Development of a Low-Budget Robotic Sailboat

Christoph Schröder and Lars Hertel

Abstract. Building a boat is the first of many steps in robotic sailing. In this paper, we describe the development of a low-budget robotic sailboat based on the MaxiMOOP. This includes a conceptual design for entering the Microtransat Challenge, a approach for constructing the hull out of styrofoam, the development of a balanced swing rig using low-priced materials only and the use of a reduced set of sensors for autonomic control in order to decrease energy consumption. Moreover, a short field test showing the overall performance of our prototype boat and its seaworthiness, regarding boat speed, course stability and energy consumption is presented.

1 Introduction

Robotic sailing is a challenging task, in both building and controlling the boat. Therefore, it brings together many different disciplines, such as naval architecture, electrical engineering and computer science. In the past, our focus was put on the latter, i.e. the development of efficient and stable algorithms in order to control small robotic sailboats [7]. In this paper however, we will describe the design and construction of a low-budget prototype robotic sailboat. Its main advantages are the affordable price, the flexible area of operation due to its low weight and rather small size, as well as the ability to exchange hull and sail because of its modular design. Our boat therefore presents a low priced alternative to more advanced robotic sailboats such as the French VAIMOS [3], the Austrian Roboat [8] and the Portuguese FASt [2]. It costs around €350 (parts only, 2013 prices), is approximately 1,2 m long

Christoph Schröder · Lars Hertel
Institute for Robotics and Cognitive Systems, University of Luebeck,
Ratzeburger Allee 160, D-23562 Luebeck, Germany
e-mail: {cschroeder,hertel}@informatik.uni-luebeck.de

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and weighs not more than 13 kg. Its original goal was to compete in the Microtransat Challenge [2]. The development process, however, is still ongoing and we hope to meet that goal in the near future.

In the following paper, we will present the construction of the hull, sail and electrical components of the boat and point out the main ideas and design decisions. While building the boat, our emphasis was on designing a low-budget and at the same time robust prototype that would be able to perform well under difficult weather conditions. The latter needs future evaluations.

2 Methods and Material

In this section, we will first define a conceptual design for the boat including its components and then present the construction process of our prototype. A cost distribution of the used material is summarized in Table 1.

2.1 Concept

For the Microtransat Challenge we assume 80 to 140 days of autonomous operation. The exact time depends on the route [6] and the speed of the final boat. In Table 1 we give an overview of the planned power consumption of each electrical component together with an estimated time each component operates per hour. As a result our boat consumes approximately 20 W per day. Accordingly, a solar panel that produces about 25 W per day is needed.

Table 1 Cost distribution of the used material for our robotic sailboat

Name	Description	Price in Euro
Hull	MaxiMOOP [10] made of styrofoam, epoxy resin and glass fibre cloth	50
Computers	Raspberry Pi and Arduino Uno	60
Sail	Swing Rig made of pond liner and aluminum tubes	23
Sail Actuator	Grill Motor	19
Rudder	Aluminum sheets and aluminum tubes	8
Rudder Actuator	Grill Motor	19
Motor Driver	Pololu Dual VNH5019 Motor Driver	50
Motor Position (2)	AMS AS5040	30
Wind Sensor	AMS AS5040	15
Battery	Lead battery (12 V, 2.5 Ah)	15
GPS	Ublox LEA4-T GPS	80
Total		369

Table 2 Planned power consumption of individual components. The second half is based on the assumed seconds the component is powered per hour (ontime s/h).

Component	V	mAh	mW/h	ontime s/h	mW/h	mW/day
μProcessor	3.3	5	16.5	3600	16.5	396
Wind sensor	3.3	2	6.6	3600	6.6	158.4
Compass	3.3	2	6.6	3600	6.6	158.4
GPS	5	39	195	3600	195	4680
Sail	12	2000	24000	30	200	4800
Rudder	12	2000	24000	60	400	9600
Spot Connect	3.3	53	174.9	240	11.7	279.8
Total					836	20072

Due to the lack of solar energy during the night we use a buffer that is charged during the day as shown in Figure 1 and has a minimal capacity of 14.3 Wh for continuous operation.

During the mission, the efficiency of a solar cell decreases because of dirt and salt on its surface. Assuming a decrease of 20 % after the first 100 days on the water as shown in Figure 1, the buffer is not charged enough to power the boat alone. Therefore, we include lithium batteries that are not charged by the solar panel but deliver the missing power when the buffer is empty. With a relatively small backup of 68.4 Wh the time of operation easily exceeds 200 days (Figure 1) as the buffer is still charged partly during the day.

2.2 Hull and Rig

The hull of our boat is based on the MaxiMOOP, a modified version of the MOOP [10] (courtesy of Paul Miller, Mark Neal and Colin Sauzé). It possesses a narrower and deeper keel which improves hull speed and upwind performance of the boat. In order to build the hull, we first cut a negative version out of large styrofoam blocks. To do this as accurately as possible, we programmed a robotic arm to melt down the styrofoam surface using a heating wire out of tungsten. Afterwards, we applied three layers of glass fibre cloth for our boat to be waterproof and robust. To build a keel we first removed the styrofoam inside the boat, melted 5 kg of lead and filled it inside the bottom of the boat. Furthermore, to stabilize our boat, we installed five frames made of wood. At last, we covered our open hull with a fitting deck, made of wood as well, coated with glass fibre cloth. For debugging purposes, hull and deck are fixed with duct tape as a start. This allows to easily open the deck and quickly fix occurring errors.

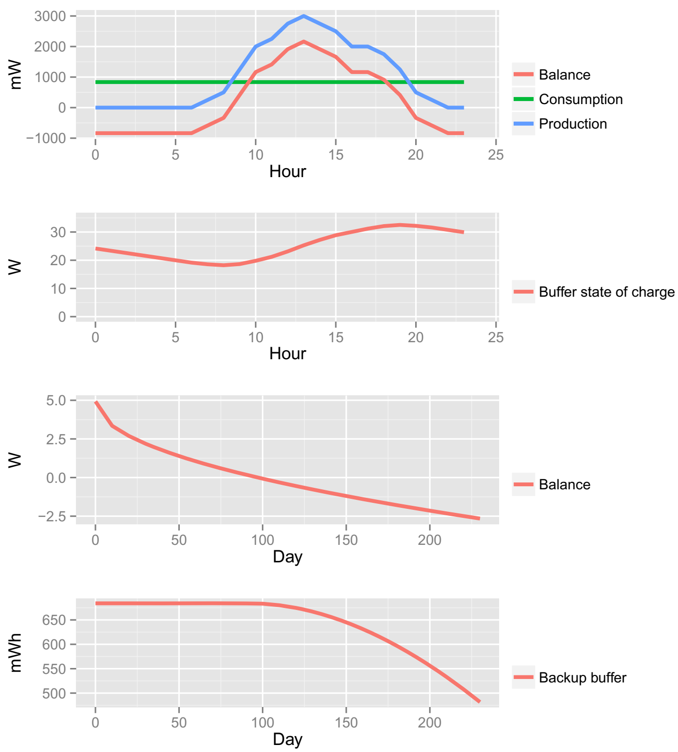
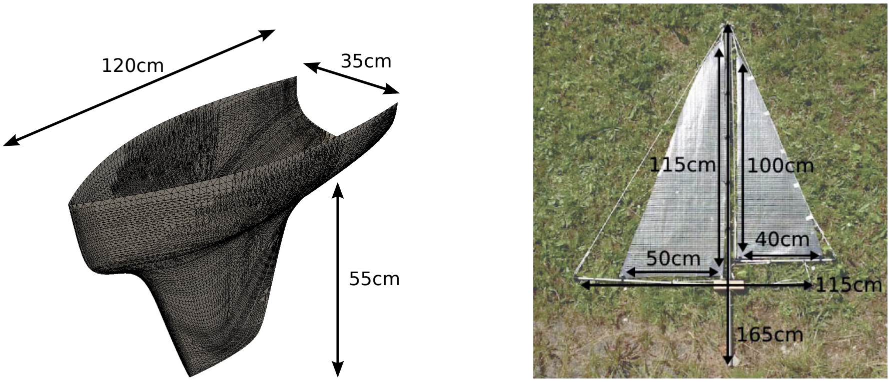


Fig. 1 The first figure describes the power balance during the day. It considers a total power production of $25000mW$ per day provided by the solar panels and a constant drain of $836.36mW$. The power consumption is based on Table 1. The second plot shows the buffer state over the day while the solar panel operates at 100% efficiency. In the third plot, the sum of production and consumption during the mission is shown, assuming 80% efficiency of the solar panels after 100 days on mission. The bottom plot shows the backup buffer charge which decreases after the solar cells can not charge the main buffer anymore.

Every opening in the final boat is a possible way for water to come in. Therefore, we reduced the number of holes needed by using a balanced swing rig. Thus, we sacrificed speed and agility for a robust and simple design which is also used by a number of other boats such as IBoat [4] and Avalon [5]. Again this simplifies the mechanical construction and algorithmic maneuvers since we gain agility through the rudder. Design and construction of sail and rudder are based on rough calculations. Their simple design and construction allows a fast iteration of size, form and trim.



(a) (b)

Fig. 2 The design of our prototype sailboat. Subfigure a) shows the hull of the MaxiMOOP (courtesy of Paul Miller, Mark Neal and Colin Sauzé) and its dimensions. In Subfigure b) the dimensions of our balanced swing rig are illustrated.

2.3 Sensors and Motors

Besides hull and rig, sensors and motors are important for robotic sailboats. They are crucial not only for optimal maneuvers but also need to be low-priced and robust to minimize money and time spent on maintenance. Consequently, we kept the number of sensors low and abstained from e.g. magnetometer, gyroscope and accelerometer. Our algorithms only depend on position and speed from GPS and the relative wind direction. In the current prototype we use ublox LEA4-T GPS chipset (ublox, Switzerland) that allows fast testing and accurate data for narrow maneuvers in small bays. The wind direction sensor is based on the AS5040 chip (Austria MicroSystems, Austria) [11] which is low-priced and reliable. It is placed on top of the rotating mast and the wind direction is calculated considering the current orientation of the rig.

On the mechanical side, rudder and sail are not rotated by industrial servo motors but grill motors. These DC motors come with a gear to achieve a high torque and low speed. The high torque saves energy by holding the position of the sail once it is in the right angle for a point of sail. Furthermore, we use the same rotation sensors as for the wind sensor to keep track of the gears rotation which reduces implementation complexity on the software side.

2.4 Electronics and Software

For quick development and easy live debugging we chose the Raspberry Pi (Pi) as our main control unit (see Figure 3 for a system overview). With a

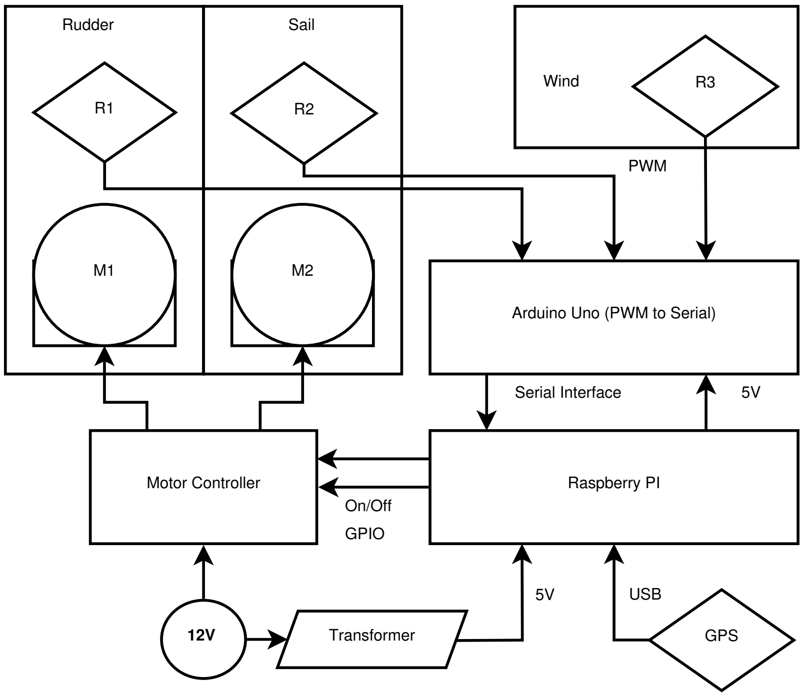


Fig. 3 Schematics of the boats control circuit. M1 and M2 denote Motors, R1-3 are AS5040 chips. The Raspberry Pi is the main control unit reading the sensor data converted by the Arduino and controlling the motors of sail and rudder by its GPIO pins. GPS is connected directly via USB.

700 Mhz ARM processor it runs a full Debian Linux environment. Communication for programming and debugging purpose is established over Wi-Fi with a USB dongle (Netgear N300). Although the Pi is good for fast iterations in software development there is no easy way to read the PWM signals from the wind and motor rotation sensors. To overcome this problem the Arduino reads the PWM signals and transmits the current sensor values via a serial connection to the Pi.

The GPS module is powered by and communicates to the Pi via USB, while the Pi itself is powered by a lead battery located in the keel of the boat. With a switching regulator the 12 V from the battery are converted to the 5 V input for the Pi. The motors however, are driven at their designed input voltage of 12 V. Consequently, we lose about 15 % during the conversion for all non motor electronics at about 240mAh. Rudder and sail are controlled by a separate motor driver. Although the driver allows linear regulation of the motor's speed, we currently only use the GPIO pins of the Pi to control both, the direction and the off states of each motor.

On the Raspberry Pi we use Java 1.8 for ARM which supports hardware floating point operations and JIT compilation. Further we can use existing libraries of our past projects and benefit from Java's ecosystem. Most notable are the Pi4J[1] project for easy access to the serial port and GIO pins of the Pi and GPSd4Java[2] for GPS module handling. Due to the computational power of the Pi's processor and sufficient amount of RAM, we are able to run the autonomous behavior not only on onshore and send the commands via Wi-Fi, but also we are able to do all necessary calculations on the boat itself.

3 Results

In the following, we give an impression of the general performance of our boat. Therefore, we divide the results of our field tests into three main categories, namely boat speed, course stability and energy consumption. Images of our prototype during the field tests are shown in Figure 4.

(a) (b) (c)

Fig. 4 The images show our prototype during the field tests, sailing on different points of sail

3.1 Boat Speed

In order to obtain data regarding the boat speed over ground, the boat was set up to sail a triangular course. The autonomous run lasted for 15 min

[1] `http://pi4j.com` The Pi4J project provides a bridge between the native libraries and Java for full access to the Raspberry Pi.

[2] `https://github.com/taimos/GPSd4Java` GPSd4Java is a library to use data from the GPSd daemon in Java.

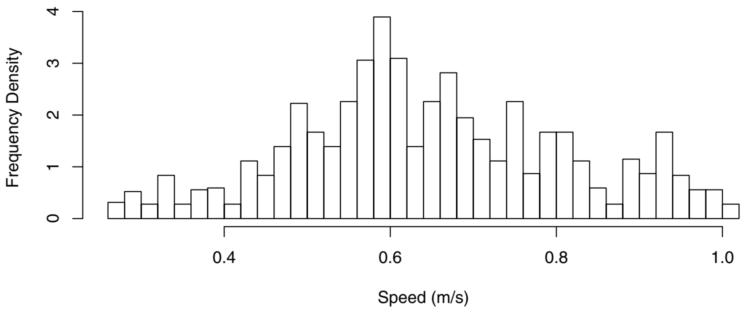
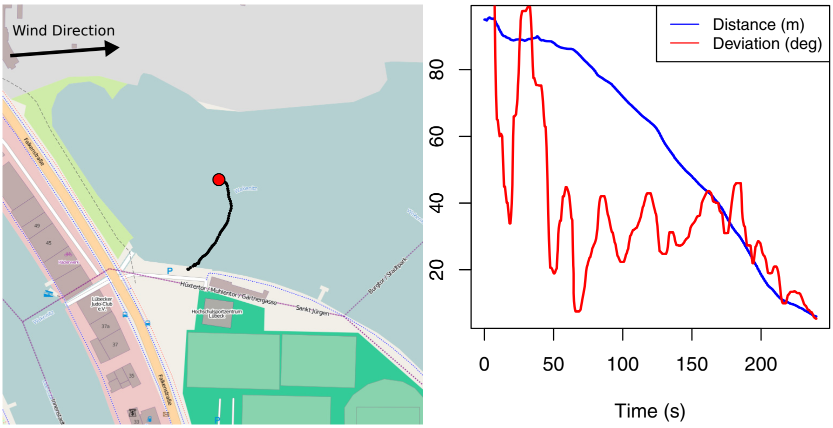


Fig. 5 A histogram showing the typical distribution of the boat speed over ground in m/s. The plot indicates that our boat reaches an average speed of 0.65 m/s and a maximum speed of 1 m/s in easterly winds of approximately 7 kn to 9 kn.

during moderate weather conditions in easterly winds ranging from 7 kn to 9 kn. The collected data was then filtered and outliers were removed. The histogram representing the speed distribution in meters per second is shown in Figure 5. It points out an average boat speed of 0.65 m/s. Furthermore, the histogram indicates that our prototype is capable of sailing at sustained speeds of more than 1 m/s, or 2 kn. Compared to the performance of the robotic racing Micro Magic (rrMM, [11]) under similar weather conditions, the results indicate a slight increase in boat speed [7].

3.2 Course Stability

Besides the boat speed, another important criterion in autonomous sailing is the stability or precision of the sailed course. In order to analyze the course stability, we measured the course deviation as well as the target distance while approaching a waypoint autonomously. The test was performed in easterly winds of 8 kn with modest gusts of wind, complicating the task additionally. Initially, the distance to the target was 100 m and the boat was facing away from the target. The test lasted for 4 min. The results are shown in Figure 6. The logged GPS data in Subfigure 6a illustrates that our boat was able to reach the waypoint autonomously, not perfectly though. More detailed information is given in Subfigure 6b. The distance to the target is constantly decreasing, indicating that the boat sailed towards the waypoint. As for the course deviation however, an unsteadiness is noticeable. Clearly, our boat did not reach the waypoint on an optimal path, but given that our boat is just a prototype and simple controllers for sail and rudder were used, the results illustrate the autonomy and maneuverability of our boat.



(a) (b)

Fig. 6 The figure illustrates the autonomy and maneuverability of our prototype. Subfigure (a) displays a map of the test area. The waypoint is plotted in red and the GPS data of the boat is plotted in black. Subfigure (b) points out the decreasing distance and course deviation to the waypoint. Map data OpenStreetMap contributors, CC-BY-SA.

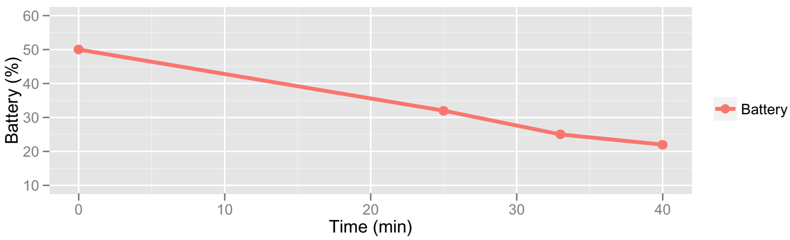


Fig. 7 Energy consumption of our boat. The battery was discharged by from 50% state of charge to 22%, indicating an average power consumption of 12.6 W/h. Note that we had to measure the voltage manually using a multimeter.

3.3 Energy

Especially important for long-term missions, such as the Microtransat, is a low energy consumption of a robotic sailboat. To test the consumption of our boat, we measured the change in voltage of the lead battery. Since no automatic measurement of the voltage is available for our boat, we had to manually measure the closed circuit voltage using a multimeter. During an autonomous run of 40 min, we measured the voltage of the battery four times while being under a discharge of 250 mAh. The connected data points are shown in Figure 7. Based on the capacity of the battery of 2.5 Ah we assume a discharge rate of C/10 [9]. During the test, the charge condition decreased from 50 % to 22 %. This corresponds to a discharge of 8.4 W and gives an average power consumption of 12.6 W/h.

4 Discussion

Being only a prototype, our boat is far from entering the Microtransat Challenge. However, some design decisions have proven to be serviceable. Using a readily available hull instead of creating a new one saved a lot of time and the MaxiMOOP has already been proved and tested. Furthermore, cutting the hull out of styrofoam using a robotic arm saved a lot of money. However, thoroughly removing the styrofoam after having applied the coats of glass fibre cloth turned out to be unnecessary.

The energy consumption of the prototype is about ten times more (Section 3.3) than planned in the concept (Section 2.1). This has two main reasons. First, the software used during the test is configured to constantly adjust rudder and sail. During a long term mission these adjustments are planned once every minute for the rudder and once every two minutes for the sail. Second, the hardware of the prototype uses far more energy than the embedded hardware of the final boat. The Raspberry Pi alone drains about ten times more power than the planned microprocessor. Additionally, the Wi-Fi connection is not needed on the final boat. Despite consuming more power than planned for the final boat, using the Raspberry Pi and a Wi-Fi connection allow us to iterate fast. Building and deploying a new version of the control software is done within less than a minute without interrupting the boats operation for more than about 10 seconds. The range of the used Wi-Fi adapter of about 100 m limits the possibilities of further tests and will be replaced by a UMTS connection in the next iteration of the prototype.

As for the sail, a balanced swing rig performs well on water and uses only a single motor. Therefore, the energy consumption is reduced, being one of our main goals designing the boat. In addition, the pond liner turned out to be an excellent low-priced alternative to sailcloth. One weak point in the design are the predetermined breaking points in the link of mast and boom. So far a threaded rod is used for the connection, requiring a hole in the mast. This should be replaced by either adhesive or friction in the future.

Another important design decision is whether to position the wind sensor on top of the mast or on the deck. Despite having a rotating mast because of the swing rig, we placed the wind sensor on top of it. The advantage of measuring the wind direction more precisely was deciding. So far we have not noticed any disadvantages yet, knowing the exact mast rotation and being able to factor it into our calculations.

As for the rudder, our field tests revealed several lacks in its design. The rudder is overpowered and unbalanced and therefore slowing the boat down. Even though the rudder serves its purpose, it will be redesigned in the future.

Another interesting alternative is the use of a magnetic linkage between the rudder actuator and the rudder itself [10]. Moreover, this would avoid cutting a hole in the hull, being a possible error source of letting water inside the boat. In the latter case, a bilge pump for successor boats is planned.

Our results show the seaworthiness and maneuverability of our prototype. Compared to the performance of the rrMM, our results indicate an increase in both boat speed and course stability, which is not surprising given the larger size of our prototype. For a more detailed analysis of the overall performance of our boat, more data during extended field tests has to be collected.

5 Conclusion

Building a boat is the first step of many in robotic sailing. We have presented the development of a low-budget robotic sailboat. For costs around €350 we have built a fully functional prototype using either existing or low-priced materials only. The hull is based on the MaxiMOOP and was cut out of styrofoam using a robotic arm. The sail is a balanced swing rig and made of pond liner. As for the electronics, a Raspberry Pi and an Arduino Uno are used so far for the prototype, but will be replaced by energy-saving microprocessors in the future.

The results show the seaworthiness of our prototype. The boat is capable of sailing at sustained speeds of 2 kn in moderate weather conditions, probably faster with increasing wind speeds. Moreover, it is able to autonomously reach a target waypoint using GPS and wind direction sensors only. This reduced set of sensors decreases the energy consumption and is therefore beneficial for long-term missions, such as the Microtransat Challenge.

However, our prototype has to be improved in the future, using more energy-saving components, collecting and analyzing more data during extended field tests and adding a solar panel to the deck. Thus, we would be able to charge the battery during long-term missions and finally enter the Microtransat Challenge.

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