MARIUS Project: Design of a sail robot for oceanographic missions

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***Abstract*—This paper deals with the design process of a specific sailing robot designed for sea sailing. So we will present the aims and the context of this student project and thus the specifications that guided the sailboat design. Next, a part will be devoted to the methods and tools chosen to define and create such a complex mechatronic system. The third part will describe the role and the influence of the embedded intelligence to safely carry out a given mission. Finally we will conclude this paper with a point about the project itself and future works to do in order to improve Marius.**

I. MARIUS PROJECT

A team of 19 final year students from ISEN (Institute of electronics engineering) and SUPMECA (Institute of mechanical engineering) was challenged in October 2012 to design a surface drone as a sailboat in order to autonomously sail through the sea not only with an energy point of view but also with a decisional point of view. The technical issues should show the possibility to sail unlimitedly by relying only on free energy (sun and wind) and so the sailboat could be trusted with long oceanographic missions that reject the use of propellers.

The main step of this project (from design to tests campain) ended up in February 2013 whereas the second step of improvement was achieved in June 2013, when MARIUS sailed autonomously for the first time. Many other sail robots already exist (AVALON [2], VAIMOS [8], BREIZTH SPIRIT, IBOAT II) but our project is different to them because MARIUS was designed in priority to resist and sail in harsh and unknown environments. To meet this requirement, the design process included robustness as a priority in mechanical parts, in electronics and instruments parts, and at the embedded intelligence level too.

The other particulariy of this project holds in the fact it started from the scratch. Indeed after sharing the experience of Avalon during its challenge in Mediterranean Sea in Septembre 2012 (where its rig got broken off Saint Tropez), the authors decided to create a new sailboat that will be able to survive off shore although the weather is terrible. It means that the sailboat will have to resist to big waves and strong winds without getting broken and then it will have to resume its task as soon as possible to carry out its mission. So the mechanical resistance has been chosen as a prior criterium of success.

Next the reliability of the instruments was considered as very important to keep the sailboat aware within any kinds of environment. For this reason, most of electronic stuff aboard are marine dedicated devices. Finally a reliable program of skippering was chosen to assure a good level of coherence and a whole robustness. For this reason the authors relied on the algorithms that were implemented on Vaimos, which is presently the distance record holder.

So this paper will adress all this three aspects by starting with design specifications. Next the process of design will tackle the CAD modeling, instrumentation and embedded intelligence that compose our final concept.

II. GOALS AND SPECIFICATIONS

Nowadays many investigations are carried out on AUV to explore underwater environment and the surface of the oceans as well [1]. All these systems have to adapt to an unknown and varying environment to usually carry out some long missions. The energy management is a key issue for mobile robots such as AUV, this is the reason why there is a great interest in exploiting green and free energy to increase the AUV autonomy (to say nothing of combustible energy). Gliders are based on very known marine principles since they intelligently use electric energy from a battery and the ballast principle to carry out long range missions. Such a way to move in water involves dealing with water streams, which make the system's states very dependent on environmental parameters. This is also the case for sailing robots that rely only on wind to move and reach a desired location. Numerous sailing robots work as autonomous surface vehicles to demonstrate their capabilities to move within an unknown and harsh environment, to make do and manage its own energy production and also to move within

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a varying environmment by relying only on a natural energy source, i.e. the wind. All these challenges are very ambitious but also very exciting.

The interest of such drones is to sail unlimitedly by remaining as environmentally friendly as possible. So some natural phenomena related to marine wildlife can be monitored provided there is no disturbance generated by the instruments carrier. In this context, the authors decided to create a new sailboat that performs such kinds of long missions. For safety reasons, a sail robot cannot be as big as classical sailboats to reduce the risk of damage to others in case of trouble. Indeed, we cannot claim that an embedded controller is always as safe as a skipper for sailing in any cases. Therefore it was decided to design a sailboat shorter than 2 meters and lighter than 100 kg as total weight. In addition, such a size is big enough to embed several instruments for oceanographic inspection.

In order to control the sail robot, two modes are required, i.e. manual and automatic modes. This means the manual mode allows a user from a follower boat to remotely pilot the sail robot through to a GUI that runs on a laptop. This mode is necessary to edit the route, to have a look at the logged and current data of the sail robot and to possibly keep a hand on the actuators in order to command the sail robot to stop, for instance (It means to heave to). The automatic mode controls the sailboat in order to 1) follow a desired route defined by GPS waypoints 2) to track a specific phenomenon or 3) to stay on the spot to monitor what happens within a desired location. Both these modes will guide us to specify the embedded control unit of the sailboat and its software architecture.

Finally, because of the location of our lab (south of France), we have designed a sailboat primarily to sail in the Mediterranean Sea, which represents a great interest in terms of marine observations. Incomparable to Atlantic ocean, the Mediterranean Sea is however often very windy which sometimes generates big waves. Avalon had a bad experience in this environment because its rig got broken in last September off Saint Tropez [7]. Our sailbot is thus named MARIUS, which stands for Mediterranean Autonomous Robot ISEN Union SUPMECA to include both our institutes (ISEN and SUPMECA TOULON).

III. Process of design

Such a complex mechatronics system cannot reasonably be tackled linear way. Indeed, an iterative process is necessary to face issues like energy management, navigation skills and so on. An organic description is given below but we keep in mind that numerous interactions happened during the design process between the mechanics, electronics and control processing.

A. *Mechanical part*

In opposition to other sailbots (ASAROME, VAIMOS, Erwan I), the whole design of Marius started from scratch instead of starting from an existing hull (MiniJi for instance) [1], [5], [6]. The hull was designed with Delftship software, which allows creating chines hulls that are easy to manufacture and cost-efficient (Fig. 1). So the hull has a shape that favors good stability and balance of the sailboat rather than a potential high speed (beam: 80 cm). The hull is composed of a bottom, three chines and buttocks and its global shape gives the sailboat

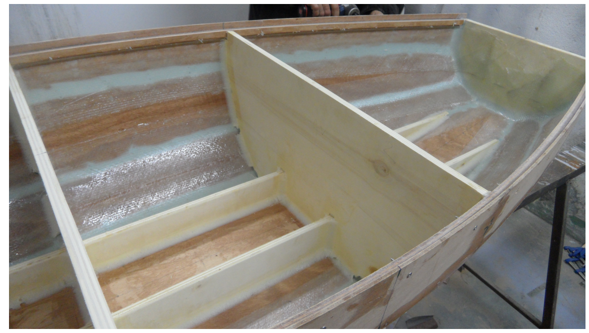


Fig. 1: Marius' hull under construction

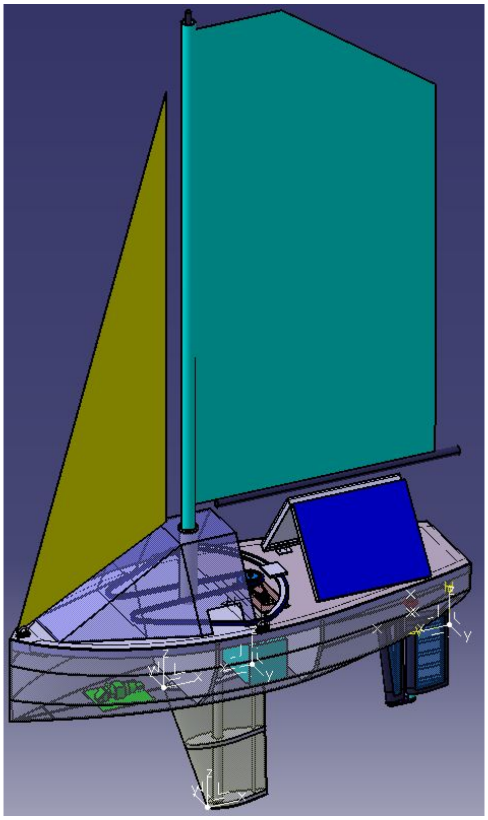
a very good stability to follow the desired direction. Indeed, when Marius is heeling, the hull centre does not move so much and thus the sailboat globally keeps the same heading. Such a behaviour helps to save energy because there is no need to continuously act on the rudder to control the heading. The technic of sew and glue was used to create the assembly of all the part of the hull. Afterwards,the whole hull was covered with fiberglass and expoxy resin to give a good rigidity and water-resistance to the hull. The net weight of the hull (hull included the deck) is about 35 kg.

A long keel was chosen instead of a bulb-shaped keel to prevent the sailboat from dragging objects that might remain stuck on the keel (Fig. 2). So the fin shape of the keel helps potential braced objects such as plastic bags, nets and fishlines… to glide away. The keel is 60 cm high and has a frame made of steel to assure a high balance torque (because of the mass) with a good rigidity. The bulk of the keel is made of fiberglass coated foam and epoxy resin.

figure

The skeg placed just in front of the rudder has also a fin shape to protect the rudder from the same hazards. Its composition is the same as that of the keel. The skeg contributes to guide the rudder in rotation. The whole hull works in water displacement mode and uses its whole length to raise its maximal speed. The water line passes just at the bottom level of the buttocks provided the total floating weight nears 100 kg as planned. Obviously, such an assumption takes into account the weight of all the components of Marius (including the battery, the instruments, wires and the computer unit), the wind force depending on the dragging force (thus the hull shape and the waterline) that lead consequently to size the balance torque generated by the keel (thus the draft and the keel mass). We notice here that we are facing a complex design issue that implies an iterative process to design and to size all these interactive parts.

In addition, we mention that a 30 kg payload can get aboard Marius without significantly changing its behaviour for sailing (provided this additional load is well placed within the hull). Indeed, with a total weight of 100 kg the top of the keel (the bottom of the hull) is 12 cm under the waterline, whereas with a total weight of 150 kg, it is 17 cm under the waterline. For both these cases the resistant force to drag the boat increases from 13 to 15.5 N to move with a speed of 2.5 knots. We notice that with a mass 50% higher, the boat undergoes a 20%



((a)) Marius CAD Drawing

((b)) Marius on a trailer

Fig. 2: Marius design

higher drag force, for a speed of 2.5 knots, which is its critical speed. This characteristic confirms that the pay load can reach 50 kg without altering the sail skill of Marius since all the additional elements are correctly placed and fixed aboard.

A doghouse is fixed upon the deck to help the sailboat to turn back in case it rolled over. Moreover, the dog house protects the kinematics chain that drives the boom. So the main sprocket, the chain and the mast foot with its electrical connectors are so covered by the doghouse. The doghouse is made of foam and epoxy for lightness. The entirely equipped hull weight is 70 kg (including 35 kg of the keel) and so the draft is 70 cm long. These features provide the sailboat with a very good balancing torque, which highly contributes to the robustness of the mechanical part.

The rig is composed of an carbon-epoxy mast that is 2.4 m long (upward from the deck), a 2.2 m^2 main sail, and a 0.7 m^2 jib sail. The mast is fitted in a 80 cm long stainless tube fixed to the bottom of the hull and the deck, whereas the mast top is braced to the deck by 3 dyneema ropes to give more rigidity to the rig (each rope withstands static loads higher than 1000 kg). The boom and thus the main sail are driven by a slider that moves along a circular rail from 60° at port side to 60° at starboard (Fig. 3). The belt follows a W shaped path and is composed for a part of a chain and for another part of a dyneema rope. The chain is driven by a sprocket fixed on the motorized shaft whereas the rope is guided by the cheek blocks (pulleys) and the circular rail. A short rope is tied to the moving slider and to the sail boom to make them move together.

This dof is controlled by a 12 V DC gearmotor fixed on the inner side of the deck. The ratio of the gear is 1/375 which implies this device to be irreversible. With such an actuator the boom can rotate along 120° angle in 6 seconds. The chosen controller is a simple propotional gain feedback. Because the angular resolution is very accurate (less than 1°) and the sensor is placed on the driving shaft (sprocket shaft thus no play in rotation between the driving shaft and the sensor), the boom controller reaches less than 3° of accuracy in position. This error is low enough to properly drive and set the boom during sailing as required.

The rudder shaft is also driven by the same type of actuator fixed under the deck, that transmits its torque through a chain and a cog system. Each dof is equipped with a rotative pot entiometer, which provides an absolute angle measurement for the rudder and the main sail. The DC motor driver boards are placed into an electric box, which includes and gathers the

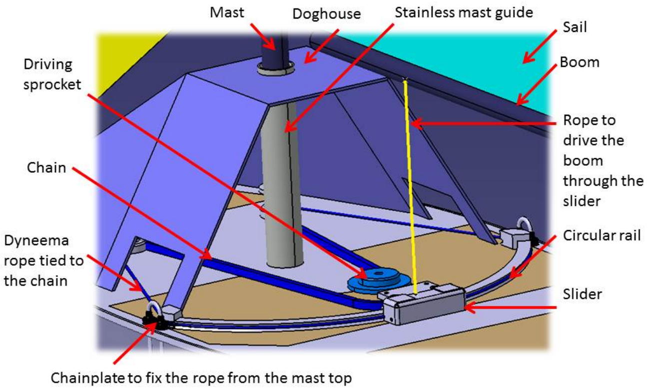


Fig. 3: Main sail actuation principle

supply sockets for all the instruments and also the control unit.

B. Instruments and energy

The skipper mode chosen to control MARIUS aims at reproducing the best as possible what skippers usually do. This means relying on several measured data, i.e. heading, GPS position, wind speed and direction, in order to properly control both actuators, i.e. the rudder and the main sail. Many other data related to the states of the sailbot could be monitored as well in order to improve to sailing skills but this might make the skippering algorithm much more complex without assuring any noticeable improvements. Such improvements will be studied as future works.

So MARIUS is equipped with a magnetometer compass, a GPS and a wind sensor that are NMEA standard instruments. The wind sensor is an ultrasonic sensor that is placed on the mast top. The GPS is fixed on the deck close to the buttocks whereas the compass is fixed in the hull below the deck to the front of the boat far from any magnetic disturbances. These three instruments are plugged to the control unit through serial ports. Moreover a 3 axis accelerometer has been added not in order to directly control actuators but to monitor MARIUS' behaviors in relation to the wind and waves conditions. This sensor works as inclinometer and primarily helps the programmers to determine the best settings for the main sail angle (depending on the wind speed/direction and on MARIUS' velocity) and also to know whether MARIUS has rolled down.

A 90 Ah gel battery supplies energy for all electronic stuff. The free space inside the keel was initially supposed to be filled with NIMH batteries, but for economic reasons, such a solution was given up. Therefore a much bulkier (23 kg) and classical battery was chosen to be fixed on the bottom of the hull. Two 35 W photovoltaic pannels placed like a tent on the deck provide the battery with energy through a MPPT charger. This charger can simultaneously work with solar pannels and a wind generator. The design of this latter device is presently in progress. A dedicated vertical Savonius wind generator with helicoidal blades should equip Marius soon in order to contribute to the energy production (30 W targetted).

C. Control Unit

The control unit has been concurrently specified with the rest of the robot. Because of the short duration of the design phase of this project, a high level of programming language was required. The potential evolution of Marius missions and of its features have pushed the authors to select a modular control unit compatible with many types of signal (digital, analog...). For safety reasons, Marius must be remotely controlled if requested from 100 m around. This feature is necessary to request Marius to stay on the spot (sailing facing the wind), this allows the staff to catch it in order to drag it into the harbor for example. To do so the control unit must be compatible with a wireless communication type to create a private link to a host PC, which runs a GUI program aboard the follower boat. Finally the control unit must be able to be embedded aboard the sailboat and be compatible with the energy requirements (low consumption, low supply voltage if possible). For all this reasons, a Real Time target from National Instrument was chosen. The Compact-RIO 9076 provides four slots for C modules. It can be power supplied from 9 to 30 volts and its consumption cannot exceed 15 W. Presently, three connected C modules feature four RS232 serial ports where the GPS, the compass and the wind sensor are plugged, eight analog inputs for the 3 axis accelerometer and the both potentiometers (main sail and rudder), and four analog outputs to drive the both DC motors. About the half of the whole ressources remain avalaible therefore the actual energy consumption of the control unit is about 6 W. This control unit offers a USB port and a RS232 ports to connect peripherals and an internal storage memory of 512 MB. A bluetooth dongle (1,2 W) plugged on the control unit provides it with a long range wireless communication way (up to 300 m according to the manufacturer and tested up to 100 m).

The control unit, a supply board and the two motor driver boards are placed in a watertight box, that protects the electronic stuff from water but allows evacuating heat thanks to a large alloy wall. This electronic box is fixed on the bottom of the hull in the front. The inside frame of the hull includes drilled walls to help the convection thanks to a natural air flow. A thermal sensor has been added to monitor the temperature inside the hull in summer time especially during very sunny days. The overheat ought to be avoided even during sunny days thanks to the shade of the solar pannels and the shade of the doghouse and also to the average temperature of the bottom of the hull (the water temperature rarely exceeds 30 degrees Celcius in Mediterranean Sea in summer).

IV. Embedded Intelligence

The programs implemented on the control unit meet two main requirements, i.e. to remotely control Marius and to let Marius manage autonomously its behaviour in relation to its current mission. For this reason, the authors decided to split the embedded intelligence into two modes, i.e. the manual control mode and the automatic mode. All the programs are coded in LabVIEW language, which is a graphical language. It is especially interesting because the programs are hierarchically sorted and can easily interact with the hardware inputs/outputs.

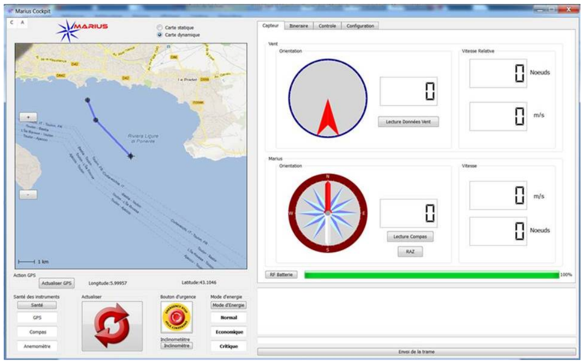


Fig. 4: Snapshot of Marius Cockpit - GUI for the remote control mode

Many functions dedicated to signals like acquisition, measurement, treatement and analysis are already preprogrammed. The control unit Compact-RIO 9076 includes FPGA chips that give the opportunity to speed up the code execution and also to reduce to power consumption. In the first step, all the programs are implemented in scan mode, this means that inputs/outputs are scanned and the FPGA functions are not used. In this mode, the execution frequency reaches 500 kHz, which is very confortable for our application (the classical sample time for sensors and instrument does not exceed 20 Hz).

A. *Manual control mode*

In the manual mode, the pilot remotely controls Marius. It means collecting and displaying all the data about Marius' states provided by the embedded sensors/instruments, editing the path to follow as a GPS waypoint file and directly driving the both actuators of the main sail and the rudder. The GUI that runs on the host laptop has been programmed in QT language. The main window gives the possibility to edit the path by clicking on the static or dynamic (if Internet is available) Google Map. All the waypoints are stored in a list, which can be easily modified before uploading it to Marius. The map displays the desired and the actual paths. From the main tab, the pilot can check if all the instruments work properly. A big double-arrow button allows refreshing the data including the battery level. A permanent led shows the user if Marius is connected or not. There is a command window to send requests to Marius. The sail robot does not transmit its data unless requested and connected. This helps to save energy by using the bluetooth module only when necessary. A second tab is dedicated to the manual control of each actuator. The heading, the wind direction and the wind speed are continuously refreshed to help the pilot to easily control Marius (Fig. 4).

The manual mode includes also an emergency button that launches an automatic function, which drives both actuators so that Marius turns until facing the wind. During this maneuver Marius goes upwind to heave to (i.e. keeping the rudder 10 $^\circ$ on one side and the sail 10 $^\circ$ on the other side). Of course the pilot can switch whenever he wants to the automatic mode. In this case, Marius will target the next waypoint it has not passed through.

B. *Automatic mode*

The automatic mode was first designed to make Marius follow a path defined as a list of GPS waypoints. To do so, it was decided to get inspired from the algorithms that control Vaimos [3]. Despite the experience we gained from Avalon's challenge in last September in Toulon, we could not adopt the same control method because Marius' rig is not based on a balestron, thus it cannot jibe by turning its sail further than the 120 $^\circ$ range given by the circular rail and limited by the position of both lateral shrouds. The chosen algorithms take the wind conditions into account but do not consider potential obstacles. Indeed no device of obstacles detection was implemented aboard Marius yet. The implemented automatic control mode has to follow a path where each waypoint owns a value of dangerosity. This value illustrates the proximity of dangerous areas or shore. Therefore Marius is allowed to pass more or less close to the considered waypoint to validate its path.

Marius manages its energy through three levels of energy. We distinguish two main modes (normal and economy modes) where the sampling frequency switches from 5 Hz to 0.1 Hz for the instruments and the control of actuators. A third mode is a critical mode that prevents the battery from the deep discharge by turning Marius in idle mode (Marius gets to heave to). Afterwards it lets itself drift until the battery be charged again above 50%. The energy management has to be experimented during a long mission to validate its relevance, but it has not been done so far. All the recent experiments with only one solar panel laid on the desk showed that this solution of energy production fits the energy needs of Marius while two-hour missions. Indeed the battery level remained very close to 100%. These experiments were done during sunny days in June in Toulon harbor, where the weather conditions are optimal for electric energy production through solar pannel. We cannot conclude that our energy solution is oversized because weather conditions are very changing with seasons and this solution has to be reliable in any conditions.

V. Marius as a students project

This project started in October 2012 from the clean sheet and gave birth of Marius as a functional sail robot in February 2013. The team composed of 19 students who spent 100 hours (officially scheduled on the scholar planning) on this project was hierarchically organized. Indeed there was a head manager, a logistics manager and four interactive groups respectively focused on mechanics (hull, rig and whole integration), instrumentation (electronics stuff, sensors and actuators), energy (battery sizing, energy production and supply) and computer (embedded control unit, programing, wireless control and GUI). Each group autonomously worked under the responsibility of a manager, but communicated a lot with each others to progress in concurrent engineering. This project was a real challenge for all the participants especially because of its short duration and the lack of experience in this domain. Nevertheless it was successful because the sail robot was achieved on schedule although all the planed experiments could be done as expected.

This is the reason why the project was continued from March to July thanks to the participation of 3 graduate students who were in charge of many small improvements. Indeed they had to check the reliability of all the electromechanical solutions implemented on Marius. This led to some small design modifications about the top mast for example and a central electronical board for instruments. Moreover the main algorithm was simplified and several test programs were created to validate the right functioning of each elementary function (communication between instruments, control of the rudder and the sail in relation to instrument signals, and so on). Finally a part of their work was dedicated to the creation of a web site on Marius [9]. So you can visit this web site to get more information about the sail robot and the students projects.

To carry out this project during the last scholar year, both institutes ISEN and SUPMECA have totally supported the cost of Marius design, that does not exceed 11 000 euros. This reasonable budget covers all the components (from the hull to the control unit) included in Marius.

Fig. 5: Marius in test

VI. Conclusion and future works

Marius project is a very young and ambitious project, which led to an operational sail robot designed to resist harsh environments and climatic conditions. For a beginning, its control modes are basic but are supposed to be improved after several missions in forthcoming months (Fig. 5). This very motivating project was a success and a very good engineering experience for students and involved teachers, so that we decided to carry on working on Marius next year through another students project to improve the sailboat. Indeed, as it was mentionned before, some important features related to security and navigation skills are still missing on Marius. This is the reason why the obstacles detection and obstacles avoidance are included in future works to do. A long range transmitter for GPS position will also equip Marius in a short future. Finally, some other evolutions will certainly stem from requirements of various oceanographic missions.

Acknowledgement

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References

[1] Romero-Ramirez, M.A. PhD thesis: Contribution la commande de voiliers robotiss. January, 23rd, 2012, Universite Pierre et Marie CURIE, Paris, France. 206p.

[2] Erckens, H., Busser, G.-A., Pradalier, C., Siegwart, R.Y. Navigation Strategy and Trajectory Following Controller for an Autonomous Sailing Vessel. Volume: 17 , Issue: 1. March, 2010. pp. 45-54.

[3] Jaulin, L. and Le Bars, F. A simple controller for line following of sailboats. In IRSC 2012, Cardiff, UK, 2012.

[4] Guo, Y. Romero Ramirez, M.A., Leng, S.H.,Plumet, F., Benosman, R. et Gas, B. Reactive Path Planning for Autonomous Sailboat using an Omni-Directional Camera for Obstacle Detection. In: IEEE International Conference on Mechatronics (ICM). Istanbul,Turkey, 2011, p. 445450.

[5] L'Ifremer en videos. http://wwz.ifremer.fr/webtv/Liste/Nouveautes/VAIMOS Available on May 5th, 2013.

[6] Erwan I, le MiniJI de l'Ecole Navale. https://sites.google.com/site/minijiecolenavale/project-definition Available on May 5th, 2013.

[7] Grundmann, S. Avalon Toulon 2 HD. http://youtu.be/H7PBQG_crzY Available on May 5th, 2013.

[8] Le Télégramme. http://www.allboatsavenue.com/le-voilier-robot-vaimos-fait-tomber-le-record-de-liboat-ii Available on May 5th, 2013.

[9] Marius, le voilier autonomone qui va traverser la méditerranée. http://88.191.144.136/marius Available on May 5th, 2013.