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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

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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

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

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

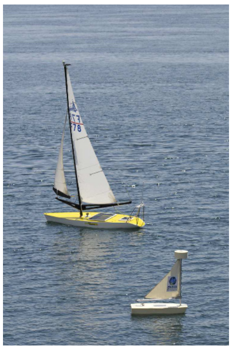

Fig. 1. Vaimos sailboat

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:

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\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]

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