9th IFAC Conference on Control Applications in Marine Systems
The International Federation of Automatic Control
September 17-20, 2013. Osaka, Japan

Control Algorithms for a Sailboat Robot with a Sea Experiment

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Abstract: A sailboat robot is a highly nonlinear system but which control is relatively easy, however. Indeed, its mechanical design is the result of an evolution over thousands of years. This paper focuses on a control strategy which remains simple, with few parameters to adjust and meaningful with respect to the intuition. A test on the sailboat robot called Vaimos is presented to illustrate the performance of the regulator with a sea experiment. Moreover, the HardWare In the Loop (HWIL) methodology has been used for the validation of the embedded system. Last point is that this HWIL simulation compared to the real experiment is also a confirmation that the dynamic model used for control is correct.

Keywords: autonomous vehicles; nonlinear control; sailboat; marine systems

1. INTRODUCTION

The development of autonomous surface vehicle (ASV) is motivated by several civil and military applications: oceanographic research, marine charts development, meteorological data collecting for civil part, and operations of coastal protection, port monitoring and demining for the military part. These devices are generally motorized ASVs and they have been studied for a long time but have strong energy limitations. The sailboats have a number of advantages over boats powered by motors: energy self-sufficient in the first point but also the fact of being noiseless (which can be an asset for military applications or biodiversity observation). Romero-Ramirez [2012] and Stelzer [2012] PhD Thesis propose a complete state of art about ASV with historic perspectives of the main issues.

1.1 Sailboat robots

While sailing has a long tradition, robotic sailing is a fairly new area of research. Indeed, first references concerning automatisation for sailing is in Warden [1991] and the projects initiated in the late 90' show that it is a young issue (Elkaim [2009], Neal [2006]). On one hand, the sail propulsion allows long range and long term autonomy; on the other hand, the dependency on changing winds presents a serious challenge for short and long term planning, collision avoidance, and boat control. Moreover, building a robust and seaworthy sailing robot is not a simple task, leading to a truly interdisciplinary engineering problem. The characteristics of a sailing boat can be defined as follows (Schlaefer and Blaurock [2011]): wind is the only source of propulsion, it is not remotely controlled (the entire control system is on board), it is completely energy self-sufficient. Sailing robot are efficient solutions for fuel saving on any boat; Schlaefer and Blaurock [2011] have summarized the state of art on this subject. Various aspects of system design and validation are discussed, further highlighting the interdisciplinary nature of the field. Methods for collision avoidance, localization and route planning are covered but few papers are dedicated to the automatic control aspects. Indeed, most of rudder control laws are based on PID heading control with overshoot, oscillations problem and difficulty to reach a waypoint. This is the main reason which leads to a reflexion about the change of strategy, the line following defined later in the paper. It is important to notice that the development of autonomous sailboat is mainly due to robotic challenges: such as *Microtransat* [1] or *World Robotic Sailing Championships* [2] and the accompanying *International Robotic Sailing Conference* which provides a venue to discuss the broad range of scientific problems involved in the design and development of autonomous sailboats (Schlaefer and Blaurock [2011]).

1.2 Vaimos robot

As mentioned, the ASV development is a multidisciplinary problem; this paper focus on the algorithmic aspects with the comparison between an HWIL (Hardware In The Loop) simulation and a real experiment. This has been performed with the autonomous sailboat robot VAIMOS developed by IFREMER and ENSTA Bretagne for oceanographic issues. Indeed, as mentioned in Thomas et al. [2011] recent publications revealed that the mixed layer may present surface singularities for bio-geochemical parameters (temperature, salinity, turbidity, chlorophyll). Those studies question the common view of a homogeneous mixed layer. However, the degree of ubiquity of these surface singularities and their horizontal structures remains largely unknown because of the lack of adequate instruments to sample the first centimeters of the ocean. In order to be able to document the gradients of several parameters between the top centimeters and the sub-surface of the ocean, wan autonomous sailboat has been developed which is able to sample the ocean surface at two depths (the first

[1] website: http://www.microtransat.org/
[2] website: http://www.roboticsailing.org/

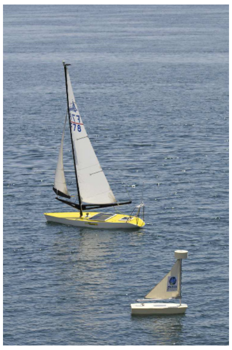

Fig. 1. Vaimos sailboat

10 centimeters and about 1 meter). The sailboat is shown on figure 1.

1.3 GNC (Guidance, Nagigation, Control), Simulation, Experimentation

As in any robotics activities, the simulation takes an important part for hardware and software validation but it is even more important when the experiment is not so easy to perform as for a marine robot. In these conditions, choosing an appropriate model is essential for success. As mentioned in Fossen [1995], and the references inside, the precise modeling is an difficult task due to fluid-solid interactions and do not answer to the robotician need which is a macroscopic model. In the literature, one can found various analytic models for sailboats control as Yeh and Binx [1992], Elkaim [2009], Briere [2008], Cruz and Alves [2010] but a simple state space representation has been chosen; it is based on Lagrangian Mechanics proposed in Jaulin [2004] with smooth modifications. The model equations are described in a section dedicated to modeling. This model has been used to develop the control algorithms but also to perform the HWIL simulation to prepare the sea test. Moreover, the real robot is described, particularly the sensors and actuators with a comparison between the model and the robot.

1.4 Organization of the paper

The aim of this paper is to validate the control algorithms at two levels: simulation allows to show if the behaviour is as expected, and experiment allows to definitly validate that the algorithms are robust. The experiment compared to the simulation gives some indications about the model validity. Considering the VAIMOS sailboat, this paper is organized in three parts. First a simplified model for simulation and the real sailing robot are presented; then the algorithms used for the robot guidance, navigation and control (GNC) are developed and discussed. The last part is dedicated to comparison between the HWIL simulation and the experiment at sea.

2. THE BOAT : SIMULATOR AND HARDWARE

Modeling a boat in details, and even more a sailboat, is a real challenge. The chosen model depends on the questions we wish to answer, and so there may be multiple models for a single dynamical system as mentioned in the state of art for sailboat robots, with different levels of fidelity depending on the phenomena of interest. This section presents a model that can be used for a macroscopic behavior of a sailboat. The experiment will show that this model is efficient for performing HWIL simulations. This section gives also a description of the real sailboat robot Vaimos.

There exists lots of sailboat robots and the following references gives some examples Sauze and Neal [2006], Rynne and Ellenrieder [2009], Schlaefer and Blaurock [2011], Romero-Ramirez [2012] and Stelzer [2012]. This two last work (one is in French) are the more complete and up to date state of art on the subject.

2.1 Sailboat Modeling

In this article, as the control issue is considered, the candidate model for sailboat is the one proposed in Jaulin [2004], with the difference that the input commands are not the angle between the boat and the sail but the length of the sail sheet. This model has been implemented in a simulator under QT creator for the control tuning and then for the experience simulation. There exist more complex simulators as mentioned in Romero-Ramirez [2012] but they are not adapted to control problem with state space point of view. The main advantage for our model is the simplicity: for interpretation, for running the simulation and for control tuning. The proposed model is based on the Newton's laws of motion applied to the sailboat presented in figure 2. As in space applications, the maritime environment is highly perturbated, and a very accurate model is useless for GNC. The comparision of the results of this model and the real experiement will confirm this hypothesis.

The following state space equations are derived from dynamic and kinematic considerations:

$$\begin{aligned}
\dot{x} &= v\cos\theta + \alpha_d a \cos\psi \\
\dot{y} &= v\sin\theta + \alpha_d a \sin\psi \\
\dot{\theta} &= \omega \\
\dot{v} &= \frac{f_s \sin\delta_v - f_r \sin u_1 - \alpha_v v^2}{M} \\
\dot{\omega} &= \frac{f_s(p_6 - p_7\cos\delta_v) - p_8 f_r \cos\delta_r - \alpha_\omega \omega}{J} \\
f_s &= \alpha_s a \sin(\theta - \psi + \delta_v) \\
f_r &= \alpha_r v \sin(\delta_r) \\
\sigma &= \cos(\theta - \psi) + \cos(\delta_s) \\
\delta_v &= \begin{cases} \text{if } \sigma \leq 0 & \pi - \theta + \psi \\ \text{else} & sign(\sin(\theta - \psi))\delta_s \end{cases}
\end{aligned}$$

where the variables are presented in Table 1 and the numerical value of each parameter (coefficients, geometric properties) evaluated by experiments are in Table 2.

2.2 VAIMOS Robot

The sailboat robot Vaimos objective is to collect bio-geochemical parameters (temperature, salinity, turbidity, chlorophyll) as mentioned in Thomas et al. [2011]; it is presented in figure 1. She has been built with a *Miniji* [3]

[3] http://www.chantier-naval-bretagne.com/description-1.html

Name	Description
(x, y, θ)	boat position and orientation
v	boat velocity
ω	rate of rotation
f_s	wind force on the sail
f_r	water force on the rudder
δ_v	angle between the sail and the longitudinal axis
a	wind speed
ψ	wind orientation
σ	sheet tension indicator: $\sigma \geq 0$ means no sheet tension, else the sail is efficient
δ_s	maximum angle between the sail and the boat axis
δ_r	angle between the rudder and the boat axis

Table 1. Model variables

Name	Description
$\alpha_d = 0.5$	drift coefficient
$\alpha_v = 100$	longitudinalfriction coefficient
$\alpha_\omega = 6000$	rotational friction coefficient
$\alpha_s = 1750$	lift coefficient for the sail
$\alpha_r = 250$	lift coefficient for the rudder
$p_6 = 2m$	geometric property (see figure 2)
$p_7 = 2m$	geometric property (see figure 2)
$p_8 = 4m$	geometric property (see figure 2)
$M = 200kg$	mass
$J = 1000kg.m^2$	inertia

Table 2. Model Parameters

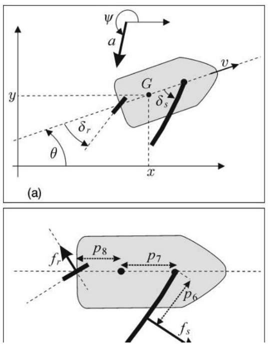

Fig. 2. Sailboat geometry

Deplacement	(kg)	160
Length	(m)	3,65
Beam	(m)	0,86
Draft	(m)	0,65

Table 3. *Miniji* Specifications

hull adapted to be autonomous. The most important change is that the rig has been turned into a spirit rig; it has been done to control one actuators instead of two.

The *Miniji* hull characteristics are given in Table 3.

Figure 3 shows the global architecture for the embedded system with the processor, the sensors and the actuators. The GNC system is composed by:

- 2 sensors: the main sensor is a weather station which provides wind speed and direction, air temperature, atmospheric pressure, GPS position and heading; an IMU for reliable kinematic parameters;
- 2 actuators to control the sail and the rudder: a brushless motor for the rudder and a stepping motor to control the angulation of the sail;

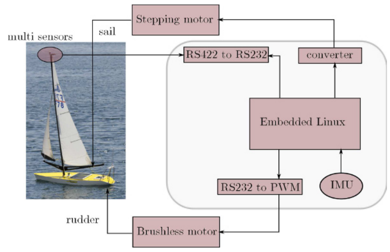

Fig. 3. Embedded system architecture

- a processor with a serial data acquisition interface;
- power supply : two 12V marine batteries to deliver 120Ah with 24V voltage.

To ensure safety during the experiments, it is always possible to have a remote control via a wifi connection.

3. GUIDANCE, NAVIGATION AND CONTROL

As in the aeronautic and space applications (Imbert and Clement [2004], Breivik and Fossen [2007]), robustness is a key issue to ensure the robot mission. the robust control strategy is then performed in a classical way:

- Control to ensure the trajectory following. A line following is proposed instead of a heading following as it is often proposed. This is done by the rudder and sail tuning.
- Guidance for the trajectory definition : direct to a waypoint or by beating to windward according to wind direction
- Navigation is defined off line by a way points collection. One can imagine that obstacle avoidance has to be included in this part of GNC.

Then for each part of guidance and control, some innovations are proposed: intuitive control laws, line following, pathway definition.

3.1 Navigation: motion planning

During a mission, the robot has to follow successive segments denoted $[\mathbf{a}_j, \mathbf{b}_j], j \in \{1, \ldots, j_{\max}\}$ such that $\mathbf{a}_{j+1} = \mathbf{b}_j$ if $j < j_{\max}$. Note that for a closed path, $\mathbf{a}_1 = \mathbf{b}_{j_{\max}}$.

It is necessary to determine an angle ξ which is the limit angle that the sailboat can have with the wind. Then a course $\bar{\theta}$ is considered as *feasible* if

$$\cos\left(\psi - \bar{\theta}\right) - \cos\xi > 0 \tag{1}$$

according to the Figure 6.

As proposed by Guillou [2010], the mission is managed by a state machine; this Petri net is presented in Figure 4. The mission starts with the transition t_1 from p_0 place (standby) to p_1 and the robot follow the first line ($j = 1$). Then according to the relative wind, it can be direct or with tacks. Then if $\cos(\psi - \bar{\gamma} - \varphi_j) + \cos\delta_{\text{prs}} < 0$ with φ_j the angle defined by the segment $[\mathbf{a}_j, \mathbf{b}_j]$, it is necessary to adapt the navigation strategy with tacks as the sailboat is not able to follow the line. When beating to windward, the sail tuning is such that $u_2 = \delta_{s\max} = 0$ which means that the sail is closed at the maximum. A line is validated as soon as the waypoint $\mathbf{b}_j$ is behind the boat: $\langle \mathbf{b}_j - \mathbf{a}_j, \mathbf{m} - \mathbf{b}_j \rangle > 0$ and next line can be followed.

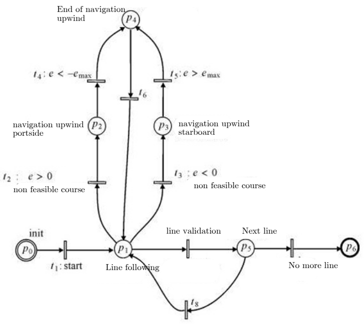

Fig. 4. Petri net for navigation

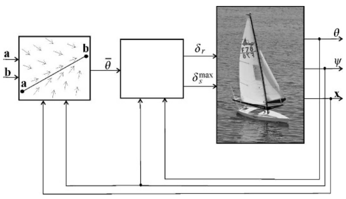

Fig. 5. Control loop

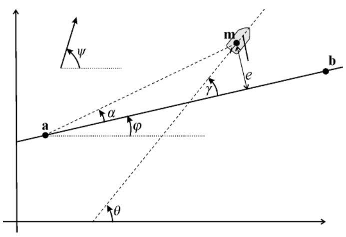

Fig. 6. Line following

3.2 Sail and rudder control

Theoretical methods have been published for sailboat regulation as Herrero et al. [2010], but it is necessary to have a precise model. As mentioned in section 2, it is not realistic. Moreover, in order to adapt the algorithms to any robot, the navigation and the control have to be easy to implement and easy to tune with a physical meaning for tuning parameter. The proposed control architecture is given by the figure 5 answers this issue.

The objectives for this control loop are:

- the boat speed optimization according to the wind,
- the line following according to the guidance algorithm demand.

Line following. The most common approach is to consider a navigation by waypoint validation as mentioned in Romero-Ramirez [2012] and references inside. To ensure a correct mission for measurements, the guidance is performed by a *line following* strategy. Indeed, due to drift and current, a heading strategy will fail because a sailboat is not able to navigate wind ahead.

Rudder control. First consideration is that if $\cos\gamma < 0$, the boat navigates to the opposite direction, then:

$$\delta_r = \delta_{r\,\max}.\mathrm{sign}\,(\sin\gamma) \tag{2}$$

where $\delta_{r\,\max}$ is the maximal rudder deflection. If the boat navigates in the good direction, $\cos\gamma > 0$, the heading error is defined by $e_{\mathrm{cap}} = \sin\gamma$. A proportional heading

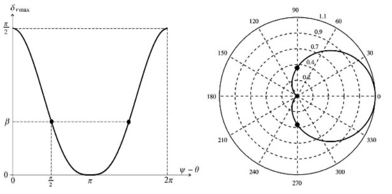

Fig. 7. Mainsheet tuning (sail angle)

control is defined by $\delta_r = \delta_{r\,\max}.e_{\mathrm{cap}}$. The line following strategy is a compromise between the distance to the line and the line heading. The distance to the line is given by:

$$e = \|\mathbf{m} - \mathbf{a}\| \sin\alpha, \tag{3}$$

where $\mathbf{m}$ is the center of gravity of the boat. Note that this allows to know which side of the line is considered. The following control strategy is used to follow the line:

$$\delta_r = \delta_{r\,\max}.(\lambda \sin\gamma + (1-\lambda) * \mathrm{sign}(e)). \tag{4}$$

where λ is the tuning parameter for the compromise. For our example $\lambda = 0.7$ has been chosen in order to avoid oscillations around the line.

Sail control The sail control tuning is based on the human behavior observation. Let us consider that β is the optimal angle when sailing with wind abeam (perpendicular to the boat). This angle is determined according to the type of boat, the sail and so on: this is the human part of the tuning.

The maximum angle between the sail and the boat, denoted δ_s, is a $(\psi - \theta)$ function that can be modeled by a *cardioid* given by:

$$\delta_{s\,\max} = \frac{\pi}{2}.\left(\frac{\cos(\psi-\theta)+1}{2}\right)^q \tag{5}$$

where q is positive and chosen in order to maximize the sail efficiency. This model is such that:

- when $\psi = \theta + \pi$, the boat is wind ahead and the model gives $\delta_{s\,\max} = 0$;
- when $\psi = \theta$, the boat is wind aft and the model gives $\delta_{s\,\max} = \frac{\pi}{2}$ (the sail is open);
- when $\psi = \theta \pm \frac{\pi}{2}$, the boat is wind abeam and by definition, $\delta_{s\,\max} = \beta$.

This last item gives the value for q. Indeed equation 5 becomes:

$$\frac{\pi}{2}.\left(\frac{1}{2}\right)^q = \beta \text{ which means } q = \frac{\log(\frac{\pi}{2\beta})}{\log(2)} \tag{6}$$

The $\delta_{v\,\max}$ function is illustrated by figure 7.

This kind of tuning has been validated by various simulations and tests as presented in Jaulin et al. [2012] or the one presented in section 4.1. The main point of this approach is that it remains very simple and can easily be adapted to any sailboat. This demonstrator is used used for various experiments and then it is shown in this paper that the control aspects are useful to control the boat and to save power to increase autonomy.

4. SIMULATION AND EXPERIMENT

These GNC algorithms are validated by HWIL simulations where the real embedded system is used and boat behavior and sensors data are simulated; it is then compared

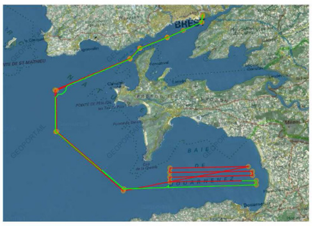

Fig. 8. Trajectories: objective in red and realized in green

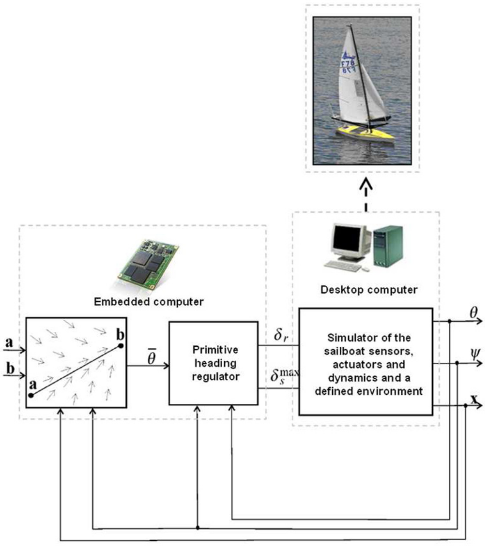

Fig. 9. HWIL architecture

with the experimentation performed between Brest and Douarnenez in January, 17th, 2012. The experiment to perform is a return trip from Brest to Douarnenez in Brittany as mentioned in Figure 8.

4.1 Description

HWIL simulation is performed according to the Figure 9. The sailboat model is described in section 2.1 and the embedded system is the real one. The sea state is not emulated and the wind is considered as constant with white noise. This noise can be considered as including the sea state effect and the current. The results are presented in figure 10. The wind data are given in direction and intensity; the trajectory and the reference are superposed (with a zoom) and the waypoints are shown with crosses; the sailboat attitudes are also plotted with the control command (rudder deflection and sail opening).

Experiment and HWIL simulation have exactly the same waypoints set and the same embedded system.

Note that the mission is not complete due to various troubles: the supervising boat had an engine problem that could not be fixed due to the night, and the sailboat was not following the planned mission any more: a part of the mechanical control system was broken. In spite of this, the duration of the mission and the good behavior of the boat lead to very positive conclusions. The wind comes

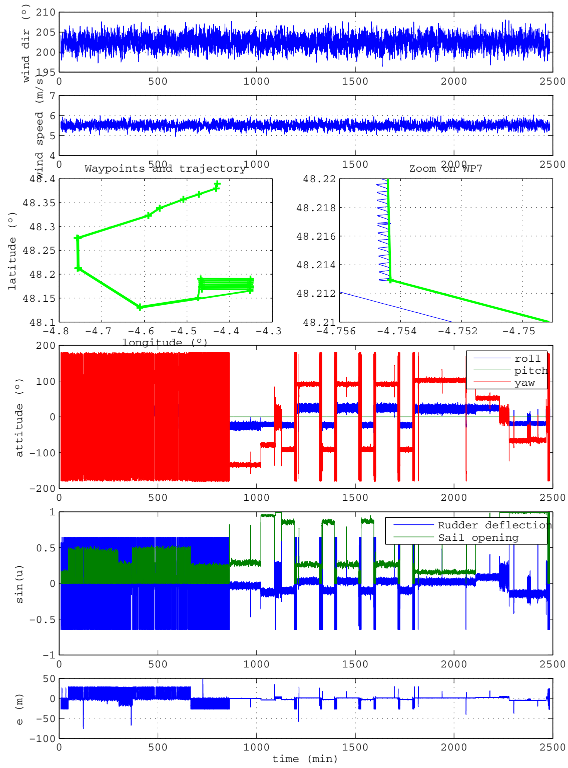

Fig. 10. Data acquisition from simulation

from the south and the robot was always at a distance less than 30 meters to its line except twice: to avoid collision with a military submarine coming back to Brest and to avoid collision with a fisherman boat. All details and data are available from the authors under request; they are not provided in this paper due to the big data. The results are presented in figure 11. The figure architecture is the same as Figure 10 to allow the comparision.

During the mission and after, a dashboard is used to analyze all the log files produced by the embedded program. For example, near the end of the experiment, it has been seen that the sail angle measured by the weather station is incoherent with the one deduced from the input. This was probably due to the mechanical problem in the sail control system that was discovered at the end. Because it was during the night, it was difficult to see the sail angle without this dashboard.

4.2 Discussion

The comparison between Figure 10 and Figure 11 rises various comments.

Even if the wind input is not similar, the real boat behavior is close to the simulated boat. Indeed, this is due to wind filtering which allows to not take into account high frequency variations of the real wind. According to the regulator, the wind input is like a slow varying input with the colateral advantage to limit the power consumption. It can be considered that the simulated wind input and the real one (regulator point of view) are similars.

The control commands (sail and rudder) are smooth according to the wind and sea; this point is also confirmed by the low power consumption logged during the experiment

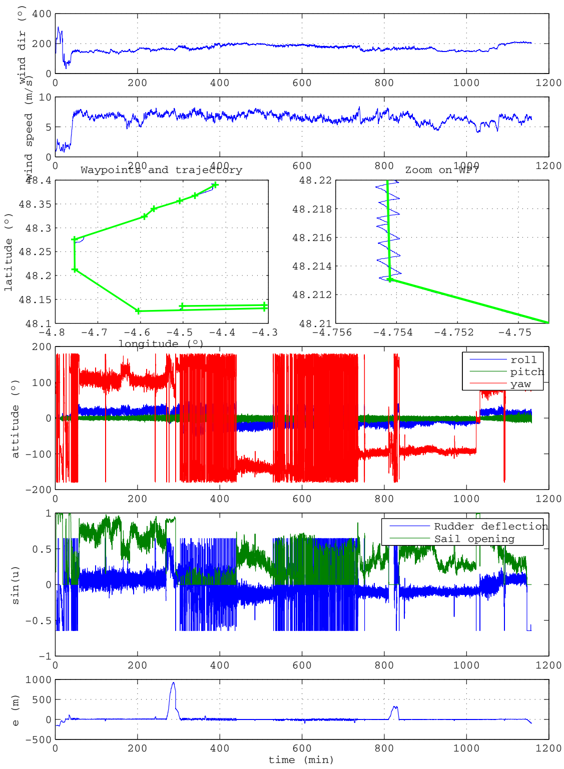

Fig. 11. Data acquisition from experiment

which was one of the control objectives. As for the wind input, it means that the sea state is also filtered by the mechanical inertia of the boat and the control laws.

Autonomy is proven: except for one team intervention for the submarine collision avoidance, the robot does not need any assistance and the power consumption remains low as the 120Ah has not been used.

As the followed path is similar in the experiment and in the simulation, it is confirmed that the HWIL simulation provided a valuable status of feasibility for the experimentation. This point is fundamental for mission preparation and allows to save time and money in experiments.

Last point does not concern the comparison between but it is important to note that the embedded system is proven as robust. Indeed the mission has been performed in rough conditions of wind and sea and all the electronic devices have remained perfect.

5. CONCLUSIONS

This paper has presented the control algorithms for an autonomous sailboat inspired from the physical behavior of a sailboat; it has been formalized with a static feedback for the sail and for the rudder; The static feedbacack approach is interesting as it limits the embedded calculation in comparison with other controllers. Moreover, as it is based on the human behaviour, it makes easier the interpretation of the controller. In the case of the use of these algorithms for an automatic pilot for yatching, as it is 'understandable', it remains 'acceptable'. A work is on going to use this algorithm for disable people. The model validation is also a result of this experiment which leads to a mission preparation tool for sailboats. Each Vaimos mission for data acquisition is prepared with HWIL simulations and a complete log analysis.

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