History and Recent Developments in Robotic Sailing

Roland Stelzer and Karim Jafarmadar

Abstract Robotic sailing boats represent a rapidly emerging technology for various tasks on lakes and oceans. In this paper we give an overview about the main building blocks of a robotic sailing boat for controlling the rudder and the sails. History of robotic sailing includes developments in mechanical, electronic, and intelligent self-steering systems as well as automatic sail control. Furthermore advantages and disadvantages of rigid wing sails in comparison to traditional fabric sails are illuminated. Early examples of robotic sailing boats and recent developments, stimulated by robotic sailing competitions such as Microtransat Challenge, SailBot and World Robotic Sailing Championships are presented. We conclude with a brief outlook on potential applications in the field of robotic sailing.

1 Introduction

Autonomous sailing robots perform the complex tasks of sailing boat navigation fully automatically and without human assistance. Bowditch [13] defines navigation as *"the process of monitoring and controlling the movement of a craft or vehicle from one place to another"*.

Robotic sailing boats therefore have to perform the complex planning and manoeuvres of sailing fully automatically and without human assistance. Starting off by calculating an optimum route based on weather data and going on to independent

Roland Stelzer
INNOC – Austrian Society for Innovative Computer Sciences,
Haussteinstraße 4/2, 1020 Vienna, Austria, e-mail: roland.stelzer@innoc.at
Centre for Computational Intelligence, De Montfort University,
Leicester, LE1 9BH, United Kingdom, e-mail: rstelzer@dmu.ac.uk

Karim Jafarmadar
INNOC – Austrian Society for Innovative Computer Sciences,
Haussteinstraße 4/2, 1020 Vienna, Austria, e-mail: karim.jafarmadar@innoc.at

tacking and jibing and avoiding collisions, stand-alone sailing boats are able to sail safely and reliably through to any and every destination. The human being merely has to enter the destination co-ordinates.

The key characteristics of a robotic sailing boat can be summarized as follows:

- Wind is the only source of propulsion.
- It is not remotely controlled; the entire control system is on board.
- It is completely energy self-sufficient; this is not a must in the sense of definition of a robotic sailing boat, but it opens a wide range of applications.

Although many technical aids are available for common sailing boats, relatively little effort has been spent on research of autonomous sailing. Research on autonomous surface vehicles (ASV) was mainly focused on short-range crafts powered by electrical or combustion engines. Such crafts are limited in range and endurance depending on the amount of fuel or battery capacity on board to run a motor for propulsion. In contrast a sailing vessel needs only a minimal amount of power to run sensors, computers and to adjust sail and rudder position.

Extensive research has been undertaken on semi-autonomous systems, where just a subset of the functionality of a robotic sailing boat is covered. The history of self-steering gears and automatic sail control will be discussed independently in the following sections. Afterwards a separate section shows history and recent research projects in completely autonomous sailing.

2 History of robotic sailing

2.1 Self-steering gear

Historically, the first task to be automated was the governing of the rudder. A self-steering gear is an equipment used on ships and boats to maintain a chosen course without constant human action. Self-steering gear is also referred to as *autopilot* or *autohelm*[1]. Basically the different forms of self-steering gears can be divided into two categories: mechanical and electronic.

2.1.1 Mechanical self-steering

Fishermen who bind the rudder or tiller of their boat in a fixed position to produce an optimal course can be seen as a first approach to a mechanical self-steering system [37].

A more sophisticated mechanical approach is the *wind vane* developed first by Herbert Hasler (1914-1987), who is known as one of the fathers of single-handed

[1] Autohelm is a Raymarine trademark, but often used generically.

sailing[2]. Wind vanes are now sold by a number of manufacturers, but most share the same principle: The device consists of a wind vane secured at the stern of the yacht, which is connected to the rudder respectively a trim tab on the rudder via a system of ropes, pulleys and servos (see figure 1). When the angle of the apparent wind[3] changes, this change is registered by the air vane, which activates the steering device to return the boat to the selected point of sail[4]. Wind vane self-steering does not steer a constant compass course but a constant point of sail.

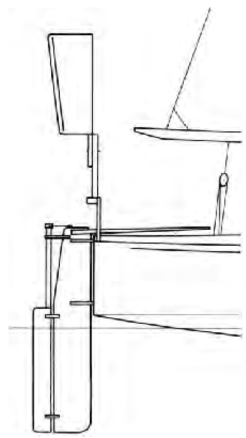


Fig. 1 Example for a wind vane with trim tab on main rudder (from [41])

2.1.2 Electronic self-steering

Electronic self-steering controls the rudder movement by electronics based on various sensor input values. At least a compass is necessary; additional sensors can deliver wind direction or GPS position in order to calculate a heading towards a given target waypoint.

Substantial progress toward automatic steering was based on the invention of electronic gyrocompasses. The earliest known gyroscope-like instrument was made by German Johann Bohnenberger, who first wrote about it in 1817 [12]. According to Bennett [9] and Roberts [37] the major contributions to the development of a practical automatic steering system were made by Sperry Gyroscope Company. Elmer Sperry developed his first automatic ship steering mechanism in 1911 [3, 46]. Sperry's gyropilot was known as *Metal Mick* as it was capturing much of the behaviour of an experienced helmsman. It compensated for varying sea states

[2] Single-handed sailing is sailing with only one crew member. The term is usually used with reference to ocean and long-distance sailing.

[3] Apparent wind is referred to as the velocity of air as measured from a moving object, as a ship.

[4] Point of sail describes the direction of a boat with respect to the direction of the wind.

using feedback control and automatic gain adjustments. This lead to a first simple adaptive autopilot.

The work of Minorsky [32] is also regarded as making key contributions to automatic ship steering. Nicholas Minorsky presented a detailed analysis of a position feedback control. He formulated the specification of a three-term controller, better known as proportional-integral-derivative (PID) controller.

2.1.3 Intelligent rudder control

Conventional electronic self-steering systems found on the majority of vessels at sea still employ PID control algorithms to control the heading [18]. Van Amerongen [52] identified two major disadvantages of this type of controller:

1. It is difficult to adjust manually, because the operator usually lacks the insight into control theory.
2. The optimal adjustment varies and is not known by the user. Changing circumstances require manual readjustment of a series of settings.

Due to the highly dynamic and ever-changing environment, artificial intelligence (AI) techniques, like fuzzy logic (FL), artificial neural networks (ANN), and combinations thereof have received considerable attention for rudder control on ships. Various publications have shown the suitability of FL for rudder control [55, 1, 56, 49]. Polkinghorne et al. [36] furthermore made a comparison to its conventional PID controlled equivalent. The experiments have shown a much smoother rudder action for the FL controller. Stelzer et al. [49] again demonstrated a reasonable performance of a FL controlled rudder, even during tacking an jibing.

Adaptive FL controllers have been presented as a promising approach to combine expert's knowledge and new experiences automatically. In Velagic et al. [53] a Sugeno type fuzzy inference system is combined with a feedback loop to adjust scaling factors of the base fuzzy system. For the mentioned FL approaches human expert's knowledge must be known a priori to design the fuzzy rule set. In contrast, Layne and Passino [26] published a learning control algorithm which automatically generates the fuzzy controller's knowledge base on-line as new information on how to control the ship is gathered. Other examples of adaptive rudder control systems are based on artificial neural networks. Both Enab [24] and Burns [18] aim to provide an ANN-based system that can adapt its parameters towards optimal performance over a range of conditions without the need of manual adjustments.

An ambitious machine-learning approach to automatic rudder control was the *RoboSail* project [51]. The project started in 1997 with the aim to build a self-learning autopilot for a single-handed sailing yacht. Agent technology, machine learning, data mining, and rule-based reasoning have been combined to a system which became commercially available after five years of development [2].

A rudderless approach on automatic heading control of a sailing boat was presented by Benatar et al. [8]. They have shown, that control of a rudderless boat with two sails can be achieved by coordinating the two sails for propulsion and turning.

2.2 Automatic sail control

While extensive research has been carried out on automatic steering devices, automatic sail trim is a more recent idea and not yet well covered by scientific publications.

2.2.1 Rigging and sails

So far several different riggings[5] have been used on robotic sailing boats. They can be characterised according the following criteria:

- **Material and shape:** traditional fabric sail or rigid wing sail
- **Rigging:** Balanced or unbalanced

In history of sailing, which lasts several thousands of years, a large variety of different sail shapes and technologies have been used. Virtually all boats apart from the recent sailing history used conventional fabric sails. This form of sails have some advantageous properties, especially when controlled by a human sailor. This includes the easy way of reefing, repairing, or that shape and camber can be altered by simply tensioning and releasing control lines.

I contrast, a wing sail is a rigid surface with an aerofoil cross-section similar to an aircraft wing. It can provide a much better lift-to-drag ratio than conventional sails [43]. Neal et al. [35] state as significant disadvantages of a wing sail that it is extremely difficult to design it in a way that it can be reefed reliably. Furthermore to construct strong, lightweight rotatable wings at reasonable costs is mentioned there to be difficult. However, they maintain after extensive testing with different wing sails that the potential gains in reliability and efficiency outweigh these problems.

Although most of autonomous sailing boats featuring wing sails have been either designed for longevity [35] or precision sailing [22] rather than for performance, the America's Cup 2010 has shown impressively the dynamic abilities of a rigid wing sail. The trimaran USA-17 (formerly known as BMW Oracle Racing 90 or BOR90) won the trophy with a rigid wing as its main sail.

On a conventional sloop rig, which is the most common rig type on sailing vessels, relatively high power is needed to tighten the sails against wind force. As being self-sufficient in terms of energy is one of the major goals in robotic sailing, the rig design has been put into the focus of attention. A balanced rig design (also known as Balestron rig, Aerorig^{TM}, swing rig, and EasyRig^{TM}) provides great potential to save power [33, 7]. A balanced rig consists of an unstayed mast carrying a main and jib (see Fig. 2). The main boom extends forward of the mast (the mast passes through the boom) to the tack of the jib. The main and jib are sized so that the force from the mainsail is slightly higher than that from the jib. That is, the combined center of effort is just behind the mast. Therefore the load on the sheets is reduced

[5] Rigging is the mechanical sailing apparatus attached to the hull in order to move the boat as a whole. This includes cordage, sails, and spars (masts and other solid objects sails are attached to)

by more than 50 % compared to a conventional rig due to the balanced distribution of the sail load caused by wind [25].

Balanced rigs have been used on the autonomous sailing boats *Avalon* [25] and *IBoat* [14]. Furthermore, most of the rigid wing sails mentioned above can be considered to be balanced rigs.

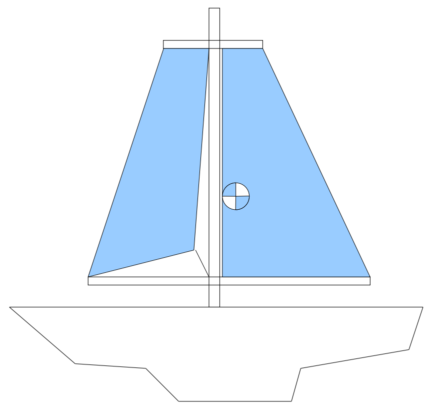


Fig. 2 Balanced rig example: the combined center of effort is just behind the mast.

2.2.2 Sail control strategies

Most sail control strategies published for autonomous sailing boats rely on locally measured apparent wind data only [1, 17, 25]. While many of them have a virtually infinite number of sail positions (limited just by the resolution of the actuator or the used data types) and therefore allow smooth sail control, just 10 discrete sail position are used on *MOOP* (University of Aberystwyth, UK) featuring a hysteresis condition to avoid permanent switching between two adjacent positions [17]. Reasons for a reduced number of sail positions are to save power on the sail actuator and to extend the lifetime of the sail gear. A state machine to allow for special sail trim during manoeuvres such as tack and jibe has been implemented on *Däumling* (University of Lübeck, Germany) *Avalon* (Swiss Federal Institute of Technology Zurich, Switzerland) and *IBoat* (ISAE, France) [25, 14, 17].

A method which does not directly calculate a sail position based on wind data was published by Stelzer et al. [49]. It firstly determines a desired heel[6] for the boat out of speed and direction of the apparent wind. A feedback-loop implemented as a Mamdani type fuzzy inference system then controls the sail position towards this heel value.

[6] Heeling is the sidewards tilt of a sailing boat usually caused by lateral wind force.

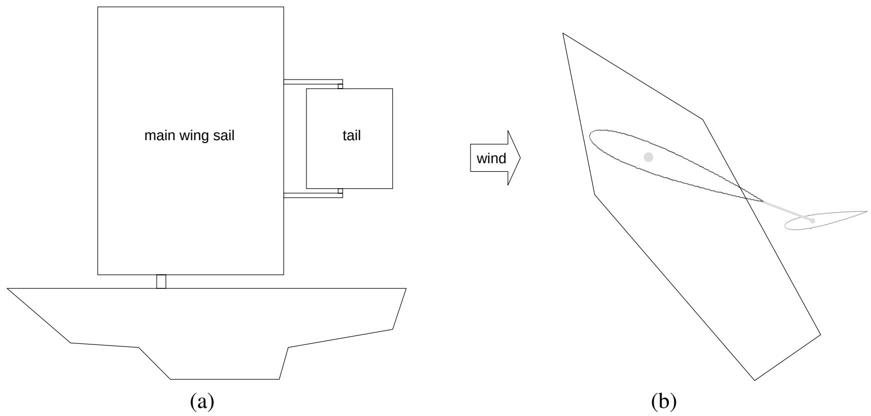


Fig. 3 Self-trimming wing sail: (a) side view of an arrangement with main wing sail and tail (b) orientation of wing sail and tail on a close hauled course

All methods described above can basically be applied to both conventional and wing sails. For the latter a further control method has been published, namely a self-trimming wing sail. A self-trimming arrangement typically consists of a wing sail vertically mounted in bearings that allow free rotation. A smaller wing called *tail* is usually mounted just behind the main wing (see figure 3). An aircraft uses tails to control the exact angle of attack of its wings. Similarly, the tail on a wing sail system is able to control the thrust obtained from the wind and will automatically take into account any changes in wind direction [54]. Extensive research on self-trimming wing sails have been carried out by Elkaim and Boyce [23]. Their experiments have shown upwind progress at $20-25$ deg and speeds of 60 % of the true wind speed under wind speeds from $12-25$ kn (approximately $6-13$ m/s) using a self-trimming wing sail on a 9.1 m catamaran.

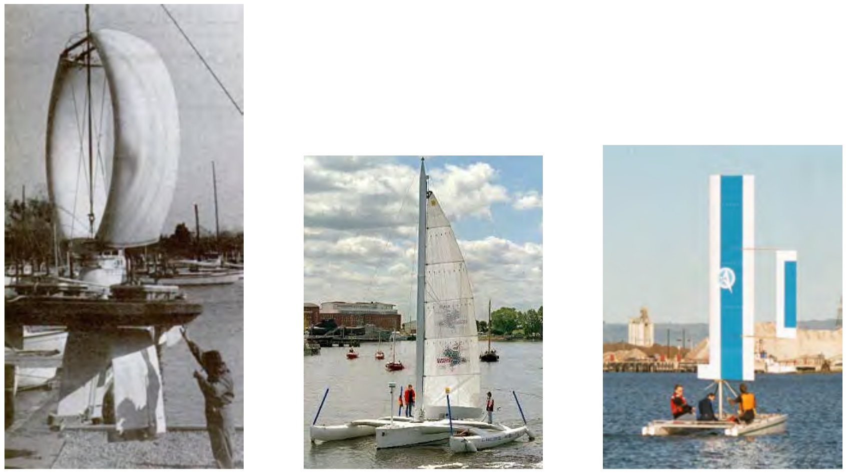
3 Scientific community and events

3.1 Early examples

Prior to 2005 when the idea of *Microtransat Challenge*[7] initiated a new era of collaborative research in robotic sailing, a large number of autonomous underwater vehicles (AUV) have been developed [11, 4]. However, research on autonomous surface vehicles (ASV), also known as autonomous surface crafts (ASC), was still in its early stage and mainly focused on motorised vessels [19, 28]. Just a few researchers worked on fully autonomous sailing robots. According to their publications these

[7] `http://www.microtransat.org`

teams seemed not to be well linked to each other. A few of the most noticeable early examples are described briefly here.



(a) (b) (c)

Fig. 4 Early robotic sailing boats: (a) SKAMP – Station Keeping Autonomous Mobile Platform [45] (b) RelationShip [27] (c) Atlantis

3.1.1 Station Keeping Autonomous Mobile Platform (SKAMP)

The first attempt to autonomous sailing recorded in the literature is a project named *SKAMP (Station Keeping Autonomous Mobile Platform)*. The *SKAMP* was a wind propelled mobile surveillance platform and utilized a curving ring-shaped rigid wing sail (Figure 4(a)). It was developed in 1968 by E. W. Schieben with the Radio Corporation of America and was optimised for autonomous station keeping rather than for dynamic performance [42, 45]. Actual sailing data have never been published, so it remains unclear whether SKAMP ever sailed autonomously [21].

3.1.2 RelationShip

The second published autonomous sailing attempt was the *RelationShip* project of University of Applied Science in Furtwangen, Germany (Figure 4(b)). The project started in 1995 with the ambitious plan to sail around the world with an unmanned trimaran. According to Elkaim [21] the initial intention was to sail autonomously. However, after some difficulties the project changed to a remote control via satellite. After some years the project was cancelled due to regulatory difficulties. They did not get the permission to circumnavigate the globe with their unmanned RelationShip. The idea to declare the boat as floatsam did not convince the maritime authorities [47].

3.1.3 Fuzzy Logic Controlled Sailing Boat by Abril et al. [1]

The first documented results of fully autonomous sailing have been published by Abril et al. [1]. They presented a fuzzy logic controller for the rudder and sail of a sailing boat. Test runs have been carried out on a yacht model with an overall length of 1.03 m, a displacement of 4.5 kg and a sail area of 36.6 dm^2.

3.1.4 Atlantis

The *Atlantis* project of Stanford University began in 1997 with the concept of an unmanned, autonomous, GPS guided, wing-sail propelled sailing boat. The boat is based on a Prindle-19 Catamaran, with a self-trimming wing-sail (Figure 4(c)[8]). The maiden voyage took place in Redwood City Harbour in January 2001. [21, 22].

3.2 Competitions in robotic sailing

In many fields of robotics competitions with memorable goals cause the attention of media and the interested public, and therefore give a strong incentive to research and development in the particular area. The most popular examples in robotics are DARPA Grand Challenge for completely autonomous cars [50] or RoboCup soccer robots which aim to beat the human world champions by 2050 [38]. The same happened to autonomous sailing during the first decade of the 21^{st} century, when different events have been founded almost at the same time.

3.2.1 Microtransat

Research in autonomous sailing has been recently stimulated by the *Microtransat* idea of Yves Briere (ISAE, France) and Mark Neal (Aberystwyth University, Wales, UK) [15, 14]. The organizers describe the *Microtransat* in on their web site [29] as follows: *"The Microtransat Challenge is a transatlantic race of fully autonomous sailing boats. The race aims to stimulate the development of autonomous sailing boats through friendly competition."* Participating sailing boats shall further be small (max. 4 m in length), unmanned, and use wind as the only form of propulsion. A few smaller Microtransat competitions took place prior to the real transatlantic

[8] ©Gabriel Elkaim

race. These allowed contestants to exchange ideas and test their boats in less harsh environments.

The first transatlantic attempt was in 2010. The only boat which entered the competition was *Pinta* from Aberystwyth University, Wales, UK. According to Colin Sauzé the boat was 49 *h* and 87 *km* under autonomous control before the computer system failed.[9]

3.2.2 SailBot

SailBot is an international competition for autonomously controlled sailboats. Aimed primarily at undergraduate student teams, the goal is to give engineering students a practical application of the topics they have learned, while also providing a fun way to learn project management in a multidisciplinary environment. A successful *SailBot* balances the needs of naval architecture, mechanical engineering, systems and electrical engineering, as well as project management.[10] *SailBot* competitions were held annually since 2006, except 2007.

SailBot is open for semi-autonomous and fully autonomous sailing boats up to 2 m in length. Since 2010 they provide an additional "open class" for boats with a maximum length of 4 m. For the 2011 competition five different events are announced: (1) fleet racing (2) station keeping (3) endurance contest (4) autonomous navigation and (5) presentation and design.

3.2.3 World Robotic Sailing Championship and International Robotic Sailing Conference

The World Robotic Sailing Championship (WRSC)[11] is an international competition for autonomous sailing boats. The first WRSC was held in Austria in 2008. Since then it took place every year: Portugal (2009), Canada (2010) and Germany (2011). The competition is open to boats of up to 4 *m* in length. Detailed rules of WRSC change every year to respond to recent scientific developments and stimulate certain areas of research. By keeping a rather low entry threshold, WRSC not only appeals to experts but also provides a platform for new teams in this recent field of research.

The competitions coincide with the International Robotic Sailing Conference (IRSC). This conference is the basis of scientific exchange in the robotic sailing community. The combination of competitions on the water and a scientific conference provides an opportunity to practically demonstrate theoretical developments.

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[9] Mail from Colin Sauzé on Microtransat mailing list from 02.10.2010

[10] Web site of SailBot 2011: `http://www.sname.org/SNAME/SailBot2011/Home/Default.aspx`

[11] `http://www.roboticsailing.org`

3.3 Competing teams and their sailing robots

This section provides an overview of the teams which participated in recent robotic sailing competitions and are covered by scientific literature. Many of them have been encouraged by these events to start research in the field of autonomous sailing. Figure 5 shows the increasing number of boats competing in autonomous sailing competitions since their invention in 2006. The teams are presented here in alphabetical order.

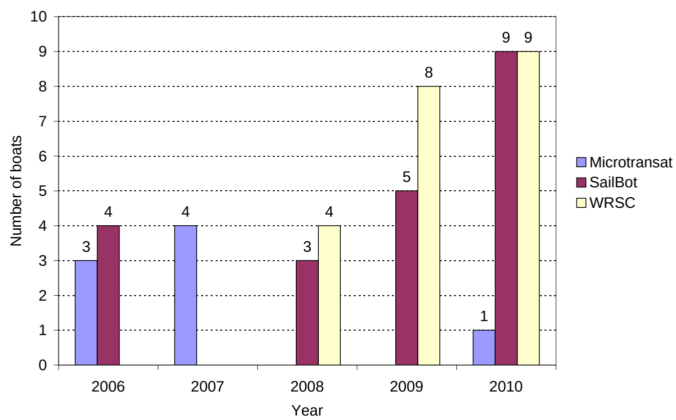

Fig. 5 Number of boats competing in Microtransat, SailBot and WRSC. In 2010 SailBot and WRSC were organised as a single event.

3.3.1 Austrian Society for Innovative Computer Sciences (INNOC)

The team of INNOC focuses on control algorithms rather than on boat design. So far, two commercially available hulls have been adapted for the purpose of autonomous sailing.

Roboat I (Figure 6(e)[12]) is based on a ready-made yacht model of type *Robbe Atlantis* intended to be remote-controlled. It is a gaff-rigged schooner[13] with a length of 1.38 m, a height of 1.73 m and a total displacement of 17.5 kg. The four sails comprise a total area of 85.5 dm^2. The boat is equiped with a 800 MHz PC running Linux, a GPS receiver, a tilt-compensated electronic compass and sensors for wind speed and wind direction. *Roboat I* won the Microtransat competition in 2006.

[12] ©INNOC

[13] A schooner is a type of sailing vessel characterized by the use of two or more masts with the forward mast being no taller than the rear masts.

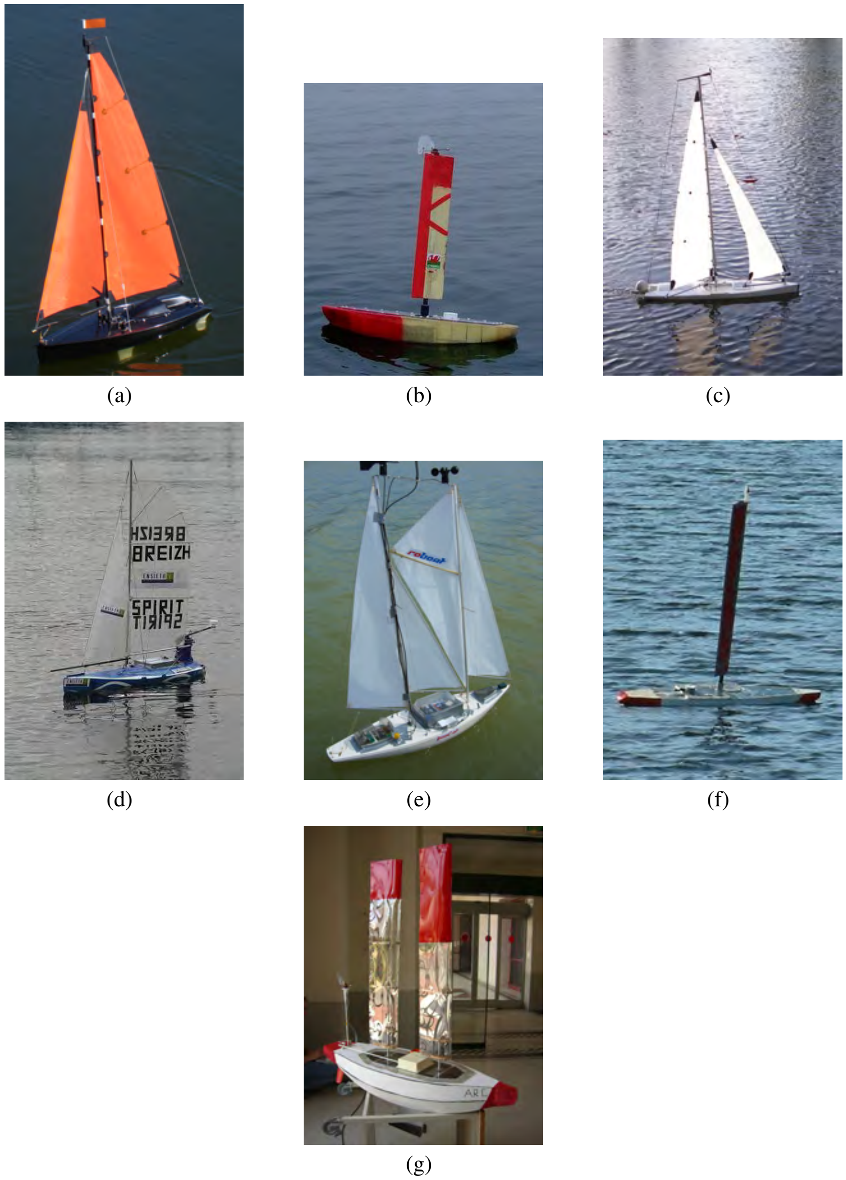

Fig. 6 Autonomous sailing vessels with a length of less than 2 m: (a) Däumling, University of Lübeck (b) MOOP, University of Aberystwyth (c) Pi-mal-Daumen, University of Lübeck (d) Breizh Spirit, ENSTA Bretagne (e) Roboat I, INNOC (f) AROO, University of Aberystwyth (g) ARC, University of Aberystwyth

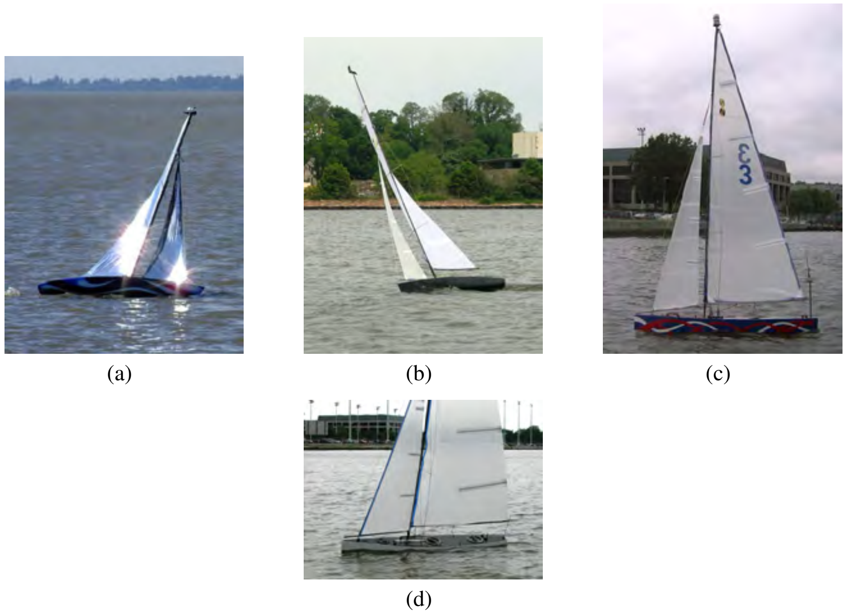

Fig. 7 Autonomous sailing vessels with a length of exactly 2 m: (a) Black Adder, Queen's University (b) First Time, USNA (c) Gill the Boat, USNA (d) Luce Canon, USNA

The basis for the *ASV Roboat* (Figure 8(e)[14]) is the commercially available boat tyle Laerling[15]. The boat was originally created for kids to learn sailing, and therefore safety and stability are its major characteristics. It has a length of 3.75 m and comprises a 60 kg keel-ballast, which will bring the boat upright even from the most severe heeling. Including batteries the overall weight of the boat is about 300 kg. The sail area of mainsail and foresail together is 4.5 m^2. It is equipped with solar panels providing up to 285 W_p of power during conditions of full sun and a direct methanol fuel cell delivering 65 W as a backup energy source. The *ASV Roboat* features a three-stage communication system, combining WLAN, UMTS/GPRS and an IRIDIUM satellite communication system, allowing continuous real-time access from shore [48]. Control software runs on a Linux-based on-board computer system using incoming data from various sensors (GPS, compass, anemometer, etc.) on an NMEA2000-bus. *ASV Roboat* won the Microtransat 2007 as well as the WRSC in 2008, 2009, and 2010.

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[14] ©INNOC

[15] `http://www.laerling.nl`

Fig. 8 Autonomous sailing vessels with a length of more than 2 m: (a) IBoat, ISAE (b) FASt, University of Porto (c) Pinta, University of Aberystwyth (d) Beagle-B, University of Aberystwyth (e) ASV Roboat, INNOC (f) Avalon, ETH Zurich

3.3.2 École nationale supérieure de techniques avancées (ENSTA) de Bretagne

A team of ENSTA Bretagne participated with their boat *Breizh Spirit* (Figure 6(d)[16]) in WRSC 2009. Their design uses a custom built hull based on the IMOCA class design with a length of 1.3 m and two traditional sails. The control system is implemented on a PIC18F2550 microcontroller. [44]

[16] ©Jan Sliwka

3.3.3 Institut supérieur de l'aéronautique et de l'espace (ISAE)

IBoat from ISAE, France (Figure 8(a)[17]) is made of fibreglass and carbon and therefore is relatively lightweight. *IBoat* has a length of 2.4 m and a height of 3 m. It features 1.5 m^2 of sail area in a combination of two sails (main sail and jib) both mounted on a balanced rig. Used sensors are an electronic compass, a wind sensor (speed and direction) and a GPS receiver. The sensors are connected to a microcontroller via CAN bus [14]. *IBoat* competed in Microtransat 2006 and 2007 as well as in WRSC 2009.

3.3.4 Queen's University

Mostly Autonomous Sailboat Team (MAST) was founded in 2004 at Queen's university. Their first vessel entering SailBot 2007 was *Black Adder* (Figure 7(a)[18]), a 2 m long carbon fibre hull with traditional sails using a PBasic Stamp for the control system. Since 2007 the team of undergraduate students made significant modifications to their first design and participated in the Microtransat Challenge 2007, WRSC 2008 and 2010 as well as SailBot 2008, 2009 and 2010. [17]

3.3.5 Swiss Federal Institute of Technology Zurich (ETH)

Avalon (Figure 8(f)[19]) was developed by a team of students from the Federal Institute of Technology, Zurich for the Microtransat challenge and participated in WRSC 2009. *Avalon* features a monohull design with a length of 3.95 m, a balanced rig and a twin rudder system. The power supply is realized with four solar panels of 90 W_p, four lithium-manganese batteries of 600 Wh each and a direct-methanol fuel cell for back-up power. The control system is implemented on an MPC21[20] industrial computer running Linux. [25]

3.3.6 United States Coast Guard Academy (USCGA)

Intuition was developed by the United States Coast Guard Academy and participated in SailBot/WRSC 2010. The USCGA's 2 m monohull design features a conventional sloop rig with a sail area of 1.7 m^2. The control system is implemented on an ISIS PC104 single board computer running Windows XPe and MATLAB. [17]

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[17] ©INNOC
[18] ©INNOC
[19] ©Patrick Moser
[20] http://www.kontron.com

3.3.7 United States Naval Academy (USNA)

USNA began their activities in 2007. They participated with their boat *First Time* (Figure 7(b)[21]) in SailBot 2008. In 2009 they entered *Luce Canon* (Figure 7(d)[22]) in SailBot and WRSC. In 2010 they participated with *Gill the Boat* (Figure 7(c)[23]) in SailBot/WRSC. The USNA team comprising undergraduate Naval Architects and Systems Engineers designs and builds new sailing vessels each year by continuously improving upon previous year's boats. Their designs use a custom built single hull with a length of 2 m and a conventional sloop rig with a sail area of about 3 m^2. [31, 30]

3.3.8 University of Aberystwyth

The team around Mark Neal and Colin Sauzé built multiple sailing robots varying in length between 50 cm and 3.5 m with the aim of performing long term autonomous missions for oceanographic monitoring.

AROO (Figure 6(f)[24]) was constructed in late 2004 as a proof of concept for a small but durable sailing robot. The hull is about 1.5 m long and is rigged with a 1 m high wing sail. [34]

ARC (Figure 6(g)[25]) is about 1.5 m in length and features two independently controlled wing sails and two rudders controlled by a single actuator. It is equipped with a gimbaled compass, GPS receiver and a combination of an AtMega128 microcotroller and a Gumstix[26] single board computer running Linux. The only power source is a bank of 20 pieces of 1.2 V AA size recharchable batteries with a capacity of 2500 mAh each. [40]

Beagle-B (Figure 8(d)[27]) is their largest boat and was constructed in late 2006 by Robosoft (a French robotics company). It is 3.5 m long and uses a 3 m solid wing sail. *Beagle-B* is intended to provide a serious oceanography platform for long term missions. Its power is provided by two 15 W solar panels and four 60 Ah batteries with 12 V. It includes a YSI 660 Sonde for gathering oceanographic data as well as an Iridium SBD transceiver and GSM modem for data transmission. *Beagle-B* participated in the Microtransat Challenge 2007 in which it sailed a total of 25 km over 19 hours. [40]

Pinta (Figure 8(c)[28]) was built for WRSC 2008 and the Microtransat transatlantic race. Unlike the other boats of the team it uses a single traditional sail controlled by

[21] ©Paul Miller
[22] ©Paul Miller
[23] ©Paul Miller
[24] ©Colin Sauzé
[25] ©INNOC
[26] `http://www.gumstix.com`
[27] ©Colin Sauzé
[28] ©Colin Sauzé

an electric winch system. *Pinta* is based on a Toper Taz sailing dinghy with a length of 2.95 m. The rudder is controlled by an off the shelf auto-helm. *Pinta* was the only boat to enter the 2010 Microtransat Challenge.

The *MOOP* (Mini Ocean Observation Platform; Figure 6(b)[29]) is a small lightweight sailing robot with an overall length of 0.72 m. Multiple *MOOPs* have been built so far with single or twin wing sail configuration, with rudders and rudderless. They are controlled either solely by a PIC microcontroller or with a combination of PIC and Gumstix Single Board Computer. Several *MOOPs* took part in the SailBot and WRSC competitions in 2009 and 2010. [17]

3.3.9 University of Lübeck

University of Lübeck started their autonomous sailing activities in 2009. They participated in Sailbot/WRSC 2010 with two boats.

Däumling (Figure 6(a)[30]) is based on a University Club (Graupner, Germany) boat model with a length of 0.53 m and two sails with a total sail area of 0.145 m^2. The boat is inteded to be used as a testbed for various methods of artificial intelligence. [16]

Pi-mal-Daumen (Figure 6(c)[31]) is based on a standard IOM (International One Meter class) hull with a length of 1 m and two sails with a total sail area of 0.4 m^2. On board control is realised with a custom built circuit board featuring an ATMega2560 microprocessor. [6]

3.3.10 University of Porto

Team *FASt* (Figure 8(b)[32]) developed a 2.5 m long custom built hull and has a total sail area of 3.7 m^2. The design was inspired by modern racing ocean yachts. The control system is implemented on a small FPGA-based single board computer, including a 32-bit RISC microprocessor running at 50 MHz. Communication with the boat is possible using Wi-Fi, GSM, Iridium SBD and a conventional RC receiver used in radio-controlled models. *FASt* entered in WRSC 2008 and 2009. [5]

4 Potential applications

Recent events, like the devastating tsunami in Asia in 2004, the Deepwater Horizon oil spill in Gulf of Mexico in 2010, accidents with refugee boats off the coast of

[29] ©Colin Sauzé
[30] ©Alexander Schlaefer
[31] ©Alexander Schlaefer
[32] ©José Carlos Alves

Lampedusa, Italy, and pirate activities in the Gulf of Aden have emphasized impressively the importance of a fully integrated ocean observation system [39]. AUVs and motorised ASVs are widely-used for ocean observations since many years [10, 39]. According to Cruz and Alves [20] the main strengths for unmanned autonomous sailing boat for this task are:

- Long mission ranges
- Negligible operational costs
- Potential for towing sensors
- Real time data transmission
- Real time localisation
- Very low noise generation

Not all of the possible applications mentioned in the list below are likely to be realised in the next few years. The current focus is clearly set on ocean monitoring. But some more tasks are possible to be fulfilled by manned or unmanned sailing robots:

- Intelligent sensor buoys
- CO_2-neutral transportation of goods
- Reconnaissance and Surveillance
- Supply Vessel
- Unmanned ferrying
- Minefield mapping

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