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Design and Construction of the Autonomous Sailing Vessel AVALON

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***Abstract*—This paper presents relevant mechanical and technical aspects about the autonomous sailing vessel AVALON. AVALON's purpose is to cross the Atlantic Ocean completely autonomously without any direct influence by humans. The system's robustness and stability are as important as an acceptable sailing performance. The entire mechanical and electronic system was developed in order to fulfill that single purpose and take up the challenge.**

I. INTRODUCTION

AVALON is an autonomous sailing vessel designed for the MICROTRANSAT CHALLENGE, a competition in which several international sailing robots are trying to cross the Atlantic Ocean autonomously. During its cruise from southern Ireland to the Caribbean, AVALON has to withstand several unfavorable weather conditions . Winds within a range of 10 up to 50 knots and steep waves with a height of about 9 meters may occur especially around the Irish coast. In spite of powerful batteries the energy of the boat is limited due to the requested autonomy of about 4500 hours. As a result, efficient and energy-saving mechanic and electronic systems are required.

A. State of the Art

1) Harbor Wing Technologies: The company HARBOR WING TECHNOLOGIES developed an autonomous, unmanned surface vehicle that was originally intended to be used with the US Navy. The vehicle is characterized by the following innovative components:

- A 60 foot Wingsail capable of turning 360 degrees
- A horizontal winglet on the Sail that controls the driving force produced by the wing
- Hydrofoils on the rudder and fin that increase the efficiency and speed of the boat

2) Microtransat Competitors:

ROBOAT was developed by the Austrian Society of Innovative Computersciences (InnoC) and is based on a sailing dinghy LAERLING that was technically modified and supplemented by a self-developed robotic unit.

FAST is like AVALON, a self-construction made of glass fiber. Contrary to AVALON, the Portuguese hull was built on a positive mould made of wood. The robotic unit is completely self-developed.

Fig. 1. Prototype of Harbor Wing Technologies [1]

Details about several other competitors are listed on the MICROTRANSAT 09-Homepage[4].

II. PROJECT ORGANISATION

A. Modules

The Team *Students Sail Autonomously* (SSA) consists of eight mechanical engineering students of the *Federal Institute of Technology, Zurich*. The Project is structured into three modules: One contains all the management and organization processes and the other two the boat structure respectively the entire control system.

B. Timetable

The Project AVALON started in August 2008 and will formally end in September 2009. The complete boat and its control system has to be developed, built and tested within this period. The timetable in figure 2 illustrates the different phases of the project, starting with the design and construction phases to the point of testing and optimization.

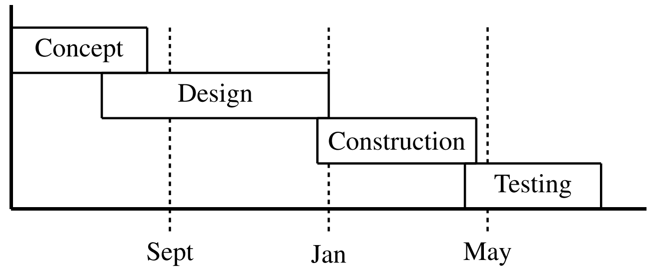

Fig. 2. Official timetable

C. Finances

The costs of the project currently amount to 209 000.- sFr. Split into Control System, Mechanical Structure, Energy Supply and Logistics (see fig. 3), it is obvious that the part for the mechanical structure constitutes the largest amount to the budget, mainly because we use high-quality materials like carbon fiber and CNC-milling of all the molds. The entire project is financed by sponsors from the national industry acquired by students of the team.

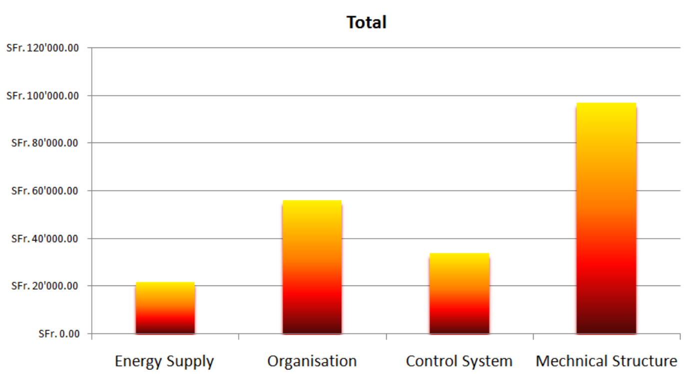

Fig. 3. Costs of different modules

TABLE I
NOMENCLATURE

Variable	*Description*	*Value*
General Variables		
B_{max}	Half maximal beam	$0.7\,m$
T	Draft without keel	$0.25\,m$
∇	Displacement	$0.44\,m^3$
Fixed Design Parameters		
L_{OA}	Length over all	$3.95\,m$
Angle	Central angle (DeckContour)	65°
Radius	Radius of DeckContour at bow	$0.05\,m$
DeckHight	Z-Position off Deck from waterline	$0.4\,m$
Variable Design Parameters		
BeamAft	Half beam at aft	
BeamMaxX	X-Position of maximal beam	
BeamMaxY	Value of maximal half beam	
DraftBow	Value of draft at bow	
DraftMax	Maximal value of draft	
DraftMaxX	X-Position of maximal Draft	
TransomEndZ	Z-Position of Transom at stern	

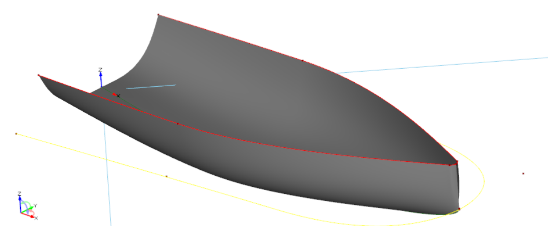

Fig. 4. Hull

III. Mechanical Structure

A. Hull

The hull design is based on form parameters, e.g. length, draft or beam. Parameters are used as input data for B-spline curves and surfaces. Instead of modifying those curves and surfaces, we use constrained optimization algorithms in order to vary parameters and generate geometry. The algorithm minimizes a target function, which is defined so that a certain combination of parameters results in a desired hull shape. The hull design of AVALON is based mainly on four fixed parameters and seven variable parameters. As a result, four B-spline curves can be derived and the hull surface generated (Figure 4). The basic data of the hull AVALON can be given in Table III-A.

The final hull was laminated inside a female mold using glass fiber sandwich. Epoxide resin was sucked into dry glass fiber material by vacuum using a so called INFUSION PROCESS. Compared to conventional laminating, this method is much cleaner and more convenient. It is the state of the art of laminating processes.

B. Rig

The rigging system is one of the most important parts of the whole assembly. A defect in its structure will inevitably cause a shipwreck of the project. Following aspects were considered for the design:

- High loads and forces on the mechanical structures due to strong winds and heavy weather conditions.
- Highest demands on reliability. There is no chance to repair anything througout the journey.
- Preferably efficient mechanical transmission in order to save as much energy as possible

During the design phase it turned out that a balanced rig (figure 5), comparable to RC-models, prevails over other solutions like a conventional rig. The criteria for the decision for a balanced rig were:

- Costs
- Mechanical energy efficiency

- Sailing performance
- Reliability

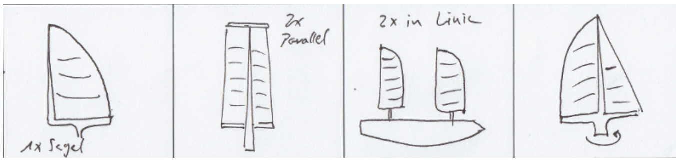

Fig. 5. Design studies of the rig

The balanced rig is much more efficient relating to energy consumption than any other conventional rig. The load on trimming ropes is reduced by over 50% due to the balanced distribution of the sail load. Furthermore, AVALON's rig doesn't use any ropes that may generate knots and jams. The rig is pivoted on a central bearing without shrouds and stays. The result is a technically simple and reliable construction.

C. Keel and Rudders

1) Keel: In order to achieve a sufficient righting moment and stability during heavy weather situations, AVALON's keel with a draft of two meters consists of a slight fin with a 160 kg ballast bulb. This configuration allows the boat to sail in winds of up to 50 knots without capsizing.

The fin and parts of the bulb were made by high-modulus carbon fiber in precisely milled polyurethane molds. After hardening and tempering, the bulb was filled with lead and the two halves were glued together.

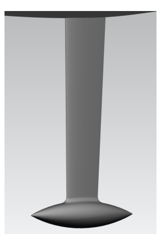

Fig. 6. Keel with fin and ballast bulb

2) Rudder: A twin-rudder system was selected for AVALON to make sure to have sufficient steering effect in every sailing situation. Angular mounted twin-rudders deliver a better grip in the water at a certain heeling compared to single rudders.

Assembled inside the hull, the rudder actuators are well sealed and protected against water and humidity.

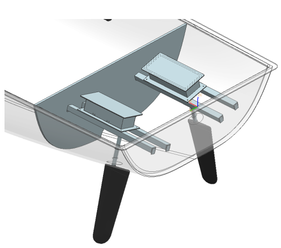

Fig. 7. Twin rudder system

IV. ELECTRONIC HARDWARE

A. Main Computer

The brain of the system consists of different hardware components located in the center of the hull. The main computer as well as different peripheral devices such as a serial-to-USB adapter, satellite modem and a wireless LAN hub are in a double sealed fiber glass box. The main computer MPC21 from

Fig. 8. Main PC and brain of AVALON [2]

DIGIALLOGIC is a 500 MHz device with 1024 MB RAM and a compact flash harddrive. With an average power consumption of about 8 watts, the protection of a metal housing and a total weight of less than 1 kg, this device is designed for operating in a rough environment.

B. Sensors

All desired information such as position, heading or speed are measured by several sensors located all over the boat. To get a fully controllable system, data is collected from the following sensors:

GPS Provides position, heading and speed. The sensor's antenna is mounted on top of the mast. The electronic unit is located in the hull.

IMU The *Inertial Measurement Unit* provides all information about velocity and acceleration in all 6 degrees of freedom. Combined with an additional GPS-antenna, the accuracy of the boat's position can be increased to $\pm 10\,cm$.

Wind Mounted on top of the mast, the windsensor provides wind speed and direction. Unlike other sailing boats, AVALON has an ultrasonic windsensor that promises less failure than a conventional sensor with a turning wheel.

AIS This Sensor receives data such as position and heading from other boats via VHF-antenna. The AIS system is an additional means of perception that ensures that collisions with large commercial ships are avoided.

C. Satellite Connection

In order to guarantee a safe connection to the boat during the transatlantic journey, a very reliable communication system is inevitable for such a project. On AVALON, the communication system will not only be used to provide periodic position and status reports, but also to have the possibility to interact with the boat in case of an emergency and to download weather updates. All these tasks can only be accomplished by using a satellite network. With our main goal to cross the Atlantic Ocean, the respective satellite network has to provide coverage in this specific region. This is only the case with the networks IRIDIUM and INMARSAT. The choice between these two options has been based on the available hardware for each of these networks. For the INMARSAT network, the favorite option is the Mini-C-System. It has an integrated GPS-receiver with position reporting capability. The IRIDIUM device which was finally chosen, the 9522-B modem, has a more flexible interface, higher data rates and lower airtime fees. Weather updates can be downloaded by the boat autonomously. As Iridium is also acting as an Internet Service Provider (ISP), there is the possibility to establish a *Secure Shell* (SSH) connection to the boat in case of a very severe malfunction of the software.

D. Power Supply

The main power supply is realized through four solar panels of 90 Wp each and a total area of two square meters. The collected power gets stored in four lithium-manganese batteries. Each battery consists of 70 single cells and has a capacity of 600 Wh at a nominal voltage of 25.2 volts. Lithium-manganese were chosen mainly because of their weight but also because they are fairly safe to use.

For back-up power, the boat has a direct-methanol fuel cell on board. This fuel cell is automatically activated when the voltage drops under a certain value, the *switch on* voltage. It then charges the batteries until the *switch off* voltage is reached. In theory, the solar cells provide enough power for the boat's systems. The fuel cell only serves in case of enduring bad weather or other unforeseeable circumstances.

E. Actuators

1) Sail Motor: The Sail is driven by a 200 watt motor by MAXONMOTORS. Motor and gear are encapsulated with a glass fibre box in order to be protected against humidity. The actuation moment is increased by a factor of three and transmitted over angular wheels to the shaft of the rig bearing. With a nominal torque of 600 Nm, the sail actuator is capable of handling most of the heavy weather situations. If the torque exceeds the nominal value, a friction clutch protects the gears and the motor from demolition.

2) Rudder Motors: Each rudder is separately driven by a 150 watt motor by MAXONMOTORS. Protected by a fiber glass box, the moment is aswell transmitted over angular wheels to the rudder shaft. In case of maximal load, the rudder can actuate with a torque of 30 Nm which is far beyond common load cases on rudders of comparable size. Therefore it was needless to implement any kind of clutch on the rudders.

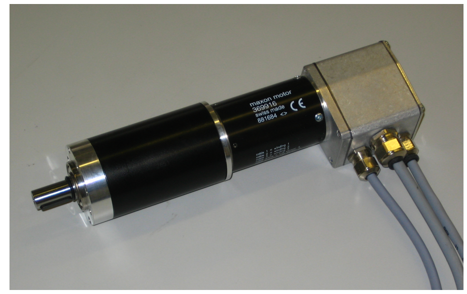

Fig. 9. Rudder motor with gear

V. SOFTWARE

A. Software Organisation

All software is LINUX-based and mostly self developed. The base of the entire software structure is the so called middleware DDX. This is a software that manages any storing activities and represents the connection between a shared memory and several independent subprograms (see figure 10). Thanks to DDX, the control system is structured in closed program parts which are connected to the store by reading and writing global variables. For instance there are sensor drivers which read out actual sensor data from the hardware and write it directly to the store. Another program requiring sensor data will read needed data from the store. A distinct advantage of DDX is the modular software structure. If ever a program part crashes, it can be restarted separately by certain watchdogs. The different subprograms are:

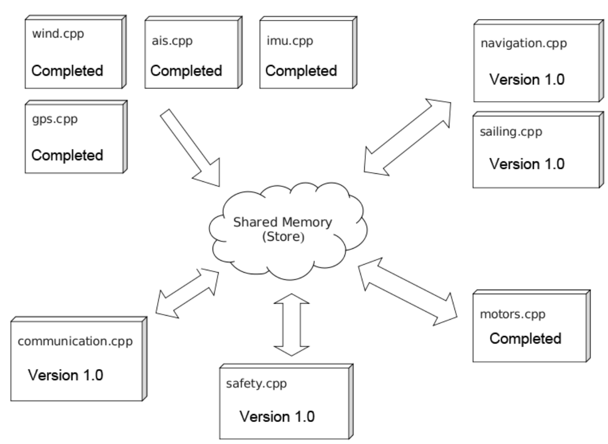

Fig. 10. Software organisation

Drivers Read out any sensor information, transmit them to the store and actuate rudder and sail.

Navigator Calculates the optimal route based on sensor data and transmits a desired heading to the store.

Helmsman Controls and steers the boat. Requires information from store respectively sensors.

Communication Establishes and ensures the satellite connection between boat and headquarters. Required to transmit status messages and logfiles.

Structure and function principles of Helmsman and Navigator are specified in the following sections. Basically the software structure is comparable to a common hierarchy on a sailing yacht. On one hand there is the Navigator deciding about the strategy and the heading. On the other hand, the Helmsman is responsible for the rudder and the trim of the sails. The only difference to a real sailing team is the fact that all positions are occupied by computers, sensors and motors.

B. Navigator

This program part collects information about weather and geography and calculates the optimal route to a given waypoint based on a grid-based A* path planning algorithm. The program is split into a global and a local planner. The global planner respects mainly weather forecasts within the entire route on the Atlantic, whereas the local planner sets local waypoints and headings and is capable of recognizing and avoiding other large boats in the area. Weather information is transmitted via a colored wind chart over the satellite communication system and will be parsed and converted to useful wind information. The calculated heading will be transmitted to the Helmsman.

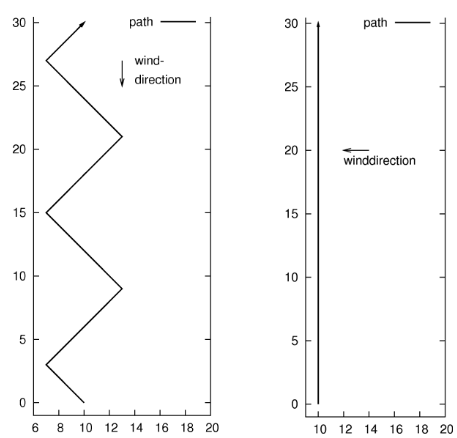

Fig. 11. Route planning at different wind directions

C. Helmsman

The Helmsman reads out the actual heading from the store and keeps the desired heading of the boat. The sail's position is directly related to the wind angle. The Helmsman also performs maneuvers such as gybing and tacking or luffing and bearing out. The program is built as a state machine with different modes:

- Upwind Mode, during tacking against the wind
- Downwind Mode, during gybing downwinds
- Normal Sailing, if a constant heading is required
- Emergency Mode, rudders crossed and sail straight in wind

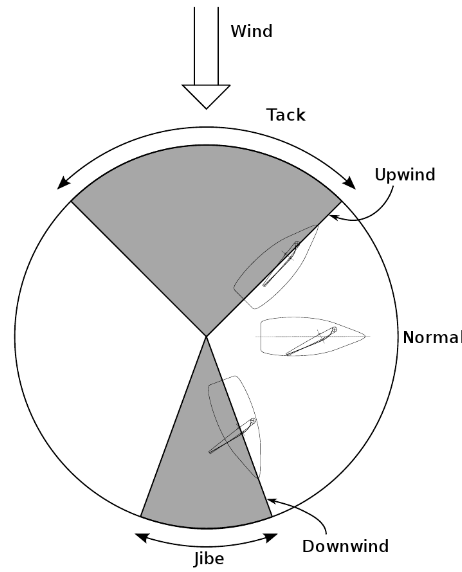

Fig. 12. Sailing modes on different headings

Depending on the required heading, the Helmsman switches to the corresponding mode. Control parameters have been optimized for every different mode in order to achieve the best sailing performance.

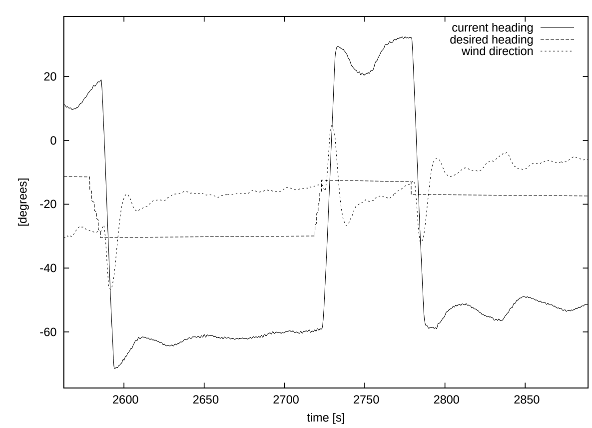

Fig. 13. Wind direction and current heading plotted over initially desired heading

VI. Conclusion

The result of all previous information is an energy-efficient and solid autonomous sailing vessel named AVALON. Construction was completed on time. Several mechanical and software tests have already taken place on the lakes of Zurich and Lucerne. The boat showed stable sailing behavior in different wind conditions. The robustness of the mechanical structure has been proofed up to 6 beaufort and the control systems already allow to navigate to a given waypoint. The team is convinced to be ready and fully equipped to start the long race over the Atlantic.

Fig. 14. Avalon ready to sail

Acknowledgment

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