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Review

Rigid wing sailboats: A state of the art survey

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ABSTRACT

The design, development and deployment of autonomous sustainable ocean platforms for exploration and monitoring can provide researchers and decision makers with valuable data, trends and insights into the largest ecosystem on Earth. Although these outcomes can be used to prevent, identify and minimise problems, as well as to drive multiple market sectors, the design and development of such platforms remains an open challenge. In particular, energy efficiency, control and robustness are major concerns with implications for autonomy and sustainability. Rigid wingsails allow autonomous boats to navigate with increased autonomy due to lower power consumption and increased robustness as a result of mechanically simpler control compared to traditional sails. These platforms are currently the subject of deep interest, but several important research problems remain open. In order to foster dissemination and identify future trends, this paper presents a survey of the latest developments in the field of rigid wing sailboats, describing the main academic and commercial solutions both in terms of hardware and software.

1. Introduction

In recent years, extensive research has been conducted in autonomous systems ranging from land to marine or aerial robots. This can be explained by the range of possible applications due to their ability to go to locations otherwise inaccessible or inhospitable and, as for automation in general, to remove humans from dangerous environments and relieve them of tedious tasks (National Academy of Engineering, 2018). Diverse applications have been envisaged for these platforms, from exploration of remote places to warfare (Springer, 2018).

Concerning marine robots, most of the research has been directed to electrically or combustion engine propelled surface and underwater vessels. Depending on the on board fuel or battery capacity for propulsion, these type of vessels have restricting limitations in range and endurance, which makes them unsuitable for long term operation in inaccessible areas attractive for unmanned operation. These limitations transform wind propelled vessels, used by mankind for more than 5000 years (Kimball, 2010), into an attractive research prospect. The main reason for this is that, instead of carrying energy for propulsion, they harvest it from the environment. In addition, by careful mechanical design of rigid wing sailboats, the need for electrical power can be reduced so that photovoltaic cells and/or wind generators are capable of producing enough power to run the complete electrical system. These features render the vessels sustainable and autonomous in terms of energy and, therefore, capable of operating continuously in remote areas for extended periods of time. However, some limitations for sail powered vessels, compared with other forms of propulsion, should be noted. Without wind there is no propulsion and, when sailing upwind, the vessels are typically limited to travelling no more than 40° to 45° towards the wind. Sailing upwind thus requires a sailing method called tacking/beating (turning the boat through the eye of the wind back and forth in order to progress upwind), therefore creating a "zig-zag" course across the wind which allows the vessel to advance indirectly upwind (Isler and Isler, 2006).

An accessible overview of autonomous sailing can be found in Stelzer and Jafarmadar (2009) and Stelzer (2012) and the key characteristics of a robotic autonomous sailing boat can be summarised as follows:

- Wind is the only source of propulsion.
- It is not remotely controlled; the entire control system is on board and, therefore, has to perform the (complex) planning and manoeuvres of sailing automatically and without human assistance.

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- It is completely energy self-sufficient; this is not a must in the sense of definition of a robotic sailing boat, but it opens a wide range of applications.

Research on autonomous sailboats has been ongoing for about 20–25 years (Sauzé and Neal, 2008) and the last years have witnessed an increasing interest in the development of wind-propelled autonomous surface vehicles (ASV). Most projects being developed are mainly based in the academia, with some commercial examples reporting impressive results. Physically, these projects are located mainly in Europe and North America.

The use of autonomous sailboats has been proposed for several different purposes, among which are mentioned long term oceanographic research (Neal, 2006; Rynne and von Ellenrieder, 2009; Ménage et al., 2013; Fernandes et al., 2016; Augenstein et al., 2016; Dhomé et al., 2018), e.g., for monitoring marine mammals where the absence of self-generated noise for propulsion during navigation is a unique advantage of robotic sailboats for underwater acoustics applications (Klinck et al., 2009; Anthierens et al., 2013; Klinck et al., 2015), for automated data acquisition in the oceans (Sauzé and Neal, 2008; Ghani et al., 2014; Cokelet et al., 2015), for surveillance of harbours, borders and other areas of interest (Elkaim and Boyce, 2007; Ocean Aero, 2018) and as intelligent sensor buoys (Stelzer, 2012; Bars and Jaulin, 2012). There are also some autonomous sailing boats developed with educational and research objectives (Miller et al., 2009; Schlaefer et al., 2011; Bishop et al., 2011; Miller et al., 2012; Cabrera-Gámez et al., 2013; Miller et al., 2014a; Gomes et al., 2016), with the main purpose of participating in competitions (Sliwka et al., 2009; Miller et al., 2009; Giger et al., 2009; Leloup et al., 2011; Schröder and Hertel, 2013), and even some projects proposed to tow large objects (Jaulin and Bars, 2014). In addition, Eriksson and Friebe (2015) suggest that due to the decreased manning and fuel costs, the use of sailing robots in other applications could become commercially viable in a near future, and its adoption may be possible for transportation of goods. Also, Stelzer (2012) presents the CO_2-neutral transportation of goods and unmanned ferrying as a potential advantage of these vessels, and add that the use of autonomous sailing boats for supplying equipment, medicine, food or correspondence to secluded regions, with a low number of inhabitants, or research base camps on islands can be cost-effective.

The influencing factors are not limited to sail control and design, but include the efficiency of the wind propelled vessels compared to other means of propulsion. Hybrid solutions, incorporating wind propulsion in combination with other solutions (Elkaim and Lee Boyce Jr., 2008; Miller et al., 2013; Cruz et al., 2015), might prove successful. Due to the huge fuel consumption and CO_2 emissions of the world global fleet of commercial ships, Shukla and Ghosh (2009) propose adopting diesel-wind hybrid systems for ship propulsion. According to these authors, the use of wind energy by installing wingsails in ships can drastically reduce the consumption of diesel fuel. In this situation, whenever there was wind the wingsails would be deployed and the ship's diesel engine would be throttled down allowing the ship to maintain the same forward speed. They have calculated net fuel saving in certain international shipping routes, and mention estimates showing that about 8.3 % diesel fuel can be saved by utilising the wind (Shukla and Ghosh, 2009). Figures from the tanker Shin-Aitoku-Maru (the world's first sail assisted commercial vessel, completed in 1980) also suggest a fuel saving of as much as 20 % to 30 % on some routes, along with a 20 % to 30 % reduction in rolling (Atkins, 1996).

Despite all these possibilities, many of the challenges in building truly autonomous sailing robots still remain unsolved and, with the objective to encourage and foster a more rapid development of such vessels, three main competitions have been promoted, namely:

- The Microtransat Challenge, conceived in 2005 by Mark Neal of Aberystwyth University and Yves Brière of the Institut Supérieure de l'Aéronautique et de l'Espace, in Toulouse, France. This is a transatlantic race of fully autonomous sailing boats, originally no longer than 4 m and since 2017 limited to 2.4 m (The Microtransat Challenge, 2019).
- The World Robotic Sailing Championship (WRSC), a spin off competition of the Microtransat Challenge, open to fully autonomous and unmanned sailing boats. However, unlike the Microtransat Challenge, the WRSC focuses on the complex task of sailing, including best routing decision, perfect handling of ever changing wind conditions and perfect timing during tack and jibe which are some of the skills an autonomous sailing vessel has to master. The WRSC is a yearly competition open to fully autonomous and unmanned sailing boats up to 4 m in length and this event coincides with a scientific conference on the topic. The papers presented at the conference show the current focus of research in the robotic sailing community (INNOC – Österreichische Gesellschaft für innovative Computerwissenschaften, 2018).
- The International Robotic Sailing Regatta, a competition mainly targeted to student teams from university, college and secondary schools, organised by Sailbot in North America. The competition is oriented to the SailBot Class (up to 2 m in length), where at least half of the team must be secondary of undergraduate students, but smaller boats are popular due to their easier logistics. There is an Open Class (with boats up to 4 m in length) for graduate student teams. Several teams use the MaxiMOOP as their first platform due to its small size (1.2 m), light weight (20 kg), greater payload capability than an RC boat and improved seaworthiness. This competition involves racing, navigation and station-keeping contests (SailBot | International Robotic Sailing Regatta, 2018b).

These competitions aim not only to boost the technology involved in autonomous sailing robots, but also to boost their public perception among the general public as well as the scientific community.

Given the recent interest in ASV, and in particular in autonomous sailboats for its potential to explore remote regions for extended periods of time mainly due to their low energy consumption, this paper addresses recent work in this area with a focus on rigid wing sailboats. This choice is based on what the authors perceive as promising due to an (on average) increased sail efficiency in a wide range of conditions, reduced need for control effort and increased mechanical robustness of the vessels. Rigid wingsails should not be confused with solid square sails or rigid sails. A wingsail is a rigid structure presenting an airfoil cross-section (like an airplane wing), which can provide a much better lift-to-drag ratio (L/D) than conventional sails. Although this concept may seem a novelty, the first rigid lift-generating devices for use as auxiliary ship propulsion were proposed and developed by Anton Flettner in 1922 (Atkins, 1996).

The survey performed is based on a literature review, mainly on papers published at the International Robotic Sailing Conference proceedings (INNOC – Österreichische Gesellschaft für innovative Computerwissenschaften, 2018), with the support from papers from other conference proceedings on this topic, papers on journals of related areas, a few PhD-theses, and also a search on the Internet for "rigid wing sailboat" and "wingsail boat". Furthermore, the authors previous knowledge of this topic, as well as their personal knowledge of some of the people involved in most of the sailboat projects described in the paper, were helpful for collecting additional information, photos and as well as clarifying some issues which remained unclear after reading the papers.

The historical perspective of this technology is not presented in this paper. Early efforts can be found in the Wingsails booklet by the Amateur Yacht Research Society (1957), and on the works from Fekete and Newman (1965) and Newman and Fekete (1983). The latter two include theoretical analyses and preliminary experiments. More recently, in 1996, Atkins (1996) presented a historical survey of wingsails and. In 2011, Elkaim (2001) also presented an accessible overview of the evolution of wingsail technology, with examples of boats developed until the end of the 20th century, as well as a clear and detailed description of his own project.

In order to be truly autonomous, sailboats need several distinct technologies, that may be organised into the following subsystems:

(*i*) propulsion; (*ii*) sensing; (*iii*) actuation; (*iv*) communication; and (*v*) control. So far, different technologies and techniques have been proposed for each of these subsystems. This paper will address the technologies that are used for each of these systems on the different vessels already developed, or under development, and, when available, present the results from their adoption and comments from developers regarding advantages and drawbacks of their use. The goal is that this paper will be a relevant source of information for those interested in this area and looking for information for developing a new ASV with this sort of propulsion.

Bearing these ideas in mind, this paper is, following the introduction, organised into four sections. Section 2 addresses a comparison between traditional sails and rigid wingsails. Next, Section 3 presents rigid wingsail ASV developed and being developed in academia, as well as commercially, during the last decades. All these vessels, and the used subsystems on them, as well as on other robotic sailboats, are analysed by the authors and a discussion of the main solutions adopted, as well as their relative advantages and limitations, is presented in Section 4. This is followed by some concluding remarks in Section 5. Finally, Appendix summarises some technical, non-mechanical, details for the different vessels.

2. Comparison of traditional sails with rigid wingsails

Sailboats can be propelled using traditional cloth sails (the most common approach), rigid wingsails and mechanical devices, such as Flettner rotors and vertical and horizontal axis turbines (Enqvist, 2016) or, more uncommonly, different sail concepts or towing kites (Marine Insight, 2017).

When air interacts with the sails of a sailing vessel, whether cloth sails or wingsails, it creates various forces. If the sails are properly oriented against the wind, the net force on the sail will move the vessel forward (Kimball, 2010).

Sailing with conventional cloth sails has been practised all around the world for thousands of years and virtually all boats, apart from those in recent sailing history, used conventional fabric sails (Kimball, 2010). According to Neal et al. flexible fabric sails have a number of useful properties, especially when controlled by a human sailor (Neal et al., 2009):

- They can be conveniently lowered and stowed when in harbour.
- They can be reduced in area relatively easily by either conventional "reefing" or by exchanging sails.
- They can be relatively easily repaired and modified.
- Their shape and camber can be altered by tensioning and releasing control lines.

However, and according to several authors, they also present a number of problems or drawbacks (Elkaim, 2001; Sauzé and Neal, 2006; Neal et al., 2009):

- They are prone to wearing and tearing when incorrectly set.
- Cloth sails must be furled when not in use in order to prevent destructive flogging.
- They are typically controlled through ropes (known as sheets and halliards), which frequently break or jam (particularly when swollen by salt water) and require regular attention from the crew. Performing such tasks autonomously would, even if it was conceivable, incur significant overheads resulting in excessive power usage, weight and financial cost.
- They lose their shape when not kept with a sufficient angle of attack, leading to "luffing", which reduces sailing efficiency when close-hauled and eventually leads to "flogging" and potentially complete loss of manoeuvrability.
- They require rigid structural spars and (often) wire rigging to maintain their shape: these introduce aerodynamic drag weight high above the waterline.
- They tend to twist, leading to different angles of attack at different points on the sail, which can reduce sailing efficiency.
- Perfectly trimmed sloop rigs (jib and main sail) have a maximum lift coefficient (C_{Lmax}) ≈ 0.8.

There are various reasons for considering the use of alternative sail types. In particular, rigid wingsails have been compared to traditional fabric sails, and several advantages have been mentioned, namely (Elkaim, 2001; Neal et al., 2009; Eriksson and Friebe, 2015):

- Modern airfoil design allows for an increased lift-drag (L/D) ratio over a conventional fabric sail, thus providing increased thrust while reducing the overturning moment, while the lift-to-drag ratio for conventional sails is about $3/5$.
- For navigating downwind, rigid sails are more efficient than cloth sails on any standard rig because at this point of sailing, cloth sails produce thrust entirely by drag, which clearly depends on the magnitude of the apparent wind. On the other hand, when sailing downwind using wing sails, thrust is obtained from lift and, maybe, also from drag (Domínguez-Brito et al., 2015).
- They can easily be designed such that they do not suffer from problems with chafing.
- They are generally more reliable and avoid the problems of sail luffing or flapping even when the control system fails to maintain the correct angle of attack.
- They maintain efficiency even when sailing close to the wind.
- They do not necessarily require any additional structural elements, e.g., shrouds or stays, to support them.
- They can be oriented directly to the wind in a way so that it experiences a minimal aerodynamic force.
- Furthermore, most rigid wingsails are balanced and it is known that a balanced rig design offers great potential in saving power (Giger et al., 2009; Stelzer and Dalmau, 2012; Eriksson and Friebe, 2015).

Finally, several authors also comment on the disadvantages of wingsails, among which they include the fact that it is extremely difficult to design a wingsail which can be reefed reliably and that it is relatively difficult to construct strong, lightweight rotatable wingsails at reasonable cost (Neal et al., 2009; Eriksson and Friebe, 2015). Nonetheless, Elkaim and Boyce (2007) state that the problem of reefing the wingsail in strong winds is not solved, but it is not in itself a problem since reducing the wingsail angle of attack (in self-trimming wingsails by reducing the tail angles) reduces the power driving the vessel, and thus effectively reefs the wing (Elkaim and Boyce, 2007).

As a conclusion of their comparison, Neal et al. (2009) state that the potential gains in reliability and efficiency outweigh these problems and, for these reasons, they describe a number of sailing robots equipped with wingsails of various designs which they have successfully constructed and tested (Neal et al., 2009).

As further inspiration for the use of wingsails, the authors feel that two examples are especially noteworthy. The trimaran USA-17 (formerly known as BMW Oracle Racing 90 or BOR90), depicted in Fig. 1, won the trophy with a rigid wing as its main sail in the America's Cup 2010 (Wikipedia, 2019a). BOR90 was able to achieve a velocity made good upwind of over twice the wind speed and downwind of over 2.5 times the wind speed during the 2010 America's Cup races, and can apparently sail at 20° off the apparent wind (Wikipedia, 2019b).

The SailRocket 2 (shown in Fig. 2) set the all-time speed record for a wind-powered vehicle on water in November 2012, averaging 33.44 m/s [65 kn] (speeds were set in 15.43 m/s [30 kn] winds sailing at over 2.4 times the speed of the wind), over a 500 m course in Walvis Bay, Namibia. The wing is asymmetrical, and was set up for a starboard tack to suit Walvis Bay (Sailrocket, 2018). According to Paul Larsen, "extreme sailor", skipper during the world record and one of the key members of the team behind Sailrocket 2: "Maybe the most important legacy of this project is to get people to rethink about the serious power that can be gotten from the wind." (Winters, 2013).

Fig. 1. BMW Oracle racing USA-17 training off Valencia, Spain in late January, 2010 (©2010 Pedro de Arechavaleta/Wikipedia).

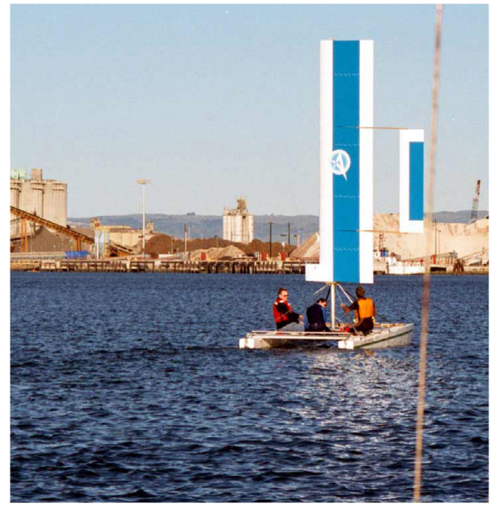


Fig. 3. The Atlantis while undergoing navigational tests (©2001 Gabriel Elkaim).

3. Academic and commercial wingsail autonomous boats

This section presents several examples of wingsail autonomous boats that have been developed in the last years, as well as some examples still under development. These are mostly from academia or within the scope of research and technology development projects, but some commercially available products are presented as well. For all these vessels, descriptions are given of:

1. The project development objectives.
2. The main characteristics of the hull and wingsail.
3. The main results of experimental tests performed.

Examples from academia follow a roughly chronological order and are followed by commercial products. For ease of comparison, technical specifications for sensors and actuators, control system architecture, together with its hardware and software, are, when available, provided in Appendix.

3.1. Academic projects

3.1.1. Atlantis

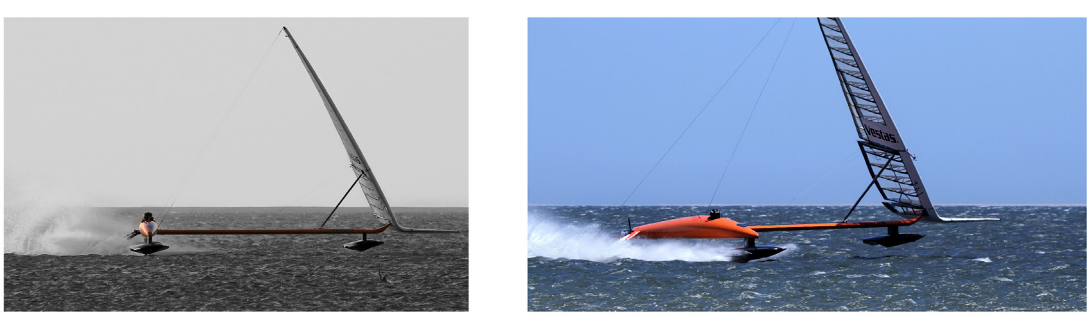
The Atlantis prototype, depicted in Fig. 3, was a 7.2 m long and 3 m wide modified Prindle-19 light catamaran, originally equipped with a sloop rig sail with 17 m^2 of sail area. The objective behind this project was to design, develop, and test an autonomous wind-propelled marine craft, to demonstrate precision guidance on a full scale prototype in the presence of disturbances such as wind, current, and waves, and to validate the entire unmanned sailing concept. Several sensors and actuators were installed within the hulls, the entire sailing system (mast, boom, main and jib sails) was replaced with a vertical self-trimming wingsail, and its development involved substantial innovations in (*i*) wind-propulsion system, (*ii*) overall system architecture, and (*iii*) sensors (Elkaim, 2001).

The wind-propulsion system is a rigid wingsail, 5.37 m tall and 1.45 m wide (7.65 m^2), mounted vertically on spherical roller bearings to allow free rotation in azimuth about a stub-mast. To ease the transportation and assembly tasks, the wing was built in three sections. Aerodynamic torque about the stub-mast is trimmed using a flying tail mounted on booms joined to the wing. This arrangement allows the wingsail to automatically attain the optimum angle to the wind and weather vane into gusts without inducing large heeling moments. The Atlantis directional control is based on rudders at the end of each hull, and retractable centreboards approximately 0.5 m behind the main crossbeam (Elkaim, 2001).

Several experimental tests were performed at Redwood City harbor, California. The catamaran was required to sail on a precise track through the water in the presence of currents, wind, and waves. During these tests, the Atlantis was able to demonstrate an improvement in control precision of a wind-propelled marine vehicle, from typical commercial autopilot accuracy of 100 m, tracking a desired line to within 0.3 m (Elkaim, 2001).

3.1.2. Aberystwyth university autonomous sailboats

The Aberystwyth University (AU) has played a key role in several projects, and these are summarised in this section. The Autonomous Robot for Ocean Observation (AROO), depicted in Fig. 4, was the first sailing robot constructed at AU (Sauzé and Neal, 2008). It was built



(a) (b)

Fig. 2. Different views of Sailrocket 2 during sailing (©2012 Helena Darvelid/Sailrocket).

Fig. 4. AROO undergoing tests on a lake (©2005 Colin Sauzé).

Fig. 5. View of ARC's dual wingsails in a schooner configuration during the Microtransat 2006 (©2006 Colin Sauzé).

during the autumn of 2004, based on a 1.52 m radio-control yacht hull and was equipped with a wingsail considered more adequate due to its ease of control, construction, efficiency and potential robustness. The vessel was a small-scale prototype intended as a proof of concept for a sail propelled robot with station-holding capabilities for as long as possible (a timescale of a few months was initially envisaged) under a wide range of wind and sea states (Neal, 2006).

The wingsail was constructed from a 1 mm aluminium sheet wrapped into an airfoil section and had a height of 1.30 m and a width of 0.18 m. A problem identified by Neal et al. (2009) with this design was that the sail could rotate continuously and the cable linking the wind sensor to the rest of the boat could easily become tangled around the mast. Other problems are also mentioned: (*i*) control system response time since sail movements were perceived as exceptionally time consuming, sometimes over 5 s, (*ii*) compass precision and manoeuvrability (due to the narrow and deep design of the keel) sometimes resulted in wild oscillations in course and in turns in excess of 90° occurring within a single boat length (Sauzé and Neal, 2006). Furthermore, the sail was considered too large for the boat and caused some stability problems and difficulties for the steering system. With no available reefing of the wingsail, this design would not have been appropriate for a sea going boat which is expected to encounter winds above 18.01 m/s [35 kn] (Sauzé and Neal, 2008). Despite these identified problems, according to the authors the wing performed exceptionally well in winds up to 15.43 m/s [30 kn] (Sauzé and Neal, 2008) and several lessons were learnt from experimentation with this prototype, which were applied in later vessels (Neal, 2006).

The Autonomous Robotic sailing Craft (ARC), illustrated in Fig. 5, was the second vessel built by AU and developed in 2006. The objectives behind its development were to rectify "many of the mistakes made in AROO and to introduce as much redundancy as possible". To counter the instability which had been observed with AROO's sail it was opted for a schooner configuration with two independently controlled wingsails (Neal et al., 2009). The hull featured a similar length to AROO's, but was wider to make the boat more stable and easier to control. ARC presented two rudders controlled by a single actuator and slightly angled to allow the boat to heel to one side while still keeping one of the rudders fully submerged in the water in order to improve steering even when the boat is leaning sideways in strong winds (Sauzé and Neal, 2008).

ARC's wingsails were constructed of lightweight acrylic wrapped around several wooden blocks to retain shape, making them significantly lighter and easier to handle than AROO's sail. Each wing had an height of 1.07 m and was 0.20 m wide (Neal et al., 2009). According to Neal et al. (2009), the design using dual sails created a very balanced sailing configuration and provided redundancy in steering, as the sails could be set to provide directional control, should the rudder fail (Sauzé and Neal, 2008). As with AROO, it was found that the sails were too big and although the boat sailed fine in winds of 15.43 m/s [30 kn], it would have heeled excessively in stronger winds. An additional problem with the wingsails was that they worked acceptably well in light winds and laboratory tests but in stronger winds the gears driving the sails would slip and the sails would drift from their original position. Originally, the control algorithm kept track of sail position by keeping a record of the distance moved since the sail was last calibrated; however, when the sail began slipping, this strategy failed. To counter this problem, a potentiometer was later added to keep track of the sail position (Neal et al., 2009). Several manual tests with this boat showed that it was able to hold a course providing the sails had been set correctly, and it was able to goosewing (setting the sails to opposite tacks) when sailing down wind, which greatly enhanced downwind stability compared to AROO's single sail configuration (Neal et al., 2009). The developers also tested "heaving too" (where the sails and rudder are configured to counteract each other and keep the boat in one place) as a method of station holding but the boat was dragged sideways by wind and currents, explained in part by its small shallow keel (Neal et al., 2009).

Although Sauzé and Neal (2006) are fully aware that the hull sizes used in AROO and ARC are not optimal for use in the open sea and that a larger hull would be more appropriate, they claim that, for development purposes, this is impractical from both a logistical and a financial point of view: these dimensions were chosen primarily to allow the boat to be moved by a single person and to fit within an estate car for easy transport (Sauzé and Neal, 2006). As a final conclusion, and according to Neal et al. the inherent stability of this configuration offers great hope for one of the key requirements of a sailing robot, a boat which requires virtually no actuator use to maintain itself on a present course, thus keeping power consumption to an absolute minimum (Neal et al., 2009).

Beagle-B, shown in Fig. 6, was constructed in late 2006 and early 2007 by the French robotics company Robosoft (Robosoft, 2017) with the purpose to take the lessons learned from AROO and ARC and produce a large scale boat that could remain at sea for long periods, providing a reliable oceanography platform. It is a 3.65 m long monohull based on a Miniji sailing dinghy intended for disabled sailors, displaying a particularly stable design and designed to self right very quickly in the event of capsize (Neal et al., 2009).

Although AU's experience demonstrated that dual sail configurations are preferable, Beagle-B's hull was not suitable for two wings and the resulting design, with just one wingsail, proved to be sufficiently stable. A first version of this boat was propelled by a 3.0 m tall and 0.85 m wide carbon fibre wingsail, which was only 60 % of the sail usually used on this hull. However, Neal et al. (2009) considered this wingsail too large for sailing under extreme conditions, and a later version of Beagle-B was equipped with a smaller wingsail with height 2.0 m (Sauzé and Neal, 2011b). Beagle-B's wingsail has proven to be

(a) Beagle-B equipped with the big sail.

(b) Beagle-B equipped with the small sail.

Fig. 6. Beagle-B during tests at sea (©2006 Colin Sauzé).

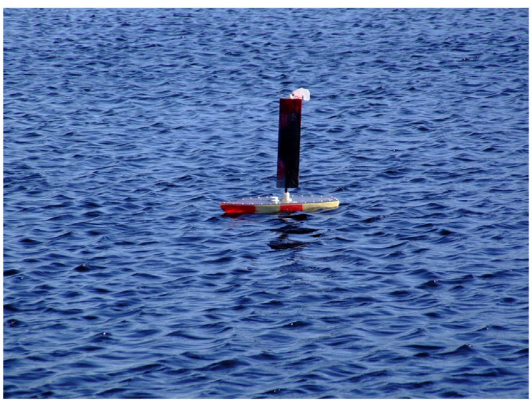


Fig. 7. The first MOOP sailing off Aberystwyth (©2008 Colin Sauzé).

highly stable, and capable of sailing in winds as light as 0.51 m/s [1 kn]. While participating in the 2007 Microtransat Challenge (The Microtransat Challenge, 2019), Beagle-B was able to successfully sail over 25 km in a single mission and demonstrated the efficacy of the wingsail design by frequently outrunning yachts being used to chase it, in particular during light winds when traditional sails on the chase boat collapsed (Sauzé and Neal, 2008). However, it has only been tested in winds of approximately 10.29 m/s [20 kn], mainly due to risks in deploying such a large boat under strong winds (Neal et al., 2009). One of the problems identified with Beagle-B was that, at least, two people were required to rig and launch the boat and that in busy waters a sufficiently fast chase boat was always required (Neal et al., 2009).

The Miniature Ocean Observation Platform (MOOP), depicted in Fig. 7, were the latest boats developed by AU. Its development started during the summer of 2008 and they were an attempt to build a set of small, simple, lightweight, cheap, easy to transport and easy to deploy, but highly robust robots that could be produced in large numbers intended for shorter term missions to research control system and autonomous power management strategies, but also capable of crossing the Atlantic (Sauzé, 2010; Sauzé and Neal, 2011a).

One of the drivers for the development of such platforms was to reduce the cost and the difficulties in handling the boat, especially when launching and recovering. It was stated that there was a desire "to develop a boat which could easily be handled by one person and that could be transported in a normal car or checked in as baggage on a flight". Therefore, a small 0.72 m long glass fibre hull (following a long keel design inspired by a Nordic folk boat) was selected, with a total weight of around 4 kg (Sauzé and Neal, 2011a). According to Neal et al. the low cost and simple construction process allowed producing a new boat in under three weeks (Neal et al., 2009). This spawned a number of variations to the original MOOP design, including boats with twin wingsails, without rudders, with a variety of wind sensor designs and, even, without wind sensors (Sauzé, 2010; Sauzé and Neal, 2011a).

Although AU's previous experience with ARC demonstrated that dual sail configurations are preferable, the small size of the hull makes it difficult to place two sails and, therefore, the MOOP vessels were equipped with a single wingsail with an height of 0.525 m and a width of 0.13 m and are intended to be small enough to remain sailing even in strong winds. The only exception to this were the MOOP3 and MOOPn, which were equipped with a double wingsail to allow steering the boat without the need for a rudder. These wingsails are constructed from a polystyrene and glass fibre composite resulting in a relatively inexpensive, easy and fast way to build wingsails. A carbon fibre rod runs through the centre of the sail to reinforce it and to run cabling through to the wind sensor. The sails could rotate a maximum of 210° and were also able to float (adding extra stability in the event of capsize) and built to keep all the internal wind sensor electronics dry (Neal et al., 2009). A variety of different configurations have been tested in the several MOOP versions (Sauzé, 2010), with the intention of testing new wind sensor designs, performing experiments in autonomous power management, rudderless control and discovering wind direction without a wind sensor. During this process several limitations have been identified: difficulty sailing upwind, problems when sailing through strong currents or tides due to low hull speeds, and difficulty sailing downwind in single wingsail models.

Summarising some characteristics, the single wingsail configuration appeared to be able to sail at least 45° to the wind and was very stable close hauled or reaching. However its stability down wind, especially under gusty conditions was poor and frequent jibes were experienced. However, the authors argue that this is suffered by all wingsails (and arguably many other sail designs) and is not unique to the MOOP vessels but because of their small size only minimal force is required to induce a jibe. One possible solution proposed to tackle this issue would be to tack down wind, never allowing the stern of the boat within at least 25° of the wind (Sauzé and Neal, 2011a). Regarding the experiments with the twin wingsails MOOP, it was discovered that it was possible to steer the boat onto any point of sail but that it was difficult to remain on course when sailing downwind in the rudderless versions. The twin wingsail designs have shown themselves to be more stable on downwind courses and offer the potential of rudderless sailing or, at the very least that the rudder and sail can be used cooperatively. When compared with other small boats developed by other institutions, the upwind performance of the MOOP vessels was much poorer, which was believed to be due to the drag caused by the wide keel design (Sauzé and Neal, 2011a).

Fig. 8. A-Tirma G2 prototype during tests at sea (©2015 Jorge Cabrera Gámez).

3.1.3. *Wind and solar-powered ASV*

In 2007–2008, a team from Florida Atlantic University (FAU) developed a wind and solar powered (WASP) autonomous surface vehicle for oceanographic measurements (Rynne and von Ellenrieder, 2009). The vehicle is based on a Sodergren 2.4 Meter Class (2.4mR) sailboat hull, with an overall length of 4.2 m, weighs approximately 350 kg, has a maximum speed of about 2.57 m/s [5 kn], and is primarily propelled with a low-Reynolds number composite wingsail, 5 m tall and 7 m^2. Additionally, a small carbon fibre folding propeller, actuated by an electric motor, is fitted beneath the ASV for use during periods with little wind (Rynne, 2008). The FAU WASP vehicle draws from 50 W to 100 W to operate the control surfaces actuators and navigation system while being propelled by a wingsail in approximately 5.14 m/s [10 kn] of wind over flat water (Rynne and von Ellenrieder, 2009). A number of near-shore deployments and ocean observation missions were conducted in 2008, in the Port Everglades Intracoastal Waterway in Dania Beach Florida, with the purpose of improved understanding of the fluxes of energy and matter across the air-sea interface. During these tests, it was concluded that the keel should be heavier and that the size of the rudder was too small for a reliable system. Regarding the wingsail, the authors propose that a future version should be made lighter (but without sacrificing its structural integrity), to increase the overall performance of the system, and smaller to have a higher wind range (Rynne, 2008).

3.1.4. *A-tirma G2*

The A-Tirma G2 ASV design tries to surpass some of the limitations found on the previous prototype (A-Tirma G1 (Cabrera-Gámez et al., 2013)), specially a better behaviour in harsh conditions, and was designed with a focus on robustness and on redundancy of critical components. For this end, it was equipped with two carbon fibre wingsails and two slanted rudders protected by skegs, and conceived for sailing in the ocean in a broad set of weather conditions. As a distinguishing characteristic, its stability curve is positive for all heel angles, meaning that it is capable of recovering autonomously from capsizing (Domínguez-Brito et al., 2015). Fig. 8 depicts an image of this vessel.

A-Tirma G2 has a length overall (LOA) of 2 m, and due to its nearly cylindrical hull shape, its smooth hull curves produce a relatively soft behaviour when an increase in wind speed makes it heel (Domínguez-Brito et al., 2015). The twin wingsails have been built on carbon fibre, using a symmetrical National Advisory Committee for Aeronautics (NACA) 0009 (Airfoil Tools, 2018a) profile, with a wingspan of 1.05 m and mean chord of 0.225 m, equivalent to an aspect ratio of 4.6. The option for a twin wingsail arrangement was due to the following reasons: (*i*) they allow propulsion in the case of breakdown of one of them; (*ii*) two smaller sails, with equivalent surface to a bigger one, produce less heeling moment as the sail plan centre descends with improved behaviour downwind and in strong winds; (*iii*) decreased power consumption with reduced torque needed to trim them; and (*iv*) a rig of two wingsails may also be interesting as a final resource for steering the boat in case of total failure of the rudders. Regarding the double rudder, each ones actuates in a given range of heeling angles at each side, overlapping its actuation at 5° on each range (Domínguez-Brito et al., 2015). According to Domínguez-Brito et al. (2015) the efforts to improve the directional stability for all wind intensities and heeling angles, allow to optimise the power consumption dedicated to govern the sailboat.

3.1.5. *Sail-vane*

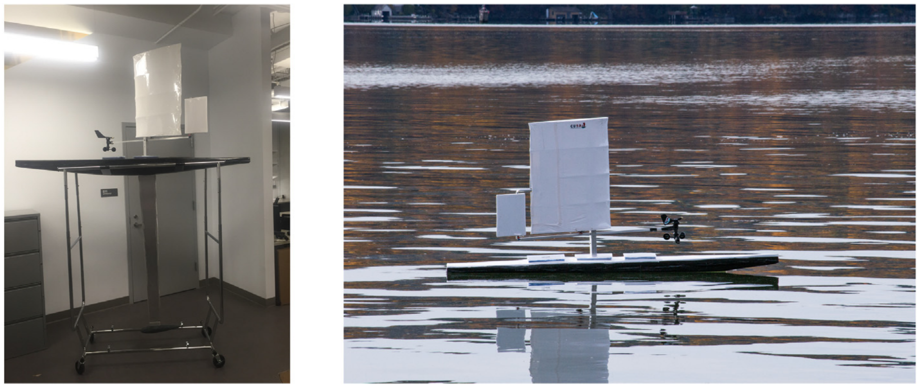
Baker et al. (2015) are developing a robotic boat capable of sailing semi-autonomously for two years on the open ocean. Their goal is to design a cheap small boat that, if produced in large quantities, would decrease the cost of obtaining various environmental data such as ocean temperature, salinity, acidity, cloud cover, etc. Additionally, their long-term planned design targets an issue not addressed in the designs of other autonomous sailboats already developed, which is achieving directional stability with low energy use, by skipping the water rudder completely and making the whole sailing rig a weather vane that the boat follows (Baker et al., 2015). Thus, the vessel can be considered a testing platform for three control concepts: (*i*) a water rudder, *i.e.*, a conventional sailboat, but with tiller position locked, (*ii*) an air rudder (replacing the water rudder) at the stern of the boat, and (*iii*) a "tail-vane" air rudder (also replacing the water rudder), located downwind of the main wing (Augenstein et al., 2016). 2D dynamical simulations confirmed that, of these three configurations, only the tail-vane air rudder would result in sailing with a stable angle-of-attack and a stable heading and, therefore, Augenstein et al. (2016) chose the tail-vane air-rudder design; for this reason, the boat, which can be seen in Fig. 9(a), is called Sail-vane (Augenstein et al., 2016).

Sail-vane is a monohull sailboat based on a pre-existing, professionally-made racing hull shape (by Sparkman and Stephens), scaled down to 1 m, with a weighted keel, a controlled-angle sail, and an air-rudder to passively control the boat orientation relative to the wind without active control. Control of the sail and the tail will be powered by solar panels mounted on the deck. The rigid wingsail, with a NACA 0015 symmetrical profile (Augenstein et al., 2016), weighs 0.66 kg and is 1.00 m tall with a cord length of 0.24 m, rotating about a carbon fibre tube axle which is mounted on bearings supported by the deck. The sail is directed at an angle of attack from the apparent wind direction to generate lift forward, which is accomplished using a mechanically controlled tail (Augenstein et al., 2016). Tests on Cayuga Lake, in Ithaca (see Fig. 9(b)), show that in light winds the boat can sail stably within approximately ±45° of the wind direction. However, the experiments also show that in heavy winds the boat has an oscillatory instability, and it then finds a stable backwards sailing mode. Due to the use of the air tail-vane, instead of water-rudder, the boat requires new tacking techniques which the authors are developing (Augenstein et al., 2016).

3.1.6. *ASPire*

The Autonomous Sailing Platform ASPire (Friebe et al., 2017), displayed in Fig. 10, has been developed as the first rigid wingsail propelled surface vehicle at Åland University of Applied Sciences. It has been built during 2016–2018 in a project partly funded by the European Regional Development Fund. The long term goal of Åland Sailing Robots was to develop the first fully autonomous sailboat that successfully crosses the Atlantic Ocean (Eriksson and Friebe, 2015), but the ASPire is developed for marine research in the Baltic Sea. The aim is to contribute to the research and knowledge on green technology and autonomous vessels.

The used hull is a 2.4mR class keelboat of the Norlin Mark III design. The length overall is 4.18 m and the keel depth is 1.05 m. The rig is a free rotating wingsail with an actuated tail controlling the wing's angle of attack (Enqvist et al., 2016). The main wingsail is



(a) Photo of Sail-vane. (b) Sail-vane sailing on Cayuga Lake.

Fig. 9. Sail-vane (©2018 Mary Essex).

Fig. 10. The ASPire outside Mariehamn, Åland Islands, Finland, on a test sailing in June 2018 (©2018 Anna Friebe).

Fig. 11. The Maribot Vane during sailing tests in Autumn 2018 (©2018 Ulysse Dhomé).

a 2.8 m high wing with a chord length of 0.74 m. The wing profile is symmetric and consists of two upper sides of the NACA 63_2–618 profile. A three-surface wingsail configuration with a canard and a tail wing was built in 2017. However, the construction turned out to have the aerodynamic centre ahead of the rotation axis and was rebuilt to use only the tail wing for controlling the wingsail's angle of attack towards the wind. In addition, the tail wing was moved further back to enable adequate steering capabilities. The tail wing has a height of 0.8 m and a chord length of 0.3 m. The wings are manufactured in carbon fibre, and the mast is of aluminium, with two stainless steel ball bearings. The resulting weight of the entire rig is less than 25 kg, and the rig's centre of gravity is 1.25 m above the deck. This allows for mounting the wind sensor in a fixed direction at the top of the mast. When beating upwind, the angle to the wind is 45°. The ASPire also beats downwind at an angle of 30° from downwind. The tail wing is controlled according to the course to steer and the wind direction. This means that in the tacking maneuver, the rudder and the tail wing are turned simultaneously, and the sail will provide a force in the new desired direction.

3.1.7. Maribot vane

The Maribot Vane project is being developed at the Maritime Robotics Laboratory of the School of Engineering Sciences of the KTH Royal Institute of Technology. Its goal is the development of new techniques to make a robust platform, able to withstand very rough conditions on long trips (several months) without assistance. The overall purpose is to monitor and collect oceanic data for other fields of research (oceanography, meteorology or fishery) in the Baltic Sea. The propulsion of the boat is by a free-rotating and self-adjusting rigid wingsail, and one of the key features that the Maribot Vane project aims is to develop a self-steering system. The objective is to have an automatic steering system that enables the boat to sail at a constant apparent wind angle, without external control (Dhomé et al., 2018).

The hull used in the project is based on a modified 2.4mR mono-hull, a one-man keel boat used in sail racing around the world and recognised as an Olympic class in Paralympics. Different wing concepts and shapes were evaluated (Tretow, 2017), based on which it was decided to equip the boat with a NACA0018 profile wingsail having a wing span of 3.5 m, with a root chord of 0.9 m and tip chord of 0.45 m (with $AR = 5$ and taper = 0.5), giving a total wing area of 2.7 m^2. The angle of attack of the wingsail is controlled using a flap (also with a NACA0018 profile) with an area of 10 % of the main wing and a flap lever arm $b/2$, although the flap is mounted on two tubes made of carbon fibre that can slide into the wing in order to adjust the flap lever arm. Is was computed that the required flap deflection needed to solve the equilibrium equation in order to achieve an angle of attack of 12°, is ≈3.0°. Placing the flap closer to the wing increases the flap deflection needed to rotate the wing to desired angle of attack, requiring more actuation force and the opposite occurs placing the flap further back. The structure supporting the rig was also designed in order that its position can be adjusted (Tretow, 2017).

The Maribot Vane includes a self-steering system that enables the boat to sail on a constant apparent wind angle (AWA) using only mechanical control by the wind, with the objective to achieve a zero electricity consumption when used. Dhomé et al. (2018) state that this system is intended to harvest energy under certain conditions. In addition, they also state that the operating principle of the self-steering system is similar to the one of a wind-rudder vane steering mechanism, but unlike conventional wind rudders found on the market, there is no additional wind-vane added to the boat to track the apparent wind. Instead, the main wing, given its property of self-adjustment to a given AWA, is mechanically coupled to the rudder, but the solution is not described in detail (Dhomé et al., 2018).

A test campaign was carried out in the fall 2017, in the Baggensfjärden area (in the Stockholm archipelago), with a focus on evaluation of the boat performance and the limits of usability in different conditions. During these tests, it was confirmed that the Maribot Vane behaves as intended and predicted in the design phase, and the ability of the self-steering system to keep the vessel at a desired wind angle was verified experimentally (Dhomé et al., 2018).

3.2. Commercial wingsail autonomous boats

Given the nature of academic projects, it is natural that most of the wingsail ASV presented so far are under development. Although remaining challenges have been identified at Higher Education Institutions, a few commercial products are already available and have demonstrated good reliability by reaching impressive milestones. The rest of the section briefly describes some of these vessels in alphabetical order.

3.2.1. Datamaran

Datamaran is a patented wingsail ASV, already on its 7th version, that is being developed by Autonomous Marine Systems (AMS) since 2009. The Datamaran product line is a platform for ocean observation able to collect data from above and below the surface. It provides a platform for sensors and communication devices that can be operated continuously in open water for long duration without human intervention or fuel. According to Autonomous Marine Systems (2018a), each Datamaran is a node in the AMS network, being self-deployable and programmed to return to a retrieval site when their mission lifetime is met and each Datamaran can be dynamically positioned for changing conditions (it can station-keep within a 25 m radius). Furthermore, using peer-to-peer communication, and redundant host systems on land, swarms of Datamarans can self-organise for maximum efficiency in carrying out their mission (five Datamarans can provide 5000 km^2 of coverage every day). This capability allows for real-time readings of wind speed, temperature, humidity, and barometric pressure, sub-sea acoustic data collection, and marine surveillance (Autonomous Marine Systems, 2018a).

The Datamaran Mk7, displayed in Fig. 12, has a length of 2.5 m and a width of 1.7 m, being equipped with a self-trimming rigid wingsail and an electric propeller for tight maneuvering and added speed. A low-power, on-board computer and proprietary navigational algorithms allow the Datamaran to sail, entirely autonomously, to commanded waypoints (Autonomous Marine Systems, 2018b).

3.2.2. HWT X-1 and HWT X-3

The company Harbor Wing Technologies, based in the USA, developed a set of fully wind propelled multi-hull ASV that were originally intended to be used with the US Navy (Harbor Wing Technologies, 2018). These vehicles are characterised by the following innovative components (Giger et al., 2009):

- A wingsail capable of turning 360°.
- A horizontal winglet on the sail that controls the driving force produced by the wing.
- Hydrofoils on the rudder and fin that increase the efficiency and speed of the boat.

As can be seen from Fig. 13, the HWT-X1 prototype is based on the Atlantis project (see Section 3.1.1), using the same wingsail design (Elkaim, 2001), but is larger and more powerful. It is based on a conventional sailing vessel (a 9.1 m modified Stiletto catamaran modified for hybrid electric/wind drive) intended for use as surveillance and sensor platform in either littoral or unprotected waters. Its main propulsion system is a vertical carbon wingsail (predicted to achieve a maximum lift coefficient of 2.2, allowing the wing to generate three times the force of an equivalently sized sail), that is 10.7 m tall and has a 3 m chord (being the wing area 28.3 m^2), suspended on bearings and controlled aerodynamically using conventional flaps and tails. The wing, which is passively stable and self-trimming, is used to propel the vehicle both up and down-wind and has a forward counter-weight suspended on booms to mass balance the wing about the stub mast. For aerodynamic control of the wing (which is free to rotate in azimuth about the stub mast), twin tails are suspended on two carbon fibre booms extending back from the semi-span of the wing (Elkaim and Boyce, 2007). Additionally, this vessel is equipped with two 7 kW electric motors (and each hull has been fitted with a folding propeller), and independent battery banks to power them, which allows the vehicle to be propelled either via wind power, electrically, or both (Elkaim and Lee Boyce Jr., 2008).

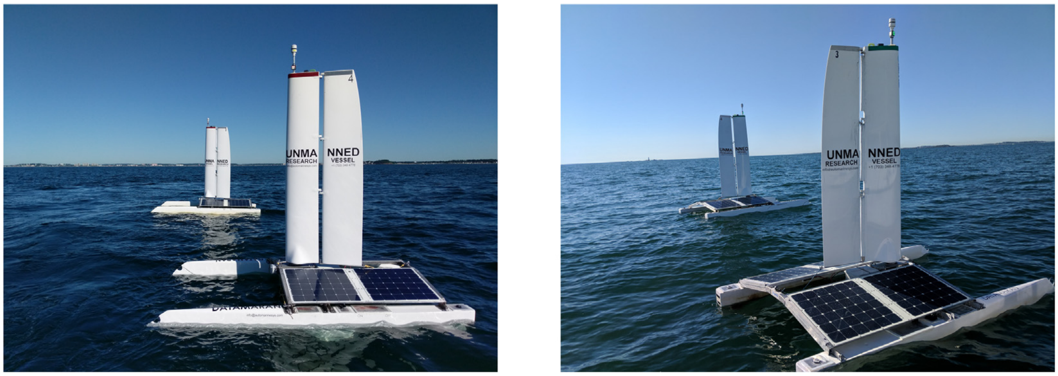
According to the results reported by Elkaim and Boyce (2007), this vessel shows upwind progress at a speed of 30 % the speed of the true wind while pointing 20° to 25° to the true wind. From an angle to the true wind of approximately 45° down to 150°, the speed ratio remains almost constant between 50 % to 60 %. Additionally, speeds of 50 % to 60 % of the true wind speed are achieved under wind speeds from 6.17 m/s to 12.86 m/s [12 kn to 25 kn], on a large range of angles (Elkaim and Boyce, 2007). The control system demonstrates experimental line tracking performance while under wind propulsion of 1.3 m on average, and 1.3 m standard deviation off of the ideal path. Additionally, by using the wind energy for propulsion, the vehicle can spend over 12 h maneuvering with little draw down in the battery charge (Elkaim and Lee Boyce Jr., 2008).

Concerning the HWT X-3 prototype, the information is scarce. It is a trimaran vessel, with bigger dimensions both for the hull and wingsail when compared with the HWT X-1, and incorporates technologies proven in the HWT X-1 prototype (Harbor Wing Technologies, 2018).

3.2.3. SailBuoy

The SailBuoy (SB), depicted in Fig. 14, is a long duration unmanned surface vehicle designed to support a wide variety of instrumentation payloads. It can keep station or follow a track and is being developed and commercialised by Offshore Sensing AS, Norway. It is the first ever unmanned surface vehicle to complete an Atlantic crossing (Offshore Sensing – Sailbuoy, 2018). Deployed in Newfoundland, it has travelled to Ireland sailing a total of 5100 km to cover the 3000 km stretch. Having crossed the Atlantic, the SB Met also reached Norway. For the total mission, it travelled for 118 days at sea and covered the total of 7800 km in all kinds of weather from Newfoundland to Norway, via Ireland. Prior, it had also been used during a two-month mission for sampling near-surface properties in the northern Gulf of Mexico in March–May, 2013. During the 62 days of the latter mission, the SailBuoy covered a total range of approximately 400 km in both meridional and zonal directions, with a cumulative total distance of approximately 2400 km (Ghani et al., 2014).

The Sailbuoy has a length of 2.0 m, a displacement of about 60 kg and is able to carry about 15 kg payload. The average speed is 0.51 m/s to 1.03 m/s [1 kn to 2 kn], and it can navigate in wind speeds between 2 m/s to 20 m/s. It uses a rigid wingsail mounted at the prow to sail toward pre-defined waypoints making it an attractive alternative to freely drifting surface buoys (Offshore Sensing – Sailbuoy, 2018). The authors have not been able to find information on the technical details of the wingsail, but from images and video it appears to turn around the attachment point, and be restricted in its movement by a rope, similar to the operation of a soft sail jib.



(a) (b)

Fig. 12. Close view of two Datamaran Mk7 sailing together (©2018 Autonomous Marine Systems Inc).

(a) (b)

Fig. 13. Different views of the HWT-X1 sailing in the ocean (©2018 Gabriel Elkaim).

(a) (b) (c)

Fig. 14. Different versions of SailBuoy during sailing (©2018 David Peddie/Offshore Sensing AS).

3.2.4. Saildrone

The Saildrone (Saildrone, 2018) is a wind- and solar-powered ASV which can be used for extended research missions in challenging environments while reporting data in real-time. Its patented wing technology was born from 10 years of R&D in pursuit of the land speed record. It is known for accomplishing a mission of approximately 11 112 km from California to Palmyra, via Hawaii, in November 2013, and also for having completed a 97-day mission in the Arctic, in 2015, on which more than 7000 km were travelled (Meinig et al., 2015; Cokelet et al., 2015).

Saildrone's design illustrates a combination of mono-hull and multi-hull features to reduce the payload and enhance the stability. However, this diminishes the motion control speed. Its length is 7 m and forward thrust is provided by a 4 m tall wingsail, with a wing area of 6.10 m^2, where the wingsail trim is controlled by a tail flap. The Saildrone wingsail is constructed from high strength carbon fibre, creating an extremely durable structure, and rotates freely but directed with the controllable tail. The tail flap design acts as a throttle, allowing for the control of both vehicle speed and heel. The Saildrone's control is accomplished with the use of an actuator that controls the wing's tail flap, and another that controls the rudder. Reportedly, it can go 1.54 m/s to 2.57 m/s and carry a 90.7 kg payload (Meinig et al., 2015; Cokelet et al., 2015). Solar panels on the hull and wing provide energy for command and control, communications, and operation of scientific sensors. Throughout the mission across the Bering Sea, the batteries were always topped off before midday and were never depleted by more than 20 % before sunrise the following day (Meinig et al., 2015).

During the three month mission operation across the Bering Sea and Norton Sound, both Saildrones experienced ≈25.72 m/s [50 kn] winds with 3.66 m to 4.57 m [12 ft to 15 ft] seas. It is believed that during this gale an actuator on the tail of a Saildrone became damaged, which resulted in a condition where it could only sail on a starboard tack. Apart from this, all sensors remained fully functional and all control surfaces and solar panels were reportedly in excellent condition at the end of the mission (Meinig et al., 2015).

3.2.5. Submaran ASV

Some of the key personnel from Harbor Wing Technologies (introduced in Section 3.2.2) founded Ocean Aero Inc., also in the USA, a company that has announced the development of the Submaran ASV, a 4.1 m long hybrid surface/sub-surface vessel, powered by wind and solar energy and designed for extended ocean observation and data collection (Ocean Aero, 2018).

For redundancy, the Submaran ASV has two steering rudders and with a wingsail that folds and retracts, it has the added versatility of underwater capability: it can submerge to evade detection, severe weather conditions as well as to perform subsurface data collection tasks (Ocean Aero, 2018).

4. Discussion

It is possible to conclude, from the above presented information, that all sailboats relying on rigid wings for propulsion present a set of advantages and limitations when compared with traditional sails. Furthermore, it is interesting to see several commercial ASV with wingsails, mainly for observation purposes, already on the market. Successful long-period missions on the open ocean, while facing severe weather conditions, offer evidence for practical use.

Given these ideas, this section presents a discussion of the main aspects identified in the different vessels presented. The discussion has a focus on wingsail characteristics, and its relative advantages and limitations when compared with traditional sails. Other aspects relevant for these ASV, such as the hull, the power system, the sensors and actuators, the control system and the communications needed for a proper functioning of the sailboat are also discussed.

Based on this discussion, a table that summarises the main mechanical characteristics of the studied vessels is presented. Before concluding the paper, some potential future research directions for tackling problems identified during this study that remain open in this area, are presented for the interested reader. In Appendix, some additional technical details of the studied boats are summarised.

4.1. Wingsail

All boats presented on this paper use wingsails with symmetrical airfoils, where profiles from the NACA00xx series are common choices. For most of the commercial examples, the airfoil profile is not disclosed. Although it is known that asymmetrical airfoils present better values for C_L and for the ratio C_L/C_D, they are not common due to the need to sail with the wind from both sides of the vessel. Nonetheless, some alternatives have been used, see, e.g., (Amateur Yacht Research Society, 1957; Miller et al., 2017). As mentioned, the main advantages over the traditional sails, identified by most authors, are the fact that these maintain their shape in light winds when traditional sails would collapse, are more robust to control since there are no ropes which could snap, jam or become entangled, suffer from less drag, have better efficiency and can sail closer to the wind (Sauzé and Neal, 2008).

However, they also present some drawbacks. The ones mentioned most often are: (*i*) the difficulty to build rigid wingsails that are rugged, light and inexpensive, (*ii*) rigid wingsails cannot be reefed to reduce their size in high winds, and (*iii*) the wingsails are not particularly stable when sailing downwind, particularly on single sail boats. Since downwind is the least stable point of sail, some suggest sailing on a broad reach instead and tack downwind (Sauzé and Neal, 2008).

As the description of the different projects reveals, there is significant variation in vessels, both in terms of hull shape and size and intended use. Still, some common attributes for a wingsail can be observed, as described in (Stelzer and Dalmau, 2012), namely:

- The sails should be waterproof and buoyant so that they can survive being submerged and aid in righting the boat in the event of capsize.
- They should also be light in order to simplify storage, transportation and rigging.
- If possible, cables should not run through the sail; if they do, then either slip rings should be used to allow transfer of power and signals, or the rotation of the sail must be limited, or cables should run through a fixed tube.
- The size of the sail should be kept small. When designing boats for racing it is tempting to increase sail size for increasing speed, but this is often counterproductive when sailing in winds over 15.43 m/s [30 kn] as this can lead to heeling angles of more than 45° most of the time, which may decrease the efficiency of the rudder if not properly designed for such situation.
- Given the current lack of reliable and simple reefing mechanisms for wingsails, boats expected to encounter strong winds must be equipped with a correspondingly small sail.
- A balanced wingsail is much more efficient relating to energy consumption than any other conventional rig. Results of computer simulations showed that for a traditional sail autonomous robot a balanced rig can save about two-thirds of the power needed for the sail trim.

4.2. Hull

Several possible hull designs exist for autonomous sailing boats. Miller et al. (2014a) present a series of performance trade-off studies concerning the hull design features and the corresponding performance effects. An ideal hull would be cheap to manufacture, able to self-right in the event of capsize (Holzgrafe, 2013), small enough for easy transportation and keeping collision-related damages small, but large enough to be able to sail effectively in heavy seas. Additionally, the hull should be waterproof in order to eliminate costly ways to remove excess water (Sauzé and Neal, 2006). As a less expensive and perhaps more reliable alternative, some choose to make a completely unsinkable sailboat by building it from blocks of closed cell foam (Leloup et al., 2011).

Miller et al. (2012) briefly compare monohulls with multihulls and state that catamarans and trimarans have demonstrated significantly higher performance than monohulls in many applications that do not include large changes in displacement. On the other hand, they identify two challenges with multihulls: (*i*) relatively heavy, and (*ii*) typically are not self-righting and might therefore be difficult to recover from a capsize (Miller et al., 2012).

Regarding monohulls, there are three main possibilities for the hull LOA: (*i*) a hull intended for radio controlled model boats (under 2 m long) (Schlaefer et al., 2011); (*ii*) a small dinghy hull (3 m to 5 m long); and, (*iii*) modify a yacht sized hull (plus than 5 m long) (Sauzé and Neal, 2006). In the last years, option (*ii*) seems to be gaining momentum for both academic projects and commercial products.

4.3. Power system

The choice of power system has a significant impact on the weight, lifetime and cost of a sailing robot. The simplest (and most common) approach is to power the robot with batteries, although this limits mission lengths to a few weeks at best. This might, however, be sufficient for many applications and will decrease development costs. If long term operation is the goal, onboard batteries must be recharged while vessels are performing their missions or alternative energy sources must be used. Rynne and von Ellenrieder (2009) discuss the use of different renewable energy sources in ASV, namely wind turbines, water turbines and solar panels. Cao et al. (2017) investigate the use of hybrid systems, *i.e.*, systems that harvest multiple renewable energy resources including solar, wind and wave, for reducing variations and dependency compared to single sources. Their analysis shows that the majority of the oceans are complimentary in solar and wind power, most notably in the South Pacific ocean, Indian ocean and North Atlantic ocean, and that hybrid systems are more suitable for small vessels, craft or maritime robotics system, e.g., ASV, UAV and oceanographic buoys.

Given the current state of technology, the most obvious choice is to use photovoltaic solar panels to charge batteries during the day and use these batteries to power the boat at night and during cloudy weather (Giger et al., 2009). In this case the battery must be able to hold sufficient charge to power the robot through the night, and preferably for several days should bad weather reduce solar panel efficiency. The main drawback of this solution is that the solar panels add complexity to the electrical systems and increase costs. For choice of batteries, lead acid have the advantage of their reliability, durability, low cost, low self-discharge rates and ability to deliver high peak currents. Placed at a low point in the hull, these batteries further provide additional ballast (Elkaim, 2001; Neal, 2006; Leloup et al., 2011). Rechargeable AA NiMH batteries provide a higher energy density than lead acid's, they are also relatively cheap, easily available and, if required, individual cells can be replaced. In addition, their shape and size allows them to be placed in the keel for ballast. These characteristics motivate their use in several autonomous sailboats, in particular ones with smaller size (Sauzé and Neal, 2006; Miller et al., 2009; Cabrera-Gámez et al., 2012). Anthierens et al. (2013) considered using these type of batteries, but later decided to adopt a 90 A h gel battery for economic reasons. The Avalon sailboat used four lithium-manganese batteries, each consisting of 70 single cells and with a capacity of 600 W h at a nominal voltage of 25.2 V (Giger et al., 2009). This battery technology was chosen mainly because of its weight, but also because they are fairly safe to use. Also Miller et al. (2012) choose the batteries technology based on their safe potential and, in this case opted by using Lithium-iron batteries.

For use and installation of solar panels, two main configurations have been used: (*i*) place the solar panels flat on the deck (Klinck et al., 2009; Stelzer and Dalmau, 2012), or (*ii*) place the panels on an angled frame (Anthierens et al., 2013; Miller et al., 2014b; Autonomous Marine Systems, 2018a). A particular case is ASPire, where a solar tracking prototype was constructed (Friebe et al., 2017), but never installed due to the additional system complexity and moving parts. Another option is to use the area of the wingsail for the solar panels as can be seen on Saildrone.

Some less common solutions for energy management, mainly for back-up purposes, have also been proposed, namely direct-methanol fuel cell (Giger et al., 2009; Klinck et al., 2009; Stelzer and Dalmau, 2012), and Miller et al. (2012) mention that they were considering using a wind turbine for onboard power generation. Anthierens et al. (2013) also planned to use a dedicated vertical Savonius wind generator with helicoidal blades in the Marius autonomous sailboat. Miller et al. (2013) propose three power generation options for the ARRTOO hybrid (sail and electric motor) autonomous boat, namely photovoltaic solar panels, two Forgen 1000NT vertical axis 45 W wind turbines and the option to use the boat diesel engine to recharge the LiFePO4 battery (Miller et al., 2013).

Finally, Jaulin and Bars (2013) propose to make a sailboat robot rotate as fast as possible and, this way, "transform" it into a wind turbine (or windmill) corresponding to the boat itself. When the wind opens the sail, the mainsheet is able to pull a generator in order to produce electric energy. This operation mode can be chosen in cases where the vehicle has to wait for a rendezvous, or when it has its batteries almost empty. Simulations performed by these authors allowed to conclude that the proposed technique could generate an average power of 93 W.

Irrespectively of the adopted power system, a common problem to most autonomous robot systems (and not just to sailboats) is the limited power available onboard, which has to be carefully managed if the mission is over extended periods of time. Several authors mention this as one of the major problems facing the ASV they have developed (Miller et al., 2012).

A possibility that some authors have been using is to control the maximum duty cycle for any part of equipment. As a way to save energy, some authors use distinct frequencies for processing the sensor data, setting the servo positions, and running the communication processes (Schlaefer et al., 2011) or even alternate the boat control between two states: (*i*) a "control-off" (idle) state that uses no electrical energy, and (*ii*) a "control-on" state, during which data collection and/or navigation mechanisms are active, which Augenstein et al. (2016) denominate as intermittent control (Augenstein et al., 2016). Dahl et al. (2014) introduce different modes of operation (classified in five essential categories) for an autonomous sailing vessel, motivated from a nautical as well as an energy efficiency point of view, to enable autonomous missions over long periods with propulsion by sails alone. In order to deal with a limited and varying supply of electricity, these authors apply heuristics to define the different operational modes for operating different sensors and actuators at different, and varying, sampling rates and the microcontroller at different, and varying, clock rates.

Other authors propose adopting strategies on which the frequency of the use of the sensors and actuators depends on the energy level available. For instance, Sauzé (2010) developed power management algorithms based upon an abstraction of the mammalian endocrine system, which is responsible for controlling a number of biological processes within the body. Several experiments showed that it was possible to use an artificial endocrine system to modulate the magnitude of rudder and sail actuator movements to control power consumption of a sailing robot, and that these could be adjusted in response to internal conditions, such as battery level, or external conditions, such as sunlight levels (Sauzé, 2010). A similar strategy is proposed by Anthierens et al. (2013) for the ASV Marius. This boat manages its energy through three levels of energy: there are 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, and a third mode (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%.

Leloup et al. (2011) describe a charge controller which can turn off the electronics and actuators power in the case of a loss of battery power. A memory system allows the boat to restart when the battery voltage reaches sufficient capacity to ensure proper operation. Without power, the boat behaves like a drifting raft.

4.4. Sensing

In order for the control system to be able to control the sailing boat, several sensors are needed. In this subsection the focus is on the sensors needed for controlling the angle of attack of the wingsail and the heading of the ASV. A common requirement to most sailing ASV is a wind sensor to measure direction and, possibly, speed. The most common wind sensor designs are based on moving wind vanes, although these are potentially susceptible to mechanical failure and are more likely to present reliability problems. Furthermore, there are also reports of situations on which, for high heel angles or light winds, these instruments do not register properly. For this reason, many boats avoid using mechanical anemometers, and, instead, opt for ultrasonic anemometers. An alternative approach without moving parts operates on a thermal principle and is constructed of a 2D-array of discrete, surface-mount components. Although the resulting wind sensor is lightweight, small, and inexpensive, it requires significant signal processing, particularly to correct for temperature dependent offsets (Barton and Alvira, 2012).

In order to avoid the use of an explicit physical wind sensor on board, Sliwka et al. (2011) propose the use of a wind vane self steering device for their boat L'improbable and, furthermore, do not actuate the sail to increase the robustness of the boat. Also, Cabrera-Gámez et al. (2016) present an approach that allows to estimate the wind direction and speed based on a particle filter approach. According to the authors, the results of a series of simulations performed in Matlab prove that this approach is capable of providing acceptable estimates of wind conditions at a modest computational cost. The approach does, however, require access to a dynamical model of the boat. Also, it is not discussed how unknown parameters and model uncertainty are handled.

For controlling heading, most autonomous sailboats rely on an electromagnetic compass. The most popular choices are Inertial Measurement Units (IMU) that provide tilt-compensated heading information, along with pitch and roll angles, accelerometer and often gyro output. This information can be used for state estimation purposes. Another common sensor adopted in autonomous sailboats is a Global Navigation Satellite System (GNSS) receiver. Differential GPS (DGPS) is an option that can be utilised for heading information. Compared to an electromagnetic compass, it is not affected by electromagnetic fields.

4.5. Actuation system

For autonomous rigid wing sailboats, the wingsail (directly or through the actuation of a tail or flap) and the rudder need actuators. The actuation subsystem is often the most significant electrical power-consumer. For example, Miller et al. (2012) mention that 75% of power requirements are in support of moving the system actuators to control the rudder. For this reason, the actuation subsystem must be carefully designed. Miller et al. (2012) adopted actuators that incorporated a worm screw mechanical design, so that there is little to no power consumption when the actuators are not moving, even under load. Furthermore, high gear ratios were chosen to limit servo throw. A particular solution, due to its low cost, was adopted by Schröder and Hertel (2013) that used grill motors, which come with a gear to achieve a high torque and low speed, to actuate the rudder and sail.

4.6. Control system

Autonomous sailboats control systems typically present two or three distinct operation modes: fully autonomous sail and navigation control, autonomous sail control with manual rudder control, and full manual control for launching and recovering the boat and for control under unpredictable conditions (Miller et al., 2009; Anthierens et al., 2013; Cabrera-Gámez et al., 2013; Dhomé et al., 2018).

For fully autonomous sail and navigation control, at least three basic functions should be included: global route planning, collision avoidance, and track following control (Stelzer, 2012). Global route planning finds an optimal and obstacle-free travel path between the starting and destination points, based on an objective function and available environmental and meteorological data. Collision avoidance is planning in real-time, with possible changes in course due to dynamic obstacles. Finally, track following control ensures that the boat sails along the prescribed path through feedback control using sail and rudder. The first two functions place emphasis on the application of decision-making theory, while track following control focuses on control theory (Wang et al., 2015). The autonomous mode of many of the boats in this survey so far only support track following. Global route planning is often performed manually, and collision avoidance may or may not be present.

In the field of ASV sailboats, the sail controller and the rudder controller are usually separate and independent. The sail is controlled for achieving propulsion and the course is controlled by the rudder. Different controllers have been adopted for controlling these vessels, and each of these brings a different set of trade-offs between power consumption, computing power, ease of use and reconfigurability. Two important requirements for a main control unit are low power consumption and easy programming. A single microcontroller system is most suited for achieving low power consumption, but this typically comes at the expense of the ease of development and testing. Modularity and redundancy are other reasons to consider more than one microcontroller.

4.7. Communications

Although autonomous sailboats should operate autonomously, there are a number of reasons to keep a permanent communication link. First, it is always advisable to have a fallback to manual control, either in emergencies or to avoid collisions with objects unknown to the boat. Second, to be of any scientific use, a sailing robot for ocean observation needs to include some telecommunication system to download data at regular intervals since there is no guarantee that the robot will be retrieved. To ensure the manual control of the sailboat (typically of the rudder and the sails), the most common option is to use a remote-controlled receiver. This link is normally wired at low level for direct control of the vessel's actuators and is used when the sailboat is at sight.

4.8. Summary of rigid wing sailboats

Table 1 summarises the main mechanical features of the rigid wing sailboats presented in Section 2.

4.9. Potential future research directions

In order for an autonomous sailing boat to successfully remain at sea for months at a time, it will need to be physically robust, able to sail in all sea conditions and feature robust and fault tolerant electronics and software. However, these requirements have not yet been fully achieved and, although several wingsail boats have been developed and some deployed on inspiring missions, robustness is still a key for success. Therefore, further work should be invested to improve the reliability and robustness of the vessels, and to ensure that they can stand prolonged periods at sea.

Several aspects contribute to the lack of robustness and reliability of these ASV and a few problems remain open in this research area. Among them, the authors feel the following would benefit from further research:

- As discussed, modern airfoil design allows an increased lift-drag (L/D) ratio over a conventional sail, thus providing increased thrust while reducing the overturning moment (Atkins, 1996; Elkaim, 2001). Still, experience of rigid wings for sailing is quite limited and further study might provide more efficient and robust solutions (Atkins, 1996; Miller et al., 2017).
- One area of hardware development which particularly requires focus is that of sail reefing (adjust the size of the sail); solving this issue will dramatically reduce the strains of sailing in high winds (Sauzé and Neal, 2006).
- It is also proposed to introduce redundancy into sailboats in the form of redundant actuators, sensors and computers. This will support the goal of long term autonomy, even in the event of component failure (Sauzé and Neal, 2006). Also, the authors feel that a communicating fleet of vessels might open up new possibilities for robustness and redundancy.

Table 1
Summary of the main mechanical characteristics of the presented rigid wing sailboats.

Boat name	Type of hull	LOA (m)	Airfoil profile	Wingsail dimensions $h \times l$ (m)	Wingsail area	Auto-Trim
Atlantis	Catamaran	7.2	Custom developed	5.37×1.45	7.65 m^2	Yes
AROO	Monohull	1.52	Custom developed	1.30×0.18	0.002 25 m^2	No
ARC	Monohull	1.5	Custom developed	1.07×0.20	0.002 14 m^2	No
Beagle-B	Monohull	3.65	Custom developed	3.0×0.85	2.55 m^2	No
WASP	Monohull	2.4	Custom developed	5× n.a.	7 m^2	No
MOOP	Monohull	0.72	Custom developed	0.525×0.13	0.0068 cm^2	No
A-Tirma G2	Monohull	2.0	NACA 0009	1.05×0.225	n.a.	No
Sail-vane	Monohull	1.0	NACA 0015	1.00×0.24	n.a.	No
ASPire	Monohull	4.18	2× NACA 63_2-618	2.8×0.74	2.1 m^2	Yes
Maribot Vane	Monohull	4.2	NACA 0018	3.5× n.a.	2.7 m^2	Yes
Datamaran Mk 7	Catamaran	2.5	n.a.	n.a.	n.a.	Yes
HWT X-1	Catamaran	9.1	n.a.	10.7×3.0	28.3 m^2	Yes
HWT X-3	Trimaran	15.25	n.a.	18.3× n.a.	65 m^2	Yes
Sailbuoy	Monohull	2.0	n.a.	n.a.	0.4 m^2 and 0.6 m^2	No
Saildrone	Monohull	7	n.a.	4× n.a.	6.10 m^2	Yes
Submaran ASV	Monohull	4.14	n.a.	n.a.	n.a.	No

(n.a. - information not available or not found by the authors.)

- Another critical problem relates to the limited power autonomy achieved by state-of-the-art wingsail boats. Additional work on power management strategies is required to allow platforms to perform long oceanic missions and, furthermore, maximise the amount of power available for running sensors, mainly oceanographic instruments, in cases where it is intended to use these vehicles as oceanographic study platforms. As an example, Hertel and Schlaefer (2012) studied how a large set of sensor data (sensors included apparent wind direction, apparent wind speed, 3D compass, 3D accelerometer, 3D gyroscope, GPS data, and servo angles) gathered in different conditions can be used to obtain the optimal parameter settings to control a sailing robot for optimal performance. According to their conclusions, a "lazy" approach to controlling the sail position seems preferable with respect to course stability and energy management (Hertel and Schlaefer, 2012). Decreasing the power requirements for rudder control by use of mechanical self steering devices, such as proposed by Sliwka et al. (2011) and evaluated in the Maribot Vane (Dhomé et al., 2018), is an appealing alternative. Decreased electric power and increased system robustness could also be achieved if the potential to remove the rudder altogether as in the Sail-Vane (Baker et al., 2015; Augenstein et al., 2016) was explored further.
- An important problem to be solved for long-term unmanned and autonomous missions on sea is reliable obstacle detection and avoidance (Alves and Cruz, 2015). A significant body of work on automatic detection, tracking and classification of obstacles for unmanned applications over the last years has been focused on ground and aerial vehicles. However, marine applications present specific requirements (Advanced Autonomous Waterborne Applications Initiative, 2016), and for small sailing vessels especially heeling in addition to heave, pitch and roll must be considered with significant clutter from waves. Besides static obstacles, such as landmasses, which can be predefined on the sea map which is the basis for the routing system, the obstacle avoidance task is different for sailing vessels, as they cannot navigate in any direction directly, depending on wind conditions (Alves and Cruz, 2015). Some work has already been developed in this area. Gal (2011) presents an automatic method for Unmanned Surface Vehicles (USV) to acquire, identify, and track obstacles location in marine environments, using 2D Commercial Of The Shelf (COTS) video sensors, and analysing video streams as input. The algorithm performances were tested in various scenarios with real-time USV's video streams, and Gal states that the algorithm can be used for real-time applications with high success rate and fast time computation. Later, Gal and Zeitouni (2012) presented a multi-target automatic algorithm stages to acquire, identify, and track targets from a USV located in marine environments with LIDAR sensor challenging clutter.
- A final problem that also needs attention is the one of route planning. In the case of autonomous sailboats there are several factors that must be considered when planning a route for the vehicle, namely the prevailing winds, currents, ice, gales, calms, sea state, sunlight, starting date, boat characteristics and ship traffic (Gibbons-Neff and Miller, 2011). Gibbons-Neff and Miller (2011) discuss the research that went into the route planning for the USNA 2011 SailBot, Spirit of Annapolis, for an autonomous crossing of the North Atlantic Ocean. Langbein et al. (2011) present an algorithm for long-term routing of autonomous sailboats, based on the A*-algorithm and incorporating changing weather conditions by dynamically adapting the underlying routing graph, which finds an arbitrarily accurate approximation to the optimal route for a sailboat for real-life wind conditions. Cabrera-Gámez et al. (2012) propose a deterministic route planner for a sailboat suitable for areas where high quality wind and currents forecasts are available and discuss its application to the problem of optimising the route of a sailboat with the objective of minimising the time required to arrive to a destination. The selection of the best route between two points, given winds and currents forecasts, is performed by an unconstrained nonlinear optimisation of the time needed to reach the destination, based on the Nelder–Mead simplex algorithm. Wirz et al. (2015) developed a path planning method based on a cost function approach that allows for multi-objective optimisation of the boat trajectory, adding tactical considerations and changing the calculation of the obstacle cost to include the bearing towards obstacles. These authors introduce a smoothing of the cost function (that considers the target/wind cost, the obstacle cost, the manoeuvre cost and a tactical cost) in order to reduce the impact of local minima and increase the safety distance towards obstacles. Tynan (2017) proposed an alternative navigation method avoiding the use of traditional waypoints and cross-track error. The proposed method utilises an array of waypoint attractors and repellors of different strengths and polarities. A range of possible headings either side of the bearing to the waypoint are considered, and the velocity made good (VMG) on each heading is computed. The heading with the optimal VMG is chosen. Several simulations performed for a set of distinct situations, using this navigation algorithm, allowed to conclude that it works as intended. However, actual field tests under real-world conditions, with the boat subjected to real tidal set and drift, are necessary to further validate the algorithm. Finally, Friebe et al. (2018) introduce a higher level route-replanning algorithm based on interval analysis. Also, methods for interpreting the amount of free space in different

directions from the thermal imaging camera output are described here, along with the incorporation of this into a voter based control system.

As a concluding remark, it must be stated that the development continues in this field, and just as an example of the novelties that keep appearing, a patent has recently been requested for a rigidwing ASV that presents an underwater hull (Jones et al., 2018).

5. Conclusions

This paper presents a state of the art survey of rigid wing sailboats primarily based on available literature. Several examples of sailing ASV already developed, or under development, at academia as well as of commercial products were presented. For each one, its main characteristics in terms of their propulsion, sensing, actuation, communication and control systems have been described and analysed by the authors, and a discussion of the main solutions adopted, as well as their relative advantages and drawbacks were presented.

Regarding the future of these vessels, the authors share the opinion that rigid wing autonomous sailboats will become increasingly more common, mainly due to their robustness when compared with traditional cloth sailing boats, although several problems remain open to research and development. Among the topics that deserve further investment, technical developments in different areas related to energy consumption, materials, control, signal processing, communications and more can be mentioned. Legal and regulatory factors are also important and affect the speed of this development substantially (Advanced Autonomous Waterborne Applications Initiative, 2016).

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Appendix. Technical specifications: actuators, sensors, hardware and software for control and communication, electrical power

This appendix summarises the main features of the systems for control, communication, actuators and sensors for the presented projects in the cases with readily available information. The purpose is to provide an accessible comparison of different alternatives that can be valuable in the development of similar projects.

A.1. Actuators

For the **Atlantis**, the rudders were driven by (one) 24 V Pitman (derated to 12 V) direct drive brushed DC-motor. Four identical actuators, positioned within the wing, controlled the three trailing edge flaps (one for each wing section) and the tail (Elkaim, 2001).

The actuator for the wingsail of **AROO** was a 12 V DC AirMax electric motor and gearbox assembly mounted inside the hull (at the base of the mast) with position feedback received from a potentiometer (Neal, 2006).

ARC was developed based on the AROO and had, for redundancy as well as improved manoeuvrability, two rudders and two wingsails. These were controlled by three identical stepper motors, two for the wingsails and one for the rudders. Additional redundancy was provided by the three stepper motor controllers, each of which could control two of the three motors.

Beagle-B was equipped with two LINAK LA12 linear actuators including position feedback for rudder and sail control (Sauzé, 2010). The sail actuator was mounted on the deck below the sail, limited to only 130° of rotation by stays on either side. The end of the actuator arm consisted of a toothed plastic rack, and the base of the sail contained a circular pinion (Neal et al., 2009).

For **MOOP**, the wingsail was positioned by a Futaba S3306MG heavy duty servo (Neal et al., 2009). To avoid holes in the hull, magnetic linkage was used between the rudder servo and the rudder (Sauzé and Neal, 2011a).

For **A-Tima G2**, the wingsails were actuated with the use of the sheet system for Remote Controlled (RC) sailboats based on a servo with a drum.

On the **ASPire**, the tail wing was controlled by a LACT6P-12V-20 linear actuator located in the hull with potentiometer feedback. The vertical movement of the actuator at the lower part of the mast was translated mechanically via an inner mast part and ball bearings to a vertical movement on the outside of the main wing. This vertical movement was then translated to angular control of the tail wing through a connecting rod. The rudder was controlled by an Octopus SailDrive RS unit.

The **Maribot Vane** first used a Hitec HS-1100WP RC-servo for rudder control. This was later replaced by a stepper motor and its driver with the self-steering system installed. For flap control, an Actuonix L16P linear actuator chosen for its capability to hold position even when powered off was used. In addition, an electric thruster (the model T200 from BlueRobotics) was mounted on the hull and can be used for easier manoeuvring (Dhomé et al., 2018).

The **Sail-vane** used two servomotors, one for controlling the sail (with respect to the hull) and the other to control the tail-vane (with respect to the sail) (Augenstein et al., 2016).

For the **HWT-X1**, the actuators for tail and flap were 24 V brushed DC motors with incremental encoders for position feedback and connected to microprocessor(s). The actuators were located at the base of the wing, and each used a drum with Spectra line running up through pulley blocks in the wing and attached to control horns on their respective surfaces. Flap and tail limits are read from Hall effect switches located on the surfaces themselves. The electric drive system consisted of two air-cooled pancake DC motors, each rated at 7 kW, driven at 24 V through a 400 A H-bridge. The rudder actuator was a 24 V brushed DC motor running through a custom gear head with incremental and absolute encoder feedback. The rudder actuator accepted commands from the GNC computer, and reports back actual rudder angles (Elkaim and Lee Boyce Jr., 2008).

A.2. Sensors

The **Atlantis** sensor system used DGPS (based on a Trimble Ag122 GPS receiver) augmented by a custom built attitude system for position and velocity, consisting of a three-axis magnetometer, two-axis accelerometer, and a Siemens 515 microcontroller. Also, the ASV was equipped with an anemometer and weathervane from Standard Marine Electronics, a hullspeed transducer from Standard Communications Electronics Corporation and an additional Honeywell HMR2003 three-axis magnetometer to determine the angle of the wing, with reference the centerline of the boat (Elkaim, 2001).

Not counting internal sensors for the servos, **AROO** used only three sensors: it was equipped with a mechanical wind vane and a potentiometer (placed on top of the wingsail) to sense the wind direction, had an additional potentiometer to detect sail position, and a Devantech CMPS03 magnetic compass provided heading information (Sauzé and Neal, 2008).

For **ARC**, no feedback of motor position was initially included, but feedback potentiometers were latter installed due to positioning problems. Compared to the AROO, ARC also included a Devantech CMPS03 gimballed compass and a Psion 12 channel GNSS receiver for navigation purposes. To remove the problem of cables running through the mast identified in AROO's, the wind sensor was moved from the sail to its own mast near the stern where it was also less likely to experience any turbulence caused by the sails (Neal et al., 2009).

Beagle-B included a tilt compensated Furuno PG500 flux-gate compass, an ultrasonic wind sensor, Furuno GP-320B GNSS and a YSI 6600 sonde for gathering oceanographic data. The Furuno Rowind ultrasonic wind sensor was mounted on top of the sail on an aluminium tube which ran down the centre of the sail and did not rotate (Sauzé and Neal, 2008; Sauzé, 2010).

The **WASP** was equipped with a 32 Channel Etek GNSS for determining the global position, a OS5000-S Tilt Compensated Compass for determining the heading and a 200-WS-02 NovaLynx anemometer for wind speed and direction. The vessel was also equipped with a suite of oceanographic sensors for measuring the water temperature, the Oxidation Reduction Potential and the water salinity (Rynne, 2008).

MOOP were equipped with a Honeywell HMC6343 solid state tilt compensated compass and a SiRF3 GNSS receiver and a wind sensor (Sauzé and Neal, 2011a).

The **ASPire** had a CV7 ultrasonic wind sensor, a Honeywell HMC6343 tilt compensated 3-axis compass and accelerometer, a Class B AIS CTRX Graphene with accompanying GNSS, an additional GNSS, a BU353, a forward-looking Thermal Imaging Camera, FLIR MD324.

For navigation, the **Maribot Vane** had a GNSS for position and velocity relative to earth and a 3-Space Attitude and Heading Reference System (AHRS) from Yost Labs. The AHRS was mounted in the hull to measure roll, pitch and yaw, along with rotational rates and linear accelerations in all three directions. A second AHRS unit was placed in the mast in order to measure mast attitudes, rates and accelerations used for, *e.g.*, calculating true wind direction. For air temperature, apparent wind speed and wind direction relative to the rig, an ultrasonic anemometer CV7-V from LCJ Capteurs mounted at the top of the rig was used (Dhomé et al., 2018).

The **Sail-vane** was equipped with a sensor array composed of a magnetic rotary encoder on a wind-vane, an IMU with compass, and a GNSS sensor. The IMU provided roll, pitch and yaw (Augenstein et al., 2016).

Examples of other sensors used in robotic sailing are (*i*), the AS5040 sensor from Austria MicroSystems found to be low-priced and reliable (Schlaefer et al., 2011; Schröder and Hertel, 2013), (*ii*) ublox LEA4-T GPS chipset as receivers (Schröder and Hertel, 2013).

A.3. Control and network

Before presenting specific solutions for the discussed vessels, a brief summary of adopted solutions for hardware and development environments is provided.

For the necessary computational environment, several authors adopt common solutions on the market, such as Raspberry Pi, Arduino, or a combination of both (Schröder and Hertel, 2013; Augenstein et al., 2016; Dhomé et al., 2018), or commercial boards based on a ATmega1281 microcontroller (Cabrera-Gámez et al., 2013). This solution presents the advantage of faster development, but presents as a main drawback the fact that these boards have power consumption well above alternatives, in addition to unneeded features for sailing applications (Dahl et al., 2014). According to Dahl et al. (2014), and with respect to power consumption only and in active mode, a Raspberry Pi presents a power consumption 100–250 times higher when compared with the ATMSAM4L microcontrollers, based on the Cortex M4 processor core. An alternative are the Olimexino 32U4 boards, which are used in the Morwyn autonomous sailboat, and that have been selected for their very low power consumption of approximately 20 mA (at 3.3 V) when active and less than 1 mA in sleep mode (Miller et al., 2014b). A particular solution used by the United States Naval Academy (USNA) ASV is based on a custom computation and sensing USNA (TSD) Rabbit Navigation Board version 3.0 (NavBoard3), that includes a Rabbit3000 Microprocessor, MicroMag 3-axis compass, Trimble IQ GPS, accelerometer, Pulse Width Modulation (PWM) outputs, Zigbee modem, ten channels of 12-bit analog-to-digital conversion, four serial ports, external interrupt, general purpose I/O port, and status LED (Bishop et al., 2011).

Naturally, the presence of a full operating system greatly simplifies the development and testing of control system code, "over the air" code updates, allows threading/locking or concurrent processes and allows logfiles to be easily stored and accessed (Miller et al., 2014b). The same opinion is defended by Bruder et al. (2009), that use a PDA for controlling their sailboat. The PDA has a weight of 139 g and includes WLAN, Bluetooth, an SD slot and a battery. Alvira and Barton (2012) present a computer board designed for autonomous robotic sailboat control primarily for its low cost and power consumption, and small size. The system is made up of a baseboard with a 32-bit ARM processor main CPU (LPC3130 from NXP) running Linux, as well as a general-purpose M12 MC13224v module from Freescale Semiconductor, running the Contiki Operating System, and serving as a real-time coprocessor. At the same time, the system is not excessively specialised: it runs 32-bit Linux, has network capability via Ethernet, WiFi, cellular or Bluetooth USB sticks and mass storage is accomplished with the SD card interface on the LPC3130. Autonomous boat operation is achieved by running Python scripts in Linux, allowing very quick prototyping and development of the boat's behaviours without impeding crucial real-time control operations. According to Alvira and Barton (2012), the computing system presented in this work is applicable to a variety of robotic sailboat applications.

As an alternative, Cabrera-Gámez et al. (2014) present the development of a multithreaded open source sailboat controller based on low cost Arduino DUE board hardware and ChibiOS/RT. The software architecture is made up of several threads running at different frequencies, each one implementing a specific function or service. According to these authors, this approach has produced a more stable, easily modified and predictable controller (Cabrera-Gámez et al., 2014). Another alternative is suggested by Schlaefer et al. (2011). These authors propose a new one-design class based on the kit robotic racing Micro Magic, which presents as distinguishing characteristics being small, lightweight and with good sailing performance. This new boat class has an onboard microcontroller mainly reading and pre-processing sensor data, setting the servo positions, and running the communication and it is proposed to use onshore computers for the higher level control, this way simplifying the programming and testing.

The system architecture for the **Atlantis** was based on distributed sensing and actuation with a Controller Area Network (CAN) bus connecting the various modules together. Sensors were sampled at 100 Hz, and a central main computer - the Guidance-Navigation-Control (GNC) computer - performs the estimation and control tasks at 5 Hz (Elkaim, 2001).

For **AROO**, rudder position control was enforced by the servo, and desired rudder position was given by a proportional controller for heading. Sail adjustments were made through an algorithm which linked wind directions (relative to the boat) with appropriate sail settings via a look-up table. Actuators and sensors were connected to a Basic Stamp 2sx microcontroller which was, in turn, connected via a serial port to a HP Jornada 720 personal digital assistant (PDA) running the higher level control algorithms. The PDA also allowed remote access at distances of dozens of metres via wireless network (Sauzé and Neal, 2006).

For **ARC**, the original control algorithm kept track of sail position by keeping a record of the distance moved since the sail was last calibrated, but when the sail began slipping this strategy failed. To counter this problem, a potentiometer was later added to keep track of the sail position (Neal et al., 2009). For computations, initially a combination of an ATmega128 microcontroller and a Gumstix Connex single board computer running Linux was used, but the ATmega128 was later removed in favour of controlling everything from the Gumstix (Sauzé and Neal, 2008).

For communication, **Beagle-B** included a Iridium Short Burst Data (SBD) transceiver and a GM-862 GSM modem. A pair of Gumstix single board computers, one for the control of the robot and one for the oceanography sensors and communications, were used (Sauzé and Neal, 2008). In addition, low level control of actuator positions used a PIC18F4550 microcontroller with position setpoints provided by the Gumstix (Sauzé and Neal, 2011a).

On the **WASP**, the control system was on an LPC-2138 ARM microcontroller and used a proportional controller for rudder control while the sail control was based on a scalar "trimming code" (Rynne, 2008).

MOOP used a Microchip PIC 18LF4550 microcontroller, with two line Liquid Crystal Display (LCD) screen for debug messages (a Newhaven NHD 0220JZ FSPG GBW), and a Gumstix Connex Single Board Computer. The system was split into two parts, a low level layer on the PIC microcontroller and interfaced to the servos, compass, wind sensor and GNSS. It received commands via a 4900 bit/s software serial port from the Gumstix Single Board Computer with a Linux based operating system. Latter versions of MOOP eliminated the Gumstix and placed the entire control system on the PIC microcontroller in order to reduce the power consumption (Sauzé and Neal, 2011a).

The **ASPire** used a Raspberry Pi 3 Model B running Arch Linux with message based software in C++ for control and communication. The system was connected through a Controller Area Network (CAN) bus, to which an Arduino Mega controlling the rudder and sail was connected. The system also connects a BU353 GNSS over USB to the Raspberry PI and a Thermal Imaging Camera over a Pi camera port via a PiCapture SD1. In addition, an Inter-Integrated Circuit (I^2C) protocol was used for connecting the compass and accelerometer.

For calculations and control, the **Maribot Vane** used two Arduino DUE, the main controller in the hull, the auxiliary in the mast connected to the sensors and the actuators in the wing. In the top compartment on the rig, a 433 MHz RF antenna for real time telemetry was installed enabling communication at distances up to a few hundred meters. The main controller was responsible for sensor acquisition, steering and flap control, data logging and external communication. All sensors were updated at a frequency of 2 Hz, also used for transmission of data and reception of commands to/from an external source (Dhomé et al., 2018).

For calculations, the **Sail-vane** used an Arduino Due (Augenstein et al., 2016).

For robustness, the **HWT-X1** had a modular design for the internal network architecture. Each sensor and actuator was a node on a dedicated CAN bus with six subsystems: (1) Guidance Navigation and Control (GNC) computer, (2) Electric Drive system, (3) Rudder Actuator, (4) Wing/Flap Actuators, (5) Lighthouse Unit, and (6) Environmental Sensor Module. The GNC computer was a Pentium class PC running MATLAB's XPC target. A Microbotics MIDG II integrated GPS/INS receiver was attached via serial communications and a Mac MINI running custom software to log all CAN messages on the system was used as a data logger for debugging purposes. For the control architecture, simple controllers were combined in a hierarchical state machine for switching between controllers as appropriate. The basic controllers were the heading hold control, a line tracking control that consists of two successive proportional control loops closed around heading and cross-track error, and a proportional integral controller with feedforward for velocity (Elkaim and Lee Boyce Jr., 2008).

For **SailBuoy**, data was transmitted to and from shore in real time via the Iridium satellite system, either for communicating measured parameters and diagnostics, or for transferring the data collected by the instrumentation payloads (Offshore Sensing – Sailbuoy, 2018).

As a general summary of alternatives for external communication, it can be noted that, (*i*), short range (about 1 km to 2 km) typically use wireless LAN (Stelzer and Jafarmadar, 2011) or XBee radio communications (Santana-Jorge et al., 2017), (*ii*) mid range, and when the ASV is situated in areas of mobile network communication coverage (typically coastal areas), typically use Universal Mobile Telecommunications System (UMTS)/General Packet Radio Service (GPRS) (Stelzer and Jafarmadar, 2011) or 3G/GPRS (Santana-Jorge et al., 2017) mobile communications via the mobile phone network, and, (*iii*) oceanic long range, i.e., without mobile network access, is based on Iridium SBD satellite communications. The relative availability, costs, bandwidth, and real-time abilities of these different modes of communication have been analysed in (Stelzer and Jafarmadar, 2011). The use of GPRS and Iridium SBD communication infrastructures implies paying network operator fees, which are considerably higher in the case of the Iridium operator.

A.4. Electrical power

AROO had a 12 V 4.2 A h sealed lead acid battery, capable of powering the vessel for up to 36 h of operation depending on the frequency of actuator use (Neal, 2006).

ARC was powered by twenty 1.2 V, 2500 mA/h Nickel–metal hydride (NiMH) AA rechargeable batteries, connected in two banks of 10 to provide 12 V and a peak current of around 4 A (Sauzé and Neal, 2008).

Beagle-B was equipped with two 45 W (peak) solar panels and four 12 V 60 A h lead acid batteries, which according to estimates should be sufficient to enable it to remain at sea continuously (Sauzé, 2010).

For the **WASP**, electrical power was provided by a 2000 W h set of batteries that can be continuously recharged by 50 W solar cells, which cover part of the top deck of the vehicle (Rynne, 2008).

The **MOOP** was equipped with ten size F, 1.25 V, 13 A h batteries connected as two parallel packs of five batteries (Sauzé and Neal, 2011a).

The **ASPire** had a 50 W solar panel connected to a 110 A h 12 V gel battery with 1.3 kW h of energy storage. With this configuration, the produced energy was not sufficient to cover the power consumption.

For the **HWT-X1**, the main battery banks were positioned within the hulls and consisted of 16 lead-acid deep cycle marine batteries, arranged in series and parallel to create a large capacity 24 V battery (Elkaim and Lee Boyce Jr., 2008).

The **Sailbuoy** had a battery pack for powering the internal autopilot with energy to navigate for six months without charging. It was also equipped with solar panels for powering the electronics and actuators. Sensors and the communication system have a separate battery – typical capacity is 240 W h, 20 A h at 12 V (Ghani et al., 2014).

The **Submaran ASV** was equipped with solar rechargeable lithium batteries to power a payload comprised of a range of distinct sensor systems.

References

Advanced Autonomous Waterborne Applications Initiative, 2016. Remote and Autonomous Ships – The Next Steps. Tech. Rep., Rolls-Royce plc.

2018. Airfoil Tools. http://airfoiltools.com/. (Accessed 24 November 2018).

Alves, J.C., Cruz, N.A., 2015. AIS-enabled collision avoidance strategies for autonomous sailboats. In: Robotic Sailing 2015 – Proceedings of the 8th International Robotic Sailing Conference. pp. 77–87, ISSN 978-3-319-23334-5. http://dx.doi.org/10.1007/978-3-319-23335-2_6.

Alvira, M., Barton, T., 2012. Small and inexpensive single-board computer for autonomous sailboat control. In: Robotic Sailing 2012 – Proceedings of the 5th International Robotic Sailing Conference. pp. 105–116. ISSN 978-3-642-33083-4. http://dx.doi.org/10.1007/978-3-642-33084-1_10.

Amateur Yacht Research Society, 1957. Wingsails, A.Y.R.S. Publication no. 14. https://www.ayrs.org/repository/AYRS014.pdf. (Accessed 26 April 2019).

Anthierens, C., Pauly, E., Jeay, F., 2013. MARIUS: A sailbot for sea-sailing. In: Robotic Sailing 2013 – Proceedings of the 6th International Robotic Sailing Conference. pp.3–12. ISSN 978-3-319-02275-8. http://dx.doi.org/10.1007/978-3-319-02276-5_1.

Atkins, D.W., 1996. The CFD Assisted Design and Experimental Testing of a Wingsail with High Lift Devices (Ph.D. thesis). University of Salford.

Augenstein, T., Singh, A., Miller, J., Pomerenk, A., Dean, A., Ruina, A., 2016. Using a controlled sail and tail to steer an autonomous sailboat. In: Robotic Sailing 2016 – Proceedings of the 9th International Robotic Sailing Conference. pp. 91–103. ISSN 978-3-319-45452-8. http://dx.doi.org/10.1007/978-3-319-45453-5_8.

Autonomous Marine Systems, 2018a. Datamaran. http://www.automarinesys.com/datamaran/. (Accessed 22 November 2018).

Autonomous Marine Systems, 2018b. Datamaran: General specifications. http://www.automarinesys.com/wp-content/uploads/2014/05/Datamaran_DataSheet.pdf. (Accessed 22 November 2018).

Baker, R., Kambourian, L., Hajarian, S., Augenstein, T., Harnett, S., Lee, G.-M., Sudarshan, M., Richter, C., Trouillot, C., Williamson, P., Ruina, A., 2015. Design and development of a self-stabilizing, autonomous sailboat with zero-net stored-energy use. In: botic Sailing Conferen Sailing 2015 – Proceedings of the 8th International Robotic Sailing Conference. pp. 39–57. ISSN 978-3-319-23334-5. http://dx.doi.org/10.1007/978-3-319-23335-2_4.

Bars, F.L., Jaulin, L., 2012. An experimental validation of a robust controller with the VAIMOS autonomous sailboat. In: Robotic Sailing 2012 – Proceedings of the 5th International Robotic Sailing Conference, pp. 73–84. ISSN 978-3-642-33083-4. http://dx.doi.org/10.1007/978-3-642-33084-1_7.

Barton, T., Alvira, M., 2012. A discrete-component 2D-array wind sensor without moving parts for a robotic sailboat. In: Robotic Sailing 2012 – Proceedings of the 5th International Robotic Sailing Conference. pp. 95–104. ISSN 978-3-642-33083-4. http://dx.doi.org/10.1007/978-3-642-33084-1_9.

Bishop, B.E., Bradshaw, J., Keef, C., Taschner, N., 2011. A Systems Engineering approach to the development of an autonomous sailing vessel. In: Robotic Sailing – Proceedings of the 4th International Robotic Sailing Conference. pp. 87–99. ISSN 978-3-642-22835-3. http://dx.doi.org/10.1007/978-3-642-22836-0_6.

Bruder, R., Stender, B., Schlaefer, A., 2009. Model sailboats as a testbed for artificial intelligence methods. In: Proceedings of the 2nd International Robotic Sailing Conference. pp. 37–42.

Cabrera-Gámez, J., de Miguel, A.R., Domínguez-Brito, A.C., Hernández-Sosa, J.D., Isern-González, J., Adler, L., 2014. A real-time sailboat controller based on ChibiOS. In: Robotic Sailing 2014 – Proceedings of the 7th International Robotic Sailing Conference. pp. 77–85. ISSN 978-3-319-10075-3. http://dx.doi.org/10.1007/978-3-319-10076-0_7.

Cabrera-Gámez, J., de Miguel, A.R., Domínguez-Brito, A.C., Hernández-Sosa, J.D., Isern-González, J., Fernández-Perdomo, E., 2013. An embedded low-power control system for autonomous sailboats. In: Robotic Sailing 2013 – Proceedings of the 6th International Robotic Sailing Conference. pp. 67–79. ISSN 978-3-319-02275-8. http://dx.doi.org/10.1007/978-3-319-02276-5_6.

Cabrera-Gámez, J., Domínguez-Brito, A.C., Hernández-Sosa, J.D., Valle-Fernández, B., de Miguel, A.R., García, J.C., 2016. A virtual wind sensor based on a particle filter. In: Robotic Sailing 2016 – Proceedings of the 9th International Robotic Sailing Conference. pp. 69–78. ISSN 978-3-319-45452-8. http://dx.doi.org/10.1007/978-3-319-45453-5_6.

Cabrera-Gámez, J., Isern-González, J., Hernández-Sosa, D., Domínguez-Brito, A.C., Fernández-Perdomo, E., 2012. Optimization-based weather routing for sailboats. In: Robotic Sailing 2012 – Proceedings of the 5th International Robotic Sailing Conference. pp. 3–33. ISSN 978-3-642-33083-4. http://dx.doi.org/10.1007/978-3-642-33084-1_3.

Cao, Y., Townsend, N., Tan, M., 2017. Hybrid renewable energy system for ocean going platforms. In: OCEANS 2017 – Aberdeen. pp. 1–7. http://dx.doi.org/10.1109/OCEANSE.2017.8084799.

Cokelet, E.D., Meinig, C., Lawrence-Slavas, N., Stabeno, P.J., Mordy, C.W., Tabisola, H.M., Jenkins, R., Cross, J.N., 2015. The use of saildrones to examine spring conditions in the bering sea: Instrument comparisons, sea ice meltwater and yukon river plume studies. In: OCEANS 2015 – MTS/IEEE Washington. pp. 1–7. http://dx.doi.org/10.23919/OCEANS.2015.7404357.

Cruz, N.A., Alves, J.C., Guedes, T., Rodrigues, R., Pinto, V., Campos, D., Silva, D., 2015. Integration of wind propulsion in an electric ASV. In: Robotic Sailing 2015 – Proceedings of the 8th International Robotic Sailing Conference. pp. 15–27. ISSN 978-3-319-23334-5. http://dx.doi.org/10.1007/978-3-319-23335-2_2.

Dahl, K., Bengsén, A., Waller, M., 2014. Power management strategies for an autonomous robotic sailboat. In: Robotic Sailing 2014 – Proceedings of the 7th International Robotic Sailing Conference. pp. 47–55. ISSN 978-3-319-10075-3. http://dx.doi.org/10.1007/978-3-319-10076-0_4.

Dhomé, U., Tretow, C., Kuttenkeuler, J., Wängelin, F., Fraize, J., Fürth, M., Razola, M., 2018. Development and initial results of an autonomous sailing drone for oceanic research. In: Marine Design XIII – Proceedings of the 13th International Marine Design Conference, vol. 1.

Domínguez-Brito, A.C., Valle-Fernández, B., Cabrera-Gámez, J., de Miguel, A.R., García, J.C., 2015. A-TIRMA G2: An oceanic autonomous sailboat. In: Robotic Sailing 2015 – Proceedings of the 8th International Robotic Sailing Conference. pp. 3–13. ISSN 978-3-319-23334-5. http://dx.doi.org/10.1007/978-3-319-23335-2_1.

Elkaim, G.H., 2001. System Identification for Precision Control of a WingSailed GPS-Guided Catamaran (Ph.D. thesis). Stanford University.

Elkaim, G.H., Boyce, C.L., 2007. Experimental aerodynamic performance of a self-trimming wing-sail for autonomous surface vehicles. IFAC Proc. Vol. (ISSN: 1474-6670) 40 (17), 271–276. http://dx.doi.org/10.3182/20070919-3-HR-3904.00048, http://www.sciencedirect.com/science/article/pii/S1474667015321078, 7th IFAC Conference on Control Applications in Marine Systems.

Elkaim, G.H., Lee Boyce Jr., C., 2008. An energy scavenging autonomous surface vehicle for littoral surveillance. In: Proceedings of the ION Global Navigation Satellite Systems Conference.

Enqvist, T.J., 2016. Undersökning av Vingsegel Anordning för Robotsegelbåt – Wingsail Arrangements for Robotic Sailboat (B.S. thesis). Högskolan på Åland – Åland University of Applied Sciences.

Enqvist, T., Friebe, A., Haug, F., 2016. Free rotating wingsail arrangement for Åland sailing robots. In: Robotic Sailing 2016 – Proceedings of the 9th International Robotic Sailing Conference. pp. 3–18. ISSN 978-3-319-45452-8. http://dx.doi.org/10.1007/978-3-319-45453-5_1.

Eriksson, R., Friebe, A., 2015. Challenges for autonomous sailing robots. In: Proceedings of the 14th International Conference on Computer Applications and Information Technology in the Maritime Industries.

Fekete, G.I., Newman, B.G., 1965. Analysis and Development of a Sailboat With Self-Trimming Wing Sail. Tech. Rep. T.N. 65-1, Mechanical Engineering Research Laboratories, McGill University.

Fernandes, P.C., Marques, M.M., Lobo, V., 2016. Barlavento – considerations about the design of an autonomous sailboat. In: Robotic Sailing 2016 – Proceedings of the 9th International Robotic Sailing Conference, pp. 19–30. ISSN 978-3-319-45452-8. http://dx.doi.org/10.1007/978-3-319-45453-5_2.

Friebe, A., Casanova, G.R., Gallic, M.L., Rolinat, C., Waller, M., 2018. Situational awareness and obstacle avoidance for a wind propelled marine research ASV. In: Proceedings of the 17th Conference on Computer Applications and Information Technology. pp. 211–225.

Friebe, A., Olsson, M., Gallic, M.L., Springett, J.L., Dahl, K., Waller, M., 2017. A marine research ASV utilizing wind and solar power. In: OCEANS 2017 – Aberdeen. pp. 1–7. http://dx.doi.org/10.1109/OCEANSE.2017.8084648.

Gal, O., 2011. Automatic obstacle detection for USV's navigation using vision sensors. In: Robotic Sailing – Proceedings of the 4th International Robotic Sailing Conference. pp. 127–140. ISSN 978-3-642-22835-3. http://dx.doi.org/10.1007/978-3-642-22836-0_9.

Gal, O., Zeitouni, E., 2012. Tracking objects using PHD filter for USV autonomous capabilities. In: Robotic Sailing 2012 – Proceedings of the 5th International Robotic Sailing Conference. pp. 3–12. ISSN 978-3-642-33083-4. http://dx.doi.org/10.1007/978-3-642-33084-1_1.

Ghani, M.H., Hole, L.R., Fer, I., Kourafalou, V.H., Wienders, N., Kang, H., Drushka, K., Peddie, D., 2014. The sailbuoy remotely-controlled unmanned vessel: Measurements of near surface temperature, salinity and oxygen concentration in the northern gulf of Mexico. Methods Oceanogr. (ISSN: 2211-1220) 10, 104–121. http://dx.doi.org/10.1016/j.mio.2014.08.001, http://www.sciencedirect.com/science/article/pii/S2211122014000395, (special Issue: Autonomous Marine Vehicles).

Gibbons-Neff, P., Miller, P., 2011. Route planning for a micro-transat voyage. In: Robotic Sailing – Proceedings of the 4th International Robotic Sailing Conference. pp. 183–194. ISSN 978-3-642-22835-3. http://dx.doi.org/10.1007/978-3-642-22836-0_13.

Giger, L., Wismer, S., Boehl, S., Büsser, G.-A., Erckens, H., Weber, J., Moser, P., Schwizer, P., Pradalier, C., Siegwart, R.Y., 2009. Design and construction of the autonomous sailing vessel AVALON. In: Proceedings of the 2nd International Robotic Sailing Conference. pp. 17–22.

Gomes, L., Costa, A., Fernandes, D., Marques, H., Anjos, F., 2016. Improving instrumentation support and control strategies for autonomous sailboats in a regatta contest. In: Robotic Sailing 2016 – Proceedings of the 9th International Robotic Sailing Conference. pp. 45–56. ISSN 978-3-319-45452-8. http://dx.doi.org/10.1007/978-3-319-45453-5_4.

Harbor Wing Technologies, 2018. Harbor wing technologies – autonomous unmanned surface vessel – AUSV. http://www.harborwingtech.com/index.htm. (Accessed 07 November 2018).

Hertel, L., Schlaefer, A., 2012. Data mining for optimal sail and rudder control of small robotic sailboats. In: Robotic Sailing 2012 – Proceedings of the 5th International Robotic Sailing Conference. pp. 37–48. ISSN 978-3-642-33083-4. http://dx.doi.org/10.1007/978-3-642-33084-1_4.

Holzgrafe, J., 2013. Transverse stability problems of small autonomous sailing vessels. In: Robotic Sailing 2013 – Proceedings of the 6th International Robotic Sailing Conference. pp. 111–123. ISSN 978-3-319-02275-8. http://dx.doi.org/10.1007/978-3-319-02276-5_9.

INNOC – Österreichische Gesellschaft für innovative Computerwissenschaften, 2018. Robotic sailing. https://www.roboticsailing.org/. (Accessed 16 November 2018).

Isler, J.J., Isler, P., 2006. Sailing For Dummies, second ed. Wiley Publishing, Inc., Hoboken, NJ, ISBN: 978-0-471-79143-0.

Jaulin, L., Bars, F.L., 2013. Sailboat as a windmill. In: Robotic Sailing 2013 – Proceedings of the 6th International Robotic Sailing Conference. pp. 81–92. ISSN 978-3-319-02275-8. http://dx.doi.org/10.1007/978-3-319-02276-5_7.

Jaulin, L., Bars, F.L., 2014. Towing with sailboat robots. In: Robotic Sailing 2014 – Proceedings of the 7th International Robotic Sailing Conference. pp. 31–44. ISSN 978-3-319-10075-3. http://dx.doi.org/10.1007/978-3-319-10076-0_3.

Jones, M., Tooter, C., Ott, M., 2018. Submerged sailing vessel. http://www.sumobrain.com/patents/WO2018204048A1.html.

Kimball, J., 2010. Physics of Sailing. CRC Press – Taylor & Francis Group, Boca Raton, Florida, ISBN: 978-1-4200-7376-8.

Klinck, H., Fregosi, S., Matsumoto, H., Turpin, A., Mellinger, D.K., Erofeev, A., Barth, J.A., Shearman, R.K., Jafarmadar, K., Stelzer, R., 2015. Mobile autonomous platforms for passive-acoustic monitoring of high-frequency cetaceans. In: Robotic Sailing 2015 – Proceedings of the 8th International Robotic Sailing Conference. pp. 29–37. ISSN 978-3-319-23334-5.http://dx.doi.org/10.1007/978-3-319-23335-2_3.

Klinck, H., Stelzer, R., Jafarmadar, K., Mellinger, D.K., 2009. AAS endurance: An autonomous acoustic sailboat for marine mammal research. In: Proceedings of the 2nd International Robotic Sailing Conference. pp. 43–48.

Langbein, J., Stelzer, R., Frühwirth, T., 2011. A rule-based approach to long-term routing for autonomous sailboats. In: Robotic Sailing – Proceedings of the 4th International Robotic Sailing Conference. pp. 195–204. ISSN 978-3-642-22835-3. http://dx.doi.org/10.1007/978-3-642-22836-0_14.

Leloup, R., Pivert, F.L., Thomas, S., Bouvart, G., Douale, N., Malet, H.D., Vienney, L., Gallou, Y., Roncin, K., 2011. Breizh spirit, a reliable boat for crossing the atlantic ocean. In: Robotic Sailing – Proceedings of the 4th International Robotic Sailing Conference. pp. 55–69. ISSN 978-3-642-22835-3 http://dx.doi.org/10.1007/978-3-642-22836-0_4.

Marine Insight, 2017. Top 7 green ship concepts using wind energy. https://www.marineinsight.com/green-shipping/top-7-green-ship-concepts-using-wind-energy/. (Accessed 26 November 2018).

Meinig, C., Lawrence-Slavas, N., Jenkins, R., Tabisola, H.M., 2015. The use of saildrones to examine spring conditions in the bering sea: Vehicle specification and mission performance. In: OCEANS 2015 – MTS/IEEE Washington. pp. 1–6. http://dx.doi.org/10.23919/OCEANS.2015.7404348.

Ménage, O., Bethencourt, A., Rousseaux, P., Prigent, S., 2013. VAIMOS: Realization of an autonomous robotic sailboat. In: Robotic Sailing 2013 – Proceedings of the 6th International Robotic Sailing Conference, pp. 25–36. ISSN 978-3-319-02275-8. http://dx.doi.org/10.1007/978-3-319-02276-5_3.

Miller, P., Beeler, A., Cayaban, B., Dalton, M., Fach, C., Link, C., MacArthur, J., Urmenita, J., Medina, R.Y., 2014. An easy-to-build, low-cost, high-performance SailBot. In: Robotic Sailing 2014 – Proceedings of the 7th International Robotic Sailing Conference. pp. 3–16. ISSN 978-3-319-10075-3. http://dx.doi.org/http://dx.doi.org/10.1007/978-3-319-10076-0_1.

Miller, P., Brooks, O., Hamlet, M., 2009. Development of the USNA SailBots (ASV), in: Proceedings of the 2nd International Robotic Sailing Conference. pp. 9–16.

Miller, P.H., Hamlet, M., Rossman, J., 2012. Continuous improvements to USNA SailBots for inshore racing and offshore voyaging. In: Robotic Sailing 2012 – Proceedings of the 5th International Robotic Sailing Conference. pp. 49–60..

Miller, P., Hamlet, M., Sauzé, C., Neal, M., Capper, D., Clark, D., Iles, A., Taylor, L., 2014. MaxiMOOP: A multi-role, low cost and small sailing robot platform. In: Robotic Sailing 2014 – Proceedings of the 7th International Robotic Sailing Conference. pp. 17–30. ISSN 978-3-319-10075-3. http://dx.doi.org/10.1007/978-3-319-10076-0_2.

Miller, P., Judge, C., Sewell, D., Williamson, S., 2017. An alternative wing sail concept for small autonomous sailing craft. In: Robotic Sailing 2017 – Proceedings of the 10th International Robotic Sailing Conference. pp. 3–17. ISSN 978-3-319-72738-7. http://dx.doi.org/10.1007/978-3-319-72739-4_1.

Miller, P., Sauzé, C., Neal, M., 2013. Development of ARRTOO: A long-endurance, hybrid-powered, oceanographic research vessel. In: Robotic Sailing 2013 – Proceedings of the 6th International Robotic Sailing Conference. pp. 53–65. ISSN 978-3-319-02275-8. http://dx.doi.org/10.1007/978-3-319-02276-5_5.

National Academy of Engineering, 2018. In: Olson, S. (Ed.), Autonomy on Land and Sea and in the Air and Space: Proceedings of a Forum. The National Academies Press, Washington, DC, ISBN: 978-0-309-47852-6, http://dx.doi.org/10.17226/25168, https://www.nap.edu/catalog/25168/autonomy-on-land-and-sea-and-in-the-air-and-space.

Neal, M., 2006. A hardware proof of concept of a sailing robot for ocean observation. IEEE J. Ocean. Eng. (ISSN: 0364-9059) 31 (2), 462–469. http://dx.doi.org/10.1109/JOE.2006.875101.

Neal, M., Sauzé, C., Thomas, B., Alves, J.C., 2009. Technologies for autonomous sailing: Wings and wind sensors In: Proceedings of the 2nd International Robotic Sailing Conference. pp. 23–30.

Newman, B.G., Fekete, G.I., 1983. Analysis and preliminary design of of a sailboat with a self-trimming wingsail. Mar. Technol. 20 (4), 370–376.

Ocean Aero, 2018. Ocean aero submarine | marine AUV | maritime security | unmanned surface and submarine systems. http://www.oceanaero.com/submaran/. (Accessed 07 November 2018).

Offshore Sensing – Sailbuoy, 2018. Sailbuoy – unmanned surface vessel. http://www.sailbuoy.no/. (Accessed 09 November 2018).

Robosoft, 2017. ROBOSOFT consulting – a team of experts. http://robosoft.com/. (Accessed 09 November2018).

Rynne, P.F., 2008. Design & Performance of a Wind and Solar-Powered Autonomous Surface Vehicle (Master's thesis). Florida Atlantic University – The College of Computer Science and Engineering.

Rynne, P.F., von Ellenrieder, K.D., 2009. Unmanned autonomous sailing: Current status and future role in sustained ocean observations. Mar. Technol. Soc. J. (ISSN: 0025-3324) 43 (1), 21–30.

2018. SailBot | International Robotic Sailing Regatta. https://www.sailbot.org/. (Accessed 16 November 2018).

Saildrone, 2018. Saildrone – Ocean data redefined. https://www.saildrone.com/. (Accessed 07 November 2018).

Sailrocket, 2018. Sailrocket. http://www.sailrocket.com/. (Accessed 08 November 2018).

Santana-Jorge, F.J., Domínguez-Brito, A.C., Cabrera-Gámez, J., 2017. A component-based C++ communication middleware for an autonomous robotic sailboat. In: Robotic Sailing 2017 – Proceedings of the 10th International Robotic Sailing Conference. pp. 39–54. ISSN 978-3-319-72738-7. http://dx.doi.org/10.1007/978-3-319-72739-4_4.

Sauzé, C., 2010. A Neuro-Endocrine Inspired Approach to Power Management in Sailing Robots (Ph.D. thesis). The University of Wales.

Sauzé, C., Neal, M., 2006. An autonomous sailing robot for ocean observation. In: Proceedings of the 7th Towards Autonomous Robotic Systems (TAROS) Conference. pp. 190–197.

Sauzé, C., Neal, M., 2008. Design considerations for sailing robots performing long term autonomous oceanography. In: Proceedings of the International Robotic Sailing Conference. pp. 21–29.

Sauzé, C., Neal, M., 2011. MOOP: A miniature sailing robot platform. In: Robotic Sailing – Proceedings of the 4th International Robotic Sailing Conference. pp. 39–53. ISSN 978-3-642-22835-3 http://dx.doi.org/10.1007/978-3-642-22836-0_3.

Sauzé, C., Neal, M., 2011. Simulating sailing robots. In: Robotic Sailing – Proceedings of the 4th International Robotic Sailing Conference. pp. 113–124. ISSN 978-3-642-22835-3. http://dx.doi.org/10.1007/978-3-642-22836-0_8.

Schlaefer, A., Beckmann, D., Heinig, M., Bruder, R., 2011. A new class for robotic sailing: The robotic racing micro magic. In: Robotic Sailing – Proceedings of the 4th International Robotic Sailing Conference. pp. 71–84. ISSN 978-3-642-22835-3. http://dx.doi.org/10.1007/978-3-642-22836-0_5.

Schröder, C., Hertel, L., 2013. Development of a Low-Budget Robotic Sailboat. In: Robotic Sailing 2013 – Proceedings of the 6th International Robotic Sailing Conference. pp. 13–24. ISSN 978-3-319-02275-8http://dx.doi.org/10.1007/978-3-319-02276-5_2.

Shukla, P.C., Ghosh, K., 2009. Revival of the modern wing sails for the propulsion of commercial ships. Int. J. Math. Comput. Phys. Electr. Comput. Eng. 3 (3), 207–212, http://waset.org/Publications?p=27.

Sliwka, J., Nicola, J., Coquelin, R., de Megille, F.B., Clement, B., Jaulin, L., 2011. Sailing without wind sensor and other hardware and software innovations. In: Robotic Sailing – Proceedings of the 4th International Robotic Sailing Conference. pp. 27–38. ISSN 978-3-642-22835-3. http://dx.doi.org/10.1007/978-3-642-22836-0_2.

Sliwka, J., Reilhac, P.-H., Leloup, R., Crepier, P., de Malet, H., Sittaramane, P., le Bars, F., Roncin, K., Aizier, B., Jaulin, L., et al., 2009. Autonomous Robotic Boat of ENSIETA. In: Proceedings of the 2nd International Robotic Sailing Conference. pp. 1–7.

Springer, P.J., 2018. Outsourcing War to Machines – The Military Robotics Revolution. Praeger Security International, Santa Barbara, California, ISBN: 978-1-4408-3085-3.

Stelzer, R., 2012. Autonomous Sailboat Navigation – Novel Algorithms and Experimental Demonstration (Ph.D. thesis). De Montfort University.

Stelzer, R., Dalmau, D.E., 2012. A study on potential energy savings by the use of a balanced rig on a robotic sailing boat. In: Robotic Sailing 2012 – Proceedings of the 5th International Robotic Sailing Conference. pp. 87–93. ISSN 978-3-642-33083-4. http://dx.doi.org/10.1007/978-3-642-33084-1_8.

Stelzer, R., Jafarmadar, K., 2009. History and recent developments in robotic sailing. In: Proceedings of the 2nd International Robotic Sailing Conference. pp. 31–35.

Stelzer, R., Jafarmadar, K., 2011. Communication architecture for autonomous sailboats. In: Proceedings of the 4th International Robotic Sailing Conference. pp. 3–23.

2019. The Microtransat Challenge. https://www.microtransat.org/index.php. (Accessed 09 November 2018).

Tretow, C., 2017. Design of a Free-Rotating Wing Sail for an Autonomous Sailboat (Masters thesis). KTH Royal Institute of Technology – School of Engineering Sciences.

Tynan, D., 2017. An attractor/repellor approach to autonomous sailboat navigation. In: Robotic Sailing 2017 – Proceedings of the 10th International Robotic Sailing Conference. pp. 69–79. ISSN 978-3-319-72738-7. http://dx.doi.org/10.1007/978-3-319-72739-4_6.

Wang, Q., Kang, M., Xu, J., Xu, J., 2015. Autonomous sailboat track following control. In: Robotic Sailing 2015 – Proceedings of the 8th International Robotic Sailing Conference. pp. 125–136. ISSN 978-3-319-23334-5. http://dx.doi.org/10.1007/978-3-319-23335-2_10.

Wikipedia, 2019a. 2010 America's cup. ISSN 978-3-319-45452-8. https://en.wikipedia.org/wiki/2010_America's_Cup#Regatta. (Accessed 07 May 2019).

Wikipedia, 2019b. USA 17. https://en.wikipedia.org/wiki/USA_17. (Accessed 05 May 2019).

Winters, J., 2013. Flying boat – An innovative sailboat design didn't just set a new record–it skimmed over the water at highway speed. will the sailrocket usher in a new age of sail?. Mech. Eng. Mag. Sel. Artic. (ISSN: 0025-6501) 135, 50–57. http://dx.doi.org/10.1115/1.2013-AUG-3, http://memagazineselect.asmedigitalcollection.asme.org/data/journals/meena/936986/me-2013-aug3.pdf.

Wirz, J., Tranzatto, M., Liniger, A., Colombino, M., Hesse, H., Grammatico, S., 2015. AEOLUS, the ETH autonomous model sailboat. In: Robotic Sailing 2015 – Proceedings of the 8th International Robotic Sailing Conference. pp. 103–112. ISSN 978-3-319-23334-5..