Chapter 1
An experimental validation of a robust controller with the VAIMOS autonomous sailboat

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Abstract A sailboat is a strongly non-linear system that has, however, been proven to be easily controllable. Indeed, its mechanical design has been evolved over thousands of years with two main concerns: having a fast, reliable and efficient vehicle which can be easily controlled by humans. This article describes the functionality, the validation process and the performance of a simple controller, inspired by what navigators do, through tests made on the sailboat robot *VAIMOS* built by IFREMER for oceanography. This controller requires tweaking a few parameters with real physical meaning while ensuring accurate trajectory following, needed to make oceanographic measurements in a specific area.

1.1 Introduction

In order to make oceanographic measurements, IFREMER (Institut Français de Recherche pour l'Exploitation de la Mer) has designed a sailboat robot (see e.g. [4] [1] [16] [15] [6] [17] [2] [14] [18] for more information on autonomous sailboat robots) with a length of 3.65 m based on a Mini-J hull: *VAIMOS* (Voilier Autonome Instrumenté pour Mesures Océanographiques de Surface, see figure 1.1 and [7] [11] [12]). This robot has:

- An oceanographic probe and pumps that make it possible to measure various parameters near the water surface and at a depth of about one meter (temperature, salinity, chlorophyll, turbidity, etc.).
- A Linux-based embedded computer.
- A weather station that measures the wind speed and direction as well as GPS position.
- An AHRS (Attitude and Heading Reference System).
- A Wifi and Iridium communication system.
- Actuators for sail and rudder control (step-by-step motor that controls the maximum sail angle and servomotor to control the rudder angle).

Fig. 1.1 The autonomous sailboat *VAIMOS* in the sea.

Its aim is to assist and / or replace currently used oceanographic boats and fixed or floating buoys, which have several drawbacks: oceanographic boats need a crew and their missions are expensive, it is sometimes difficult to set up fixed buoys in deep seas, floating buoys move randomly according to wind and currents and do not always stay in desired areas, etc. An autonomous sailboat has several advantages:

- Almost unlimited energy: it uses wind to move, sun and sea to charge its batteries while its power consumption is low compared to that of a motor for instance.
- Interesting payload capabilities with respect to its dimensions.
- Accuracy (vs floating buoys) and ease of setup (vs fixed buoys). The operators need only program a predefined trajectory and launch the sailboat from a harbor: it should then go on the area of interest and cover it while storing measurements and communicating by satellite, sending subsets of data and status information before coming back to its harbor.
- Cheap (about 20000€, probe excluded).

In addition to oceanographic missions, this type of robot could be used for other applications [3] [5]:

- Continuous harbor main entrance monitoring. Thanks to their important energetic autonomy and their low cost, several robots like *VAIMOS* could be deployed to monitor local surface and submarine traffic and would notably reinforce systems currently used.

- Heterogeneous swarms of robots. Submarine swarms of autonomous robots can quickly and covertly monitor a given area, however the use of small submarines alone can have several limitations:
  - It is more difficult to retrieve energy underwater. Therefore, small autonomous submarine robots can rarely work for long distances or time.
  - Localization and communication are difficult in passive mode (it is not always possible to use active sensors if covertness is a requirement).

Adding autonomous sailboat robots to submarine swarms could solve some problems: long distance transport, energy backup, communications with the base or surrounding boats, localization thanks to GPS, etc.

VAIMOS has been automated to be able to cover autonomously an area as accurately as possible, while saving energy. For this purpose, a line following algorithm [10] [11] has been developed to guarantee that the robot always stays in a predefined strip (of 25 m width for example), despite maneuvers inherent to course changes, tacks, etc. In this way, the sailboat becomes as accurate as a motorboat. Because some courses are difficult to follow depending on wind orientation (a problem inherent to any sailboat), its regulator has 2 types of strategies: nominal route or tack. A basic controller stage provides heading control. In tack mode, heading should be around 45° from the wind orientation (this is the close-hauled angle). Therefore, the boat oscillates around the wind direction, the amplitude of the oscillations being the strip width, and the sail angle is at its minimum. In nominal route mode, the heading to follow is around the line made by the 2 current waypoints (the previous one and the next one), with an attractiveness angle to the line depending on the distance to the line (maximum of 45° for example). The sail is opened depending on the wind direction and the desired heading using a simple formula.

The main idea of this article is to show that in order to have a reliable autonomous robot, theoretical validation of its algorithms, using interval methods for example (see [9] for more information on interval analysis) is needed but we must also validate the assumptions made (state equations, bounds on errors, coefficients, etc.) using other methods to complete the validation process. For these reasons, we first made a theoretical validation using interval analysis and Lyapunov methods [12]. Then, a HIL (Hardware In the Loop) simulator was developed. Finally, real experiments in Brest harbor and between Brest and Douarnenez (Brittany, France) were made.

The robust sailboat controller developed will be explained in section 1.2. Section 1.3 will be about the theoretical validation of the controller. The HIL simulator used as an additional validation method and tool to plan real experiments will be described in section 1.4. Finally, section 1.5 will show the results of real tests with *VAIMOS*.

1.2 Controller

Due to the functioning of a sailboat, some headings are difficult to follow depending on wind orientation. Therefore, most of the controllers have 2 different modes: nominal, when the heading to follow is feasible, or tacking i.e. oscillation around 45° from the wind orientation (close-hauled angle), when it is not directly feasible. Most existing regulators use waypoint following instead of line following for reachable headings [17]:

- The robot takes a heading in the direction of the waypoint.
- The waypoint is reached when the boat is in a predefined radius.
- Unfortunately, nothing prevents it from drifting between waypoints (because of water currents, wind, etc.).

Some use also potential fields to define no-go zones for the sailboat [14], cost functions, fuzzy logic and the polar speed diagram of the sailboat (VMG: Velocity Made Good) [18]. One of the first sailboats using a line following approach was *Atlantis* (and *HWT X-1*, its successor) [5] [4].

The inputs of a sailboat such as *VAIMOS* are δ_r the rudder angle and $\delta_s^{\max}$ the sail maximum angle (δ_s, the angle of the sail should depend on $\delta_s^{\max}$ and the wind orientation w.r.t. the sailboat orientation). The outputs are the position $\mathbf{x}$ obtained from the GPS and expressed in a local coordinate system, the wind speed V and orientation ψ from the weather station and the heading θ of the sailboat from the AHRS, used as a compass (see figure 1.2). Note that it is possible to avoid using a weather station and keep $\delta_s^{\max}$ as a constant using the methods described in [19]. The line following controller of *VAIMOS* (described in detail in [10], [11] and [12])

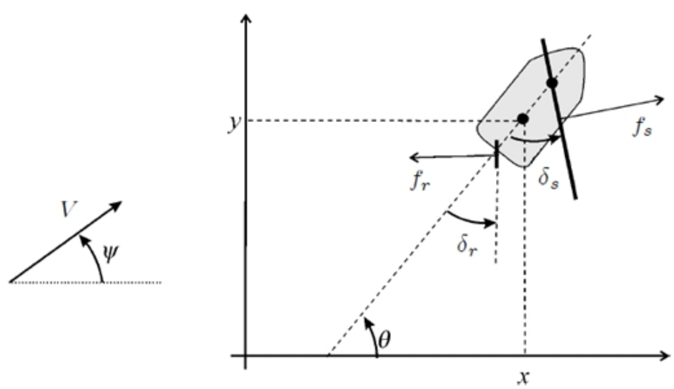

Fig. 1.2 Notations: ψ and V define the wind orientation and speed, f_s is the force of the wind on the sail and δ_s the angle of the sail, f_r is the force of the water on the rudder and δ_r the rudder angle, $\mathbf{x} = (x, y)$ and θ are the boat position and orientation.

is composed of several parts (see figure 1.3):

- A primitive controller stage for heading control. The angle of the rudder is set by proportional regulation w.r.t desired heading $\bar{\theta}$ if we are close to this desired heading, bang-bang regulation (two point control) if far from desired heading:

$$\delta_r = \begin{cases} \delta_r^{\max}.\sin\left(\theta - \bar{\theta}\right) & \text{if } \cos\left(\theta - \bar{\theta}\right) \geq 0 \\ \delta_r^{\max}.\text{sign}\left(\sin\left(\theta - \bar{\theta}\right)\right) & \text{otherwise,} \end{cases} \tag{1.1}$$

  with $\delta_r^{\max}$ the maximum rudder angle. The sail is opened depending on the wind direction and the desired heading using a simple formula:

$$\delta_s^{\max} = \frac{\pi}{2}.\left(\frac{\cos\left(\psi - \bar{\theta}\right) + 1}{2}\right). \tag{1.2}$$

- A supervisor decides between 2 modes: nominal route or tack. It should always send feasible headings to the primitive controller. In nominal route mode, the heading to follow is given by the line made by the 2 current waypoints **a** and **b**, with an attractiveness angle to the line depending on the distance to the line. In tack mode, the heading is $\pm 45°$ from the wind direction where $45°$ is the close-hauled angle: the sailboat oscillates around the wind angle, the amplitude of the oscillation being the width of the strip around the line.
- A navigation manager sends lines formed by 2 waypoints $\mathbf{a}_j$ and $\mathbf{b}_j$ to the supervisor and validates lines. A line is validated when the sailboat reaches the perpendicular of the line at $\mathbf{b}_j$, i.e. the validation condition is:

$$\left\langle \mathbf{b}_j - \mathbf{a}_j, \mathbf{x} - \mathbf{b}_j \right\rangle \geq 0 \tag{1.3}$$

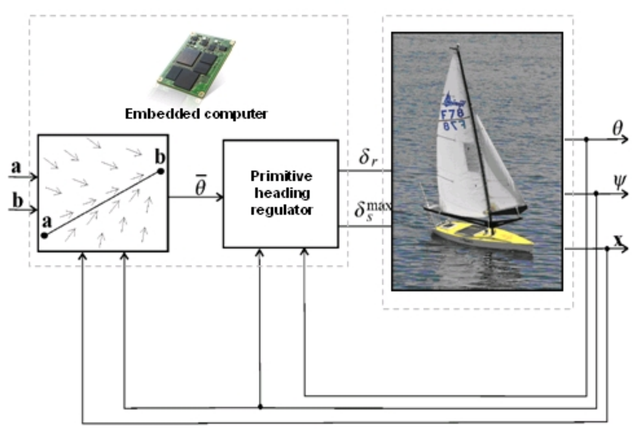

Fig. 1.3 Principle of the line following controller of *VAIMOS* (with previous notations).

1.3 Theoretical validation of the controller

In order to validate the line following controller developed, several tools have been used:

- Validation using interval analysis and Lyapunov methods.
- HIL (Hardware In the Loop) simulator.
- Real experiments in Brest harbor and between Brest and Douarnenez (Brittany, France).

A new interval method for nonlinear stability analysis has been developed (it is described in detail in [12]). The main idea is to represent uncertain systems by differential inclusions and then apply Lyapunov analysis methods to transform the stability problem in a set inversion problem (see [13] and [9] for more information on interval analysis and set inversion problems). In this way, it is possible to demonstrate that for all possible perturbations:

- There exists a subset of the state space which the system cannot escape when it enters it.
- If the system is outside this subset, it will not stay outside forever.

However, even if these methods can validate theoretically the robustness of the controller (i.e. the robot will stay in a strip around its target line), additional methods must be used to adjust the hypothesis (state equations, bounds on sensors errors, etc.). To prepare as much as possible for real experimentation, an HIL (Hardware In the Loop) simulator (inspired by [8]) has been developed to simulate the robot's trajectory and sensor data on a computer while using the controller directly on the sailboat as if it were at sea.

1.4 HIL simulator

Most existing simulators use the polar speed diagram of the sailboat to determine its movement, or alternatively use several predefined scenarios. Therefore, they might miss some singular situations which should be detected and acted upon to fully validate a controller. State equations inspired from [8] were used for our controller validation purposes:

$$\begin{cases} \sigma &= \cos(\theta-\psi)+\cos(\delta_s^{\max}) \\ \delta_s &= \begin{cases} \pi-\theta+\psi & \text{if } \sigma<0 \\ \delta_{s\max}\,\mathrm{sign}(\sin(\theta-\psi)) & \text{otherwise} \end{cases} \\ f_r &= \alpha_r v \sin(\delta_r) \\ f_s &= \alpha_s V \sin(\theta+\delta_s-\psi) \\ \dot{x} &= v\cos(\theta)+\beta V\cos(\psi)+V_c\cos(\psi_c) \\ \dot{y} &= v\sin(\theta)+\beta V\sin(\psi)+V_c\sin(\psi_c) \\ \dot{\theta} &= \omega \\ \dot{\omega} &= \frac{(l-r_s\cos(\delta_s))f_s-r_r\cos(\delta_r)f_r-\alpha_\theta\omega+\alpha_w h_w}{J_z} \\ \dot{v} &= \frac{\sin(\delta_s)f_s-\sin(\delta_r)f_r-\alpha_f v^2}{m} \\ \ddot{\varphi} &= \frac{-\alpha_\varphi\dot{\varphi}+f_s h_s\cos(\delta_v)\cos(\varphi)-m_{eq}l_{eq}g\sin(\varphi)}{J_x} \\ \dot{\varphi} &= \dot{\varphi} \end{cases} \tag{1.4}$$

with v the sailboat speed, ω the rotation speed, φ the roll, assumed to be pendular, with coefficients α_φ (fluid friction), h_s (height of the sail force application point), m_{eq} (mass of the equivalent pendulum), l_{eq} (length of the equivalent pendulum), J_ω (inertial moment), V_c and ψ_c the sea current speed and orientation, h_w the height of waves, β the coefficient of drift due to wind, α_r, α_s, α_f, α_θ, α_w various fluid friction coefficients and r_r, r_s, the distance from the sailboat mass center to the rudder and mast respectively (see also figure 1.2). Then, the behaviour of the state equations was tested on a 3D simulator. Using these results, an HIL (Hardware In the Loop) simulator was finally developed to simulate the robot trajectory and sensors data on a computer depending on the input lines, expected wind and sea conditions and a user-defined initial position while using the developed controller on the embedded computer to control the robot actuators as if the sailboat were in the sea to study mechanical wear as well as the robustness of most of the embedded electronics. HIL simulation means that the real hardware (here the embedded computer and actuators) is used in simulations (see figure 1.4):

- First, the simulator using the state equations previously defined is started on a normal computer with a user-defined initial state. It generates simulated sensor data (θ, ψ, $\mathbf{x}$) from rudder (δ_r) and sail ($\delta_s^{\max}$) inputs that will be decided by the controller and user-defined sea (h_w, V_c, ψ_c) and wind (V, ψ) conditions.
- Then, the controller is started on the embedded computer of the sailboat. It takes a list of lines to follow (formed by waypoints $\mathbf{a}_j$, $\mathbf{b}_j$) as for a real experiment and controls its actuators as usual, but also sends a copy of its outputs for the actuators (δ_r and $\delta_s^{\max}$) to the simulator, and uses simulated sensor data (θ, ψ, $\mathbf{x}$) rather than the data from its real sensors.
- Finally, log files generated by the controller are retrieved and displayed in real time using GOOGLE EARTH and a custom-built dashboard.

The communications are made possible by the fact that all the embedded devices are accessible by Wifi.

Several simulations were made in different configurations to prepare for real experiments, for example navigating a course of more than 100 km between Brest and

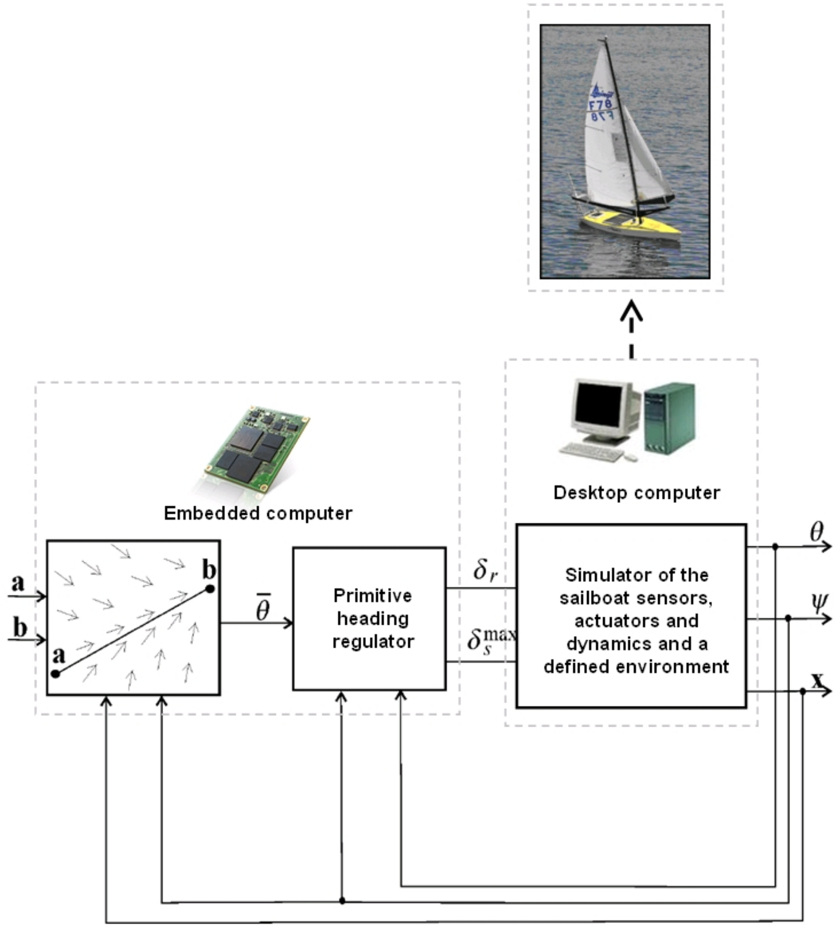

Fig. 1.4 Principle of the HIL simulator of *VAIMOS*.

Douarnenez. A first simulation made with a North wind of 14 knots is shown in figure 1.5. An initial position just in front of Brest harbor was indicated to the simulator at start. Other simulations were made as the expected weather conditions for the date fixed for the real test was changing, and to test different ways of covering the bay to minimize the tacks and shorten the total time (here around 40 hours).

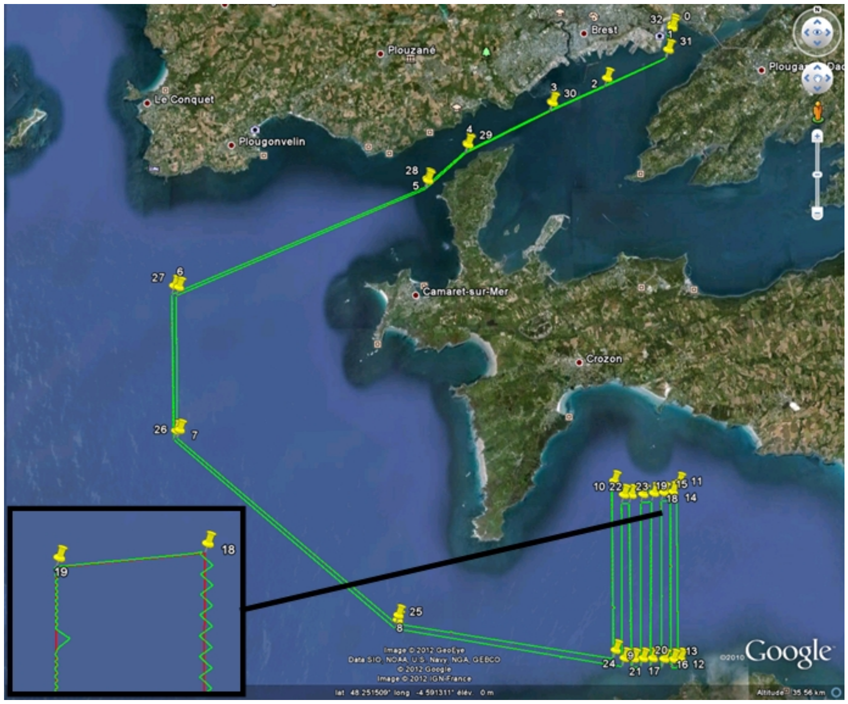

Fig. 1.5 Simulation of *VAIMOS* going from Brest to Douarnenez. The desired trajectory (red lines made by yellow waypoints) and the effective (simulated) trajectory (green) seem to overlap. However, if we zoom, we see there were tacks. We can also see sail motor calibration steps (every 2 hours) which make the sailboat drift for one minute.

1.5 Real experiments

Real experiments of particular trajectory patterns have been made in Brest harbor to test *VAIMOS* in all wind configurations while taking oceanographic measurements for IFREMER (see figure 1.6). Small real tests are important. For example, some magnetic perturbation problems making it necessary to move the AHRS far from the rest of the electronics were detected during these tests.

Finally, a long autonomous mission between Brest and Douarnenez on the 17-18th January 2012 was attempted with *VAIMOS* (see figure 1.7). It made more than 500 oceanographic measurements over 105 km in 19 h. The wind was around 12 knots and from South.

During the mission and after, a dashboard was used to analyse all the log files produced by the embedded program. For example, near the end of the experiment, we see that the sail angle measured by the weather station (which is on top of the sail and has an integrated compass), in purple is incoherent with the one deduced from the input, in pink. This was probably due to the mechanical problem in the sail

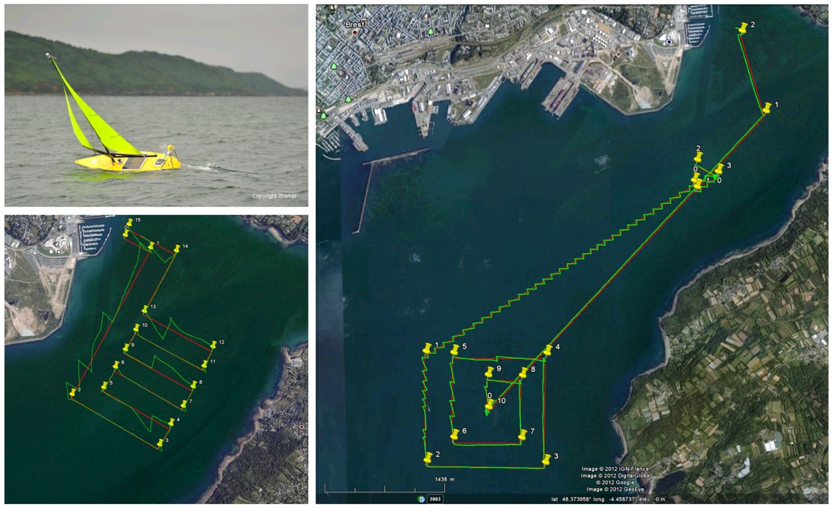

Fig. 1.6 Tests in Brest harbor. Desired trajectory (red lines made by yellow waypoints) and effective trajectory (green). South-West wind on the left, South-West wind of around 15 knots on the right. 27 km (17 nm) was travelled in less than 5 hours in the journey shown on the right.

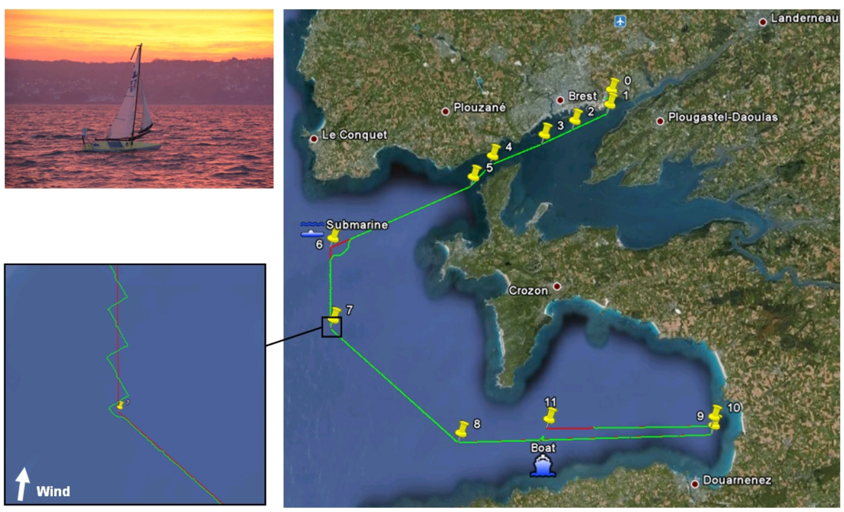

Fig. 1.7 Brest-Douarnenez. The sailboat needed to be deviated twice: first because of a submarine coming back to Brest naval base, then because of a static boat in the sailboat trajectory. During these perturbations, the autonomous program was not changed nor stopped, the sailboat was taken by our chase motorboat. Therefore, the submarine and boat deviations illustrate the robustness of the controller, which was able to continue the mission as if nothing happened.

control system that we discovered at the end. Because it was during the night, it was difficult to see the sail angle without the dashboard (see figure 1.8).

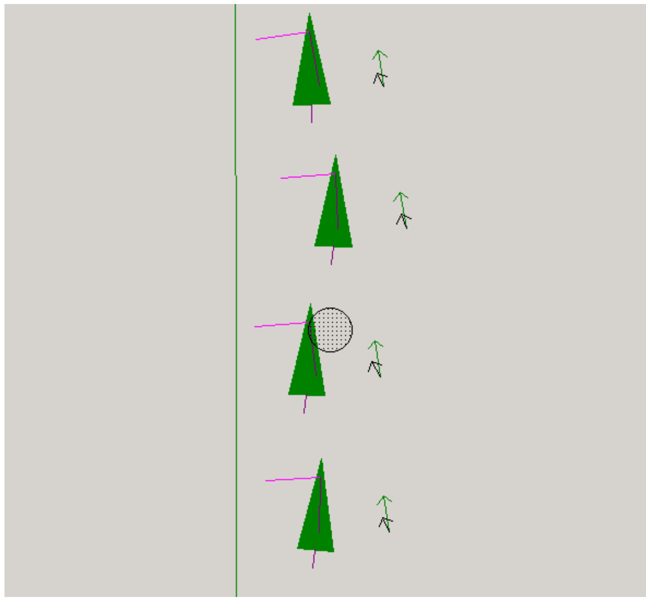

Fig. 1.8 Analysis of log files using a dashboard. The green vertical line is the line to follow, the small black arrow is the wind direction (measured by the weather station), the small green arrow is the desired heading, the big green arrow represents the sailboat (from GPS and compass data), with its rudder in purple and 2 estimations of its sail angle in pink (estimated from the inputs) and purple (measured by the integrated compass of the weather station, placed on top of the mast). As we see, these two estimations are in contradiction. These information are drawn at regular time intervals.

1.6 Conclusion

In this article, we showed that theoretical methods such as interval analysis can be used to theoretically validate robot control algorithms. However, in robotics we must use other validation methods such as HIL simulation and real tests to check and correct any hypotheses made. Different experiments were carried out with the *VAIMOS* robot for that purpose, while demonstrating the operational interests of an autonomous sailboat for oceanography.

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