VAIMOS: Realization of an Autonomous Robotic Sailboat

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Abstract. This paper demonstrates the relevance of using autonomous sailboats for the realization of long missions (several weeks) devoted to collecting measurements and observation of the marine environment at low cost. Ultimately, such a system should be used in place or in addition to current conventional systems such as drifting buoys or oceanografic ships. The paper introduces the electrical, mechanical and algorithmic realization of the sailboat and then demonstrates its robustness through several missions.

1 Introduction

The Ifremer *(Institut Français de Recherche pour l'Exploitation de la Mer)* Department of Technological Development has recently developed a small coastal vessel, electrically powered and remotely controlled. This boat, realized on the basis of a kayak of about four meters long, accepts several sensors mounted on demand, either fixed to the hull or on two small winches. This allows the realization of mini-profiles over a distance of thirty meters. The ASV (Autonomous Surface Vehicle) is not intended to go offshore. Its all-electric propulsion does not provide with more than a few hours of autonomy. Furthermore, it possesses no embarked intelligence: all the commands are deported on a computer where an operator controls his evolution.

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For the past three years, ENSTA Bretagne has developed a sailboat capable of crossing the Atlantic Ocean in a total autonomous way [2]. The first prototype is about one meter long and has already performed several convincing experiments. During last tests, it showed strong ability for navigation despite some problems related to mechanical design.

The objective is to build an autonomous prototype equipped with sensors of temperature and salinity and capable of measurements in two depths [2] [20]. This demonstrating sailboat will have to be able to sail autonomously, but also be piloted remotely. Objectives will include :

• Sail autonomously according to pre-given instructions (steering trajectory and / or goals and / or areas to avoid).

• Sail remotely controlled by an operator on land or on a ship via direct radio link.

• Endure difficult sea conditions.

• Provide information about its state (position, heading, speed, power, etc ...), regardless of its position.

• Receive orders for control and management of on-board equipment.

• Have sufficient energy independence for several days of operation, ultimately 3 to 4 weeks.

• Measure the temperature and salinity parameters on two depths.

• Store the acquired data: scientific data and overhead data.

• Transfer the scientific data at the lowest possible cost.

• Have a system of independent backup location. (The electronic for the GPS is completely separated from the rest of the ship, so even is everything else crash, the location of the sailboat would still be recorded.)

This paper is organized as follows : Section 1, 2 and 3 respectfully present the electrical, mechanical and I.T. realization of the *VAIMOS*. Section 4 presents the tests and missions realized and section 5 conclude the paper.

2 Electrical Realization

The purpose of this study is to realize a prototype robotic sailboat for two main reasons:

• Show viability of such a project, and provide results to support funding requests for the project.

• Serve as an experimental base for autonomous navigation algorithms developed by Ifremer or ENSTA Bretagne.

Given these objectives, it is clear that the "ultra low power" model, common to many embedded systems aspect, is not the top priority. However, the prototype must have some modularity to accommodate any sensor needed both to validate the algorithms and the scientific measurements. In addition, to validate the various tests, and debug the behavior of autonomous boat, it seems necessary to have access to all parameters of the boat from shore or nearby ships. That is why we chose to build the digital architecture of the sailboat around an Ethernet board. The adoption of this technology will completely separate the embedded computer from the offshore computer. Both will seek information from the sensors or actuators to send their orders directly on the network. In addition, this architecture also provides the advantage of being able to implement any card on the boat easily, as long as it works with TCP / IP.

For this project, a new architecture has been implemented around existing radio technologies such as WiFi and Iridium satellite communications. This architecture can efficiently exchange information in real time (instrumentation, sensors, ...) and manage (control) mobile or stationary equipment without wired connections. All information, proprietary or not, can be multiplexed and encapsulated by a radio modem. This information, once submitted, are dispatched to different devices in real time. The choice of wireless radio technology in this architecture is justified partly by its reliability, robustness, and by its availability in many industrial applications, showing great maturity for this technology.

For this project, the wireless connection can convey information at high speed and over a distance of several kilometers. This information can be of several types: environmental data, measurements, navigation data, audio and video streams, proprietary data flow, etc...

3 Mechanical Realization

3.1 Building the Sailboat

Hull. For the basis of the hull, we chose to use a *mini-J*. This hull offers several advantages:

- It has a reasonable size (3.65 m) and a comfortable embeddable load (90 kg).
- It is self-righting and unsinkable.
- It is made locally and is available within two months.
- It can be purchased without the deck and original rigging.

For cons, there is no digital file of the hull, and changing the rigging requires full modeling of the hull to determine the new position of the sprit. It was therefore necessary to make an accurate manual hull model using specialized software in ship design.

Deck. The deck was made from the rib recorded directly on the hull, it consists of five layers of glass fabrics of 500 gr/m^2 associated with epoxy resin. To allow easy access to various electrical and mechanical components, it was drilled and reinforced to receive two panels of waterproof deck.

Rudder. For the sake of simplicity and speed, we decided to keep the rudder of origin. It has a surface area of 0.2 m^2 and a 8% offset. Doubling the size of the rudder and the offset to 25% increased control of the ship without raising efforts. We chose to use a servo-motor to control the rudder. The winch comes with a roll of 32 mm diameter, which gives a tensile strength of 30 kg/cm divided by 3.2 cm which equals 9.375 kg, almost 10 kg, a distance of $10 * (1.6 * 2\pi) = 100$ cm which is a displacement of 1 meter. To be effective at tacking, the rudder must turn 45° port to starboard. We adjusted the length of the control arm to these values to give it the maximum torque. We obtained a lever arm of 38 cm. Moreover, to achieve the maximum angle values, the end of the arm moves only 22cm on each side, which allowed us to fit a hauling system on the cable channel. The pulley system allows us to carry a tension of about 20 kg on the control arm, providing a couple on the rudder of 20 kg x 38 cm = 720 kg.cm. We chose a *spectra* cable of a 1mm diameter with a 60 kg breaking point. This security coefficient of 3 gave us a margin that allowed us to limit the flow. We then added a support system on the cable tray to keep it always on.

Sail motorization. The sprit, with its offset design, can be operated without significant efforts. However winch trimming the sail should be able to absorb the constant efforts of the wind on the sail, and the jerks when tacking. No commercial winch meet the requirements, so we had to develop and to manufacture it ourselves. In order to monitor the movement of the sprit, we opted for a stepper motor which can be controlled via a dedicated card, in relative or absolute position.

3.2 Integration of the Scientific Measurement System

The system has to be able to perform measurements of temperature and salinity in two depths, one at the maximum depth possible on the shell (ideally two meters), and the other as close as possible to the surface (ideally within the first ten centimeters). The first solution was two small loggers (STPS type) and set them just under the hull outings. This solution had the advantage of being very quick and easy to make. However, these devices might be damaged when maneuvering or in case of grounding. In addition, the two protuberances from the hull would have hung algae and various objects. Finally, this solution prevented any real-time communication with the sensors, prevented real-time recovery of sensor data.

After some research, we decided to use the *NKE multiparameter probe MP*. The probe can be powered and interrogated remotely via an RS232 connection. It is equipped with temperature, salinity, chlorophyll, turbidity and oxygen sensors beyond our original specifications. The probe is placed onboard and its sensors in a measurement chamber. This chamber is supplied with sea water by two circulation pumps, mounted head to tail, and successively removing the water through two small holes in the shell open, close to the one surface and the other to the base of the keel. This solution,

Fig. 1 The hull with its sprit

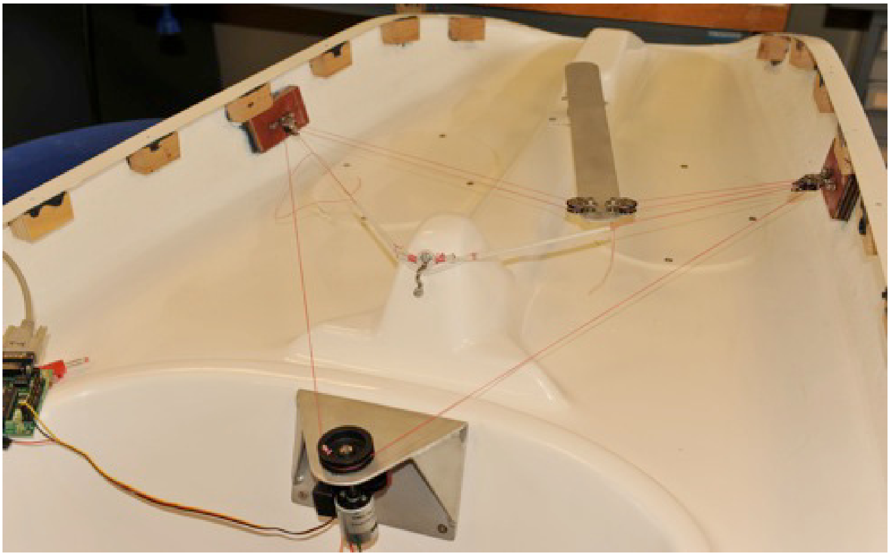

Fig. 2 Saffron control system composed of a halyard block, a tension spring, saffron arms and a winch

Fig. 3 Sensor apertures

although more complicated and time-consuming to develop, overcomes all the shortcomings of the previous.

4 I.T. Realization

4.1 Human-Machine Interface

Before starting to implement algorithms on the boat, it seemed rather necessary to try to control it remotely. Accesses to the various actuators and sensors of the boat is made through a network, and by opening a telnet port on the associated IP / serial converter. Ifremer, for *Mobesens* project had already developed a HMI using VB.net to control a kayak model with a remote, and retrieve all the information from the sensors graphically on a computer. To reduce development time, we sought and obtained the support of the team that had developed the previous HMI. We drafted the specifications of the *VAIMOS* HMI, and provided them all the frames of communication with the sensors and actuators of the boat.

Fig. 4 *VAIMOS* project and realization

4.2 Implementing Algorithms

To make the sailboat completely autonomous, it was necessary to provide it with robust navigation algorithms [6] [4] [14] which were implemented in the embedded Linux system. Two algorithms were needed to navigate the boat : rudder control and sail control [9] [18].

5 Testing

The first test of the boat was held at St Anne Portzic, June 24, 2011. Weather conditions were excellent, the wind was blowing west and stable at about 10 knots. During the first two hours of evolution, the boat showed a great aptitude to navigate which validated the choices made on the structural design. We were also able to validate the entire chain of command of the boat, from the remote control of the boat to the sensors and operating winches on board.

Thereafter, the sprit began acting strangely and it quickly became impossible to work on the sail trim. After unsuccessfully trying to restart the applications, we decided to stop the test and return to the Ifremer to

Fig. 5 First test of *VAIMOS* and OPTIMOUSSE

diagnose the problem. Back in the lab, it appeared that the cable used to control the sprit was stuck in the rear deck panel, which had the effect of dragging the stepper motor, which has lost its index position .

Then we performed various tests that helped to highlight two weak points:

• The tacking with a shocked sail, the cable flattens on the deck and can therefore blocks the rear deck panel.

• The index of the stepper motor is calculated by the control board. When the engine skid, this index is not related to the actual position of the sprit anymore.

The following solutions were implemented.

Changing the rear panel. The most effective and quick fix was to replace the rear panel adding a chamfer to the periphery so the cable would ride on it without any possibility to get hooked.

Establishing a procedure for setting the origin of the stepper motor. The most obvious way to solve this problem would be to add an encoder to the stepper motor that would have provided us with the actual position of the motor. However, given the price and availability of a good encoder, this solution was not possible. It would also have been possible to use a reed relay with a magnet set on the control cable of the sprit. That would have provided us with information on the return to zero but all the cables being outside, it would have exposed some electronic component to salt air.

Following these reflections, we opted for a software solution fairly simple and inexpensive. The solution was to lower the maximum torque on the

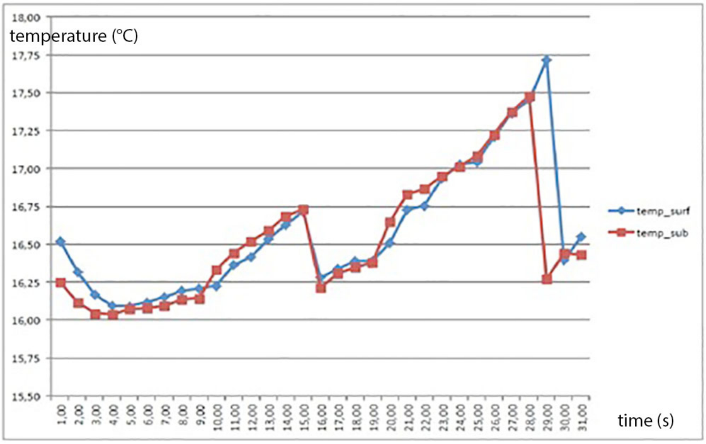

Fig. 6 Temperature measurements in two depths

stepper motor by giving it the order to border the sail for a time greater than that necessary to cover the total distance. After 60 seconds, the engine is in lined position and begin slipping. Therefore, we re-assign the origin at this point. This simple procedure will in future be carried out at regular intervals or in case of doubt about the consistence of the operations of the stepper motor.

During second test on July 1, 2011, we tried many times to put the boat in failing position, from which it recovered every time. Changes to the hatch made it impossible for the cables to jam. We also made several readjustments of the origin of the stepper motor with success. The boat was therefore fully functional.

First results of the probe. During the two tests, we launched the automatic acquisition of the NKE probe with the following cycles:

- 1 minute for ground pumping.
- Double measurement of all sensors.
- 1 minute for surface pumping.
- Double measurement of all sensors
- Wait 1 minute then start new cycle.

Although the test area was not suitable for measurements made by the boat, the system worked perfectly. Acquired data are displayed Fig.6.

First long term mission. Fig.7 gives a track in the Brest harbor by the sailboat. The desired trajectory is in red and is made by yellow waypoints and the effective trajectory is in green. Conditions were : South-West wind on the left, South-West wind of around 15 kn, 27km (17nm) in less than 5h for the right. For the parameters of the controller, we checked that the resulting controller guarantees the stability, provided that *VAIMOS* with its heading controller satisfy. The robot was always at a distance less than 30 meters to

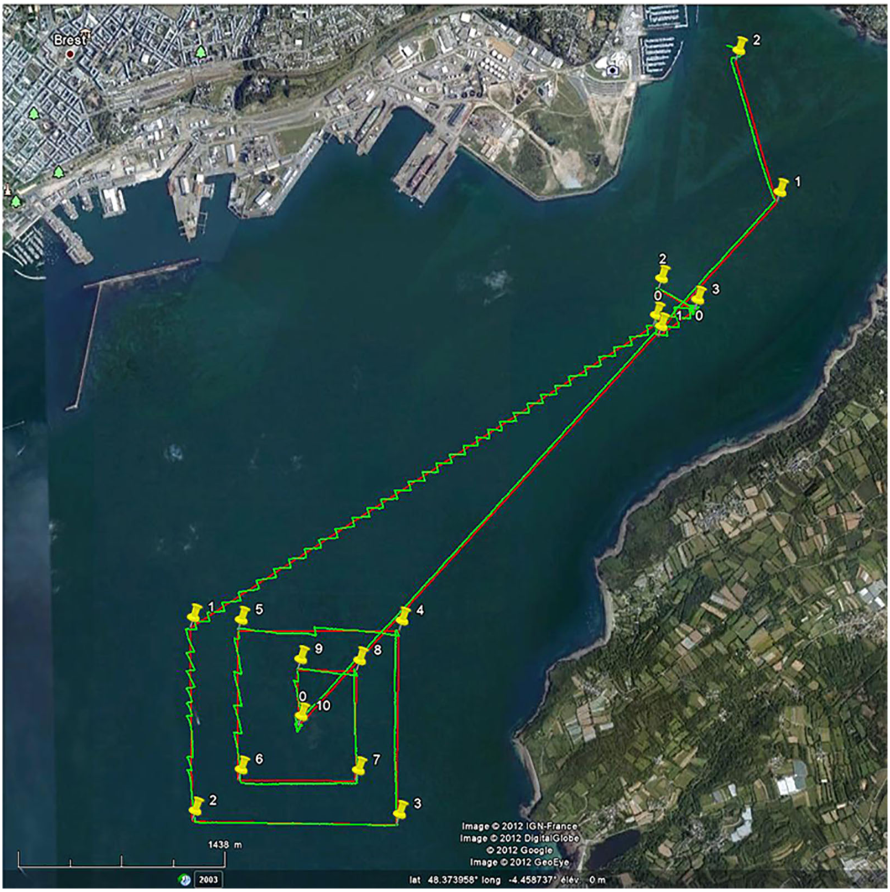

Fig. 7 GPS trajectory of the first long term mission

its line. Inside the square, the robot had to move upwind. It was in a close hauled mode and alternated starboard tacks with port tacks.

The second long term mission was 100km long between Brest and 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, that was able to continue the mission as if nothing happened.

More details related to this mission and to the method (photos, C++, source code, videos) are available on http://www.ensta-bretagne.fr/jaulin/checking.html

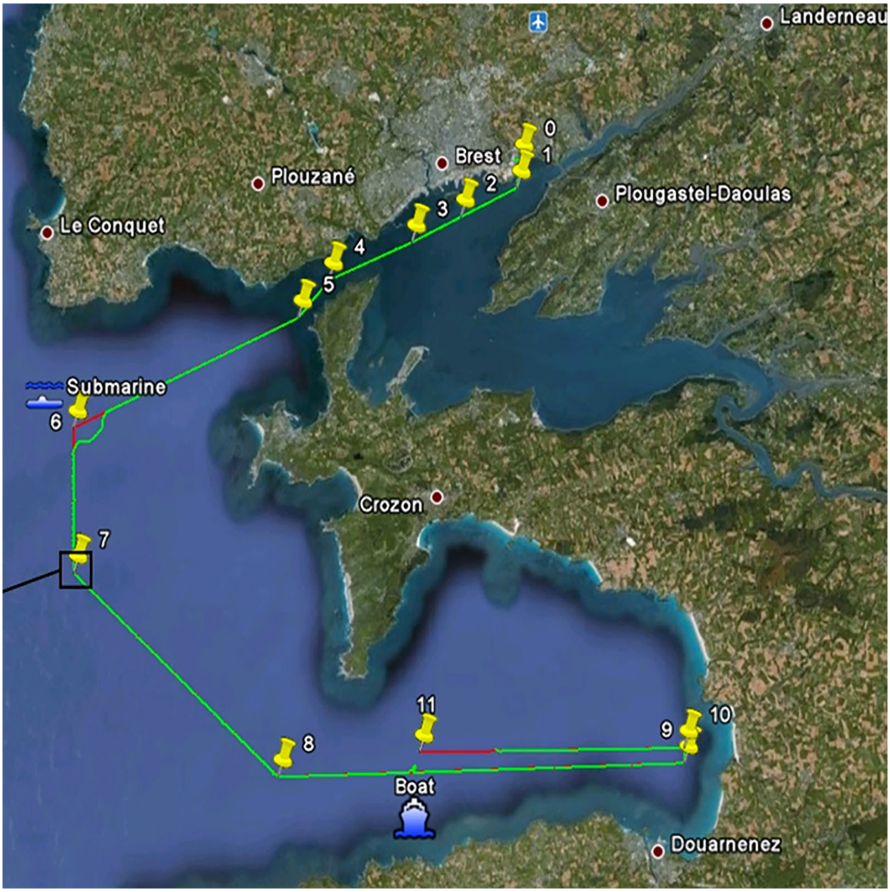

Fig. 8 Second long term mission

6 Conclusion

This paper has presented the different development phases of the autonomous sailboat *VAIMOS*. From a technological point of view, the project has opened a new path to an independent means of measuring environmental impact. From a scientific point of view, the project has brought a way to researchers to access data previously not easily measurable. Many tests and large scale missions of more than 100km have been performed. During those missions, the robot has never been at a distance more than 30 meters to its line. To our knowledge such accurate tracks for a sailboat robot in the ocean has never been done before.

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