Integration of Wind Propulsion in an Electric ASV

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Abstract This paper describes the steps taken to integrate wind propulsion in the Zarco ASV, a small size electric powered catamaran. In terms of hardware, the original structure of the vehicle has been enlarged to accommodate one or more sails, and the proper interfaces have been included to allow measurement of wind speed and direction and independent sail actuation. The sails are lightweight rigid wings assembled from a core of balsa wood, reinforced with aluminum and epoxy. Each sail angle can be controlled by a servo, commanded by the main CPU and taking into account the wind speed and direction, as well as the lift and drag curves of the wing sails, according to some predefined control strategy.

1 Introduction

Robotic surface vehicles are extremely valuable scientific devices that have been playing a consistent role in many areas of marine science, by providing an effective and affordable way to sample the ocean. These vehicles are commonly referred to as

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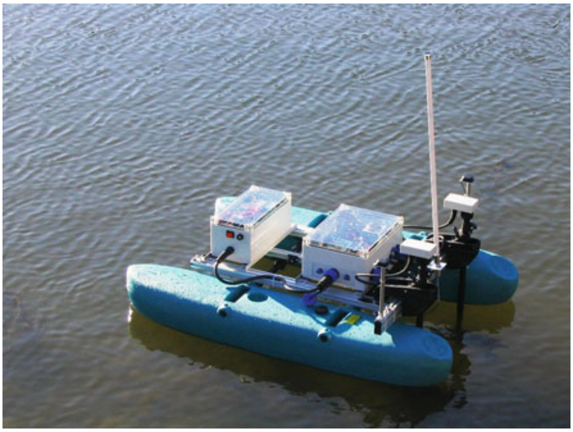


Fig. 1 Zarco typical configuration, with two independent electrical thrusters in the stern

Autonomous Surface Vehicles (or *ASV*s), and they combine the ability to transport a large variety of sensors and actuators with real time, high-bandwidth communications, resulting in advanced systems for tele-presence in the marine environment.

There are several options to provide propulsion to an ASV, both in terms of technology involved and also in terms of configuration, and there are several successful examples using these different options. Zarco is a small size electric powered Autonomous Surface Vehicle, in operation at the University of Porto since 2005 [1]. It can be seen in Fig. 1 in its original configuration, with an overall length of 1.5 m, weighting approximately 50 kg and propelled by two independent electrical thrusters, with a maximum velocity of 4 knots. Our default choice was a configuration with differential drive provided by modified COTS trolling motors, due to a combination of price, availability and simplicity of control. These thruster are relatively inexpensive, available of the shelf from several manufacturers in a variety of power levels, and there are also many off-the-shelf solutions of electronic boards to control them from a computer.

In a typical operation, the electric propulsion of Zarco accounts for about 90 % of the power consumption, yielding about 4–6 h of autonomy at a nominal velocity of 2 knots. This percentage depends on many operational factors, like velocity and payload, but it is largely dominated by the hydrodynamic drag, therefore it is always a significant portion of the total power of any ASV mission. In the case of Zarco, the vehicle construction is highly modular and the energy enclosure can be swapped for a fresh pack to extend the mission duration. However, there are many situations in which the vehicle has to operate without interruptions, and therefore the possibility of integrating wind propulsion and harvesting energy from the environment to increase autonomy are very appealing as they open up the possibility of permanent ocean presence.

The remaining of the paper is organized as follows. In Sect. 2, we provide some background on technologies of wind propulsion, mainly intended for robotic vehicles. Then, in Sect. 3, we detail the construction of a wing sail and report its characteristics as an independent propulsion system. We proceed, in Sect. 4, to the steps taken to integrate such a propulsion system in Zarco, and, in Sect. 5, we discuss some possibilities of taking advantage of the hybrid propulsion system. Finally, we draw some conclusions regarding the accomplished work and we provide some ideas regarding the tasks planned for the near future.

2 Background and Related Work

2.1 Using Wind for Propulsion

The wind has been the major source of ship propulsion for thousands of years, until the advent of fossil fuels. Recently, with the rising prices of oil and the urgent need to reduce CO_2 production, the use of wind for ship propulsion has been regaining a growing attention. Some new concepts have been proposed for harvesting wind energy [8] and some companies are already delivering products for new or existing vessels. For example, SkySails GmbH, in Germany, offers wind propulsion systems as an auxiliary fuel-saver for cargo ships, based on a large towing kite [19], while Eco Marine Power Co. Ltd., in Japan, is developing the EnergySail, a rigid sail that can be fitted with solar panels to take advantage of both wind and solar energy [3].

In the case of robotic systems, the typical scale is much smaller, but the prospect of using wind as a major source of energy for ASV propulsion is also very appealing as it reduces a very significant portion of the total energy delivered by the onboard batteries during a mission. Moreover, the remaining electronics typically require such a small amount of energy that it can be provided by a simple management system based on rechargeable batteries fed by a renewable source (for example, a solar panel). However, the use of this infinite source of energy for the propulsion of a robotic system still presents a multi-disciplinary challenge that is being addressed in the latest years. Most wind propelled ASVs employ either a fabric-based or a wing sail, each with its own pros and cons, both from the performance point of view, but also in practical terms [13]. Fabric based sails, or *soft* sails, mimic the usual sails of standard sailboats, but are very difficult to monitor in terms of 3D shape and automatic detection of improper tuning, like luffing. Although there has been some work to detect the correct trimming of soft sails [12], it is easier to control single-element, symmetrical wing sails from a robot, with very reasonable performance [4].

2.2 Wind Propelled ASVs

Autonomous Sailboats are a particular class of ASVs that rely on wind to provide propulsion and only need electrical energy for the onboard electronics and rudder/sail adjustments. They have gained particular attention in the last few years for their unique ability to maintain long term unassisted operations in the sea surface, with a wide range of application scenarios spanning the scientific, civil, or military communities [2, 15].

One important point to address for the permanent ocean presence is the ability to withstand the harsh conditions at sea during long periods of time, and a few recent successful projects have demonstrated the capability of long range navigation with robotic autonomous sailboats. The Saildrone project is one example, a 19 ft long trimaran rigging a wing sail, demonstrated in the end of 2013 with a 100 day autonomous mission in the Pacific Ocean, and an announced plan to try a circumnavigation [16]. Other projects of small sea worth autonomous sailing robots have also been developed in Europe, as the Austrian ASV Roboat exploited in research on marine mammals [20], the BeagleB project of the University of Aberystwyth, United Kingdom [17], the Vaimos sailboat from ENSTA Bretagne, France [10], and the Portuguese FASt, used for acoustic monitoring of mammal activity [18]. In terms of hybrid propulsion for small ASVs, the University of Aberystwyth has developed a 2 m long prototype of a hybrid sail and electric drive boat [11], but unfortunately it has not evolved into the intended full-scale oceanographic version.

On a related application scenario, the utilization of wind as a complementary source of propulsion has also been proposed to ensure station keeping of buoys, as in the case of the Norwegian SailBuoy vessel, from CMR Instrumentation [5], or the *Station Keeping Buoy* from John Hopkins University, in the USA [6].

On a more commercial front, Harbor Wing Technologies, in the USA, developed a few prototypes of fully wind propelled multi-hull surface vehicles, mainly intended for the US Navy, but the company stopped reporting any new developments in 2010 [7]. Some of their key personnel later founded Ocean Aero Inc., also in the USA, a company that has announced the development of the *Submaran*, a 4.1 m long hybrid surface/sub-surface vessel, powered by wind and solar energy [14].

3 Design and Construction of the ASV Sail

3.1 Design Considerations

Given the pros and cons of fabric-based sails and wing sails, we've decided to take advantage of the simplicity of implementation and repeatability of wing sails behavior. Our initial requirements for the sail characteristics were mainly dictated by physical constraints, not only in terms of manufacturing and mechanical integration, but also in terms of logistics. Ideally, a large sail area provides the most actuation and this may be achieved by a long wing sail with a large cord. On the other hand, a longer sail will increase wind-induced pitch and roll and, at the same time, will shade a similar sail in the case of using multiple instances.

We've decided to limit the length of the sail to one meter and the cord to 40 cm, yielding a design that we could easily transport, if detachable from the main structure. We've also analyzed the impact of the aspect ratio in construction and control and we've decided to use a NACA 0015 profile, a well studied design with a symmetrical shape enabling similar lift generation in both sides of relative orientation.

3.2 Sail Construction

The first sail prototype was assembled from a core of balsa wood with aluminum and epoxy reinforcements and wrapped in a thermal foil. Figure 2 shows some of the construction stages. To ensure the overall NACA 0015 profile, 10 cross sections were machined from 5 mm thick balsa wood, to become the backbone of the sail. These were drilled with guiding holes to ensure a proper alignment: a central hole with 20 mm diameter for an aluminum tube that is used as the sail mast, and smaller holes for 8 mm aluminium tubes that reinforce the structure. To facilitate construction and avoid sharp edges, we've modified the leading and trailing edges of the sail to round shapes. The leading edge is then provided by a 16 mm PVC tube and the trailing edge is formed by a 4 mm carbon rod.

Fig. 2 Different stages of the construction of the wing sail prototype, from the CAD drawings to the final result

The wooden cross sections were held in place using aluminum rods evenly spaced along the sail mast, and passing through it, and everything was held together with epoxy, resulting in a very sturdy backbone. On the outside, this backbone had 8 slots (4 on each side) meant to hold balsa wood battens, in order to provide an outer shell with a profile close to NACA 0015. These battens were also glued with epoxy before being wrapped with the resin-coated thermal foil, which was carefully glued to the wood using a heatgun.

With this assembly, both the top and bottom of the wing sail had sharp edges, which could cause turbulence and affect aerodynamics. To avoid this, we've designed two mechanical parts to round both ends of the sail, and we've used a 3D printer to fabricate them in ABS plastic. The final assembly weights 1.3 kg and it can be seen in the last picture of Fig. 2.

3.3 Aerodynamic Characteristics of the Sail

In order to evaluate the aerodynamic characteristics of a single sail under various wind profiles and compare it to the theoretical values of a NACA 0015 profile, we've used a Computational Fluid Dynamics (CFD) software, *Autodesk Flow Simulation*. We've conducted simulations for wind velocities of 3, 5, and 10 ms^{-1}, with an angle of attack varying from 0 to 180°. Figure 3 shows an example of the graphical output of the CFD with the velocity field around the sail.

With the resulting forces, we've interpolated the lift and drag coefficients in one degree intervals and the results can be seen in Fig. 4 for a linear interpolation. Note

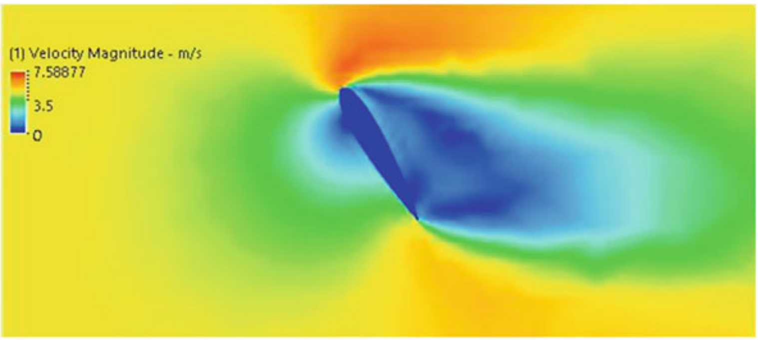


Fig. 3 Cross section of the velocity field around the wing sail, simulating a 5 ms^{-1} wind speed and an angle of attack of 60°

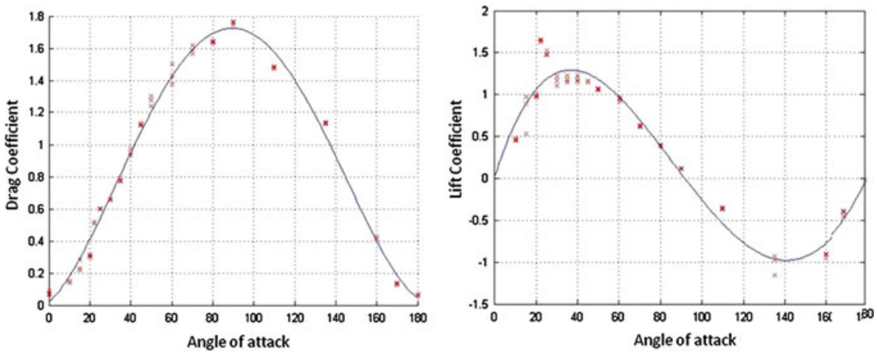
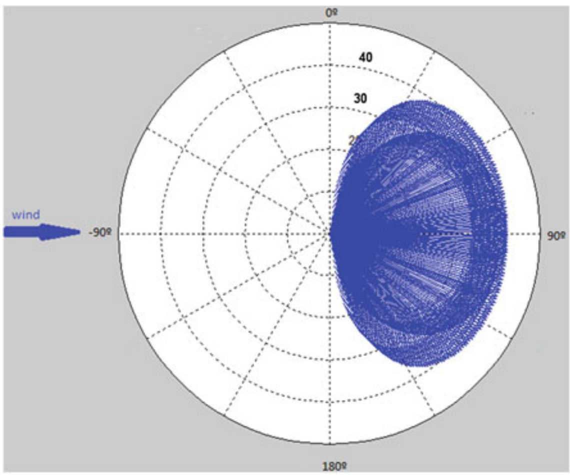


Fig. 4 Interpolation of drag and lift coefficients obtained by CFD analysis of the wing sail

that this linear interpolation of the lift coefficients has a significant error around 20–30°, therefore a practical implementation has to use a higher order interpolation to yield more accurate results.

With these coefficients, it is possible to estimate the drag and lift forces provided by a sail, for each apparent wind angle and magnitude. The combined effect of these forces represent both the magnitude and the angle of the actuation force provided by the sail. As an example, the plot of Fig. 5 shows the magnitude (in Newton) and the angle of the resulting force, when the wing sail is under a 10 ms^{-1} wind.

Fig. 5 Magnitude and angle of the combined drag and lift forces, for different angles of attack



4 Integration of Wind Propulsion

4.1 Physical Integration

Zarco has a catamaran configuration, assembled from a set of T-Slot aluminum structural profiles, supported in a couple of COTS flotation pontoons, one meter apart. To allow enough room for the sails, the structure was extended from 1.5 to 2.5 m and the pontoons replaced by longer, thinner versions, resulting in a larger configuration but with a similar weight and buoyancy. This extra length also helps in compensating any torque induced by the resulting force on the sail (affecting roll and pitch). Each sail angle can be controlled by a waterproof servo, commanded by the main CPU using a simple servo motor controller. In order to measure the wind speed and direction, we've installed an Airmar 150WX weather station, that outputs NMEA sentences into a CPU serial port. Figure 6 shows the configuration of Zarco with a wing sail at the stern, during initial testing.

4.2 Hybrid ASV Model

The integration of additional propulsion to the Zarco ASV results in a small change in the model of the vehicle. Note that we assume that Zarco is equipped with an

Fig. 6 Zarco being tested with a single wing sail at the stern

electrical propulsion system that is able to answer adequately to its dynamic and kinematic tasks, described in [9] for the particular case of positioning control. The installation of sails aims at lowering the power consumption, consequently enlarging the endurance of the vehicle. The number of sails is restricted by physical limitations of the boat and disturbance that may arise if two or more are placed close together.

Take a body fixed coordinate system $\{B\}$ fixed to the center of mass of the vehicle, whose longitudinal axis indicates the surge speed and transversal axis the sway speed. The thrusters, placed on the rear of the vehicle, are responsible for the force on the longitudinal axis $X_{act\,motor}$ and torque $N_{act\,motor}$. Each i_{th} sail produces forces in the longitudinal $X^i_{act\,sail}$ and transversal axis $Y^i_{act\,sail}$ and a torque $N^i_{act\,sail}$. Consequently the input actuation can be described as:

$$X_{act} = X_{act\,motor} + \sum_{i}^{n} X^i_{act\,sail} \tag{1}$$

$$Y_{act} = \sum_{i}^{n} Y^i_{act\,sail} \tag{2}$$

$$N_{act} = N_{act\,motor} + \sum_{i}^{n} N^i_{act\,sail} \tag{3}$$

Note that the sails allow actuation in the transverse axis (the term Y_{act}) which was not possible when propulsion was provided only by thrusters. However, the sail actuation in this transverse axis may quickly saturate and the catamaran hull configuration offers much resistance to lateral motion. Therefore, no reference should be set to Y_{act} as, from the control perspective, the vehicle remains underactuated. Note also that the forces produced by the sails result in pitch and roll moments that cause the vehicle to heel, but, fortunately, our catamaran configuration minimizes such effects and therefore they can be neglected in our equations.

Consider the wind coordinate system $\{W\}$ fixed to the aerodynamic center of a sail, where x_w is aligned with the apparent wind direction. Let θ^B_W denote the angle between the vessel and the wind, and $R(\theta^B_W)$, the rotation matrix from frame $\{W\}$ to $\{B\}$. The actuation provided by each sail is then

$$\begin{bmatrix} X^i_{act\,sail} \\ Y^i_{act\,sail} \end{bmatrix}_B = R(\theta^B_W) \begin{bmatrix} F^i_D \\ F^i_L \end{bmatrix}_W \tag{4}$$

$$N^i_{act\,sail} = \begin{bmatrix} X^i_{act\,sail} & Y^i_{act\,sail} \end{bmatrix}_B \begin{bmatrix} pos^i_x \\ pos^i_y \end{bmatrix} \tag{5}$$

where F^i_D and F^i_L are the drag and lift forces, respectively, and (pos^i_x, pos^i_y) are the position of the sail wrt the center of mass.

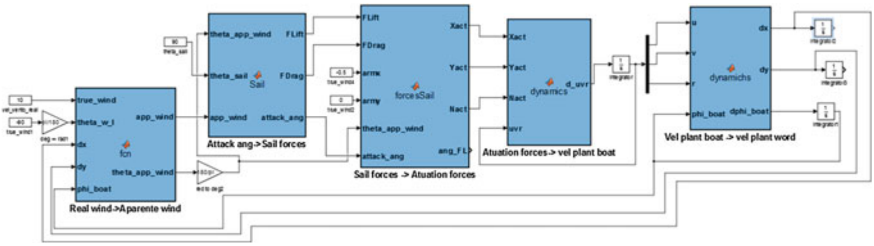


Fig. 7 Complete simulation model of the hybrid ASV developed in Simulink

Note that in the original electrical system, the actuation was simply given by:

$$X_{act\ motor} = \left[F_{port}\ F_{starboard} \right] \begin{bmatrix} 1 \\ 1 \end{bmatrix} \tag{6}$$

$$N_{act\ motor} = \left[F_{port}\ F_{starboard} \right] \begin{bmatrix} \frac{dist_{motor}}{2} \\ -\frac{dist_{motor}}{2} \end{bmatrix} \tag{7}$$

In order to simulate the dynamics of the ASV under different control strategies, we’ve developed a model of the various blocks in Simulink, shown in Fig. 7.

5 Strategies for Propulsion of a Hybrid ASV

The wing sails can be considered as additional inputs for the propulsion system, as described in the previous section, but with the remark that its characteristics are dynamic, depending on apparent wind speed. In this section, we provide two examples of possible uses of the wing sails in different application scenarios.

5.1 Using the Wind as the Main Propeller

Given that the Zarco ASV does not have any rudder, the use of a single sail can only be effective for apparent wind angles up to 90 degrees. In many situations, however, this may be sufficient to bring the vehicle to a safe area if the batteries are at a critical level, or in case of some other major failure.

In this case, the strategy to use is to compute the required direction of motion and then search for the closest direction of the combined drag and lift forces, according to the real time measurement of the wind direction.

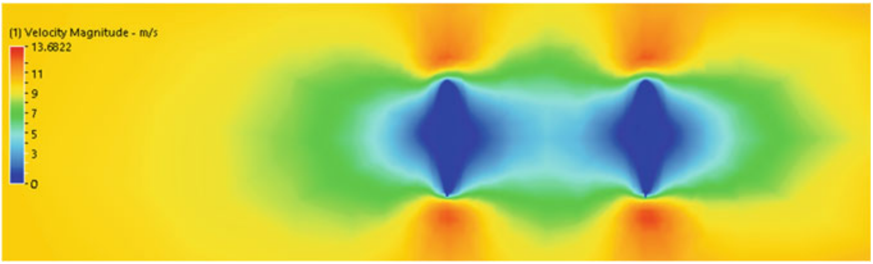


Fig. 8 Cross section of the velocity field around two wing sails separated by 2 cord-lengths (80 cm), simulating a $10\,\mathrm{ms}^{-1}$ wind speed and an angle of attack of 90°

5.2 Coupled Wind and Electrical Thrust

One of the most promising uses of the sail(s) is to provide extra propulsion to alleviate the power required by the electrical thrusters. In practical terms, the problem can be formulated as determining the angle of attack of the sail that given an actuation reference $\tau_{ref} = [X_{act}, N_{act}]$, minimizes the power required by the thrusters.

The nonlinear model of the drag and lift forces increase the complexity of a classic control approach. Moreover, it may happen that the minimization of total power required by the electrical is obtained when the resulting forces of the sails are not pointing towards a given target. Therefore, the method proposed relies on a searching algorithm, considering that the sail can be oriented in a finite number of angles of attack. For each of these angles, we can calculate the drag and lift forces, and the sail actuation on the body fixed frame. We can then compute the complementary propulsion that the thrusters have to deliver in order to follow the specified reference. Finally, we choose the sail orientation that corresponds to the minimum power consumption.

6 Conclusions and Future Work

This paper describes the steps taken to integrate wind propulsion in Zarco, evolving from a purelly electric ASV into a hybrid vehicle. We've built a wing sail prototype with one meter of height and 40 cm of cord. A CFD software was used to simulate this sail in various wind conditions, to extract the hydrodynamic coefficients and therefore characterize the sail propulsion as a function of the wind. This sail has been physically installed in Zarco and it is currently being tested in the field. After validation of the expected performance, a second wing sail will be built to provide further thrust and more directional control.

The paper also provides some ideas on how to explore the available propulsion, and these will be explored in the near future. The validation of these techniques will benefit from the full dynamic model of the vehicle, available in Simulink, which will allow us extensive testing before the experimental work in the field. In the final experiments, we'll register the wind profile together with electrical power consumption with and without sails to quantify the benefits of sail propulsion.

Given the relatively small size of Zarco, we've also started evaluating the influence of two sails when the physical separation is small. Ideally, the cumulative effect should be the sum of individual effects, but preliminary results using CFD indicate that in certain relative positions, there is a significant influence of one sail in the other (see Fig. 8 for a visual example). This may indicate the need to develop more complex algorithms to take full advantage of multiple sails.

Finally, we will also analyze the influence of the wing sails in terms of pitch and roll moments. Although the catamaran configuration of Zarco minimizes the impact of such moments, this analysis may be useful for other hull configurations.

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References

1. Cruz N, Matos A, Cunha S, Silva S (2007) Zarco—an autonomous craft for underwater surveys. In: Proceedings of the 7th geomatic week. Barcelona, Spain
2. Cruz NA, Alves JC (2008) Autonomous sailboats: an emerging technology for ocean sampling and surveillance. In: Proceedings of the MTS/IEEE international conference on oceans'08. Quebec, Canada
3. Eco Marine Power Co. Ltd.: EnergySail. http://www.ecomarinepower.com/en/energysail (accessed May 2015)
4. Elkaim GH, Boyce Jr CO (2007) Experimental aerodynamic performance of a self-trimming wing-sail for autonomous surface vehicles. In: Proceedings of the IFAC conference on control applications in marine systems, IFAC CAMS 2007. Bol, Croatia
5. Fer I, Peddie D (2013) Near surface oceanographic measurements using the SailBuoy. In: Proceedings of the MTS/IEEE international conference on oceans'13. Bergen, Norway
6. Frizzell-Makowski LJ, Shelsby RA, Mann J, Scheidt D (2011) An autonomous energy harvesting station-keeping vehicle for persistent ocean surveillance. In: Proceedings of the MTS/IEEE international conference on oceans'11, pp 1–6. Kona, HI, USA
7. Harbor Wing Technologies, Inc.: http://www.harborwingtech.com/ (accessed May 2015)
8. Kantharia R (2013) Top 7 green ship concepts using wind energy. Marine Insight. http://www.marineinsight.com/marine/marine-news/headline/top-7-green-ship-concepts-using-wind-energy/
9. Matos A, Cruz N (2008) Positioning control of an underactuated surface vessel. In: Proceedings of the MTS/IEEE international conference on oceans'08. Quebec, Canada
10. Ménage O, Bethencourt A, Rousseaux P, Prigent S (2013) Vaimos: realization of an autonomous robotic sailboat. In: Robotic sailing 2013. Springer, pp 25–36
11. Miller P, Sauz C, Neal M (2014) Development of ARRTOO: a long-endurance, hybrid-powered, oceanographic research vessel. In: Bars FL, Jaulin L (eds) Robotic sailing 2013. Springer International Publishing, pp 53–65

12. Murray-Davis H, Barrett D (2015) Piezoelectric vibrational sensor for sail luffing detetection on robotic sailboats. In: Morgan F, Tynan D (eds) Robotic sailing 2014. Springer International Publishing, pp 87–93
13. Neal M, Sauz C, Thomas B, Alves JC (2009) Technologies for autonomous sailing: wings and wind sensors. In: Proceedings of the 2nd international robotic sailing conference. Matosinhos, Portugal
14. Ocean Aero Inc.: http://www.oceanaero.us/documents/OAHandout15MetricFeb172015.pdf (accessed May 2015)
15. Rynne PF, von Ellenrieder KD (2009) Unmanned autonomous sailing: current status and future role in sustained ocean observations. Mar Tech Soc J 43(1):21–30
16. Saildrone Inc.: http://www.saildrone.com (accessed May 2015)
17. Sauzé C, Neal M (2008) Design considerations for sailing robots performing long term autonomous oceanography. In: International robotic sailing conference, Breitenbaum, Austria, pp 21–29
18. Silva A, Matos A, Soares C, Alves J, Valente J, Zabel F, Cabral H, Abreu N, Cruz N, Almeida R, Ferreira RN, Ijaz S, Lobo V (2013) Measuring underwater noise with high endurance surface and underwater autonomous vehicles. In: Proceedings of the MTS/IEEE international conference on oceans'13. San Diego, CA, USA
19. SkySails GmbH: http://www.skysails.info/english/ (accessed May 2015)
20. Stelzer R, Jafarmadar K (2012) The robotic sailing boat ASV Roboat as a maritime research platform. In: Proceedings of 22nd international HISWA symposium

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