THE ROBOTIC SAILING BOAT ASV ROBOAT AS A MARITIME RESEARCH PLATFORM

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SUMMARY

Robotic sailing boats represent a rapidly emerging technology for various tasks on lakes and oceans. They offer the possibility of sampling an area of interest with high temporal and spatial resolution at low cost. This paper gives an overview about the main building blocks and maritime research missions of the *ASV Roboat*. The boat won several international competitions in robotic sailing in recent years and is therefore at the forefront of international excellence. The *ASV Roboat* has just returned from a several-day research mission in the Baltic Sea. By using a hydrophone attached to the boat's keel, the acoustic signals of a number of whales were recorded during the survey, and valuable information was collected on the presence of these animals in the study area. To the authors' knowledge this is the first time that an autonomous sailing boat has been successfully deployed as part of a scientific research project.

1. INTRODUCTION

By robotic sailing we mean that the whole process of sailing boat navigation is performed by an autonomously acting system of technical devices. Bowditch (2010) 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 tacking[1] and jibing[2] 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 remote 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.

Many technical aids, such as self-steering gears, chartplotters[3], electric winches, or weather routing software are available for common sailing boats. However, relatively little time and effort has been spent on autonomous sailing. Research on autonomous surface vehicles (ASV) has been mainly focused on short-range crafts powered by electric 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.

2. MOTIVATION

Recent events, like the devastating tsunamis in Asia, the Deepwater Horizon oil spill in Gulf of Mexico, accidents involving refugee boats off the coast of Lampedusa, Italy, and pirate activities in the Gulf of Aden have clearly emphasized impressively the importance of a fully integrated ocean observation system (Rynne and Ellenrieder, 2009). Robotic sailing boats represent a rapidly emerging technology for various tasks on lakes and oceans. Beside ocean monitoring a few more applications are possible. However, not all of the following applications are likely to be realised within the next few years.

- CO_2-neutral transportation of goods and unmanned ferrying: The price of fuel is expected to increase dramatically in the next few decades and additionally, penalties for CO_2 emissions might add to transport costs. Therefore better alternatives for the transportation of goods or people need to be sought. Traditional sailing boats are environment-friendly but they require a rather large input in terms of human intervention and therefore incur high personnel costs.

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[1] A tack or coming about is the manoeuvre by which a sailing boat or yacht turns its bow through the wind so that the wind changes from one side to the other.

[2] A jibe (also referred to as jib or gybe) is when a sailing boat turns its stern through the wind, such that the direction of the wind changes from one side of the boat to the other.

[3] A Chartplotter is a device that displays an electronic navigational chart along with the position, heading and speed of the boat, and may display additional information from radar or other sensors.

- Reconnaissance and surveillance: An autonomous sailing boat can be sent out to remote areas or dangerous regions. Due to its silent, unmanned and energy self-sufficient attributes it is a safe alternative for surveillance of critical areas (piracy, smugglers, fisheries, etc.).
- Supply vessel: Secluded regions with a low number of inhabitants or research base camps on islands can be cost-effectively supplied by autonomous sailing boats with equipment, medicine, food or correspondence.
- Minefield mapping: Unmanned vehicle systems are useful in their ability to remove humans from dangerous environments. Unmanned robotic sailing boats can explore hazardous regions on the water without exposing people to risks.

A principal problem in ocean monitoring is the limitation in spatial and temporal coverage of the observations (see Figure 1). Measurement can either be done with a moving platform (e.g. research vessel) or stationary recording devices (e.g. anchored recorders). Moving platforms offer the possibility of sampling a large area in a short period of time. However, because of the high costs of ship time temporal coverage is very limited. In contrast, stationary recording devices allow continuous sampling of an area. Their disadvantage lies in the limited spatial coverage of the devices (Multirig, 2009).

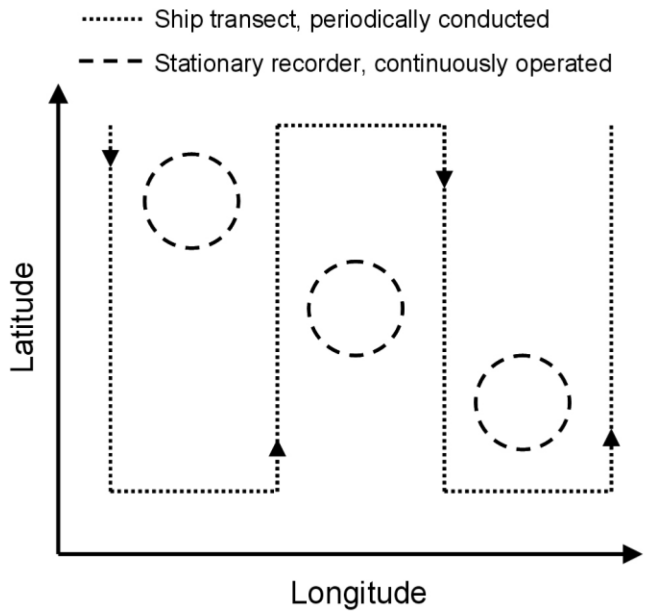

Figure 1 *Comparison of the spatial and temporal coverage of a research vessel (dotted line) and stationary recorders (dashed circles)*

Autonomous and remotely navigable ocean observation platforms offer the possibility of sampling an area of interest with high temporal and spatial resolution at low cost. To date, two autonomous and remotely navigable platforms are available for research on the ocean: wave-powered vessels, e.g. the Wave Glider™ (LiquidRobotics, 2009) and ocean gliders, e.g. the Seaglider™ (Eriksen et al., 2001). The Wave Glider provides a submerged (swimmer) and a surface (float) unit.

Both units are connected via a tether and allow the swimmer to move up and down as a result of wave motion. The swimmer includes several fins which interact with the water as the swimmer moves up and down, and generate forces which propel the vehicle forward. The Wave Glider, developed by Liquid Robotics, Inc., has proven long-term capabilities in a five-month test trial, and the device seems well-suited for long-term observations.

Gliders are commercially available from several manufacturers (e.g. Seaglider, 2009), and all types are based on the same principle. Changes in buoyancy cause the glider to move down and up in the water, and as with an aeroplane glider, wings transform this vertical motion into forward motion. A stable, low-drag, hydrodynamic shape allows the glider to fly efficiently through the oceans. These devices are optimized for extremely low energy requirements and designed to operate at depths up to 1000 m. Gliders are capable of long-term operation and have been used extensively for oceanographic research for a number of years.

An advantage of submerged operated vehicles is the limited surface time, which minimises the risk of a collision with other obstacles, reduces damage from highenergy surface phenomena (wind and waves), and reduces the possibility of potentially harmful human action. Furthermore gliders can be deployed in polar regions, where ice coverage prohibits the usage of surface vehicles, and in areas with high wind and waves where the traditional visual means of marine mammal observation are ineffective. On the other hand, submerged operated platforms such as gliders also suffer from some drawbacks:

- **Speed:** The typical horizontal cruise speed of most gliders is approximately 0.25 m/s (0.5 kt). This low speed does not allow surveying a large area in a reasonably short time period. To be able to conduct a survey in a shorter amount of time, a larger number of gliders (number depending on the size of the area of interest) must be deployed. A larger number of devices significantly increases the complexity and cost of a survey.
- **Payload:** Most gliders are relatively small instruments and provide relatively limited payload capacity. Larger payloads allow for more batteries and sensors, so the small capacity of gliders limits both their deployment duration and their capability for measuring a wider suite of oceanographic parameters. An additional constraint in gliders is that the payload must be horizontally balanced.
- **Continuous real-time access:** As gliders stay submerged most of time, these platforms do not provide continuous real-time access. For real-time monitoring the minimum response time of a glider is the time it takes to rise to the surface - potentially several hours - plus a small amount of data transmission time.
- **Sensors:** The operating power for gliders comes from batteries. Because of constraints in payload mass, the amount of energy available for operating powerintensive electronics such as optical sensors is small.
- **Computational power:** Because of the energetic limitations, sophisticated and thus energy-intensive computations cannot be run continuously onboard a glider.
- **Reliability:** A malfunction at depth can cause the loss of a glider.
- **Duration:** Because of the limited energy capacity, glider deployments for longterm studies are limited to a duration of several weeks.

With an unmanned, autonomous, and energy self-sufficient robotic sailing boat, it is possible to overcome many of the disadvantages and limitations of today’s technologies for ocean monitoring.

3. THE ASV ROBOAT

Similar to all relevant research groups in robotic sailing, the authors used robotic sailing boat prototypes for field experiments as one of his main research method. Two robotic sailing boats have been developed especially for this purpose.

The authors started with a 1:38 m long first prototype Roboat I, based on an off the shelf yacht model. The advantages of such a small robot are that it is cheap, lightweight, easy to handle and easy to build. Test runs can easily be arranged without the need for any special infrastructure (slip ramp, crane) or a chasing boat. On the other hand a boat of this size is extremely sensitive even to small waves and wind gusts. This makes it difficult to reproduce experimental results and to evaluate the implications of minor changes in the control system. Furthermore, with its restricted space for additional equipment and a relatively short operating time, it is not a serious platform for maritime applications.

Due to these limitations a second and significantly larger prototype named *ASV Roboat* has been built. This boat is 3:72 m in length and provides enough space for additional equipment, which enables it to be used for the first real-world applications of autonomous sailing technology. Furthermore, due to the fact that both boats run the same software, the scalability of the control methods could be demonstrated.

The *ASV Roboat* is the second prototype developed by the INNOC research team and it was built to take part in the Microtransat Challenge 2007 in the Irish Sea off the coast of Wales, UK. The Roboat I would not have been suitable for the conditions that prevail there. The 24-hour competition, in particular, made a larger boat essential to accommodate the on-board batteries required.

Furthermore, it was hoped that the larger boat would allow the experiments to be reproduced more accurately, as small waves or gusts of wind do not have such a large influence on handling as was the case with the significantly smaller Roboat I.

3.1 Laerling class boat

The basis for the *ASV Roboat* (Figure 2) is the commercially available boat type Laerling. 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 5:4 m^2.

Figure 3 shows the technical infrastructure that was set up during the conversion to a robotic sailing boat. It includes sensors, actuators and power supply. The individual areas will be discussed in more detail below.

Figure 2 *ASV Roboat at field tests on the Baltic Sea (2012)*

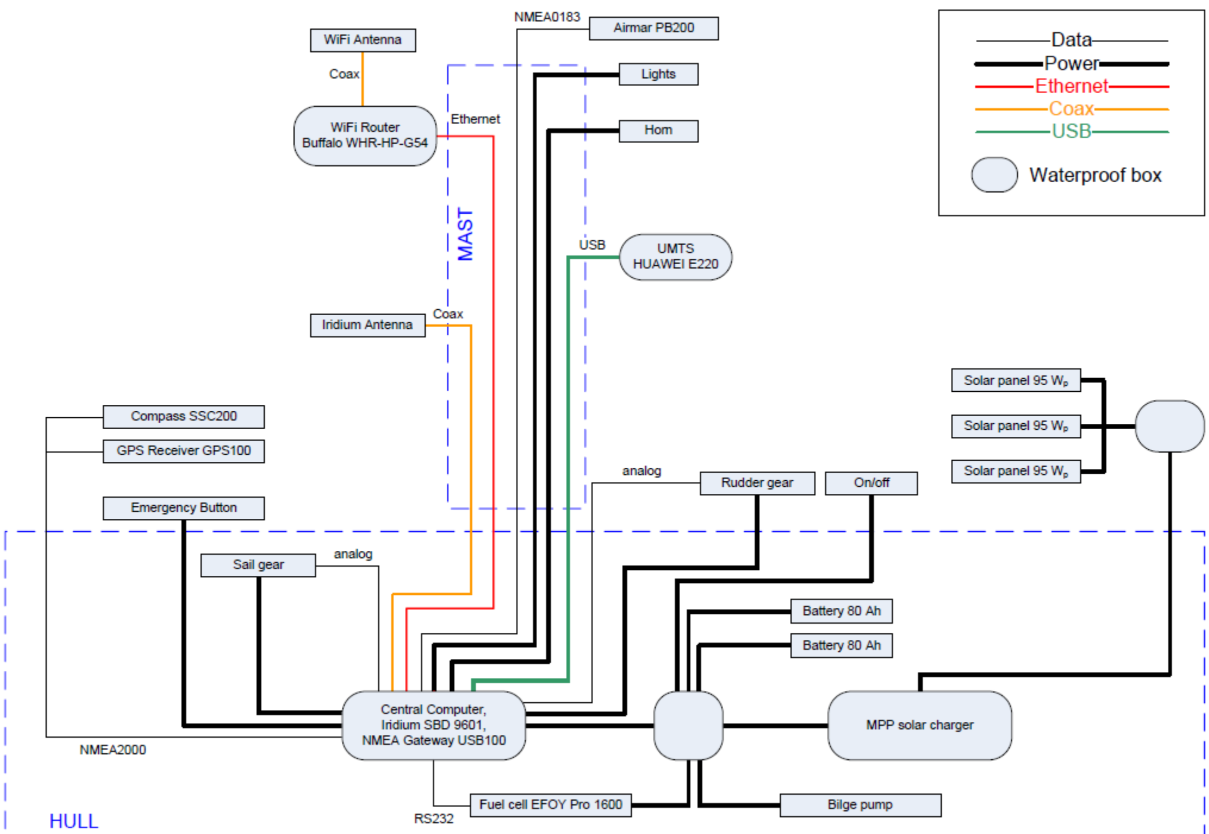

Figure 3 *Technical infrastructure on ASV Roboat*

3.2 Computer and communications

The control software runs on a Linux-based on-board computer system using incoming data from various sensors (GPS, compass, anemometer, etc.).

The computer, together with the other electronic components, is housed in a water-tight case (Peli 1500, Protection Class IP67) and connected with the sensors and actuators on the boat using plugs of Protection Class IP67 (Phoenix M12 and Phoenix 7/8"series) (Figure 4).

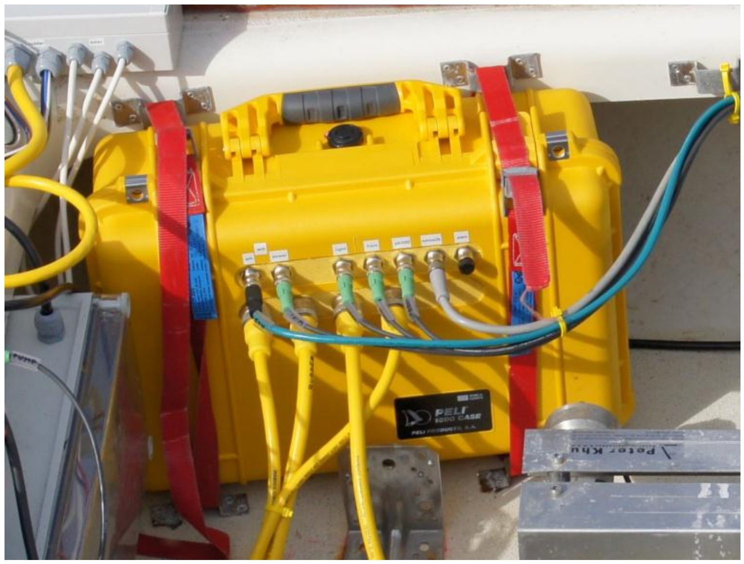

Figure 4 *Waterproof box with IP67 Connectors*

The *ASV Roboat* features a three-stage communication system, combining WLAN, 3G and an iridium satellite communication system[4], allowing continuous real-time access from shore.

Although the boat fundamentally sails itself, in some cases it may be necessary to take control using the actuators. To make this possible, remote control software was developed that runs on a netbook with a touchscreen (Figure 5). The software is written in Java and communicates with the boat via WiFi.

3.3 Sensors

The following environmental data must be measured by sensors to control the ASV Roboat:

- wind speed
- wind direction
- heading
- rate of turn
- heel angle
- boat position

In addition, other values are measured that are not directly required for navigation, but are recorded every second:

- boat speed
- depth of water
- water temperature
- air temperature
- humidity
- atmospheric pressure

[4] www.iridium.com

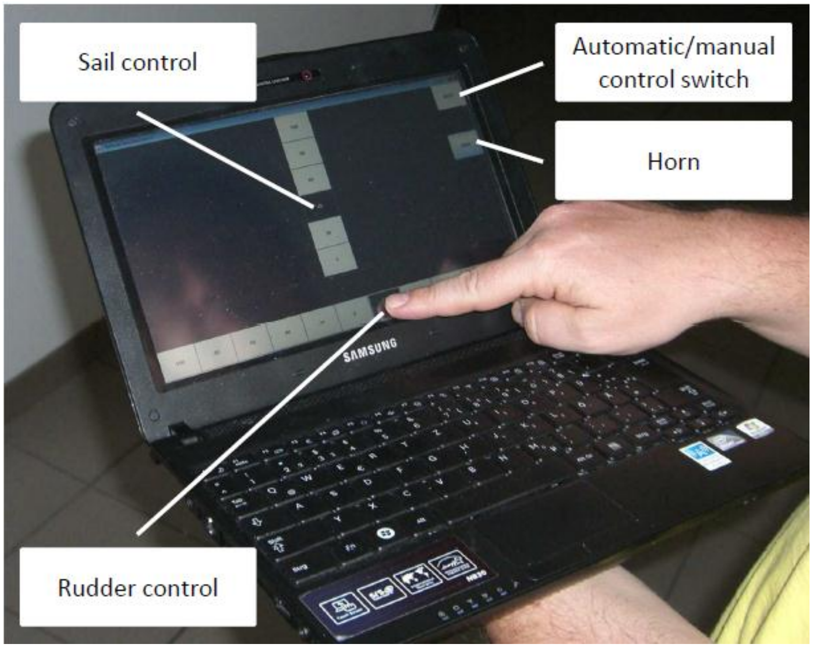

Figure 5 *Remote control software written in Java running on a netbook with touch screen*

In order to increase the availability of the system, many of the sensors are redundant. If a sensor fails, a secondary sensor can be activated.

The PB200 digital weather station manufactured by Airmar is used as the primary sensor unit. This device contains all of the sensors required to take the environmental readings. Table 1 summarises the information that the Airmar PB200 provides to control the *ASV Roboat*. The data is transferred in the NMEA0183 serial format.

NMEA0183 sentence	**Description**	**Frequency**
$WIMWV	Wind speed, apparent wind direction	2 Hz
$HCHDT	Heading	2 Hz
$TIROT	Rate of turn	2 Hz
$YXXDR	Pitch, roll	1 Hz
$GPRMC	GPS data (position, speed)	1 Hz

Table 1 *Primary sensor data on ASV Roboat from Airmar PB200 (Airmar, 2009)*

Table 2 provides a summary of the secondary sensors that are connected to an NMEA2000 bus, which is also fitted on board the boat. This is connected to the computer via a gateway (Maretron USB100). This gateway in turn converts the NMEA2000 records into NMEA0183 records, which can then be read via the serial interface in the computer.

Device	**NMEA0183 sentence**	**Description**	**Frequency**
Maretron SSC200	$IIHDG $IIROT $PMAROUT	Heading Rate of turn Pitch, roll	10 Hz 5 Hz 1 Hz
Maretron GPS100	$IIGGA	GPS data (position, speed)	1 Hz

Table 2 *Secondary sensor data on ASV Roboat from Maretron NMEA2000 bus (Maretron, 2009; Maretron, 2006)*

3.4 Actuators

In order to sail a boat autonomously, the rudder and sails must be adjusted automatically. Electric drives were designed for both and mounted on the *ASV Roboat*.

Initially, the original rudder of the *ASV Roboat* was used. A linear drive was connected to the tiller to control the rudder (Figure 6). However, this rudder drive was replaced in 2009 with a balanced rudder system specially built for the *ASV Roboat* to reduce power consumption (Figure 7).

Figure 6 *Linear actuator connected to the tiller controls rudder (2006–2008)*

Figure 8 illustrates the concept of a balanced rudder. The rotational axis of the rudder is shifted to a point approximately in the middle of the rudder blade. This means that when the rudder is turned, the flow of water actively works on the forward part to increase the angle of deflection, whereas the same flow acts on the rear part to reduce the angle. The area in front of the axis is kept slightly less than that behind in order to avoid rudder instability.

The *ASV Roboat* has two sails (mainsail and foresail). The two sails are controlled by a single drive; in other words, they are always trimmed in parallel. The mainsheet is operated with a 2:1 gear reduction, while the jib sheet is attached directly to the drive. The mainsheet therefore covers twice the distance of the jib sheet. (see Figure 9)

Sailing ships normally use winches to control the sheets. As the sheets sometimes become slightly entangled as a result, a linear drive has been designed for the *ASV Roboat* instead. The drive consists of a slide that is moved by a belt. The maximum travel of the slide is 75 cm. The jib sheet can therefore be tightened and slackened by 75 cm and the mainsheet by 150 cm. A self-locking worm gear on the motor ensures that power is only consumed when the sail position is being adjusted.

In order to make the adjustment of the fore sail easier, especially during tacking, the *ASV Roboat* was fitted with a self-tacking jib (see Figure 10). A self-tacking jib is a fore sail that does not require operation of the jib sheet when tacking, as it automatically changes from one side to the other. The jib sheet does not lead directly to the sail drive but is diverted over rollers. The first roller moves freely on a curved rail mounted in front of the mast. From there, the jib sheet is fed forward to a deflection roller near the bow, before running back into the cockpit, where it is attached to the sail drive.

Figure 7 *Self-constructed rudder gear with balanced rudder (since 2008)*

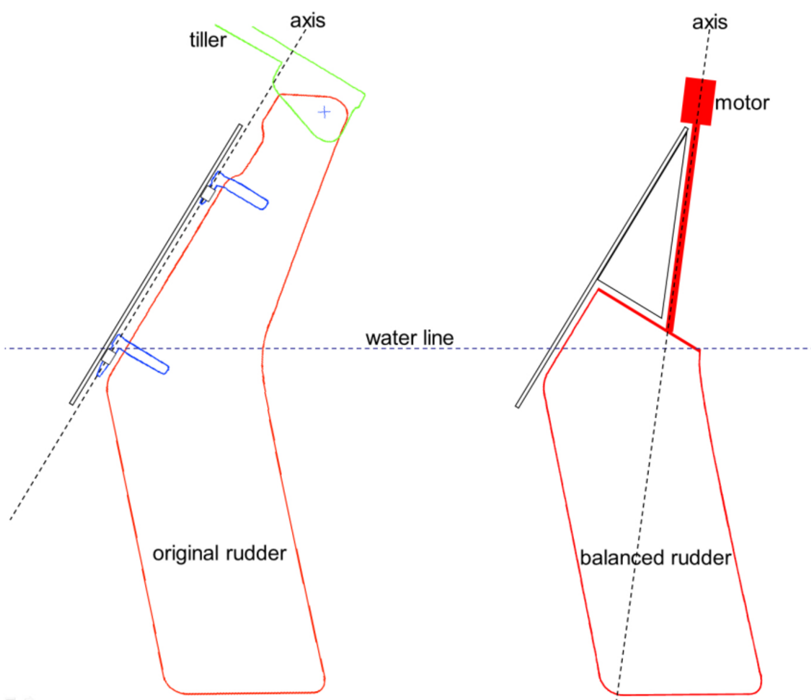

Figure 8 *Illustration of concept of balanced rudder*

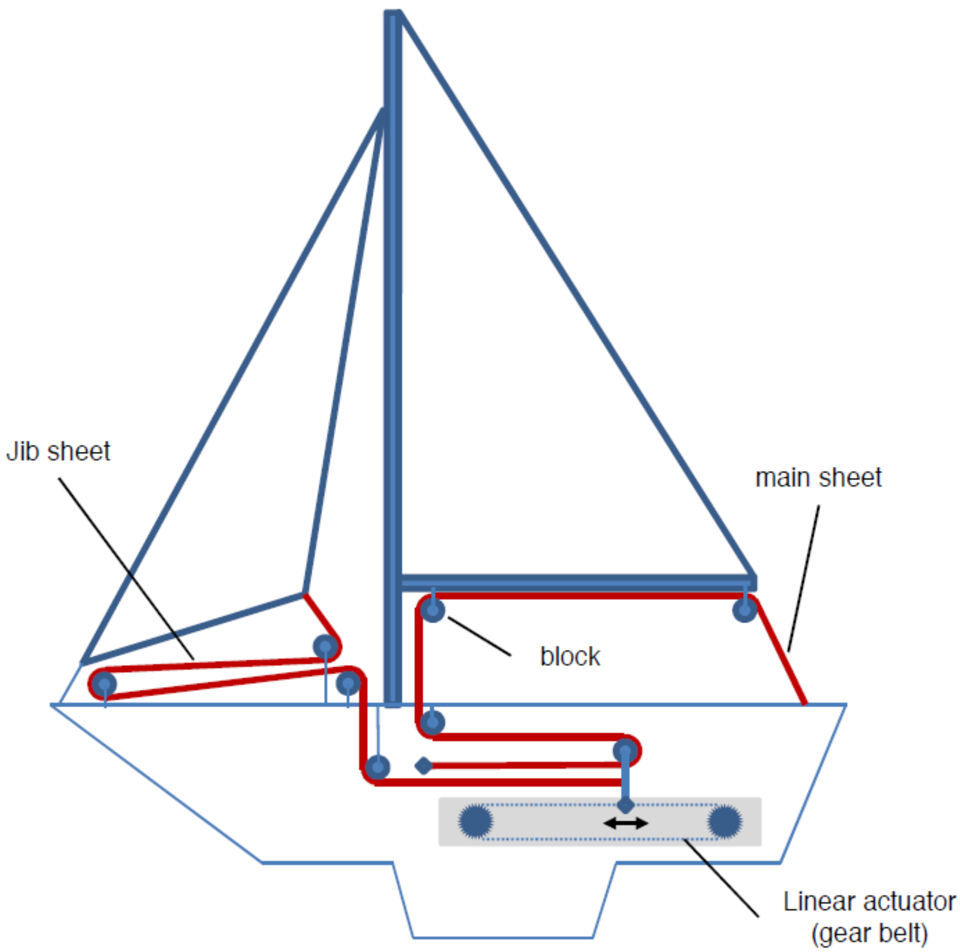

Figure 9 *Sheet guidance and sail gear on ASV Roboat*

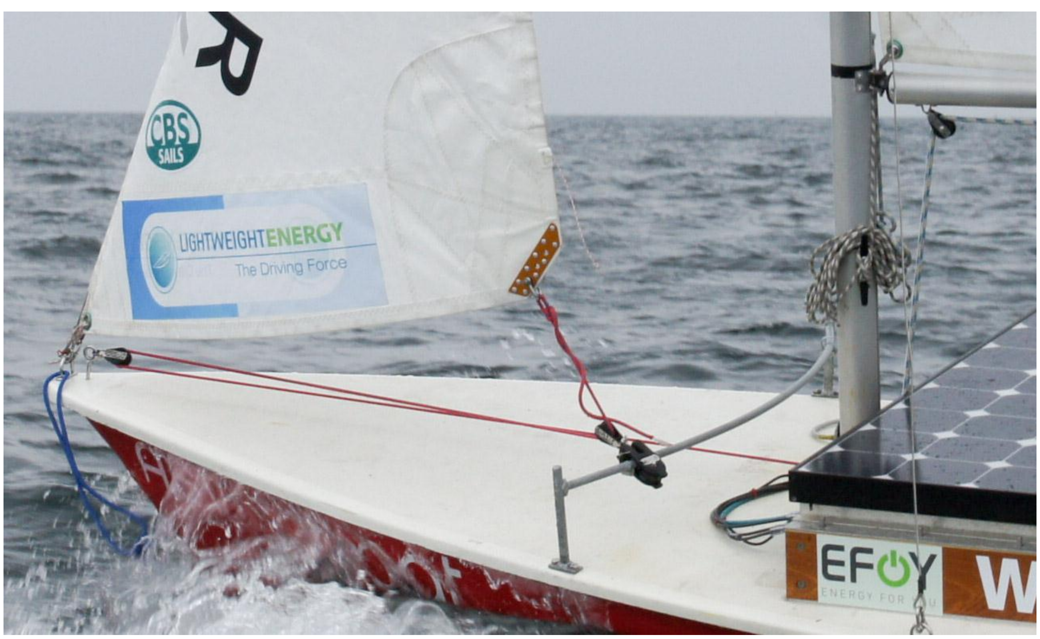

Figure 10 *Self-tacking jib on ASV Roboat*

In addition to the rudder and the sails, there are other actuators on board, but these are not directly required for autonomous navigation:

- navigation light
- fog horn
- bilge pump (with automatic switch)

3.5 Power supply

The average power consumption of the *ASV Roboat* is between 35 W and 85 W depending on wind conditions and sea state. The main power source of the *ASV Roboat* are solar panels providing up to 285 W_p of power during conditions of full sun. 285 W_p corresponds to approximately 30 W of average output over a whole year under central European weather conditions (Finanztest, 2006; Schrag, 2022). To cover the night period, electricity is stored in two deep-cycle batteries of 1:92 kWh together (80 Ah at 12 V each).

In order to be able to operate the boat at least for a limited period in conditions of reduced sunlight (night, bad weather) or if the solar power system breaks down, the boat is also equipped with a direct methanol fuel cell (EFOY Pro 1600). It delivers 65Wand features as a backup energy supply. The fuel tank contains 5 l of methanol. With a methanol consumption of 1:11 l/kWh as stated in the data sheet, the boat can operate several days with the fuel cell as its only source of electricity.

The boat is therefore currently showing a slightly negative energy balance. The largest consumer is the drive for the sail trim followed by the central computer and the WiFi access. These three consumers together account for more than two-thirds of the power consumption.

The following steps can be taken to lower the power consumption and achieve a positive energy balance (see Table 3):

- *Rig design:* a balanced rig[5] (also known as Balestron rig, Aerorig™, swing rig and EasyRig™) provides great potential in saving power (BalancedRig, 2009; Multirig, 2009). According to Giger et al. (2009) and based on experience with the balanced rudder system of the *ASV Roboat* (see Section 3.4), we anticipate a potential saving of at least 50 per cent from a balanced rig design.
- *Computer migration*: by converting to an energy-efficient embedded industrial PC, the power consumption can be reduced further. A Vortex86SX 300 MHz could be used, for example. This computer runs Linux and provides all of the interfaces required. Its power consumption of 3:24Wis almost 80 per cent lower.
- *Avoiding short-range communication:* WiFi and 3G communication are extremely practical when it comes to being able to receive large amounts of data from the boat and adjusting the settings of the boat during accompanied trial runs. However, in most applications the boat operates unmanned, unaccompanied and outside the range of these two technologies. In these cases, WLAN and 3G are not practical and the WLAN access point and 3G modem on board can be switched off. The iridium satellite modem can remain on standby to enable communication with the boat if required.
- *Removing sensors:* currently almost all of the sensors are present on board in duplicate, once in the Airmar PB200 using NMEA0183 and secondly on the NMEA2000 bus. The entire NMEA2000 bus could therefore be removed without losing any significant sensor data for autonomous sailing. Of course, availability could suffer if redundant systems are omitted.
- *Increase in efficiency in the control algorithm for rudder and sails:* methods that require little adjustment of the rudder and sail settings can lead to significant power savings. However, this always involves a compromise between sailing quality and energy consumption. The specific application for which the robot sailing boat is being used must always be considered when it comes to making adjustments of this sort. Power efficiency in the control algorithms has not been considered in this study and therefore provides room for further research.

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[5] A balanced rig consists of a single mast carrying a main and jib. 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 in such a way that the force from the mainsail is slightly stronger than that from the jib. That is, the combined centre of effort is just behind the mast. Therefore the load on the sheets is reduced significantly compared to a conventional rig due to the balanced distribution of the sail load causedby wind.

Component	Model	Power	Pct.
Embedded PC	Vortex86SX	3.24 W	39:3 %
Weather station	Airmar PB200	2.64 W	32:0 %
Satellite modem	Iridium SBD 9601 (switched 2 min/h)	0.06 W	0:7 %
Sail gear	self-construction (balanced rig)	2.29 W	27:7 %
Rudder gear	self-construction (balanced rudder)	0.02 W	0:2 %
Overall sum	**8.25W**		

Table 3 *Power consumption: optimised configuration shows great potential for saving electric energy.*

4. RECENT RESEARCH MISSION ON THE BALTIC SEA

The *ASV Roboat* has returned to Vienna following a several-day research mission in the Baltic Sea in July 2012. In cooperation with researchers from Oregon State University (USA), the *ASV Roboat* team from the Austrian Society for Innovative Computer Sciences (INNOC), studied the endangered harbour porpoise population in the Kiel Bight and Little Belt. Using an underwater microphone (hydrophone) attached to the boat's keel, the acoustic signals of a number of whales were recorded during the survey, and valuable information was collected on the presence of these animals in the study area. To the authors' knowledge this is the first time that an autonomous sailing boat has been successfully deployed as part of a scientific research project.

After launching from Eckernf¨orde (Germany) the boat sailed towards north to Faaborg (Denmark) before it was heading south again (Figure 11). At an average wind speed of 7:7 m/s and wind gusts up to 15:2 m/s (Beaufort 7) an average boat speed of 1:5 m/s (2:9 kn) was achieved.

In total, *ASV Roboat* sailed 71 nm (131:5 km) fully autonomously. Severe weather conditions resulted in a malfunction of the motor necessary to trim the sails. Due to these technical problems the mission had to be abandoned after 27 hours.

The extensive data set collected by the boat's on-board computer will now be analysed in detail and provide crucial information for further improvements of the system. To enhance the reliability of the sailing boat in stronger wind conditions, future work will focus on improvements of the boat's hardware, including the rigging.

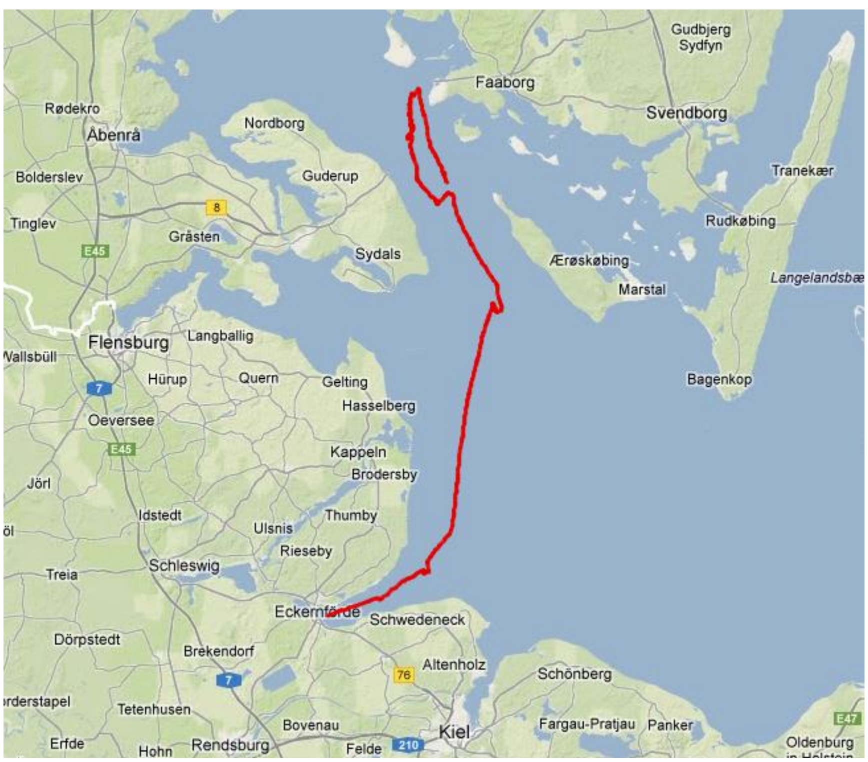

Figure 11 *Trajectory from research mission on the Baltic Sea in July 2012*

5. CONCLUSIONS AND FURTHER WORK

An autonomous sailing boat offers major advantages compared to submerged operated vehicles, including payload, speed, continuous real-time access, energy, and on-board computational power. However, gliders remain an important and powerful platform to investigate deep diving animals such as beaked whales or surveying polar regions where ice coverage prohibits the usage of surface vehicles. Both platforms are useful tools to gain knowledge of marine ecosystems, especially - as here presented - of marine mammals.

The field tests on the Baltic Sea have provided a successful proof of concept for the robotic sailing boat *ASV Roboat* as a maritime research platform. However, there are also challenges which must be addressed:

- **Collision avoidance**: While fixed obstacles such as landmasses can be predefined on the nautical chart which is the basis for the routing system, a wide range of obstacles need to be detected in real-time. Future research will be on a combination of multiple techniques, such as thermal imaging, radar, camera, and automatic identification system (AIS) to detect obstacles.
- **Energy balance:** the currently used *ASV Roboat* is showing a slightly negative energy balance. The solar system does not provide any spare power for the additional equipment for applications (e.g. sensors for environmental monitoring, search and rescue operations, etc.). In order to compensate this lack of energy, there are basically two possible approaches: generating more power or increasing efficiency. Saving power can be obtained by the use of more efficient components (computer, sensors, drives) and by optimising the control algorithms. Furthermore, a balanced rig design can help to reduce power consumption of the sail drive.
- **Adaptive control:** the proposed control algorithms are highly independent upon a specific boat type. However, a few parameters need to be adjusted in order to use the control software on another boat. A vision is to improve the software in a way that the boat automatically adjusts these parameters based on its own sailing experiences.
- **Swarm robotics:** once single robotic sailing boats work reliably and selfsufficiently in terms of power, swarm robotics technologies can be applied. Fleets of mass produced and affordable robotic sailing boats will cover the ocean surfaces and collaboratively undertake missions like measuring meteorological data, detect water pollution, rescue refugees and many more.

Robotic sailing boats are considered for a wide range of applications. A serious obstacle to successful implementation on a grand scale could be their unclear legal status. The International Regulations for Prevention of Collision at Sea (COLREGS) do not directly address unmanned autonomous surface vehicles (ASV). Nevertheless, some effort has been spent on implementation of algorithms to follow the COLREGS. However, it is not clear what type of vessel an ASV is according to the international maritime regulations. It seems, that the maritime laws need to be reexamined at least concerning vehicle classification. Once the classification is clear it then becomes difficult to identify other vessels reliably and to react properly.

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