A Layered System Architecture to Control an Autonomous Sailboat

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Abstract

A four layered control architecture is presented for an autonomous sailboat combining both reactive and planner-based approaches. The system allows autonomous sailing, where routeing, navigation and carrying out the manoeuvres run automatically and directly on the boat. Various sensors observe the highly dynamic environment and provide measured data to the control system, which steers rudder and sails. The four layers are responsible for strategic long term routeing, short course routeing, manoeuvre execution, and reflexes in case of emergency. All four layers are executed in parallel. They access sensor data directly and generate prerequisites for the succeeding, subordinate layer. Experiments using a yacht model have been carried out to demonstrate feasibility and suitability of the presented approach. Detailed log data analysis from actual sailing trips show a steering behaviour as expected by sailing experts.

1 Introduction

An autonomous sailboat has to perform many complex tasks to reach a predefined goal. To navigate to a specified target various time intensive high level tasks are required. While planning the route of the sailboat long term weather conditions have to be taken into account as well as static obstacles like islands or shoals. As sailboats operate in a highly dynamic, ever-changing environment an autonomous sailboat has to respond quickly to changing environmental conditions.

Mobile autonomous robot systems are usually divided into separate layers each responsible for a part of the problem. Basically two different architectures exist: top-down planner based and bottom-up reactive systems.

In Top-down planner-based systems sensor data together with a priori knowledge about the environment is used to generate a model of the world in which planning occurs (Chatila and Laumon, 1985; Gat, 1998). Planning mechanisms generate a detailed plan for the robot's actions to reach a previously specified goal. After the plan is finished the robot will act according to it. These systems have shown good performance in complex static environments, however generating a plan is usually a time intensive task. Thus these systems cannot react quickly in dynamically changing and unpredictable environments.

The bottom-up reactive approach connects measured sensor data directly with the robot's actuators (Brooks, 1986). Therefore the robot can respond fast to changes in the world like unexpected and moving obstacles. Reactive or behaviour-based robots have shown great performance in constantly changing environments often found in real world tasks. Since the robot only acts on local information without global knowledge about the environment it may not reach a global optimum and lack the ability to perform complex tasks. These two approaches can be combined in a hybrid architecture (Low et al., 2002; Bonarini et al., 2003; Connell 1992; Simmons, 1997).

A four layered hybrid control architecture is presented for an autonomous sailboat combining both reactive and planner-based approaches. A theoretical description of each layer is followed by a concrete implementation on an autonomous sailboat. A small selection of experiments is presented to show the suitability of this approach.

2 Architecture

2.1 System Overview

The presented system is capable of navigating a sailboat to an arbitrary target fully autonomously. The only way for a human operator to interact with the system is by setting strategic prerequisites.

The control system is divided into four layers. Each layer has access to sensor data by connecting to the data abstractor. The abstractor is a computer program which is executed directly on the boat. It gathers sensor data and transforms the raw data into semantically useable values. Preprocessing like damping, scaling, unit transformations, or plausibility checks are done at this level.

In addition to sensor data each layer gets prerequisites from the preceding superordinate layer. The task of each layer is to satisfy the prerequisites as accurately as possible (Figure 1).

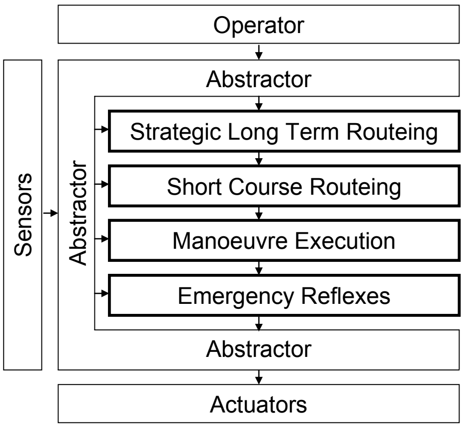

Fig. 1: System Architecture.

A high level strategic long term routeing layer produces a rough estimated course using sea maps, weather forecasts and target coordinates from the operator. Short course routeing calculates an optimal course based on local wind conditions. Reactive modules provide basic sailing skills and reflex behaviour in case of emergency.

2.2 *Sensors and Actuators*

In order to control an autonomous sailboat, data about the environmental conditions are necessary. Sensors deliver real-time information about current wind direction and wind speed. Additionally heeling (transverse inclination of a sailboat), boom position, geographic position and direction are measured on the boat. These are the minimum data needed for the autonomous sailboat used in the experiments. Optionally weather forecasts and sea maps can be taken into account for long term routeing. In short course routeing a radar system can be used to detect moving obstacles.

Based on sensor information the system calculates a desired position for rudder and sails. These are the only actuators needed to steer a sailboat autonomously.

2.3 *Operator*

The sailboat is designed to operate completely autonomously. Nevertheless a human operator has to predefine strategic goals. These prerequisites include the target of the sailing trip and intermediate waypoints to be passed, such as buoys of a regatta or ports. As the operator communicates with the strategic long term routeing layer only, he has no direct influence on path planning or manoeuvre execution.

2.4 *Strategic long term routeing*

The topmost layer reflects the general routeing strategy of the sailboat. Ship routeing can be considered as the "procedure where an optimum track is determined for a particular vessel on a particular run, based on expected weather, sea state and ocean currents" (Spaans, 1985). Optimisation can be performed in terms of

1. minimum passage time
2. minimum fuel consumption
3. safety for crew and ship
4. best passenger comfort

or a combination of the criteria above (Motte et al, 1988; Spaans, 1985).

The routeing algorithm determines an optimal rough route with respect to the boat-specific behaviour, the predicted weather conditions and sea topology. The route is divided into many short legs and described as an ordered set of coordinates to be passed. The next target coordinate is handed on to the layer below, the short course routeing layer.

2.5 *Short course routeing*

In order to steer a sailboat towards a specific target, a navigable route has to be specified in advance. Not all points of sail are navigable ("No go zone" in Figure 2). Points of sail is the term used to describe a sailing boat's course in relation to the wind direction. Some courses are navigable, but quite inefficient ("Don't go zone" in Figure 2). These restrictions have to be taken into account in short course routeing. Therefore the route may contain multiple sections, connected by manoeuvres such as tack or jibe (Figure 4). Also change of wind direction while sailing a stable compass course may cause a manoeuvre.

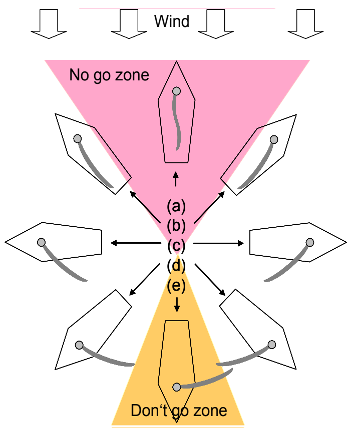

Fig. 2: Points of Sail: (a) In Irons (into the wind), (b) Close Hauled, (c) Beam Reach, (d) Broad Reach, (e) Running Downwind.

The aim of the short course routeing layer is to find an optimum way to the next target which is given by the strategic long term routeing layer. As the local wind conditions often change and accurate weather forecasts are not available for very short distances and periods, only local and present wind conditions are taken into account in order to determine an optimum heading for the vessel. The short course routeing has to provide an answer to the perennial question of when to tack on upwind courses, which can not be directly sailed. The short course routeing layer does not need a weather forecast at all. It reacts on changes of the wind conditions in real-time by recalculating the optimum heading periodically. Static obstacles like islands or shoals as well as dynamic obstacles like other vessels have to be considered here. This optimum heading acts as input for the manoeuvre execution layer.

2.6 Manoeuvre execution

The short course routeing layer delivers a desired direction for the current boat position and weather conditions in real time. If the actual boat direction deviates from the desired direction, the system adjusts the rudder position in order to bring the boat on the desired course. In parallel, a second control system assures that there is airflow in the sails in order to generate propulsion. If a tack or a jibe is required due to significant changes of the desired boat direction, this layer has to assure a smooth execution of the manoeuvres automatically.

2.7 Emergency reflexes

The manoeuvre execution layer passes desired rudder and sail movements to the emergency reflex layer. Normally the rudder and sail settings are passed down to the actuators unchanged. Only in case of an emergency, when the planned movements pose a threat to the safety of the boat the emergency reflex layer starts acting and overrule the requested actions.

These reflex actions include avoiding capsizing in case of a wind gust or cautious sailing during periods of strong wind.

3 Experimental Setup

Experiments were carried out on the 1.38 m yacht model "Robbe Atlantis" (Figure 3) under real-world conditions. The boat won in the first Microtransat competition for autonomous sailboats in June 2006 in Toulouse, France (Briere, 2006). The event was organised by Ecole Nationale Supérieure d'Ingénieurs de Constructions Aéronautiques (ENSICA) in Toulouse. The ambitious aim was to demonstrate completely autonomous sailing, where routeing, navigation and carrying out the manoeuvres have to run automatically directly on the boat.

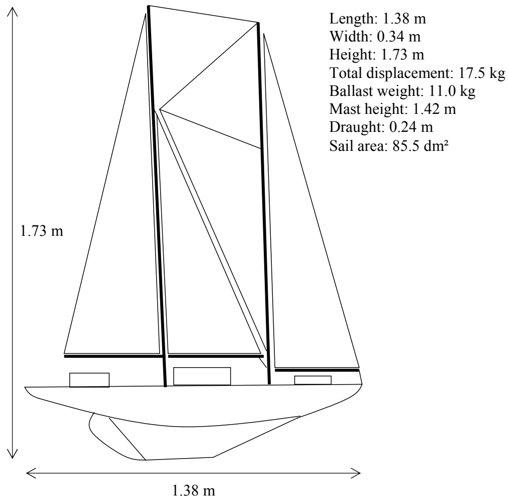

Fig. 3: Robbe Atlantis.

The "Robbe Atlantis" is usually used as a remote controlled sailboat. For our purposes, the boat is additionally equipped with various sensors to measure the environmental conditions, microcontrollers for preprocessing of sensor data and a Linux computer, where the high-level algorithms run.

3.1 Strategic long term routeing

Task of the strategic long term routeing system is to separate the complete route into short legs so that the next intermediate waypoint is within an appropriate range of the short course routeing.

For very long sailing trips such as ocean crossings long term weather routeing algorithms are applied at this layer. The existing approaches for long term weather routeing all require, more or less, certain weather predictions and a description of the boat's behaviour under certain wind conditions determined by a boat specific polar diagram (Thornton, 1993; Spaans and Stoter, 1995). The polar diagram describes the maximum speed a particular sailboat can reach dependent on wind speed and direction. Most common computerised weather routeing techniques are either an implementation of the manual isochrone plotting proposed by James (1957) – which has been used in many weather routeing facilities as a practical method to obtain the minimum time route – or optimisation methods within a discrete geographical grid system along the great circle route. Motte and Calvert (1990) illustrated the effect of incorporating various discrete grid systems in a weather routeing system, which employs Bellman's dynamic programming algorithm. Stawicki and Smierzchalski (2001) mentioned evolutionary algorithms as a promising approach to weather routeing. Actual implementations of evolutionary path planning at sea have been published (Smierzchalski and Michalewicz, 2000; Smierzchalski, 2005) but do not address the special situation of sailboats. All these approaches rely on weather forecast information on the one hand and sea charts on the other hand.

The experimental setup has been developed for a short race. The concrete implementation of the strategic long-term routeing layer provides the short course routeing layer with the coordinates of the following buoy according to race rules. Thus the whole route is separated into short legs where the next target is within an appropriate range for the short course routeing system. For these short distances no appropriate weather forecast is available. Therefore no long term weather routeing is implemented.

3.2 Short course routeing

A detailed description of the short course routeing system is given by Stelzer and Pröll (2007). They present a compact method to calculate a suitable route for a sailboat in order to reach a specified target. The calculation is based on the optimisation of the time-derivative of the distance between boat and target and features a hysteresis condition, which is of particular importance for beating upwind (taking a zig-zag course against the wind). The algorithm immediately adapts to varying wind conditions. Example routes for upwind and downwind courses based on this method are illustrated in Figure 4.

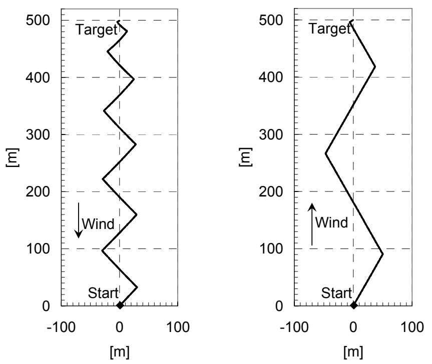

Fig. 4: Tack (left) and jibe (right) examples on a 500 m upwind/downwind course based on routeing method proposed by Stelzer and Pröll (2007).

3.3 Manoeuvre Execution and Emergency Reflexes

Stelzer et al. (2007) describe a way to control rudder and sails effectively by two independent Mamdani type fuzzy inference systems (FIS) (Mamdani and Assilian, 1975). This reflects common sailing practice where different persons act independently on rudder and sails respectively. This system keeps the boat on a predefined course set from the short course routeing layer and ensures a suitable sail position. Changes of the desired direction may lead to manoeuvres like tack or jibe.

Input data for the rudder control circuit are the current boat direction and the desired direction from the short course routeing layer. The difference between these two gives the necessary course correction, which enters directly into the fuzzy system as an input variable. In order to avoid over steering, the angular velocity of the boat is considered as an additional input variable.

The inputs for the sail control circuit are the heeling of the boat and direction and speed of the apparent wind. The sail FIS calculates direction and amount of necessary adjustment of the sail winch. The aim of the sail control circuit is to keep the boat's heeling to an optimum according to actual wind speed and wind direction.

Tacking is executed implicitly by the fuzzy control circuits. The jibe requires an additional rule in order to move the sails to the leeward side at the right point in time.

In the actual implementation, no separate layer exists for emergency reflexes. The safety mechanism to ease off the sheets in order to avoid capsizing is implicitly carried out within manoeuvre execution.

3.4 Operator

A human operator onshore can connect to the system to gather sensor data measured on the sailboat and visualize them to make strategic decisions. The operator can monitor position, environmental conditions and information about the strategy of the boat. Furthermore the operator can send new waypoints to the strategic long term routeing layer.

There are three different communication channels available. For short distances up to about 3 km, a wireless LAN link connects the operator and the sailboat. If a GPRS/UMTS infrastructure is available it can be used up to approximately 20 km offshore. For longer distances a satellite communication system using INMARSAT is utilised. To assure permanent connectivity, the availability of these three technologies is permanently monitored. If required the system automatically switches the communication channel. Decision depends on availability, transfer charges, and bandwidth of the specific channels.

The system keeps sailing autonomously even if no boat-shore communication is possible. Functionality of the sailboat is completely independent from the communication link.

4 Results

Several test runs were carried out to demonstrate feasibility and suitability of the presented approach. The data refer to the final test run prior to the Microtransat competition in France, where the wind conditions were

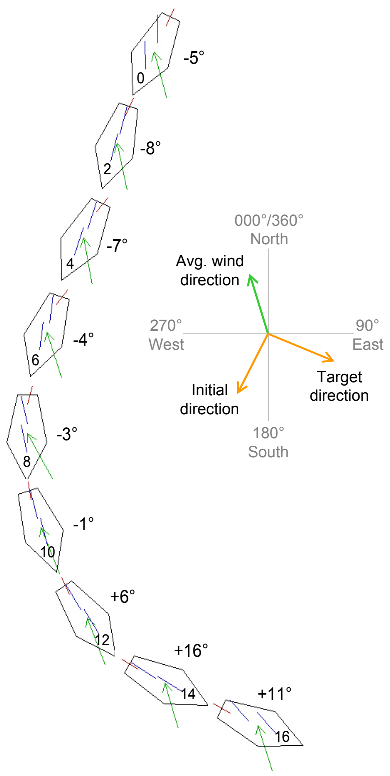

Fig. 5: Tack from test run in 2 s time interval: rudder and sail position, apparent wind direction, heeling in deg, time from beginning in s.

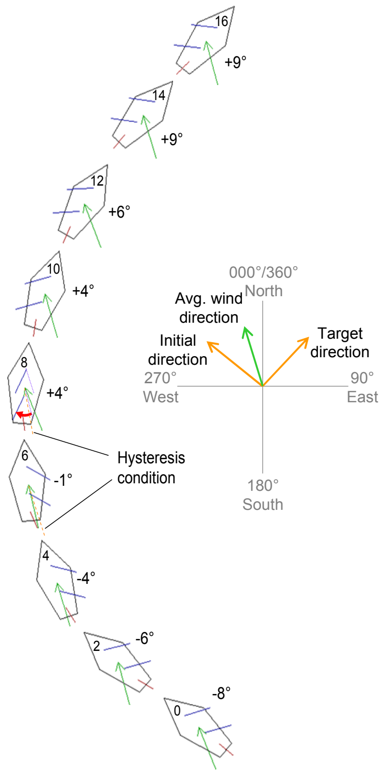

Fig. 6: Jibe from test run in 2 s time interval: rudder and sail position, apparent wind direction, heeling in deg, time from beginning in s.

Time in *s*	**Process**
0, 2	The boat is sailing close hauled on a port tack (initial course).
4	The boat receives a new direction from the short course routeing layer and initiates the tack by moving the rudder.
6	The boat begins to turn and rudder inclination increases.
8	Due to the turn of the boat the rudder inclination does not further increase, even though the boat is still far from its desired direction.
10	The boat is pointed directly upwind. Heeling decreases below the desired value due to a lack of lateral wind force. Thus the sail control circuit tightens the sheets in an attempt to reach the desired heeling. To avoid over steering the rudder is already in the central position again.
12	Due to mass inertia the boat keeps turning towards the desired direction.
14	Lateral wind forces increase, hence heeling exceeds the desired level.
16	New desired direction is reached. Sheets are eased off in order to reach desired heeling.

Table 1: Tacking Timeline (according to Figure 5)

Time in *s*	**Process**
0	The boat is sailing a broad reach on a port tack (initial course).
2	The boat receives a new direction from the short course routeing layer and initiates the jibe by moving the rudder.
4	The boat begins to turn and rudder inclination increases.
6	The boat's stern has already turned through the wind, although the sails are still on the starboard side because the hysteresis condition is not yet fulfilled.
8	Now the stern has turned significantly through the wind and the hysteresis condition is fulfilled. Therefore the sheets get tightened temporary in order to move the sails to the leeward side.
10	Now the boat is sailing a broad reach on a starboard tack. The sails are eased off completely again because the desired heeling is low on a broad reach course. The rudder inclination decreases because the target direction is almost reached.
12, 14	The rudder is back near the middle position. Due to mass inertia the boat keeps turning towards the desired direction.
16	New desired direction is reached. The sheets are eased off in order to reach the desired heeling.

Table 2: Jibing Timeline (according to Figure 6)

within the operation range of the demonstration boat. Figure 7 shows the GPS log data and simulation results from the test run, where the task was to sail from buoy 1 to buoy 2 and back to buoy 1.

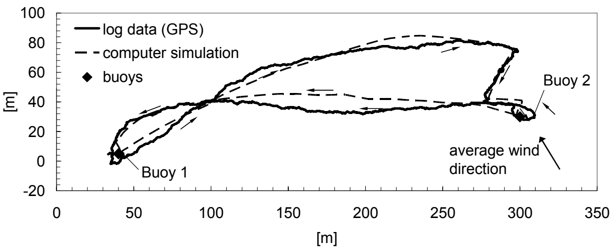

Fig. 7: Short course routeing results.

The strategic long term routeing layer ensures that the buoys are passed in the correct order. The short course routeing layer recalculates a desired direction permanently and forwards it to the manoeuvre execution layer.

The broken line in Figure 7 illustrates a simulated resulting route. The actual trajectory shows excellent agreement with the computer simulated results based on real wind data. This demonstrates the ability of the manoeuvre execution layer to fulfil the given prerequisites.

Figures 5 and 6 show the process of manoeuvre execution. Manoeuvres were carried out according to desired directions given by the short course routeing layer. Log data at 2 s intervals are illustrated. The boat drawings present boat heading, sail position, rudder position and apparent wind direction. Additionally, heeling and time lapse are stated. The detailed process flow is described in Table 1 and Table 2.

5 Conclusions

A sailboat can be effectively controlled with a four layered architecture. The system combines weather routeing, navigation, carrying out the manoeuvres and exception handling in case of emergency. These tasks are separated into layers executed in parallel. This work presents actual implementations for each layer and experimental results.

Global knowledge in the upper layers gives the ability to fulfil complex and strategic tasks like long term weather routeing and calculating the best time for tacking on an upwind course. Nevertheless, detailed local information in the bottom layers makes the autonomous sailboat react fast to unexpected changes like obstacles or wind gusts.

The architecture provides a good coexistence of these two approaches. In addition to sensor data each layer gets strong recommendations from the preceding superordinate layer. The layer below usually tries to comply with these recommendations, but if local knowledge indicates danger or the suggestions are inconsistent with precise and detailed local knowledge, the lower layer may temporarily overrule the strategic decisions of the layer above.

It turned out that this architecture deals very well with highly dynamic environments where both strategic decisions and fast reactions to local measurements are essential. The algorithm reacts in real-time to changing local conditions, like a human sailor does, although the system maintains the strategic goal to reach the target on an optimal trajectory.

Many successful test runs under varying environmental conditions have proven feasibility and robustness of the presented architecture. Log file analyses show a steering behaviour as expected by sailing experts.

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