Department of Computer Sciences

Autonomous Sailing Boats

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Contents

1 Introduction

Over the past decade there has been intense scientific work on autonomous sailing boats. As hardware gets smaller, cheaper and also better performing the possibilities increase for autonomous vessels.
Recently there is a lot of research going on with the aim of reducing CO_2 emissions. Autonomous sailing boats fit perfectly into these ambitions.

Challenges of Autonomous Sailing Boats

Building and programming an autonomous sailing boat holds several challenges:

- **Hardware challenges:** Equipping a robotic sailing boat with microcontroller, sensors, actuators and other special hardware needed (e.g. solar panels) is very difficult. Waterproofness is a major issue in this context. Sensors have to provide reliable data in an unstable environment. All components have to be small and lightweight enough to be carried by the boat.

- **Routing algorithms:** Routing of autonomous sailing boats is a challenging task since for a sailing boat not every course is directly sailable. There is also a huge difference in the maximum speed a sailboat can reach on a given course. Stelzer and Pröll also name different optimization goals: minimum passage time, minimum energy consumption, safety for crew and ship, best passenger comfort. [19]
  It is also difficult to plan routes because sailboats are operating in an unstable and ever changing environment.

- **Energy self sufficiency:** Autonomous sailing boats used in long term missions on the ocean have to carry all needed energy with them and/or gather energy from the environment.

- **Collision avoidance:** To eliminate the need to monitor robotic sailing boats all the time, they have to be able to avoid collisions with ships and other obstacles in the water.

Conference and Competitions

Since 2008 there exists a small conference, the International Robotic Sailing Conference (IRSC), and a competition, the World Robotic Sailing Championship (WRSC) [3].
Another competition, the Microtransat [1], was held in 2006 and 2007. The 2006 Microtransat was about the quality of the routing algorithms. Robotic sailboats had to reach a target (within tolerance of 5 m), then stay within a 5 meter distance of the target for 10 minutes and afterwards return to the start (also with a tolerance of 5 m). In the 2007 Microtransat two races were held, one short race (3 km) and one 24 hour endurance race. In 2010 the ambitious goal of the Microstransat was a transatlantic race from Ireland to the Carribean. Two teams enrolled for the competition, but one team withdrew as they were unable to launch their boat. The other boat sailed for 14 days near the coast of Ireland and then had a failure of the main computer.
For 2011 another transatlantic race is planned.

In this paper we will discuss the main developments of the past years in the field of autonomous sailing boats. In the first part of the paper the main applications for the use of autonomous sailboats will be introduced. Hardware aspects will be presented in the second chapter. The most common boats, sails, microcontrollers and sensors that are used for autonomous sailing will be discussed. Next the paper contains an overview about important software architectures for autonomous sailboats. Since the sailboat needs a reliable connection for monitoring, debugging and remote control in case of emergency, the sailboat needs a data link to the shore. The communication chapter will present one communication strategy. Fuzzy Logic Control Systems are commonly used to control the sails and rudder of the sailboat. Two different approaches using fuzzy logic will be introduced in the control system chapter. To detect and avoid obstacles different mechanisms are used. Regarding to that, the collision avoidance chapter will discuss two approaches. The simulation and testing part of the paper will present common simulation methods and testing approaches. The conclusion will summarize the main aspects of this paper.

2 Applications for autonomous sail boats

There are several possible fields of application for autonomous sailing boats. Stelzer and Jafarmadar named the following applications[15]:

Intelligend Sensor Buoys: Autonomous sailing boats can easily be equipped with several sensors measuring all kinds of data. As they are energy self sufficient their operation time is not limited. Therefore, it is very cost efficient to use them for surveys, mappings and ecological studies of oceans and lakes.
Ocean sampling and marine mammal research are two applications where already projects exists to facilitate robotic sailboats.

CO_2-neutral in Transportation of Goods: Conventional sailboats are unprofitable for the transportation of goods nowadays because they need a very big crew to be operated. Autonomous sailing boats do not suffer from that disadvantage and can therefore be used for the CO_2-neutral transportation of goods.

Reconnaissance and Surveillance: Sailing robots can also be sent to operate in dangerous regions. For example, they could be used to measure the nuclear radiation in the ocean near Fukushima.
Another application would be the surveillance of the borders in the Mediterranean sea.

Supply Vessel: Remote islands and regions that are sparsely populated could be supplied using robot sailing boats. For example, they could be used to supply scientists that work on small islands in the arctic ocean.

Stelzer et al. also presented a research project where an autonomous sailing boat shall be used for marine mammal research [11]. They use the sailboat for passive acoustic monitoring of marine mammals while reducing the human impact on them. They state that the advantage of using a robot sailing boat is that the area of interest can be sampled with

a very high spacial and temporal resolution for comparatively low cost.
They also equipped their boat with additional sensors measuring chlorophyll and zooplankton. An acoustic streamer, three hydrophones, a depth sensor and a compass module are towed behind the sailing vessel.

Cruz and Alves also published a paper on the possible applications of autonomous sailboats for ocean sampling and surveillance [7].
For ocean observation they name upper ocean dynamics, chlorophyll concentration, ocean acoustics, calibration of basin-wide ocean models and tracking of pollution plumes as fields of interest for scientists where robotic sailboats can collect required data for low costs.
In the field of surveillance the authors state that autonomous sailing boats can be used for the detection and prevention of illegal trading, surveillance of immigration routes and assistance in the detection and disarming of minefields in the ocean.

3 Hardware

In the design of an autonomous sailing boat the hardware is the key factor for costs, algorithmic possibilities and possible applications. There are designs that use less than 700 €[6] and on the other hand there are projects that already invested more than 209000.-sFr [9].
In this section we will present boats, sails, microcontroller and sensors that are used in the development of autonomous sailing boats.

3.1 Boats

In the World Robot Sailing Championship[3] boats are divided into three classes:

- Microtransat class for boats up to 4 m long
- SailBot class for boats up to 2 m long
- MicroMagic class (0.53 m long)

Boats competing in the Microtransat class are either based on conventional, commercially available sailboats [11] or are entirely self constructed [9]. These boats have several advantages: they can carry a lot of equipment, they can tolerate very rough sea and also the maximum speed, or hull speed, of a boat depends on its length. Disadvantages are the high costs for building and transport.

In the SailBot class the boats are self constructed [12] or based on remote controlled sailboats [6]. Remote controlled sailboats are available off the shelf in various sizes and are already equipped with servos. Figure 3 shows a small, off the shelf RC sailboat that was equipped with a wind sensor, a PDA and GPS [6].

Figure 1: Avalon sailboat (Microtransat class) [9].

The MicroMagic class was proposed for the first time for the WRSC 2011 [3]. In this class everyone has to use the MicroMagic RC sailboat from Graupner as base for their sailing robots (see figure 4). The used components (hull, deck, sails, keel) are very strictly regulated and relatively cheap (≈ 200€). Most of them have to be from the RC kits from Graupner. Therefore, the competition in this class is really about control board and sensor design and the controlling software.

3.2 Sails

In the designs of autonomous sailboats there are basically two approaches: conventional fabric sails and wingsails. Designs that are based on existing boats (real sailing boats and RC boats) mostly use conventional sails, as can be seen in figure 2. Most of the designs that built everything from scratch use wingsails.

Mark Neal et al. describe different designs of wingsails and discuss the advantages and disadvantages in their paper "Technologies for Autonomous Sailing: Wings and Wind Sensors" [12]. They state that conventional fabric sails are convenient for human use as they can be easily repaired, reefed, modified, stowed and repaired. They also name several disadvantages of fabric sails like the need for structural spars and wires in the rig. On the other hand, wing sails turn out to be more efficient, especially close to the wind, do not flog and don't necessarily need additional rigging.

Another advantage is that a wingsail can be controlled directly by a servo, whereas a fabric sail needs sheets that are connected to the servo. These sheets need a lot of space in the boat, especially in RC models, and tend to get tangled up. Mark Neal et al. also name

Figure 2: Roboat sailboat (Microtransat class) [11].

certain disadvantages of wingsails. They can not be reefed and are relatively difficult and expensive to construct as they have to be lightweight, strong and rotatable.
Therefore, they are mainly used in model ships between 1 and 2 meters of length, where the cost of constructing a wingsail is still reasonable and the savings in under deck space valuable.

Giger et al. also presented some sort of hybrid solution on their Avalon boat as can be seen in figure 1. They used a balanced rig, reducing energy consumption, and used a fabric sail fixed into a frame, reducing cost and weight. Their solution doesn't use any ropes or sheets that could tangle up, and also doesn't need any additional rigging.

3.3 Microcontroller and Sensors

The basic components of the electronic architecture of an autonomous sailing boat can be seen in figure 5(a).
The central component is the embedded intelligence. Depending on the available space in the boat this component can either be a microcontroller [10], a PDA [6] or a x86 computer (e.g. an ITX mainboard) [15].
The anemometer is a sensor that measures the wind direction and the wind speed. There are different kinds of anemometers: with moving parts (wind vanes) and without moving parts (ultrasonic).
For communication several different components can be used. For short distances wireless LAN controllers, for medium distances near the coast and on lakes GSM transmitter and for very large distances satellite communication are used. Depending on the purpose of the boat one or more of these communication systems can be used.
Actuators are the servos and winches that are used to control the rudder and the sails, but also lights and bilge pumps.

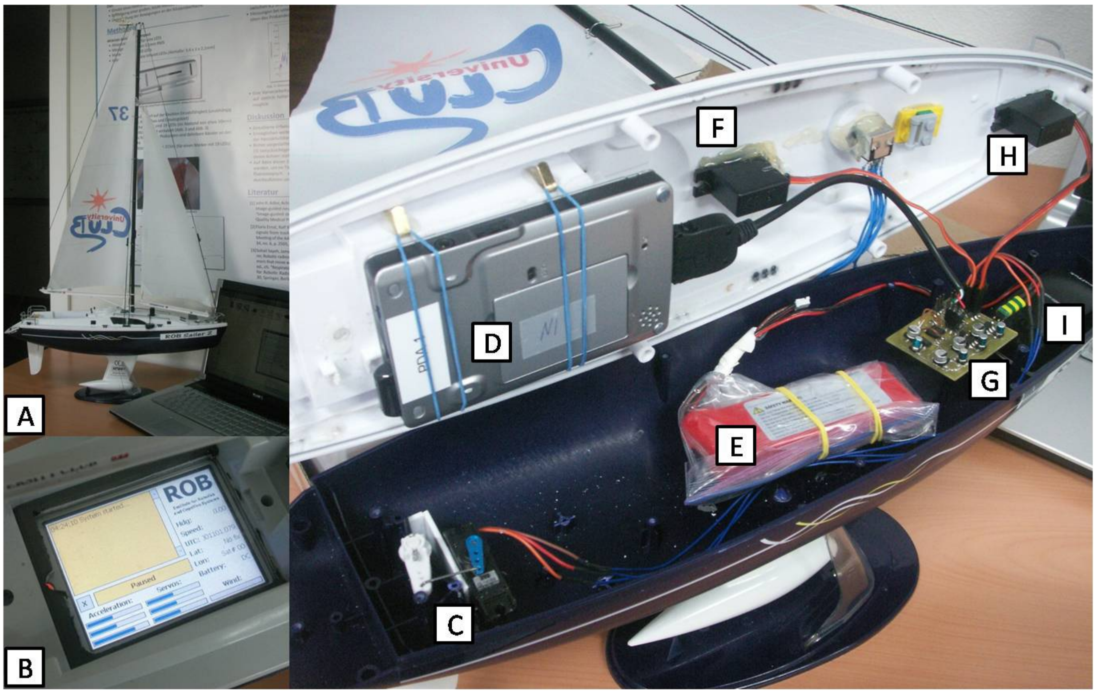


Figure 3: A testbed for autonomous sailing based on a RC sailboat [6].

The energy supply can be as simple as a battery pack in small boats like the MicroMagic, but also very sophisticated with solar panels (as seen in figures 2 and 1) and backup fuel cell to be energy self-sustaining.
GPS systems are used to determine the position and speed of the boat.
In the following paragraphs we will discuss some sample equipments of autonomous sailing boats.

Model Sailboat Testbed proposed by Bruder et al. [6]

Figure 3 shows the electronic equipment used by Bruder et al. [6]. Their main processing unit is a PDA (Dell Axim X30) with WLAN and Bluetooth (D). To control the rudder servo (C) and the two servos for main and foresail (F, H) they used a small controller board (G) with an Atmel ATMEGA8 processor. (E) is the main battery of their boat. The position of the boat is detected with the GPS module (Royaltek BT2100) (I).
Two sensors were used, an inclinometer (LIS3LV02DQ) to measure the rotation about several axis of the boat, and a self constructed wind vane to measure the wind direction. The wind vane can be seen in figure 5(b).

Autonomous Robotic Boat of ENSIETA [10]

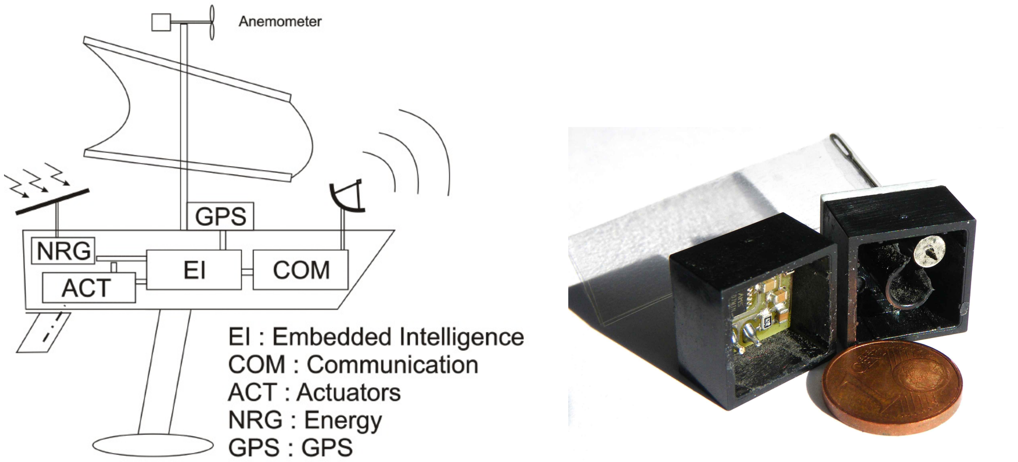
The project of the french graduate engineering school (ENSIETA) used a self constructed 1.2 meter long fiberglass hull, equipped with regular rc servos.
Figure 5(c) shows the components they used on the boat.
Their main processing unit is a PIC18F2550 that was chosen because of its low power consumption and robustness to power shortages. The GPS sensor is a EB-85A(FV-M8) and the compass is a HMC6352 with a one degree resolution.

Figure 4: RC sailboat MicroMagic.

As an energy resource they used a Lithium Polymer battery which should be enough for a 48h race. For communication with the boat during a race they used a Adeunis ARF53 HF modem connected via RS232.
The servo controller they used was also self constructed. It is needed to reduce the computation load on the PIC microcontroller.
As anemometer they used a CV7 ultrasonic anemometer from LCJ Capteurs.
Their boat is not equipped with any devices that could be used for obstacle detection.

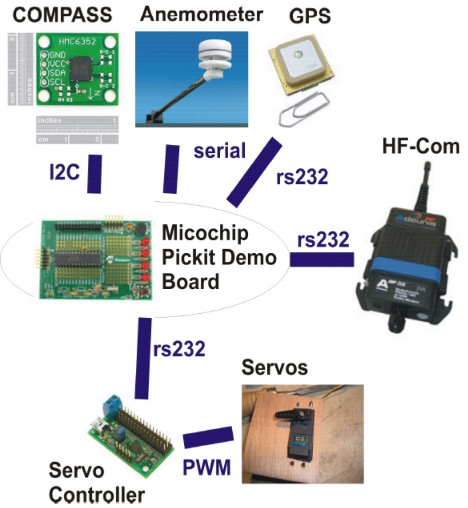
Avalon [9]

The ETH-Zürich constructed a 3.95 meter long autonomous sailing vessel called Avalon (Figure 1).
As main computer they used a MPC21 from DigitalLogic with 500 MHz, 1 GB RAM and a compact flash harddrive.
Their boat is equipped with a GPS sensor, an inertial measurement unit (all 6 degrees of freedom), an ultrasonic wind sensor and an AIS sensor that receives data about obstacles (like other ships).
Therefore, collision avoidance relies on data received from an external source.
For satellite navigation the boat is also equipped with an iridium device, the 9522-B modem.
The energy supply is realized using batteries with a capacity of 600 Wh which are charged using 4 solar panels producing 90 Wp each. As a backup energy source they built in a direct methanol fuel cell.
To control the sail, a 200 W motor and to control the rudders two 150 W motors are used, all produced by MaxonMotors.



(a) Abstract electronic architecture of a robot sailing boat[10].

(b) Wind vane constructed by Bruder et al.[6].



(c) Hardware Architecture used in the boat of Ensieta [10].

Figure 5: Sample equipments of autonomous sailing boats

4 Software Architecture

An autonomous sailboat has to perform various time intensive tasks. It has to respond quickly to changing conditions like the weather or static obstacles. Two main architectures exist for autonomous robots. Each of them divides the system into different layers. Each layer should then be responsible for a part of the problem. [16]

4.1 Top-down planner based Model

This model arose from the three-layer architecture. In this approach a control system contains three functional elements [8]:

- *sensing system:* Translates raw sensor data into a world model.

- *planning system:* Takes the world model and a goal and generates a plan to reach that goal.
- *executing system:* Takes the plan and executes the actions.

Based on this architecture the sense-plan-act approach (SPA) has been developed. Sensor data together with knowledge about the environment is used to generate a model of the world. Based on this knowledge a detailed plan is generated which should be able to reach a specific goal. The flow of the control is unidirectional and linear. Information flows from the sensor into the world model to the plan and to the actuators. Disadvantage of this model is that generating a plan is a time intensive task. Therefore, the system cannot react quickly to dynamically changing environments.

4.2 Bottom-up reactive system

This model connects the measured sensor data with the robots actuators [5]. The implementation is a simple mapping from sensorial input to actions. The robot can respond very fast to changes in the environment like moving obstacles. The performance of the system is quite good in constantly changing environments. The system only has local information about the environment. Because of the lack of global information the system may not be able to perform complex tasks.

4.3 Hybrid architecture

Stelzer and Jafarmadar [16] have introduced a new system approach for autonomous sailboats. The hybrid architecture combines the top-down planner based model and the bottom-up reactive system. Figure 6 represents the architecture of the hybrid model. The control system is divided into four layers. Each layer is connected to the abstractor. The abstractor is a computer program on the boat which gathers sensor data and transforms it into raw data.

Sensors deliver information about current wind direction, wind speed, heeling, boom position, geographic position and direction of the boat. Optionally weather forecasts and sea maps are used for long term routing. A radar system can be used to detect moving obstacles. Based on these sensor data the actuators are controlled. Typical actuators are the position of rudder and sails.

A human operator predefines strategic goals. These goals include the target of the sailing trip and intermediate way points like buoys or ports. The operator only communicates with the strategic long term routing layer. He has no influence on path planning or manoeuvre execution.

Strategic long term routing layer

The strategic long term routing layer is the topmost layer. It represents the general routing strategy. An optimum track is determined based on expected weather, sea state and ocean currents. Optimization can be in terms of

- minimum passage time
- minimum fuel consumption

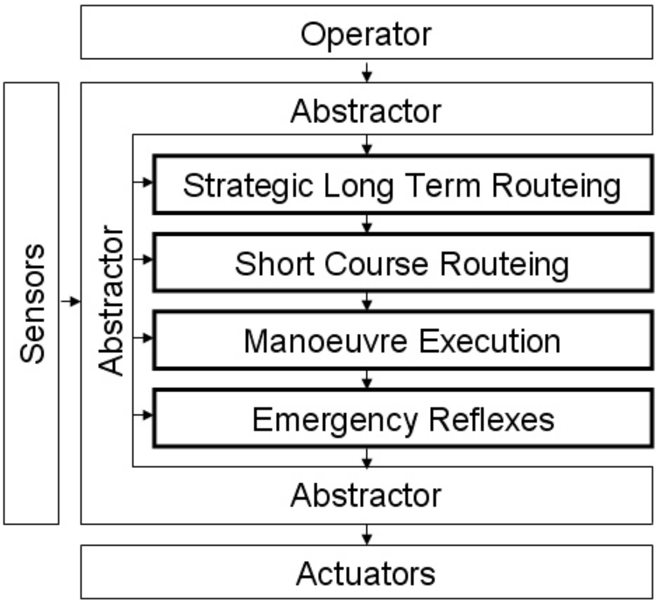


Figure 6: System Architecture by Stelzer et al.[16].

- safety for crew and ship
- best passenger comfort

Furthermore the boat's behaviour under certain wind conditions will be taken into account. A polar diagram describes these aspects. It includes the maximum speed a sailboat can reach dependent on wind speed and direction.
The routing algorithm determines an optimal rough route. This route respects boat-specific behaviour, weather conditions and sea topologies. The route is divided into smaller fields and is described by coordination which should be passed.

Short course routing layer

The short course routing handles the next target coordination. It finds an optimum way to the next target. In order to do that, a navigable route has to be specified. As shown in figure 7 not all directions of sail are navigable. Short course routing takes these restrictions into account and manoeuvres the sailboat to the next target. Since local wind conditions often change only local and present wind conditions are taken into account. It doesn't need a weather forecast at all because it reacts to changes of the wind conditions in real-time. Furthermore, static and dynamic obstacles are considered here.

Manoeuvre execution layer

The short course routing layer delivers desired directions and weather conditions. The manoeuvre execution layer

- adjusts the rudder position in order to bring the boat to the desired course and
- ensures that there is a flow in the sails to generate propulsion.

Furthermore the layer should be able to execute tack of jibe manoeuvres smoothly.

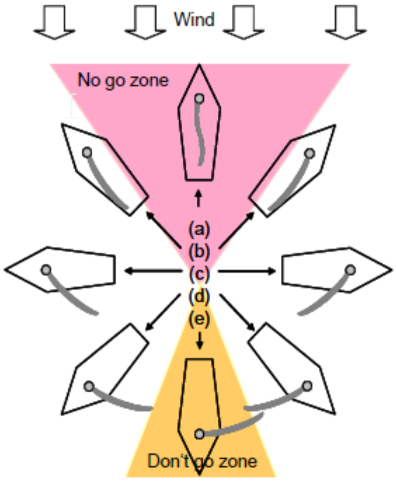


Figure 7: Points of sail by Stelzer et al.[16].

Emergency reflexes
The manoeuvre execution layer passes the desired rudder and sail position to the emergency reflexes. This layer passes the setting to the actuators unchanged. Only in case of an emergency the emergency reflex layer overrules the requested actions. Emergencies are the avoidance of capsizing in case of a wind gust or cautious sailing during periods of strong wind.

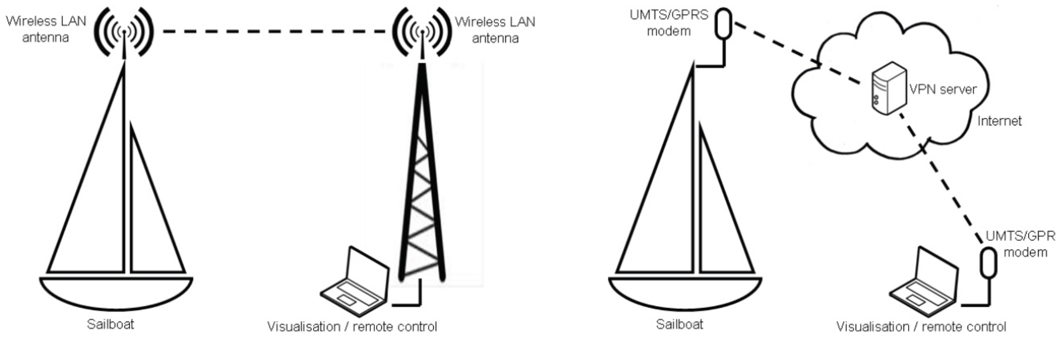
5 Communication

A permanent data link between boat and shore is necessary for

- monitoring,
- debugging,
- to control manually in case of emergency,
- for real-time monitoring. Real-time measurement data are needed for long-term observation tasks.

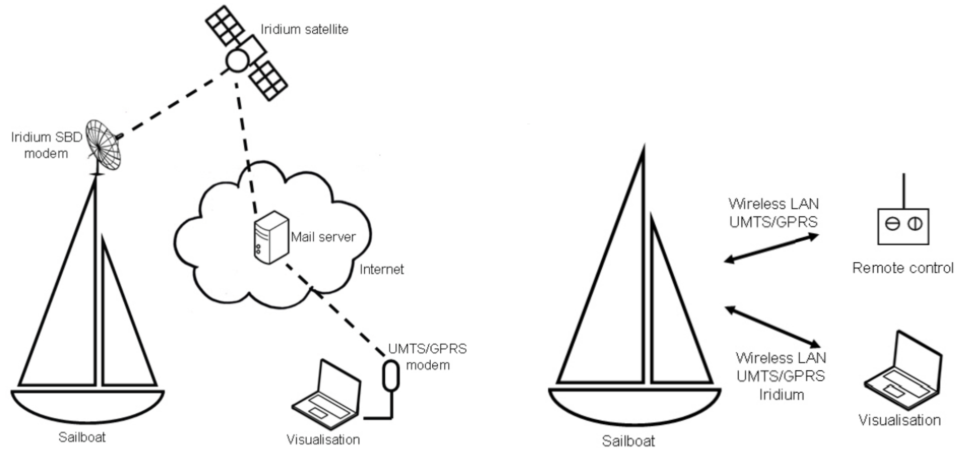
Three communication partners are involved in the communication process [15]:

- *Sailboat:* The sailboat transmits sensor values to the visualization.
- *Visualization software:* This computer program runs on a computer on the shore and represents the transmitted data. Furthermore, new target coordination, obstacle information or a new desired course can be sent from the visualization to the sailboat.
- *Remote controller:* This entity can be used in case of emergency to overrule the autonomous on-board control of the sailboat. It is especially needed during test runs. Desired actuator values like position of the rudder and sails are transmitted in real time to the sailboat.



(a) Wireless LAN communication.

(b) UMTS/GPRS communication.



(c) Satellite communication.

(d) Communication partners and communication stages.

Figure 8: Communication by Stelzer et al.[15].

Stelzer and Jafarmadar [15] introduce a three-stage communication system. It combines wireless LAN, GPRS/UMTS and satellite communication. Each communication channel features specific advantages and disadvantages. The system switches dynamically between the available communication channels.

First Stage: Wireless LAN

A wireless LAN antenna is mounted on the shore and on the mast top of the boat (Figure 8(a)). The higher the antennas are mounted, the longer the distance that can be covered. *Advantages:*

- No base or connection fee
- High bandwidth
- TCP-based communication

Disadvantages:

- The setup of the infrastructure. Antenna should be mounted high.

- Limited operation distance. Experiments have shown a 10Mb data link between boat and shore for up to 3 km.

Second Stage: Data Service of Mobile Phone Provider

The boat and the server on the shore are equipped with a data modem of a commercial mobile phone provider (Figure 8(b)). This allows internet based communication. Common data modems provide UMTS and GPRS and switch over automatically depending on the availability.

Advantages:

- Infrastructure provided by the mobile phone service provider
- High bandwidth
- TCP-based communication

Disadvantages:

- Base and connection fee can be high because of roaming
- Operating distance limited by the network coverage of the service provider

Third Stage: Satellite Communication

The boat is equipped with an Iridium satellite transceiver (Figure 8(c)). The Iridium satellite constellation allows a worldwide voice and data communication and covers the whole earth. The Iridium Short Burst Data (SBD) service is used by Stelzer and Jafarmadar. It is designed to serve a range of applications that need to send data messages with a size less than 300 B.

Advantages:

- Covers the whole earth
- It delivers rough geographic position information which can be used as a backup system for the GPS receiver on board.

Disadvantages:

- Low data volume
- High transmission latency
- Base and connection fee

The selection of the communication stage is mainly based on the availability, transfer charges and bandwidth of the specific channels. For short distances up to about 3 km the wireless LAN link is used. The GPRS/UMTS infrastructure can be used to distance of up to 20 km. For long distances a satellite communication is used. Stelzer and Jafarmader [15] used the following strategy for their implementation (Figure 8(d)):

- If a proper wireless LAN connection to the boat is available it will be used for visualization and remote control. If the connection quality decreases between a certain level the system automatically switches to UMTS/GPRS connection. For both the remote control and the visualization software this switch happens transparently. If wireless LAN and UMTS/GPRS are both not available the system switches to the satellite communication. In this stage the remote control for rudder and sail position will be switched off. To control the sailboat via remote control a line of sight to the boat is needed. Therefore, only Wireless LAN and UMTS/GPRS are suitable for the communication between sailboat and remote control.
- The system checks periodically to the best available connection. If no communication stage is available, the boat keeps on sailing autonomously.

6 Control System

The control of a sailboat consists of two main tasks: [4]

- governing of the rudder
- trimming of the sails

Basic sailing rules contain know how about steering the sails and rudder according to direction of target and wind. This knowledge will be transformed into a fuzzy inference system. This system controls the rudder and sails. The fuzzy system should be able to imitate the behaviour of an experienced human sailor. Fuzzy logic is very suitable for transmission of experts knowledge into a computer program in form of if-then-rules. [18]

The following variables have to be considered when governing a sailboat [4]:

- course
- effective course
- drift
- apparent wind angle
- attack wind angle
- rudder angle
- trimming angle of sails

6.1 Control System by Abril and Salom [4]

Abril and Salom [4] introduced 1997 a fuzzy logic system which should be able to govern the rudder and trim the sails automatically.
The optimum trimming angle can be calculated for a given wind angle by using the sail polar curve. The sailboat speed can be determined from the real wind angle with a speed polar curve. Furthermore, decisions about the course and planning the route should be

considered.

According to Abril and Salom [4] the total force which should be taken into consideration are:

- *hydrodynamic:* refers to the action of the water
- *aerodynamic:* refers to the action of the wind
- *perturbations:* fluctuations in wind, wave and current forces depending on sea conditions.

The control variables for the fuzzy controller are the rudder angle and the sail trimming angle. The controlled variables are the heading and apparent wind angle. It compares the heading with a reference and adjusts the rudder to keep the course. The sail is trimmed to achieve maximum speed. Further variables could be taken into account like the heel angle. The system could react to sudden puffs of wind. Measuring the apparent wind and boat speed would help to control in different weather conditions. [4]

Abril and Salom [4] have searched for a minimum number of rules that still govern the boat. Three basic rules have been found which mimic the behaviour of an expert sailor:

- Not much can be done regarding the course keeping when sailing close-hauled. To keep the course, the boat will be doing a lot of tacking (zig-zag).
- When the sailing is free not much can be done to improve the speed. Keeping the course becomes more important.
- The trimming angle of the sail should be half the angle of the apparent wind.

In total the system is split into two separated controllers:

- One that operates sailing close-hauled. Here, it is important to have good speed and to tack constantly.
- The second operates when the wind blows in the right direction. Tacking is not necessary and the wind angle is less important. Following the course is the main task.

6.2 Control System by Stelzer et al. [18]

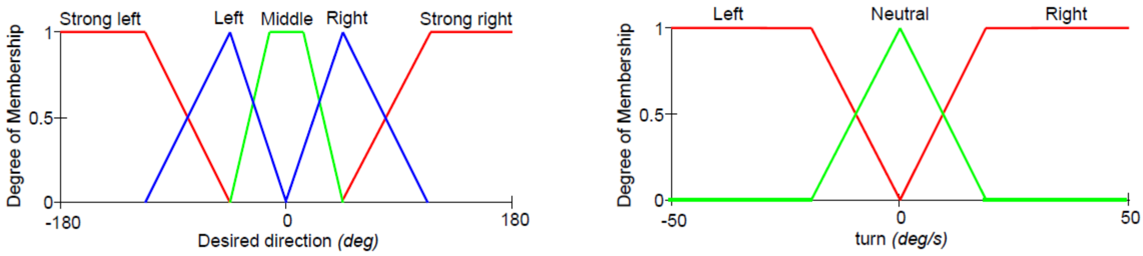
Stelzer et al. [18] have a slightly different approach. Different people can control rudder and sail without communication. Therefore, two independent working control circles are responsible for the rudder and sail.

- *Rudder controller:* keeps the boat on a predefined course
- *Sail controller:* Avoids capsize and ensures that there is enough flow in the sail.

Rudder Control Circuit

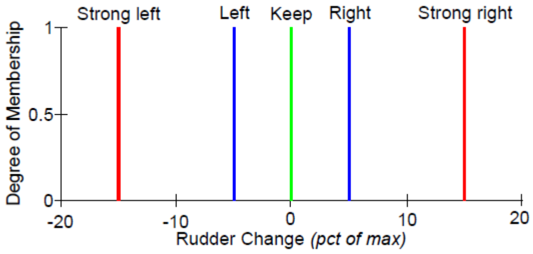
Input variables for this control unit are:

- The current boat direction and the desired direction from the weather routing system. The difference of the two gives the necessary course correction. The variable is measured in degrees. Figure 9(a) describes the fuzzy set for this variable.
- The angular velocity of the boat flow (turn) is given to avoid oversteering. It is the time derivative of the actual boat direction given by the compass. Figure 9(b) shows the fuzzy set for the turn variable.



(a) Fuzzy Sets for 'desired direction'.

(b) Fuzzy Sets for 'turn'.



(c) Fuzzy Sets for 'rudder change'.

Figure 9: Fuzzy Sets Rudder Controller by Stelzer et al.[18]

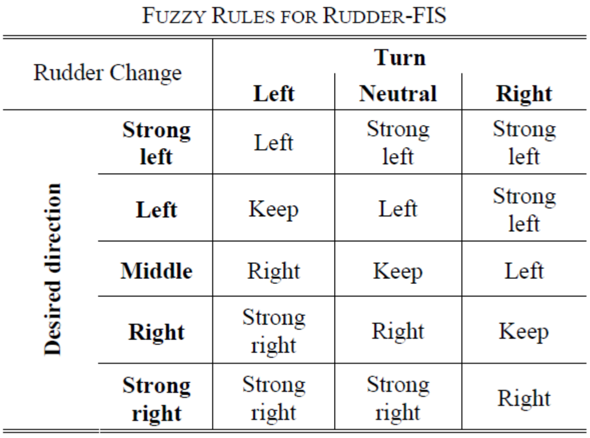
Output variable is the change of the rudder position. The variable rudder change contains five singletons. Figure 9(c) describes the fuzzy set for the rudder change.
The **fuzzy rules** for the controller are fifteen if-then-rules.
IF desired direction IS x AND turn IS y THEN delta rudder IS z.
Table 1 shows the fuzzy rules in detail. Defuzzification is done by the center of gravity of Singletons evaluation (CoGS).

Sail Control Circuit

Input variables are the heeling of the boat and direction and speed of the wind. The calculation of desired heeling is described in the following relationship:

- the higher the wind speed, the higher the desired heeling
- the more towards downwind the boat moves, the smaller is the desired heeling

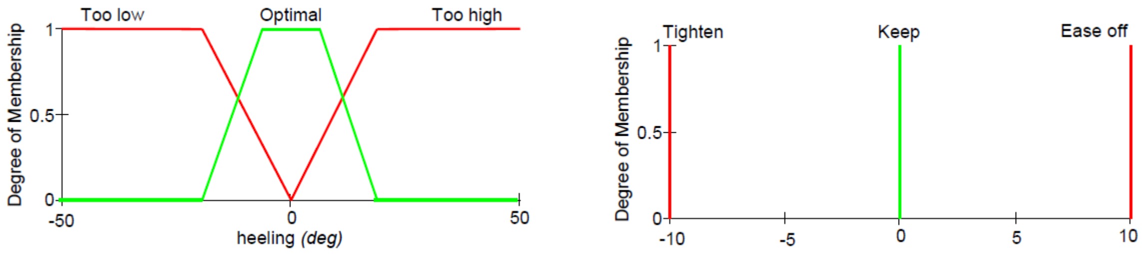
The heeling (in degree) is the difference between the desired heeling and actual heeling of the boat. Three fuzzy sets describe the variable (Figure 10(a)).



FUZZY RULES FOR RUDDER-FIS

Rudder Change		Turn		
		Left	**Neutral**	**Right**
Desired direction	**Strong left**	Left	Strong left	Strong left
	Left	Keep	Left	Strong left
	Middle	Right	Keep	Left
	Right	Strong right	Right	Keep
	Strong right	Strong right	Strong right	Right

Table 1: Fuzzy rules by Stelzer et al.[18].



(a) Fuzzy Sets for 'heeling'.

(b) Fuzzy Sets for 'sail change'.

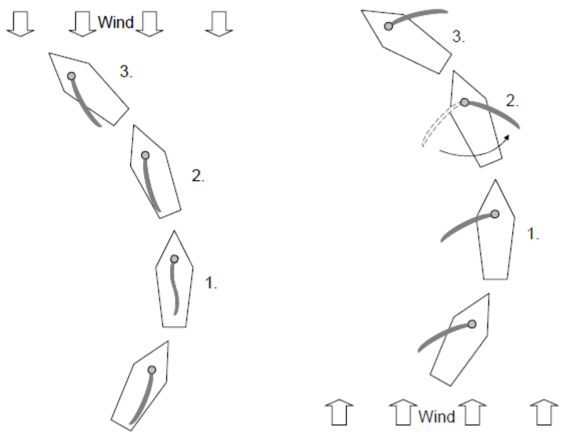
Figure 10: Fuzzy Sets Sail Controller by Stelzer et al.[18]

Output variable is the direction and amount of necessary adjustment of the sail winch. The fuzzy variable sail change contains the three singletons:
The heeling should be kept on an optimum according to the actual wind conditions. There are three If-Then-Rules to determine the output:

- If heeling is too low, then tighten sheets.
- If heeling is optimal, then keep sheets.
- If heeling is too high, then ease off the sheets.

The boat should be able to execute the following manoeuvres:

- *Keep on a given course:* The parallel execution of sail and rudder control circuit guarantees to keep on course. The rudder is adjusted in case of course deviation. Sails are adjusted to keep propulsion.
- *Execute a tack:* A tack manoeuvre turns the bow of the sailing boat through the wind so that the wind changes from one side to the other. If the target is against the wind in a straight line route it is not navigable. The boat has to take several zig-zag courses against the wind and therefore executes several tack manoeuvres.
  The following actions happen in case of a tack manoeuvres (Figure 11(a)):



(a) Tack execution (b) Jibe execution

Figure 11: Manoeuvres by Stelzer et al.[18]

  - The sail turns towards the wind. Heeling decreases and the sail control system tightens the sheets.
  - The bow turns through the wind so that the wind changes to the other side of the boat. Heeling increases again and the controller eases off the sheets.
  - The boat has reached a new course.

- *Execute a jibe:* A jibe manoeuvre turns the stern through the wind, so that the direction of the wind changes from one side of the boat to the other. The sailboat will execute several jibe manoeuvres when it changes course as it zig-zags downwind. The jibe manoeuvre is more difficult than the tack and optimal timing is more important (Figure 11(b))
  - The sail turns towards the wind. On exact downwind direction the heeling is 0.
  - Special Rule for the jibe: If the stern has turned through the wind, but the sail is still on windward side, the sail gets tightened to move it to leeward side.
  - The boat has reached the new course.

7 Collision Avoidance

Collision avoidance is a challenging task for autonomous sailboats as they operate in an ever changing, unstable environment. Sailboats can not just change their route because not every route is directly sailable (no-go zone against the wind).
This chapter will discuss two approaches to collision avoidance: a reactive approach to collision avoidance, presented by Stelzer et al. [17] and a raycast approach presented by Sauze and Neal [14].

7.1 A Reactive Approach to Collision Avoidance

Stelzer et al. already presented a hybrid, layered architecture in a previous paper [16]. They extended the short course routing layer shown in figure 6 with their approach for collision avoidance [17]. Their existing short course routing layer used the polar diagram of the boat to obtain the best possible route.

To understand their approach for collision avoidance, one first has to understand how a polar diagram works. The maximum speed of the boat is depending on the wind speed and the wind direction relative to the boat. An example of a polar diagram for a sailboat can be seen in figure 12. In a polar diagram the maximum speed of the boat for every course relative to the wind direction is plotted for different wind speeds.

In their approach for short course routing Stelzer et al. utilize the boat specific polar diagram to find the quickest route to the target. This so called "quantified target approach" presented in [19] is extended by an obstacle avoidance strategy.

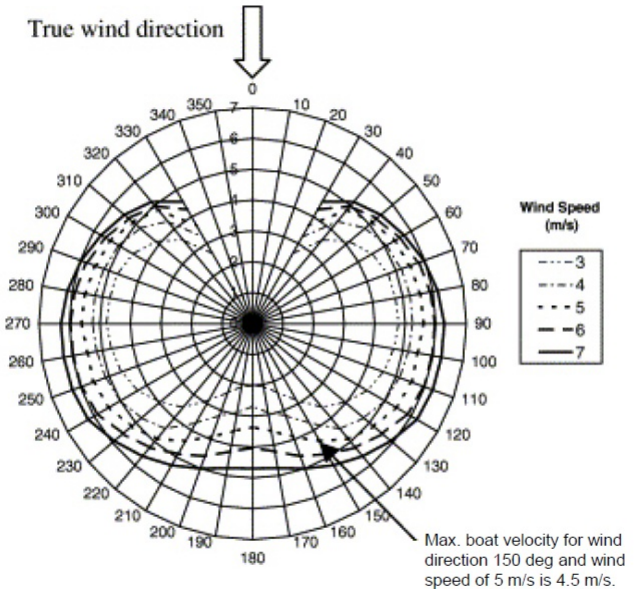


Figure 12: Polar diagram of a sailboat. [17]

The obstacle avoidance strategy can be seen in figure 13. Their basic idea is to alter the polar diagram according to the obstacles sensed in the surrounding area of the boat. In other words: the maximum speed of the boat for a given direction is reduced if there is an obstacle in the way.

The outer circle, labeled r_{max}, is called "save horizon". All obstacles outside that circle are not considered and do not have an impact on the polar diagram (as can be seen for O_4).

The inner circle, labeled r_{min}, marks the minimum distance to obstacles. Obstacles that are inside this circle have the maximum impact on the polar diagram, reducing the maximum speed of the boat in that direction to zero (as can be seen for O_3).

Obstacles that are between these two circles have an impact on the polar diagram, linearly depended on their distance to the boat. That can be seen for O_1, which has a very small impact on the polar diagram, and for O_2 that has a bigger impact.

The original routing algorithm works unchanged, just with the altered polar diagram.

To determine the obstacles in the surrounding area the boat is reduced to a point of view and the surrounding area is divided into equally sized sectors. For each sector the distance to the nearest obstacle is sensed.

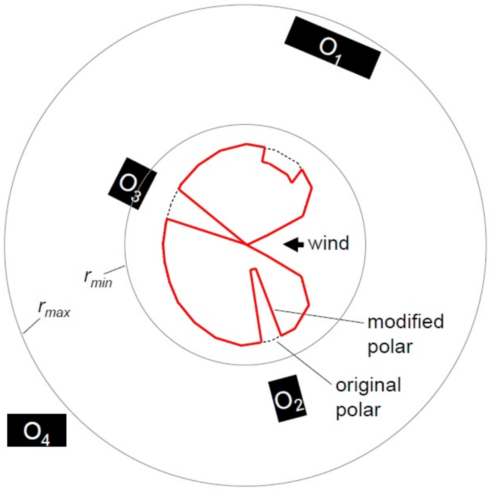


Figure 13: Obstacle avoidance using an altered polar diagram.[17]

Each sector that does not contain any obstacle gets the value of r_{max} assigned.
In order to implement this algorithm efficiently, the authors also propose a caching mechanism, combined with a sort and sweep algorithm. That way they are able to determine the closest obstacles quickly, having the nearest obstacles sorted to the front and dropping obstacles that are beyond the save horizon.

7.2 A Raycast Approach to Collision Avoidance

Sauze and Neal also used a reactive architecture for their collision avoidance system presented in [14]. They state that changing wind conditions would render most of the route planning in advance pointless. However, some higher level planning is used in the form of user defined waypoints.

Obstacle detection

Their algorithm uses a map of the coastline that could also be extended to work with other sensed obstacles. The sailboat determines its position on the map using a positioning system (e.g. GPS) and then casts rays from the robots position in every direction (every angle from 0-359 degrees) and senses the distance to the nearest obstacle in that direction. This approach is quite similar to the approach presented by Stelzer et al. [17]. It might not be necessary in every situation to do a full 360 degree scan. The authors Sauze and Neal state that in certain situations it is enough to scan a "beam" in the direction the boat is heading. However, the width of this beam (e.g. 60 degrees) has to be carefully chosen.

Obstacle avoidance

Once an obstacle is detected a new course is decided that avoids the obstacle. However, it has to be ensured that the boat makes progress towards the user defined waypoint it has to reach. Therefore, the new course that is decided here is not directly sailed, but just

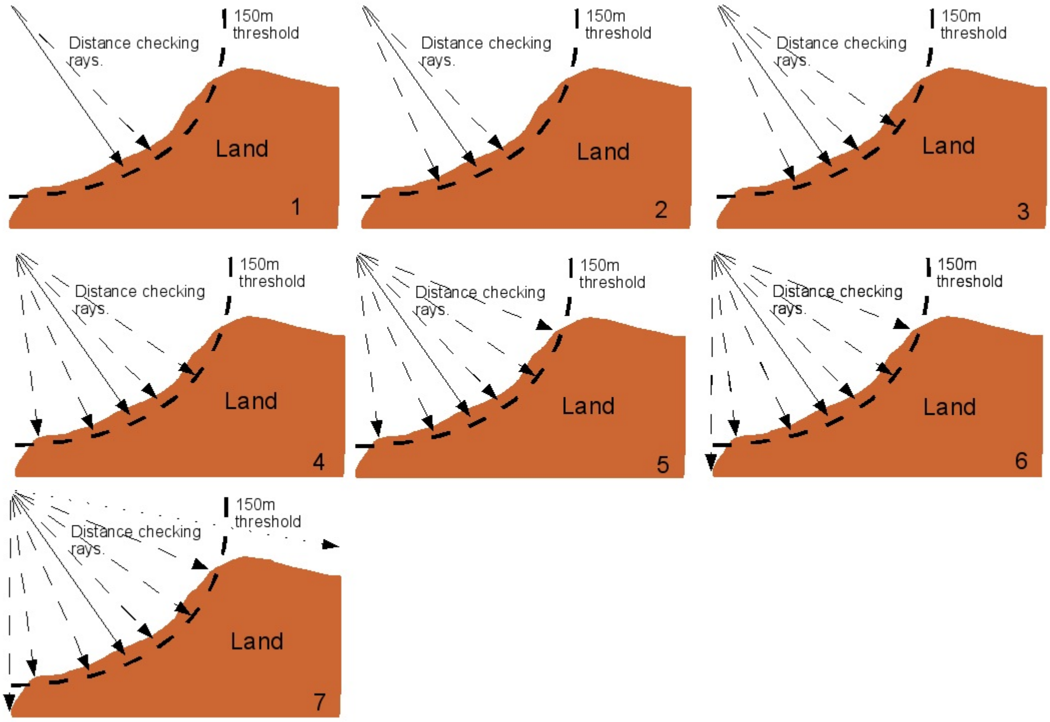
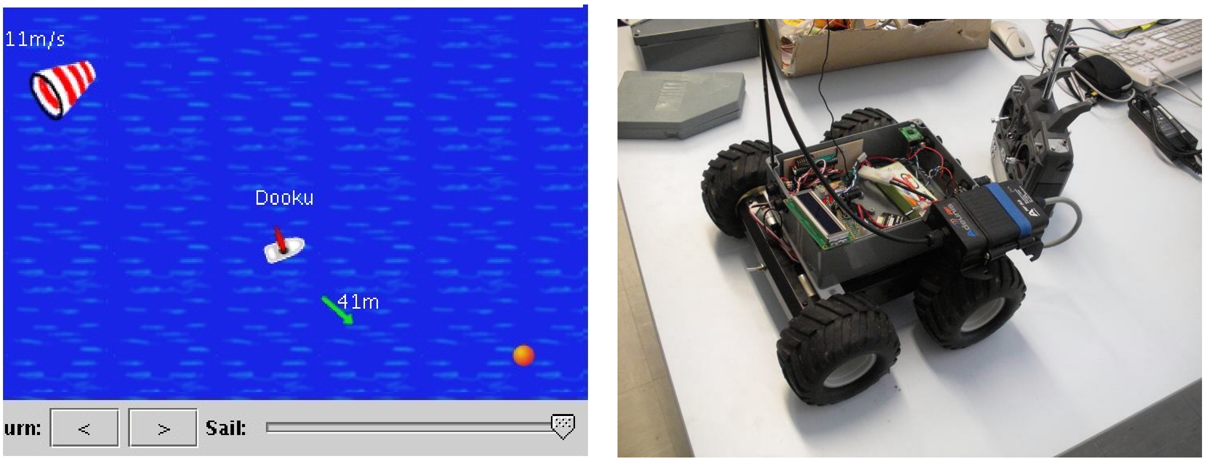


Figure 14: Determination of a new course in the raycast approach.[14]

causes a deviation from the original course.
To achieve that, the authors propose a biologically inspired system using hormones. These hormones are released once an obstacle in the way of the boat is sensed. To get a sudden change in behaviour when avoiding a collision, the hormones are stored until they reach a certain threshold and then released all in one moment. This behaviour is preferable to a slow start of the obstacle avoidance, according to the authors. The hormone quantity (between 0 and 1) is then used to determine the course. The course is determined by the difference between the direct course to the next waypoint and the new course (avoiding the obstacle) multiplied by the hormone quantity. So the hormone quantity is responsible for how large the deviation from the original course is.
As the hormone quantity slowly decreases when the obstacle has been avoided, the boat slowly returns to the direct course to the next waypoint.
To find the new course that was stated above, the authors propose to search for a free sailable route, that is closest to the direction of the next waypoint. A free route is defined by a specific length without obstacles (the authors used 150 meters in their simulations). For their algorithm the authors stated some additional rules: the new course has to be at least 5 degrees from the current course and the new course also has to be more than 5 degrees away from the course to the nearest sensed obstacle.
Figure 14 shows the procedure of choosing a new route. The algorithm starts 5 degrees to the left of the target heading and continues alternating between the left and the right of the target heading, always adding 5 degrees, until it finds a route without obstacle within the threshold.

This algorithm has certain problems when the boat gets trapped in small inlets of the coast.
The authors tested their algorithm in simulations using an actual map of a coastline near Belfast that has a lot of inlets and small islands.
They also note that the data used in the presented algorithm is very much like data that a RADAR mounted on the boat would return. Therefore, it might also be used with RADAR data and would then be able to sense and avoid any obstacle (coastline, ships, etc.).

8 Simulation and testing



(a) A screenshot of tracksail.

(b) Robot car for testing electronics and algorithms.[10]

Figure 15: Simulation and testing

Testing can be a challenging task for autonomous sailboats as real life testing of the boat is time consuming and expensive, and it is very likely for the boat to fail. Fatal errors that cause the ship to crash or sink are even more expensive and may even cause a loss of the ship. Therefore, a lot of testing has to be done before the boat can be launched.

Simulators

Sauze and Neal briefly described their use of a simulator in [13]. They used a simulator based on the open source game tracksail [2]. Tracksail is a multiplayer game with a server and several clients. Sauze and Neal replaced the user interface of the client by a client conforming to the specifications of their boat. The authors also identify a lot of differences between a simulator and the real world like too consistent wind conditions, lack of influence of waves, idealized boat behaviour and no real world noise for the sensors. They also used the modified tracksail version to carry out experiments with their collision avoidance approach. [12]
A screenshot of the tracksail game is shown in figure 15(a).
Sliwa et al. also used a simulator to test their algorithms [10]. They implemented the simulator in the SCILAB language.
It can be concluded that simulated behaviour is never equal to real world behaviour, and

that developing a simulator that would come even close to the real world would be very complex and take a lot of effort.
So it does not mean that if something works in a simulation it will also work in the real world. The only thing that can be concluded is that if it does not work in a simulation it will certainly not work in the real world.

Testing

Another way to test and debug hardware and simple algorithms was also described by Sliwa et al [10]. They facilitated a robot car seen in figure 15(b) to test the hardware setup, sensors and also simple algorithms.
It is possible to test the routing algorithms and the reactions to changing wind conditions and obstacles using such vehicles, which is a lot more comfortable than testing and debugging them on the actual boat.
So during the development a lot of things can be tried and tested very quickly in the office.

9 Conclusion

As we could see in the hardware chapter, the hardware is the key factor for costs, algorithmic possibilities and possible applications. Large boats can carry more sensors and therefore more applications are possible. Considering the available space, the embedded intelligence is either a microcontroller, PDA or x86 computer. Anemometer, communication infrastructure, actuators for sail and rudder, energy supply and GPS systems are basic components of an autonomous sailboat.
There are a number of various architectures and systems which are able to control the sailboat. A few of them have been presented in this paper. Especially hybrid architectures which combine a top down planner based model with the bottom up reactive approach are used for autonomous sailboats. Stelzer and Jafarmadar [16] have introduced a four layer approach. Based on a given goal the architecture determines a rough route and calculates intermediate goals. An optimal way to the next goal is searched and the desired sail and rudder position calculated and passed to the actuators.
Wireless LAN, GPRS/UMTS or communication via satellite are common communication methods for sailboats. Each of these methods has its advantages and disadvantages.
To translate sailing knowledge into a computer program fuzzy logic is used. The control system of an autonomous sailboat therefore mostly consists of a fuzzy system which outputs positions for rudder and sail. This paper has presented two control systems. The first one by Abril and Salom [4] split the system into two fuzzy controllers. One for sailing close-hauled and one for sailing free. The second control system by Stelzer et al. [18] split the system into rudder controller and sail controller.
Two approaches for collision avoidance have been presented. The reactive approach by Stelzer et al. [17] uses the polar diagram of the sailboat. Obstacles are included into this diagram. With this altered polar diagram a way around the objects is calculated. The raycast approach presented by Sauze and Neal [14] is a biologically inspired system using hormones.
Different simulators are used to test the system. Nevertheless, simulated behaviour is never equal to real world behaviour and developing a simulator that would come even close to the real world is very complex. To test hardware setup and sensors a simple robot car can

be used.

The construction and implementation of autonomous sailboats is an upcoming topic. Further developments in the hardware increase the possibilities for the construction. Especially in relation to the important topic of reducing CO2 emissions autonomous sailboats will be a popular topic for research. The robotic sailing conference and yearly competitions further increase the research ambitions.

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