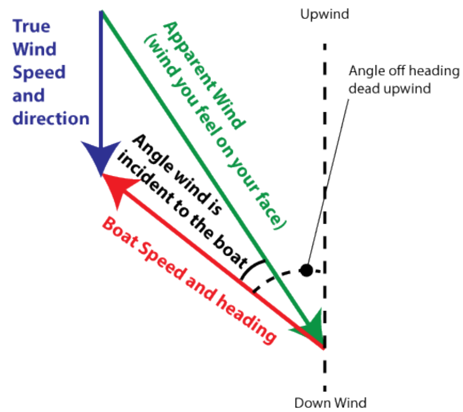

Figure 5: Apparent and true wind

The following diagram is a global overview of how these data and values are planned to evolve though the system.

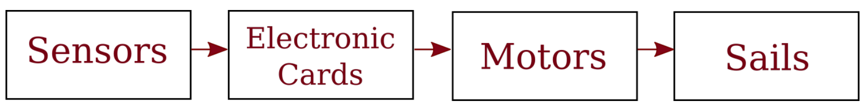

Figure 6: Data flow

In section 2.3 you will find more details about this diagram.

2.2 Sensors

As explain in the previous section, some sensors are mandatory to control the sailboat autonomously. The table below summarise the chosen sensors and their main characteristics.

GPS	XBU-353-S4	USB wiring, 53mm * 19.2mm, supply : +4.5 à +6.5 Vcc
IMU	9-dof Groove IMU	I2C/SPI interface, accelerometer, gyroscope and magnetometer
Wind sensor	7911 - Davis Instruments	All in one speed and direction
Camera	Raspberry camera v2	1080p30 fps for video

The camera is used for boat detection, buoy recognition and obstacle avoidance, see Matthieu Bouveron's report for further information.

2.3 Electronic cards

The electronic architecture is compose in two cards, which communicates each other.

- An Arduino Mega is used to acquire data from sensors and to move actuators. The maximum rate is 17Hz and it sends the sensor data to the controlling card through usb cable using ROS procedure. ROS (Robot Operating System) is a middleware that facilitate communication between several parallel programs. It is easy to use for a project to separate tasks between coders.

- A Raspberry Pi 3B+ is chosen as the controlling card. It takes raw data from Arduino, filter and use them in a controller. Then the controller sends values for actuators back to the Arduino.

The following work described in this report was only made for Raspberry integration and the programming language used is Python. If more information is needed about how to get data from sensor and how to communicate between those two cards, please refer to Alexandre Courjaud's report.

3 Filters

3.1 Inertial Measurement Unit

3.1.1 Nine degree of freedom IMU

Definition of IMU:

An Inertial Measurement Unit is a system used in vehicules (such as spacecrafts, aircrafts, unmanned underwater vehicles) to determine its attitude, which means the orientation of the system. An IMU always combines an accelerometer and a gyroscope, and sometimes a magnetometer is added.

9-DOF groove IMU :

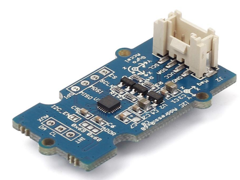

Figure 7: Groove IMU

The sensor is a tilt compensation magnetometer Groove 9-DOF IMU. It is called nine degree of freedom because it is divided in thee internal components.

- An accelerometer, which returns the acceleration of the IMU in three spacial directions (named a_x,a_y,a_z). In a static movement, regarding the second law of Newton, an acceleration of 1g (9.81 $m.s^{-1}$) is present. It is equal to a vector that points the center of the earth.

- A gyroscope, which returns the rotation speed in three spacial directions (named g_x,g_y,g_z)

- A magnetometer, which is a 3D vector that points to the magnetic north (its projections in the local geometrical marker are named mx,my,mz).

Calibration :

This type of sensor requires calibration, especially the cheap ones. Gyroscope calibration is essential and easy to do. Static offset could exist and it is crucial to remove it. Otherwise the IMU seems to rotate while it is static. To remove the offset, the IMU is let static and a mean of values of each axis taken for a long period (10-20 seconds) is stored as the static offset. Each time a new data is taken, the gyro offset has to be subtract to raw value.

Magnetometer is more difficult to calibrate. On the one hand, the norm of the magnetic field vector should be constant, because the magnetic field does not change. Nevertheless, this hypothesis is rarely verified. If the IMU is rotated in many directions, it will draw a sphere (as expected), but not centered on the origin. For the magnetometer too, an offset has to be calculated, to center the sphere. This is called 'hard iron distortion'. Two appraoches can be used. The fast one is to calculate the offset with the extremum of the shpere :

$$x_{of} = \frac{x_{max} + x_{min}}{2}$$
$$y_{of} = \frac{y_{max} + y_{min}}{2}$$
$$z_{of} = \frac{x_{max} + x_{min}}{2}$$

The other one is to use the least square method for a sphere. There are many libraries in several programming language to implement it.
On the other hand, the sphere is sometimes elliptic. To make it more circular, it is possible to find its orientation and exentricity to reshape it as a shpere.
The final transformation to obtain calibrated data :

$$X_{new} = X_{raw} * \alpha - X_{offset}$$

3.1.2 Find Euler angles

Definition of Euler angles :

Euler angles are three angles that determines the attitude of a body compared to a cartesian origin. They are named roll (aroud x axis), pitch (around y axis) and yaw (around z axis)

Using accelerometer :

The acceleration vector points to the center of the earth when the body of the object stay relatively motionless. That is why accelerometer is used to determine pitch and roll, by projecting the gravity vector g on plan xOz and yOz [2] :

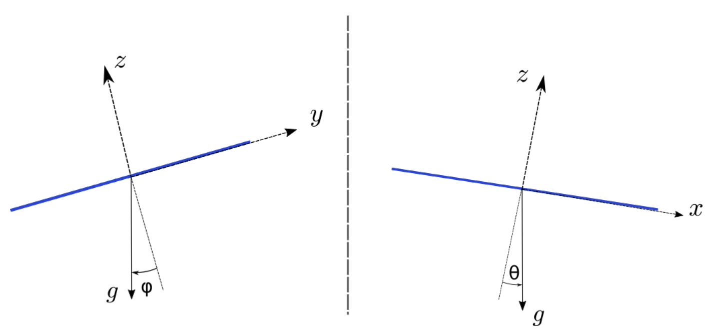

Figure 8: Roll (left) and pitch (right) from accelerometer

Thus, the equations to find pitch and roll are :

$$\phi = \arctan\left(\frac{a_y}{a_z}\right) \quad , \quad \theta = \arctan\left(\frac{a_x}{a_z}\right))$$

Using gyroscope :

To find Euler angles form gyroscope (θ for example), the rotation speed (ω) is integrate to get the angle.

$$\theta = \int_{t}^{t+dt} \omega \, \mathrm{d}t$$

For programming, the numerical integration is an approximation of the true value.

$$\phi = \omega_x * dt \quad , \quad \theta = \omega_y * dt \quad , \quad \psi = \omega_x * dt$$

Even if dt is small (10^{-2} to 10^{-3}) this generate a drift through time, which needs to be compensated.

Using magnetometer :

Magnetometer is used as a compass. As it indicates magnetic north, you cannot get pitch and roll. But, by projecting the magnetic vector in the xOy plan, it is simple to get the yaw angle and to know the heading of the IMU

3.1.3 Implementation of Kalman filter

The Kalman filter is a estimator that takes a serie of measurements and predict the output of unknown varible. It is a robust algorithm, especially to reduce noise and random values. It is manly based on two formulas :

- An evolution equation $x_k = Ax_{k-1} + Bu_k + w_k$ where A is the state transition model which is applied to the previous state, B is the control-input model which is applied to the control vector u_k and w_k is a white gaussian noise.
- An measurement equation $z_k = Cx_{k-1} + v_k$ where C is the observation matrix and v_k the observation white gaussian noise.

There are more than those two equation hidden in the Kalman filter, for more details you can refer to ENSTA Bretagne's course on Kalman filter[3].

This filter is used here as a fusion algorithm. Gyro data are taken for the evolution equation and accelerometer/magnetometer data are used in the measurement equation. This exemple will use ψ but the same kalman filter is applied to ϕ and θ. Here the state vector contains only the euler angle we need to filter.

$$x_k = [1] * x_{k-1} + [dt] * [w_{z,gyro}]$$
$$[\psi_{mes}] = [1] * x_{k-1}$$

The dt in the control matrix B is the sample period between two data from the IMU. It should be dynamically recalculate to have a true anticipation.

At the beginning it worked good, but an angle is not linear, it could switch from $2 * \pi$ to 0, and the Kalman filter is a linear estimator. That is why this phenomenon can be observed :

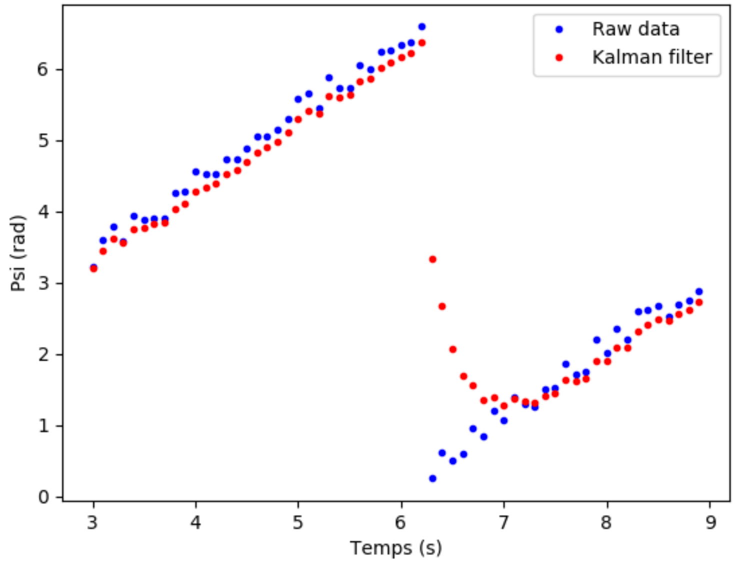

Figure 9: Kalman filter and non linearity

3.1.4 Extended Kalman Filter

The issue with a basic Kalman filter is the non linearity of angles. An Extended Kalman filter is chosen to fix this issue. Here are the full equations of the Extended Kalman Filter :

Prediction step :

$$\hat{x}_{k|k-1} = f(\hat{x}_{k-1|k-1}, uk) \tag{1}$$
$$P_{k|k-1} = F_k P_{k-1|k-1} F_k^T + Q_k \tag{2}$$

Update step :

$$y_k = z_k - h(\hat{x}_{k|k-1}) \tag{3}$$
$$S_k = H_k P_{k|k-1} H_k^T + R_k \tag{4}$$
$$K_k = P_{k|k-1} H_k^T S_k^{-1} \tag{5}$$
$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k y_k \tag{6}$$
$$P_{k|k} = (I - K_k H_k) P_{k|k-1} \tag{7}$$

With $F = \frac{\partial f}{\partial x} \quad H = \frac{\partial h}{\partial x}$

The f and h functions are replacing matrixes A,B,C of basic Kalman filter, but the filter keeps the same steps and computations. The state vector has to be redefine :

$$x = \begin{pmatrix} x1 \\ x2 \\ x3 \end{pmatrix} = \begin{pmatrix} \cos(\psi) \\ \sin(\psi) \\ \cos(\psi)^2 + \sin(\psi)^2 \end{pmatrix}$$

Cosine and sinus are linear even if ψ jumps from 0 to 2π. The filter work with only $x1$ and $x2$ (the reason is explained below) but a constraint could be added to force the convergence of $x1$ and $x2$. A trigonometric formula gives $\cos(\psi)^2 + \sin(\psi)^2 = 1 \Leftrightarrow x1^2 + x2^2 = 1$. $x3$ will be forced to converge to 1. Then f, h, F, H are set to :

$$f(x,u) = \begin{pmatrix} x1 - x2 * dt * u \\ x1 * dt * u + x2 \\ x3 \end{pmatrix} \quad , \quad F = \begin{pmatrix} 1 & -dt * u & 0 \\ dt * u & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$h(x,u) = \begin{pmatrix} x1 \\ x2 \\ x1^2 + x2^2 \end{pmatrix} \quad , \quad H = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 2 * x1 + 2 * x2 \end{pmatrix}$$

When a new raw measure arrives, the cosine and sinus are calculated to be given to the innovation step with:

$$z = \begin{pmatrix} \cos(\psi_{raw}) \\ \sin(\psi_{raw}) \\ 1 \end{pmatrix}$$

Then, the correction step returns a corrected state vector. The filterd value of ψ is

$$\psi = \arctan\left(\frac{x2}{x1}\right)$$

The same Kalman filter is applyed to ϕ and θ.

3.1.5 Complementary Filter

As it was noticed in 3.1.2, pitch and roll given by acceleration are perturbed when the IMU is accelerating. To limit tnis effect, a complementary filter can be used. This aim is to fusion two raw data (from accelerometer and gyroscope) and to give them a certain weight. The equation of this filter is :

$$\theta = \alpha * \theta_{acc} + (1 - \alpha) * \theta_{gyro}$$

α is the complementary gain, its value is between 0 and 1. Close to zero the gyroscope data is used in majority, close to one the accelerometer data is used in majority, and to 0.5 both have the same influence. Here α is set to 0.7 to avoid noise during acceleration but to preserve enough weight to accelerometer to correct drift of gyroscope.

3.2 Wind sensor

3.2.1 Filter wind direction

Filtering wind direction is easy, because it is an other angle to filter. That is why the previous Extended Kalman Filter is reused and nothing else have been developped for that sensor.

3.2.2 Filter wind speed

The wind speed does not require a Kalman filter. The only thing needed for this sensor is to filter the noise due to little oscillations of apparent wind and oscillations due to a sudden change of heading. High frequency needs to be removed, that is why a low-band filter (also known as low-pass filter) is the best choice. The formula is close to the complementary filter. It has a gain alpha too, but not to weight between two inputs, but to weigh between previous data and new data :

$$v = \alpha * v_{previous} + (1 - \alpha) * v_{new}$$

With some experiments, α was set to 0.5 to keep both influence of past and present.

4 Controller, Simulation and Display

4.1 Controller

In this section, the heading of the boat is represented by θ, the wind by ψ, the desired angle by $\overline{\theta}$, α a gain and the control value by u.

4.1.1 Heading following

The control for heading following is a proportional command for both rudder and sail. The aim was to first implement a basic controller to reuse it in higher level controllers.

Some functions, such as $\arctan(\tan(x))$ or $\cos(x)$ are used to avoid non linear jumps from angle subtractions

$$u_{rudder} = \alpha_{rudder} * \arctan(\tan(0.5 * (\theta - \overline{\theta})))$$
$$u_{rudder} = \alpha_{sail} * \pi/4 * (\cos(\psi - \overline{\theta}) + 1)$$

If α_{rudder} or α_{sail} are set more than 1, to have a faster response, the value of u has to be cut to stay between $[-\pi/4; \pi/4]$ for the rudder and $[0, \pi/2]$ for the sail.

4.1.2 Line following

Line following implemented in the sailboat is taken from Luc Jaulin and Fabrice Le Bars' paper on sailboat[5].

Function in: $\mathbf{m}, \theta, \psi, \mathbf{a}, \mathbf{b}$; out: $\delta_r, \delta_s^{\max}$; inout: q

$e = \det\left(\frac{\mathbf{b}-\mathbf{a}}{\|\mathbf{b}-\mathbf{a}\|}, \mathbf{m}-\mathbf{a}\right)$

if $|e| > \frac{r}{2}$ then $q = \text{sign}(e)$

$\varphi = \text{atan2}(\mathbf{b}-\mathbf{a})$

$\theta^* = \varphi - \frac{2.\gamma_\infty}{\pi}.\text{atan}\left(\frac{e}{r}\right)$

if $\cos(\psi - \theta^*) + \cos\zeta < 0$

  or $(|e| < r$ and $(\cos(\psi - \varphi) + \cos\zeta < 0))$

    then $\bar{\theta} = \pi + \psi - q.\zeta$.

    else $\bar{\theta} = \theta^*$

end

if $\cos(\theta - \bar{\theta}) \geq 0$ then $\delta_r = \delta_r^{\max}.\sin(\theta - \bar{\theta})$

else $\delta_r = \delta_r^{\max}.\text{sign}(\sin(\theta - \bar{\theta}))$

$\delta_s^{\max} = \frac{\pi}{2}.\left(\frac{\cos(\psi - \bar{\theta})+1}{2}\right)$.

Figure 10: Line following controller

To summarize, this controller is based on an attractive vector field pointing to the line, and the boat use the heading following to feet the vector field.

4.1.3 Station keeping

Three ways to keep the same position have been developed during this internship, with different approaches.

The turn around :

The first idea is to arrive to the station keeping point and to try to circle around it. Basically, the rudder is turned completely to the right or to the left to start to turn. For the sail, the mainsheet is released. Half time the sail is aligned with the wind (no propulsion, just inertia) and half time the wind on the back of the boat is propelling it.

The main drawback is the boat can drift away from the station keeping point without any correction. This solution is ok for around 20 seconds but not more.

The 90 degrees line :

The issue with station keeping is to maintain the control full time. That is why the No-sail-zone have to be avoided. that is why this station keeping is a line following, center on the station keeping point. Following this line allows the boat to be perpendicular to the wind and to preserve the control.

But there is a part of random in this controller. When the sailboat arrives to the end of its line, it will perform an half turn. The direction of the half turn depend on the orientation of the boat.

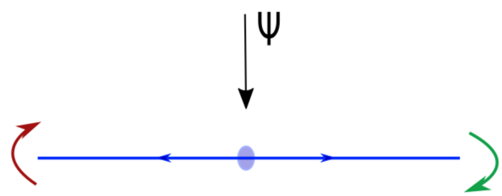

Figure 11: Station keeping line 90 degrees

In the favourable case, the sailboat will rotate with the wind on its back (green arrow). On the unfavourable case, the boat will rotate with front wind and lose control (red arrow).

The infinite symbol :

For this station keeping the same principle as the previous one is applied with a solution to avoid the unfavourable case. The goal is to replace the line by two lines with a little angle (less than 45 degrees). Then, to force the boat to turn on the right direction, it will not follow a line but a half circle. With this technique, it is sure that the sailboat is never against the wind and keeps the control.

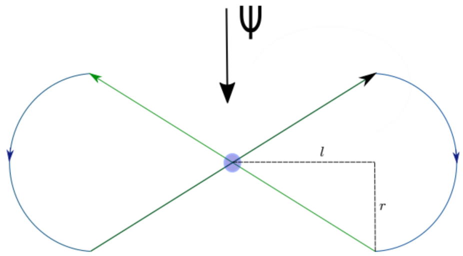

Figure 12: Station keeping infinite symbol

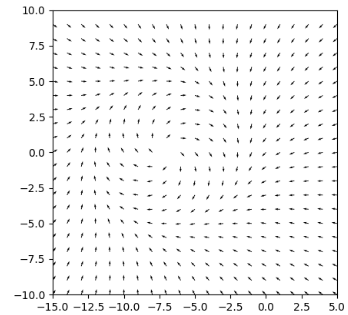

Figure 13: Vector field for attractive circle

4.2 Simulation

Simulation was crucial during this internship. It allows one to test algorithms, filter and behaviour of the boat on a virtual environment. Then, when the code is validated in simulation, outdoor tests are viable to verify if the algorithm ensures a proper functioning of the system.

To simulate the system, the dynamic of the sailboat is needed. The following equations and text are taken from RobMOOK[4].

$$
\left\{
\begin{array}{lcl}
\dot{x} & = & v\cos\theta + p_1 a\cos\psi \\
\dot{y} & = & v\sin\theta + p_1 a\sin\psi \\
\dot{\theta} & = & \omega \\
\dot{v} & = & \frac{f_s\sin\delta_s - f_r\sin u_1 - p_2 v^2}{p_9} \\
\dot{\omega} & = & \frac{f_s(p_6 - p_7\cos\delta_s) - p_8 f_r\cos u_1 - p_3\omega v}{p_{10}} \\
f_s & = & p_4\left\|\mathbf{w}_{\text{ap}}\right\|\sin\left(\delta_s - \psi_{\text{ap}}\right) \\
f_r & = & p_5 v\sin u_1 \\
\sigma & = & \cos\psi_{\text{ap}} + \cos u_2 \\
\delta_s & = & \left\{\begin{array}{cl} \pi + \psi_{\text{ap}} & \text{if } \sigma \leq 0 \\ -\text{sign}\left(\sin\psi_{\text{ap}}\right)\cdot u_2 & \text{otherwise} \end{array}\right. \\
\mathbf{w}_{\text{ap}} & = & \begin{pmatrix} a\ \cos\left(\psi - \theta\right) - v \\ a\ \sin\left(\psi - \theta\right) \end{pmatrix} \\
\psi_{\text{ap}} & = & \text{angle } \mathbf{w}_{\text{ap}}
\end{array}
\right.
$$

Figure 14: State equations

(x, y, θ) corresponds to the posture of the boat, v is its forward speed, ω is its angular speed, f_s (s for sail) is the force of the wind on the sail, f_r (r for rudder) is the force of the water on the rudder, δ_s is the angle of the sail, a is the true wind speed, ψ is the true wind angle and wap is the apparent wind vector.

f_i are different dynamic parameters which are different for each boat.

Then, an Euler step is computed with the state vector X containing all variables and its derivative vector shown in figure 14.

4.3 Display

Matplotlib, a Python library, was firstly used to draw the evolution of the sailboat computed as shown before. The inconvenient is that the plot was only in two dimensions and slow to refresh. That is why Rviz, a visualizer made for ROS, was the final choice.

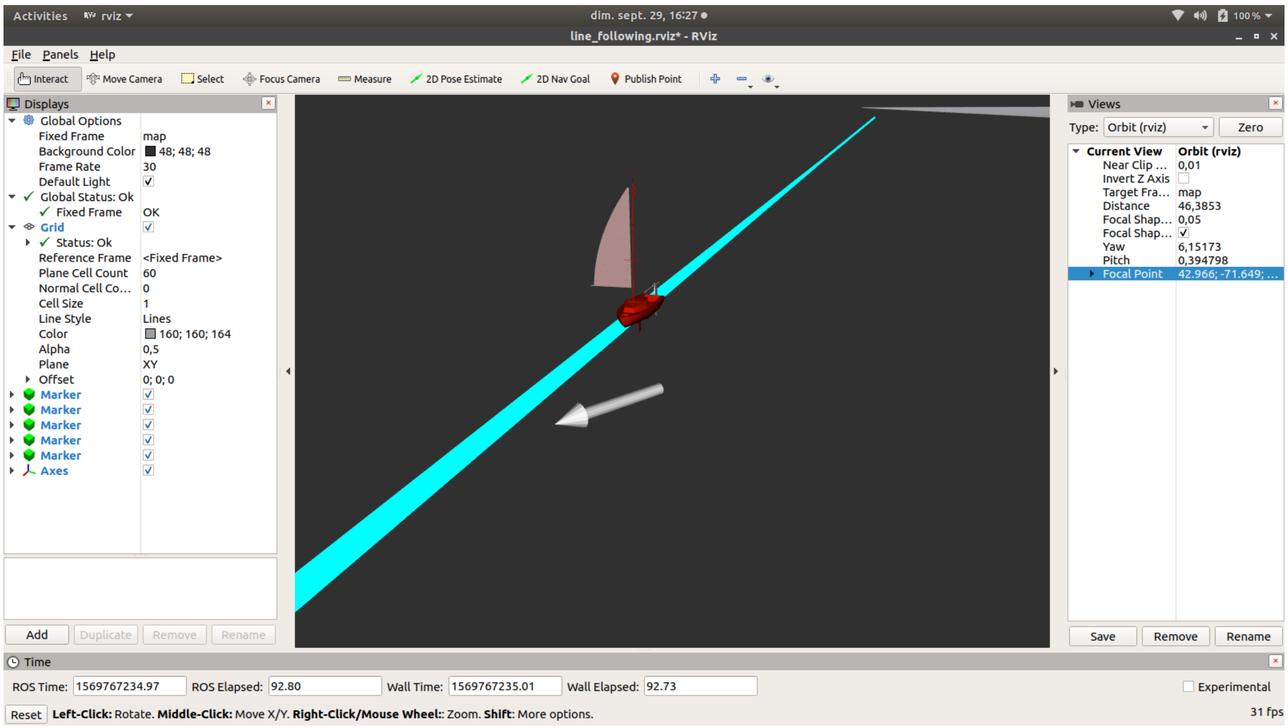

Figure 15: Rviz displayer

All codes, as heading following, line following and station keeping have been tested with a simulator made for an Rviz display. Each object is published as a Marker and each Marker is displayed as a sail, a hull, a line or a circle.

5 Participation to the World Robotic Sailing Championship 2019

5.1 What is WRSC ?

The WRSC (World Robotic Sailing Championship) is an international contest in robotic sailing. The competition is open to any autonomous sailboat (no human action for sailing) up to 4 meters long. This competition is made for students, in majority from universities.

This year, the competition took place from August 25^{th} to August 30^{st} in Ningbo, China, with 23 teams.

5.2 Rules

The contest was separated in 4 challenges, one per day. I will describe shortly each challenge but more details are available online[1].

Fleet race :

The fleet race challenge is the best challenge to start the competition with. It requires basic control of your boat as line following and global positioning. As shown in Figure 16, this challenge is composed of three lines to follow and three virtual buoys. The boat has to sail in a radius of 5 meters around a buoy to validate it. The faster you go, the more points you have.

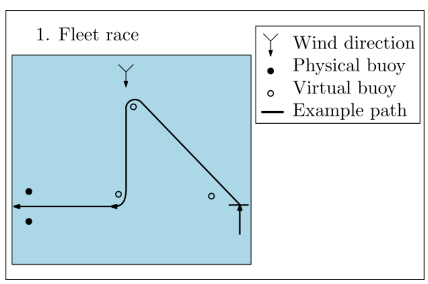

Figure 16: Fleet race

Station keeping :

This challenge is one of the favourite for PhD students. Indeed, station keeping is a current field of research : it is not trivial to keep the same position for a boat with sails. The aim of this challenge was to stay the closest to a physical and virtual buoy.

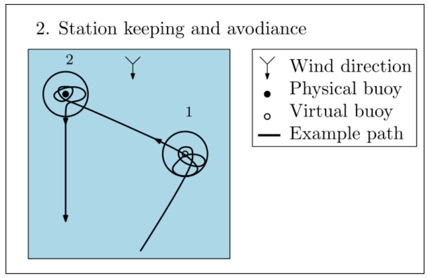

Figure 17: Station keeping

Area scanning :

This challenge is the easiest one to validate, but maybe one of the hardest to master. Five boats are launched in a scanning zone and each team gains points for each square they scan. There is a challenge of planning the best path, avoid other boats, etc ...

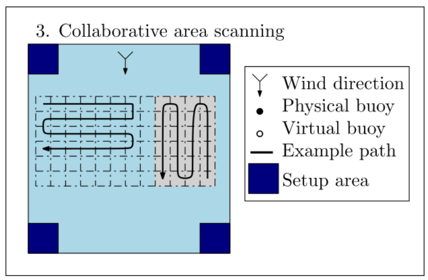

Figure 18: Area scanning

Hide and seek :

Hide and seeks consists in two challenges in one. First, two boats are sailing on two parallel lines. Then, during this sailing, each boat tries to detect an April tag (sort of QRcode) on the sail of their opponent.

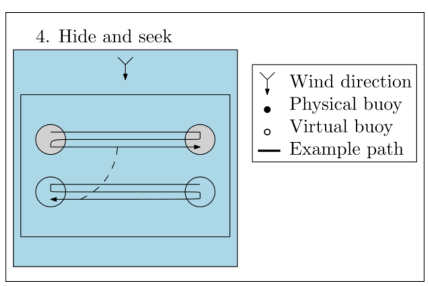

Figure 19: Hide and seek

5.3 Ningbo's lake

The lake was a nice place for that competition. There was two pontoons, which allows to split teams in two areas and to perform each challenge in only one day.

This place is in the city center, surrounded by buildings and encircled by trees. That is why the wind was scarce during the competition. This situation was favourable for many Chinese teams which had very thin sailboats with huge sails. Our boat was larger and more stable, which was better for a contest on the sea.

Figure 20: Ningbo's lake

5.4 Results

Plymouth's team finished 7th in the global ranking, first foreign team. Here is a table of the ranking for each challenge.

Fleet Race	9th
Station keeping	9th
Area scanning	10th
Hide and seek	10th

6 Conclusion

During this three months internship I developed many bricks to make a sailboat autonomous. The creation of a Kalman filter was a good challenge for me. It connected knowledge learnt in courses and real-time noisy data from a cheap IMU. Then, I implemented and tested many controllers. Finally, even if I have not worked a lot on low level coding and electronics, working with Alexandre and Matthieu on making a complete boat was a rewarding experience because we needed each other to build the entire system.

Thanks to the University of Plymouth, I was part of the WRSC 2019 and finished in an honorable place. Whether from the cultural aspect or the technical one, I highly recommend this type of event.

References

[1] *WRSC Rules on https://www.roboticsailing.org/2019/rules/*. 2019.

[2] ROBERT BIEDA and KRZYSZTOF JASKOT. *Determinig of an object orientation in 3D space using direction cosine matrix and non-stationary Kalman filter*. 2016.

[3] Luc JAULIN. *Mobile robotic, KalMOOC*. 2019.

[4] Luc JAULIN. *Mobile robotic, RobMOOC*. 2019.

[5] Luc Jaulin and Fabrice Le Bars. *A simple controller for line following of sailboats*.

ENSTA Bretagne

RAPPORT D'EVALUATION
ASSESSMENT REPORT

Merci de retourner ce rapport par courrier ou par voie électronique en fin du stage à :
At the end of the internship, please return this report via mail or email to:

ENSTA Bretagne – *Bureau des stages - 2 rue François Verny - 29806 BREST cedex 9 – FRANCE*
☎ 00.33 (0) 2.98.34.87.70 / stages@ensta-bretagne.fr

I - ORGANISME / *HOST ORGANISATION*

NOM / *Name* University of plymouth

Adresse / *Address* Drake Circus, plymouth, Devon, PL48AA, UK

Tél / *Phone (including country and area code)* +44 01752 586157

Nom du superviseur / *Name of internship supervisor* Jian Wan

Fonction / *Function* Lecturer in control systems Engineering

Adresse e-mail / *E-mail address* jian.wan@plymouth.ac.uk

Nom du stagiaire accueilli / *Name of intern* JEGAT Coyentin

II - EVALUATION / *ASSESSMENT*

Veuillez attribuer une note, en encerclant la lettre appropriée, pour chacune des caractéristiques suivantes. Cette note devra se situer entre **A (très bien)** et **F (très faible)**
*Please attribute a mark from **A (excellent)** to **F (very weak).***

MISSION / *TASK*

- La mission de départ a-t-elle été remplie ? ✓A B C D E F
  Was the initial contract carried out to your satisfaction?

- Manquait-il au stagiaire des connaissances ? ☐ oui/*yes* ☑ non/*no*
  Was the intern lacking skills?

  Si oui, lesquelles ? / *If so, which skills?* __________

ESPRIT D'EQUIPE / *TEAM SPIRIT*

- Le stagiaire s'est-il bien intégré dans l'organisme d'accueil (disponible, sérieux, s'est adapté au travail en groupe) / *Did the intern easily integrate the host organisation? (flexible, conscientious, adapted to team work)*

  ✓A B C D E F

Souhaitez-vous nous faire part d'observations ou suggestions ? / *If you wish to comment or make a suggestion, please do so here*__________

COMPORTEMENT AU TRAVAIL / *BEHAVIOUR TOWARDS WORK*

Le comportement du stagiaire était-il conforme à vos attentes (Ponctuel, ordonné, respectueux, soucieux de participer et d'acquérir de nouvelles connaissances) ?
Did the intern live up to expectations? (Punctual, methodical, responsive to management instructions, attentive to quality, concerned with acquiring new skills)?

A B C D E F

Souhaitez-vous nous faire part d'observations ou suggestions ? / *If you wish to comment or make a suggestion, please do so here* ______________________________

____

INITIATIVE – AUTONOMIE / *INITIATIVE – AUTONOMY*

Le stagiaire s'est –il rapidement adapté à de nouvelles situations ? A B C D E F
(Proposition de solutions aux problèmes rencontrés, autonomie dans le travail, etc.)

Did the intern adapt well to new situations? A B C D E F
(eg. suggested solutions to problems encountered, demonstrated autonomy in his/her job, etc.)

Souhaitez-vous nous faire part d'observations ou suggestions ? / *If you wish to comment or make a suggestion, please do so here* ______________________________

____

CULTUREL – COMMUNICATION / *CULTURAL – COMMUNICATION*

Le stagiaire était-il ouvert, d'une manière générale, à la communication ? A B C D E F
Was the intern open to listening and expressing himself /herself?

Souhaitez-vous nous faire part d'observations ou suggestions ? / *If you wish to comment or make a suggestion, please do so here* ______________________________

____

OPINION GLOBALE / *OVERALL ASSESSMENT*

❖ La valeur technique du stagiaire était : A B C D E F
Please evaluate the technical skills of the intern:

III - PARTENARIAT FUTUR / *FUTURE PARTNERSHIP*

❖ Etes-vous prêt à accueillir un autre stagiaire l'an prochain ?
Would you be willing to host another intern next year? ☑ oui/*yes* ☐ non/*no*

Fait à ______________________, le ______________
In Plymouth, on 30/08/2019

School of Engineering
University of Plymouth
Drake Circus
Plymouth
Devon
PL4 8AA

Signature Entreprise Yiawan
Company stamp

Signature stagiaire
Intern's signature

Merci pour votre coopération
We thank you very much for your cooperation