# Barlavento - Considerations About the Design of an Autonomous Sailboat

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**Abstract** Persistent monitoring of the ocean is important for several reasons, such as to: better understand the climate and ocean dynamics, improve navigation safety, make a better management of their resources and to prevent and combat abuse to the environment. However persistent monitoring can be extremely expensive. One way of decreasing costs is to use unmanned air, surface or underwater vehicles. However, energy autonomy is a major issue for this type of vehicles. For this reason, autonomous sailboats may be a good solution because they can collect renewable energy from the sea and atmosphere, thus being self-sustainable. The objective of this work is to develop and test an autonomous sailboat capable of performing persistent monitoring of the ocean. The Portuguese Naval Academy has been working on autonomous sailboats since 2010. However, the first autonomous sailboats, that used commercially available hulls, were not resistant enough to bad weather, had little available space for electronics, and were not very efficient. We now decided to design a radically different boat: a very thin and long monohull. We did so using freely available (or very low cost) software, low-cost off-the-shelf components, and simple 3D printers when necessary. This paper describes the creation of the hull using 3D CAD technologies and hydrodynamics simulation.

## 1 Introduction

There has been a lot of interest in developing unnamed systems persist monitoring of the oceans. The main applications of such systems are environmental monitoring, border and security control (mainly for preventing illegal immigration and smuggling), search and rescue, communication relay, etc. One of the main problems of

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such systems is energetic autonomy. For truly persistent ocean monitoring, the energy must be harvested from the environment. Many different approaches have been made, using solar power (e.g. Scout Boat [1]), wave power (e.g. waveglider [2]), or wind-power (e.g. FASt [3], AEOLUS [4], etc.). Windpower systems, and conventional sailboats in particular, have proven to be particularly fragile in ocean environments, particularly if they are small, and most have followed conventional designs used in yachts or larger boats.

The Portuguese Navy Research Center (CINAV), after some initial trials with conventional and commercially available model sailboats, started to develop a radically different design for an autonomous oceangoing sailboat. The aim is that sailboat be able to navigate independently of any human intervention. Sail is very dependent on the environment and is influenced by several factors, but the wind and the curl are the most important.

The wind speed and its direction defines the efficiency of the sails. The air flow passing through the boat sails generates two major forces: drag and lift. The conjugation of the boat's head, sail's angle, wind speed and direction, dictate the amount of drag and lift forces generated in each sail [5]. The shape, size, attack angle and number of sails also influence this result.

The curl affects the stability and speed of sailboat. By splitting the sea waves frequency spectrum in its components (see Fig. 1) x (forward - aft) and y (Starboard - Portside) [6], it is possible to take the following conclusions: (i) the components in y lead the ship to oscillate, and it may reach a roll angle beyond the maximum with positive stability; (ii) the components in x, if the direction of propagation of the wave is from forward to aft, leads to a decrease of speed, and otherwise leads to an increase of speed. The intensity with which those effects are felt depends not only on the sea, conditions, but also of the dimensions and type of hull [7].

Given the fact that environmental factors cannot be controlled, it is important to develop the sailboat characteristics in other to achieve its purpose even in heavy weather conditions.

This article is organized as follows: In Sect. 2 we define the most important factors taken into account in the hull design, and define the shape and dimensions of the hull; in Sect. 3 we describe the design and hydrodynamic simulations performed; in the Sects. 4, 5 and 6 we discuss aspects related to the design of the keel, rudder and centreboard respectively; Sect. 7 contains aspects related to peripheral systems; and finally in Sect. 8, we draw some conclusions about the results obtained.

## 2 Specifications Definition and Sizing

In the design process, the priority was the sailboat's capacity to resist to unpredictable weather conditions, keeping the dimensions as small as possible so that it can be easily transported. We defined the sailboat length overall (LOA) to 2000 mm, and started from there.

The next step was to define the displacement (Δ) of the sailboat. The greater the mass, the greater the inertia. This quantifies the difficulty of the sailboat to change its motion status. In certain situations, high inertia can be a benefit. On one hand, the greater the inertia, the lower is the loss of speed caused, for instance, by waves. On the other hand, the greater the inertia, the greater is the difficulty of the sailboat to gain speed or to make turns. Taking this in account, we decided that the maximum displacement of the sailboat would be 20 kg. This value is expressively low, taking into account the LOA. The hull type, materials and the stability have to be carefully chosen, in other to satisfy this parameters and still be able to perform the mission. With the LOA and the mass of the system defined, it is possible to start the shape design.

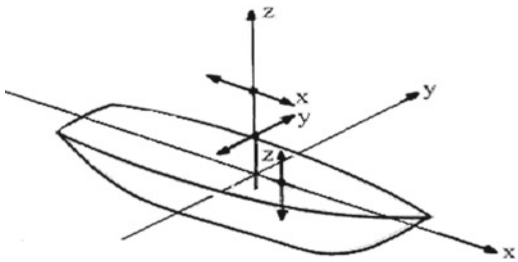
The buoyancy force is equal in module and has opposite direction to the weight of the fluid displaced [8]. We know that the weight of fluid displaced is the product of its density ($\rho$), by the volume displaced ($\nabla$) and by the acceleration of gravity [9]. Having the gravity acceleration in both sides of the equation, the Eq. (1) simplifies as shown:

$$\Delta = \rho\nabla \tag{1}$$

Using this equation, we can compute the volume of the sailboat underwater.

If the only forces acting on the sailboat were the buoyancy and the weight on the same vertical, the boat would be in balance and no movement would happen. In the real world, this is very unlikely. Many forces act on the sailboat, the main ones being related with wind and ocean waves. Depending on the localization of the application point of those forces, moments are created that tend to roll the sailboat, being necessary an opposing moment to balance it. The relations between the upsetting moment and the righting moment define the behaviour of the boat at sea [10]. The higher the righting moment produced when the boat is subject to a roll angle, the better, since, this way, the boat will be able to handle bigger upsetting moments. One way to manage this is through the design of the hull shape and size. The axles system used is represented in Fig. 1.

**Fig. 1** Axles system



The goal is that small angles of roll produce large righting moments, meaning, the transverse metacentric height ($Z_M$) ought to be as high as possible. This can be expressed through the relation expressed in Eq. (2) [8].

$$Z_M = Z_B + \frac{I_y}{\nabla} \tag{2}$$

Where $Z_B$ is fluctuation centre height and $I_y$ is the second inertia moment of the fluctuation figure area.

For a given roll angle, the sailboat is in a stable condition if $Z_M$ is higher than the gravity centre height ($Z_G$) [9]. This relationship is known as the stability condition and is represented in the Eq. 3.

$$Z_G < Z_M \tag{3}$$

Thus, the higher the $Z_M$ and the lower the $Z_G$, the greater the stability. $Z_M$ depends on the second inertia moment of the fluctuation area $I_y$, and can be calculated using the Eq. 4.

$$I_y = \int_A y^2 dA \tag{4}$$

This relation proves that the more area the sailboat has dispersed on the y axis, the higher will be the metacentric height, meaning it is beneficial to have a large beam. However, the length and the displacement of the sailboat are already set. If we want to maintain these properties and have a larger beam, we have to reduce on the draft. The draft is important in a sailboat. This type of boat relies on the wind to sail. The wind tends to drag the sailboat with it. A reaction force is required to propel the boat forward, instead of simply being dragged with the wind. This reaction force is generated between the water and the underwater body of the sailboat. The higher this force, the more it will maintain the desired course, resulting in a more precise sailing. In Fig. 2 we have a comparison between a bigger water drag force resistance and a smaller one. We consider that the force that propels the sailboat forward is the sum of the water drag resistance force and the wind force. We ignore other forces acting on it. In Fig. 2a we consider a larger drag resistance force then in Fig. 2b. It is evident that the angle between the forward force and the middle ship line is smaller in Fig. 2a, resulting in better sailing when compared with Fig. 2b.

Thus, we have to dimension the draft and the beam in order to maximize the stability and the lateral water drag resistance force.

The solution adopted was the hull in V shape [10], ensuring low hydrodynamic resistance and less speed loss caused by waves [10]. This form may not guarantee $I_y$ high enough to have a balanced $Z_M$ on the sailboat. In Eq. 3 we stated the stability condition. We can achieve positive stability either by higher the $Z_M$ or either by lower the $Z_G$. As we're not able yet to calculate this value, we design assuming that with ballast management we can ensure a low value for $Z_G$, resulting in positive stability. To avoid the possibility of this not be enough and small upsetting moments developing big roll angles, we added two lateral hulls to the main one transforming the sailboat in a Trimaran.

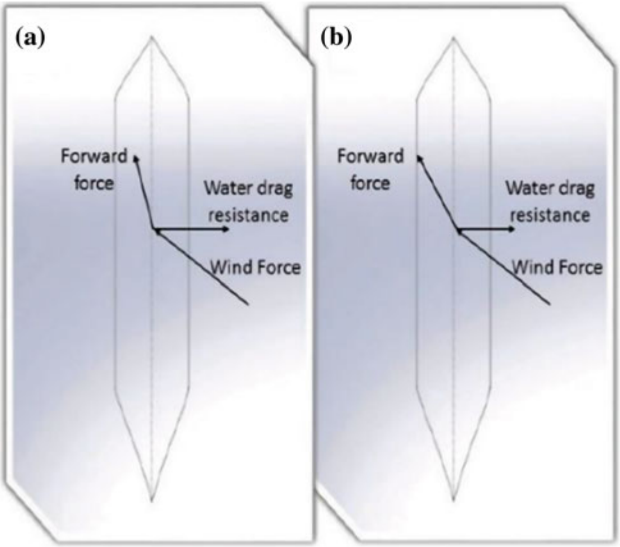



**Fig. 2** Comparison between different water drag forces

If there is no interaction between the water flow around the different hulls of a trimaran, the total resistance is the sum of the resistance of each hull [11]. Keeping the resistance of each reduced hull, you get a small total resistance. This solution has the advantage of ensuring the sailboat's stability, keeping the hydrodynamic resistance low.

## 3 Design and Simulation in 3D CAD

We used the program DELFTship$^{TM}$ Free to design the main hull. This program is very versatile and user friendly, allowing to design the hull and calculate hydrostatic and hydrodynamics parameters easily.

The dimensions of the main hull are summarized in Table 1.

Figure 3 shows the main hull drawn on this software.

Making use of the same software, the hull drag with draft of 130 mm was calculated, which corresponds to the nominal situation of 12 kg of displacement. The program makes use of the resistance series of Delft [12] in this calculation. The graphic only contemplates the main hull drag, not counting with the drag caused by the rudder, hull roughness, keel and other underbody parts. This graphic is represented in Fig. 4.

We see that the forward drag is low, about 11 N at the speed of 4 Kts. The real drag is going to be higher than this. Nevertheless, the value still points to an efficient hull. For simplicity, we used the same hull shape for the lateral ones. This addition

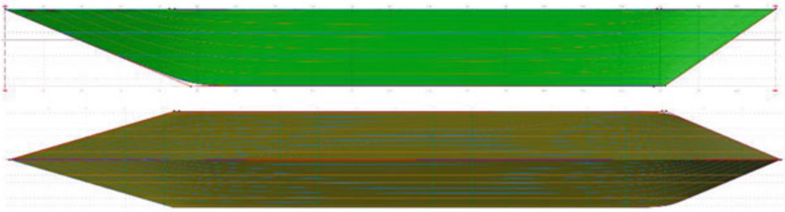


**Fig. 3** Main Hull designed in DELFTship™ Free

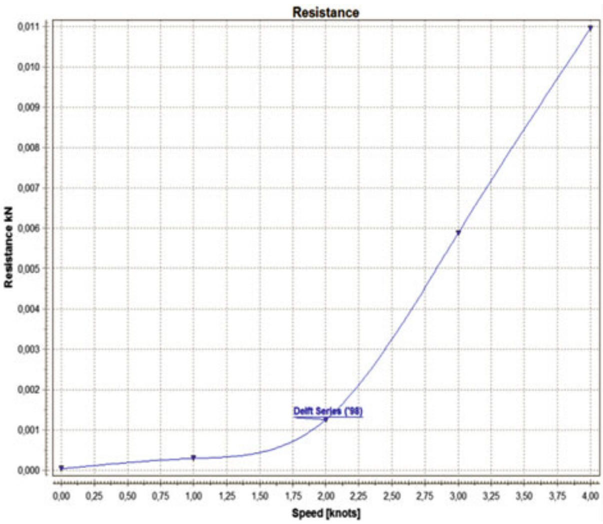



**Fig. 4** Resistance as a function of speed for the main hull

**Table 1** Hull main dimensions

| | |
|---|---|
| Maximum beam | 200 mm |
| Draft | 130 mm |
| Length over all | 1900 mm |
| Normal displacement | 12 kg |
| Maximum displacement | 20 kg |
| Cylinder block coefficient | 0.1558 |
| Prismatic coefficient | 0.6272 |

increases the maximum displacement of sailboat over the 20 kg's fixed before. The function of the lateral hull is only to increase stability, so when the sailboat in upright the lower part of the lateral hulls is on the water line. The lateral hulls also provide a buoyancy reserve. When the sailboat gets a roll angle, the lateral hull on the heeled side submerge, producing a local buoyancy force. This force generates an upright moment. This can be seen as an increase in $I_y$, conducting to a bigger $Z_M$ and better stability.

Having already defined all the dimensions and shape of the hull, we used the CAD program 3D SolidWorks Student Edition to draw all the parts of the sailboat. In this phase of the project, we stated that the mechanical resistance of the sailboat and the position of the centre of gravity are the major concern in order to achieve a robust and stable sailboat.

## 4 Keel Project

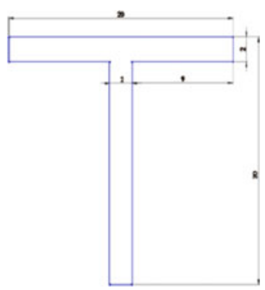
The first stage of the hull construction project was the keel design. The material used was rolled steel, since it has good mechanical resistance characteristics. However, this material has high density. Thus, we decided to use the minimum required to achieve a solid and robust part. On the other hand, the $Z_G$ component contributes to the stability of the sailboat. Being $Z_G < Z_M$, the condition of stability, if the heavier materials are placed in lower positions of the sailboat, $Z_G$ will also be lower, contributing to improve stability. It was defined that the keel would be constructed with "T" profile bars, with the dimensions shown in Fig. 5.

The "T" profile is widely used in structures for the relationship that it offers between resistances to loads verses quantity of material used. The aim is to transfer all loads applied to the sailboat to this part.

We defined that in the keel there would be three supports: two for the masts and one for the centreboard. Given major dynamic efforts in these components, these parts will also be constructed in rolled steel and directly welded to the keel.

The mast's supports are constituted by a vertical beam, welded in the bottom to the keel. On top of it, there is another beam, welded horizontally. This beam is welded to the mast guide. The mast guide is a tube with 25 mm external diameter, 1.5 mm thickness and 75 mm long. Concentrically to this tube, and directly welded to the keel, we have got another mast guide constructed with the same material and 50 mm long, leaving a gap of 75 mm between the tubes. This gap is going to be used

**Fig. 5** Profile used in Keel



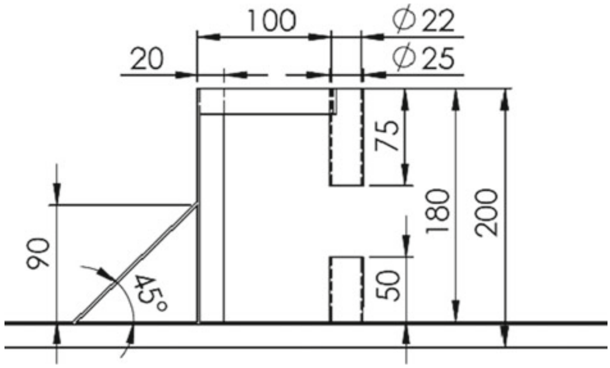



**Fig. 6** Exploded view of mast support

to control the mast. Figure 6 is the front view of mast support. The keel contains also the support for the centreboard.

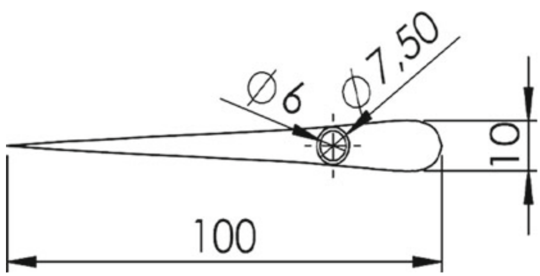
## 5 Rudder Project

The rudder plays an important role. It allows the sailboat to helm a course and increases the side drag, which is important so sail efficiently. The typical shape of the rudder is a foil.

By setting a certain angle to the rudder, the flow velocity on the two rudder faces will be different, generating a lift and a drag force. The lift force is responsible for generating a turning moment, and the drag force decreases the velocity of the sailboat. The decision of the foil shape was made using the program Designfoil Demo. This program can run simulations on a given foil at a certain angle, providing the lift and drag coefficient, and the pressure centre. The rudder profile is shown in Fig. 7.

The rudder size can be calculated by the Det Norske Veritas criterion [13], expressed in Eq. 5.

**Fig. 7** Rudder Plant



$$A_r \approx \frac{d.L_{pp}}{100}\left\{1 + 25\left(\frac{B}{L_{pp}}\right)^2\right\} \tag{5}$$

In which: $A_r$ = rudders area; $L_{pp}$ = Length between perpendiculars; B = beam and d = draft.

This equation provides the minimum rudders area. If the rudder is not placed directly behind the propeller, the area should be increased at least 30 %. The equation result for this sailboat is 48 cm$^2$. The rudder size should be well-adjusted because, on one hand, if it is too small it won't be able to turn the sailboat; on the other hand, if it is too big, it will generate too much drag force, slowing down the boat.

The rudder is in permanent contact with the water. This could be a problem because it's control would normally involve a hull passage under the waterline allowing water to go inside the sailboat. To minimize this risk, the guide of the rudder inside the sailboat goes higher than the water line, and has rubber retainers on top and bottom of the rudders guide.

## 6 Centreboard Project

It is intended that the centreboard has a high aspect ratio, because the higher this coefficient, the less drag is generated, maintaining the lift high enough to balance the lateral force generated by the sails [14]. Without this component, the sailboat would only be able to go in directions down wind. The efficiency of the centreboard is proportional to the aspect ratio. Also, for stability it is beneficial to have a big aspect ratio since need less ballast to achieve a lower $Z_G$ position. The foil used in this component is shown in Fig. 8.

This component is 1000 mm long. It has to resist to the dynamical loads. In its construction, we decided to use the same material of the keel. This heavy material can resist to the loads, and it lowers the $Z_G$. This part measures 1000 mm and will have 3 kg of ballast on its edge.

In order to simplify the transportation of the sailboat, this component can be divided in two parts, one welded to the keel, 125 mm long, and other 875 mm long that can be attached to the first part by a screw joint. The keel is represented in Fig. 9.

The bulb will be located in the end of the centreboard and will be projectile type, as shown in Fig. 10.

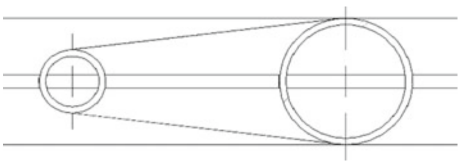


**Fig. 8** Centerboard profile.

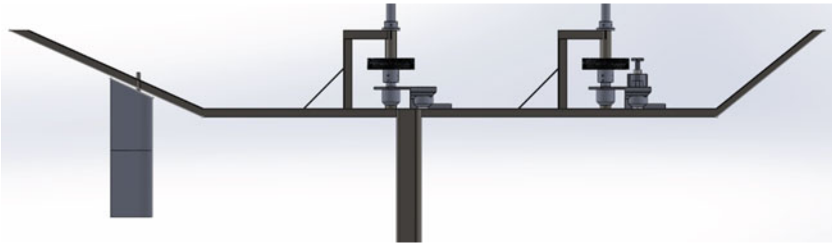


**Fig. 9** Keel drawn in Solidworks Student edition

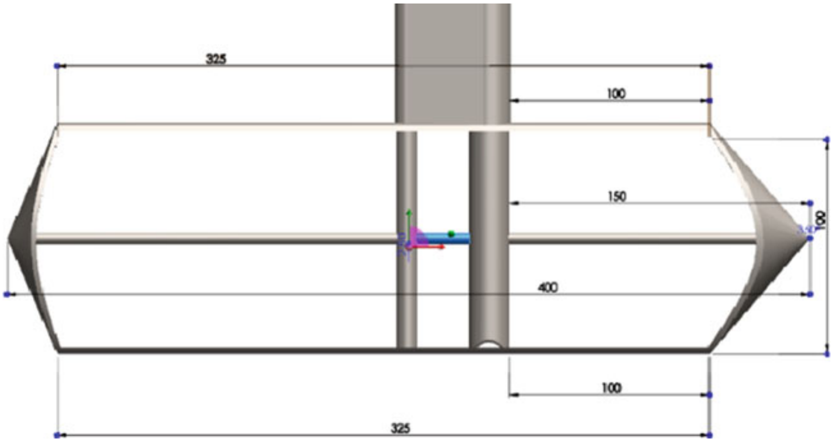



**Fig. 10** Bulb

## 7 Peripherals Systems

We intended to create an improvement capable platform, and so developed a system that easily allows the exchange of components, such as mast and rudder, in case of material damage or for testing different components.

The control of the mast angles is made using a potentiometer. This potentiometer is linked to the mast by a gear. This system was developed in 3D CAD and printed in PLA. An electrical motor with a planetary gearbox was used. This system has a stall torque of 25 kg/cm. The torque is elevated by a set of gears also printed in PLA with a ratio of 2,14:1. The final result is shown in Fig. 11.

We use an Arduino Mega 2560 in the control centre. Attached to it we have got a compass, GPS, anemometer, 100 mw RF communications, and other sensors as shown in Fig. 12.

These sensors transmit the necessary information to the control algorithm. The waypoints coordinates can be saved directly to the SD Card, or can be sent by RF in a formatted message. The algorithm follows the waypoints sequentially, calculating

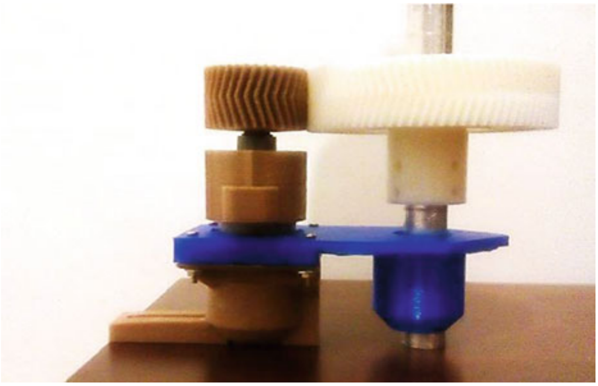


**Fig. 11** Mast control System

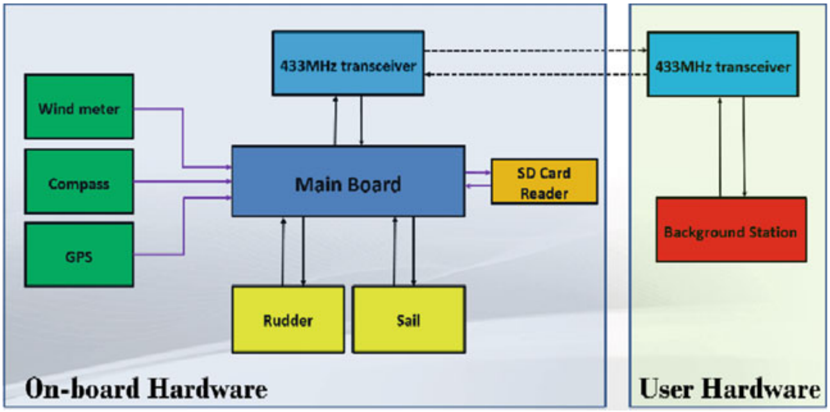



**Fig. 12** System Architecture

the azimuth the sailboat should go by the GPS coordinates, adjusting the head by the compass readings, and the sails by the anemometer information.

## 8 Conclusion

This work is about the construction project of a new sailboat for CINAV. We recognized the importance of autonomous sailboats [3] and the importance to develop new approaches to this problem.

We started this article by talking about some concerns taken into account in the sizing the hull of the sailboat. We defined the LOA, the beam and draft of the sailboat. Then, we discussed the design and simulations done in 3D CAD, in order to achieve an efficient hull shape. After that, we explained the project of the keel, rudder and centreboard. We discussed the peripherals used and finally we end this article with some conclusions.

It is important to develop an efficient underbody shape in order to achieve low drag, but generate enough lateral resistance to avoid the sailboat simply drifting with the wind. The area dispersion in the y axis plays an important role in the sailboat stability. The aim is to have the most area dispersed in this direction, in order for the metacentre to be as high as possible. Another way to increase the sailboat stability is to lower the $Z_G$.

The draft and the centreboard are very important in sailing. Those components have to generate enough lift to balance the sails lateral force. The rudder not only provides steering to the sailboat, it also contributes to avoid the sailboat to drift with the wind. The rudder can by sized by the Det Norske Veritas criterion. This criterion gives a minimum value to the rudder size, in function of the boat size and characteristics.

We are currently performing sea trials with the sailboat, and the results seem promising.

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