

Fuzzy Logic Control System for Autonomous Sailboats

Roland Stelzer, Tobias Pröll, and Robert I. John, *Member, IEEE*

Abstract—Sailing experts can explain basic sailing skills by rules about how to steer sails and rudder according to direction of target and wind. This paper describes how to transform the sailor's knowledge into Mamdani type fuzzy inference systems. The proposed system controls two actuators – rudder and sails – even during tack and jibe. In combination with an automatic weather routing system the sailboat is able to reach any target completely autonomously. Experiments on a demonstration sailboat have shown excellent results. Detailed log data analysis shows manoeuvres carried out as expected by sailing experts.

I. INTRODUCTION

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 1). 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 inefficiently (“Don't go zone” in Figure 1). These restrictions have to be taken into account in planning the route for a sailing trip. Therefore the route may contain of multiple sections, connected by manoeuvres such as tack or jibe. Also change of wind direction while sailing a stable compass course may cause a manoeuvre.

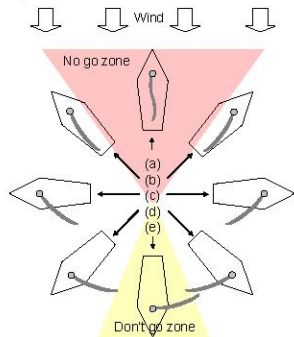


Fig. 1. Points of Sail: (a) In Irons (into the wind), (b) Close Hauled, (c) Beam Reach, (d) Broad Reach, (e) Running Downwind.

A tack is the manoeuvre by which a sailing boat turns its bow through the wind so that the wind changes from one side to the other. If the target is against the wind the straight line route is not navigable. In this case the sailor has to take a zig-zag course against the wind. The sailboat executes a tack manoeuvre when it changes course as it zig-zags upwind (Figure 2a).

Roland Stelzer and Robert John are with the Centre of Computational Intelligence at De Montfort University, The Gateway, Leicester, LE1 9BH, United Kingdom. E-mail rstelzer@dmu.ac.uk and rij@dmu.ac.uk

Tobias Pröll is with the Austrian Association for Innovative Computer Science, Kampstraße 15/1, 1200 Vienna, Austria. E-mail tobias.proell@innoc.at

A jibe is when a sailing boat (yacht) turns its stern through the wind, such that the direction of the wind changes from one side of the boat to the other. Jibing is a less common manoeuvre than tacking, as a sailboat can sail straight downwind, whereas they generally cannot sail straight into the wind. However, many sailboats are significantly faster sailing on a broad reach than sailing straight downwind, so the increased speed of a zig-zag course of alternating broad reaches can make up for the extra distance it takes over a straight downwind course. The sailboat will execute a jibe manoeuvre when it changes course as it zig-zags downwind (Figure 2b).

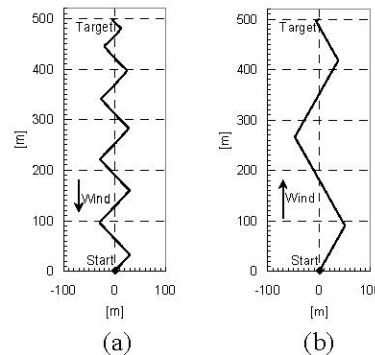


Fig. 2. Tack and jibe examples on a 500 m upwind/downwind course based on routing method proposed by Stelzer and Pröll [1].

Many different systems are available that can assist the skipper steering a sailboat. The most popular systems on market are autopilots and wind vanes [2]. Both systems can keep the boat on a predefined course. While the autopilot usually sails a predefined compass course, the wind vanes keep the boat on a certain course on the apparent wind. The systems control the rudder but have no influence on the sail position. The sheets have still to be adjusted manually. Therefore neither autopilots nor wind vanes can steer tack or jibe autonomously. Abril et al. [3] describe a fuzzy controller for the rudder of a sailboat. The sail position in their approach is a direct function of the apparent wind angle. Various methods for rudder control have been published, fuzzy [4] as well as non-fuzzy [5]. But they all do not cover sail control. Recent research activities on autonomous sailing were demonstrated in the RoboSail project [6,7] and at First Microtransat Challenge in Toulouse, France, 2006 [8,9,10].

The system proposed in this paper is able to control all manoeuvres of an autonomous sailboat. A separate software module is responsible for weather routing [1] and delivers a desired direction for the actual 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 flow in the sails in order to get speed. By means of adjustments on the sheets, the boat's heeling is controlled. The sail controller tries to keep the heeling at a calculated value dependent on speed and direction of the apparent wind.

If a tack or a jibe is required due to significant changes of the desired boat direction, the control system assures a smooth execution of the manoeuvres automatically.

Main aim of the proposed work is to imitate the behaviour of an experienced human sailor. Therefore it is not limited to a specific boat, but it is applicable to every common type of sailboat. Fuzzy logic is used to control both actuators for sail and rudder. Fuzzy logic is very suitable for transmission of experts' knowledge into a computer program in form of simple if-then-rules.

II. FUZZY CONTROL SYSTEM

In common sailing practice, different persons are able to control rudder and sail independently without the need for communication. Therefore, in the present work, each of two independently working control loops is responsible for one of the actuators, rudder and sail. The rudder controller keeps or brings the boat on a predefined course given by the routing software. The sail controller avoids capsize and assures that there is enough flow in the sails, which results in boat's propulsion.

Both actuators – rudder and sail – should be controlled fast but smooth, without jerky leaps and without oversteering. Two Mamdani type [11] fuzzy inference systems (FIS) turned out to be a very suitable method to reach this goal. Trapezoid fuzzy sets are used as inputs and singletons represent the output variables. Defuzzification is done by the centre of gravity of singletons method (CoGS).

The frequency of execution of the FIS was identified by experiment and has to be adapted for every type of boat.

A. Rudder Control Circuit

Input data for the rudder control circuit are the current boat direction and the desired direction from the weather routing system. The difference between these two gives the necessary course correction which enters directly into the fuzzy system as input variable.

In order to avoid oversteering, the angular velocity of the boat flows in as an additional input variable.

1) *Input Variables:* The inputs for the rudder FIS are *desired direction* and *turn*. The *desired direction* (deg) is

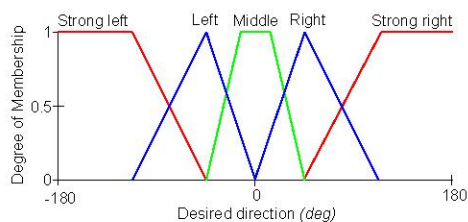


Fig. 3. Fuzzy Sets for "desired direction"

given by the weather routing system, and the *turn* (deg/s) is the time derivative of the actual boat direction given by the compass. The fuzzy sets representing the linguistic terms of the variables are trapezoids (Figures 3 and 4).

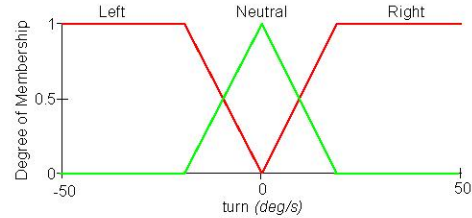


Fig. 4. Fuzzy Sets for "turn"

2) *Output Variable:* The rudder control circuit's output is the change of the rudder position. The fuzzy variable *rudder change* (in percent of extreme positions) contains five singletons representing the linguistic terms from *strong left* via *left*, *keep*, *right* to *strong right* (Figure 5).

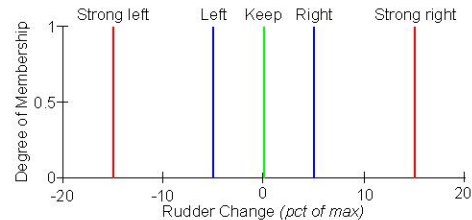


Fig. 5. Fuzzy Sets for "rudder change"

3) *Fuzzy Rules:* The rule base of the rudder FIS contains 15 rules of the form

*IF desired direction IS x AND turn IS y
THEN delta rudder IS z*

TABLE I
FUZZY RULES FOR RUDDER-FIS

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

Table 1 shows the concrete parameters of the rules. Defuzzification is done by evaluating the centre of gravity of singletons (CoGS).

B. Sail Control Circuit

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. Aim of the sail control circuit

is to keep the boats heeling on an optimum according to the actual wind conditions.

1) *Calculation of Desired Heeling*: The basic idea is to describe the following relationship between desired heeling and apparent wind.

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

The equation

$$h = \max \left(0, \left(h_{\max} - k \cdot |\alpha| \right) \cdot \frac{\min(v, v_{\max})}{v_{\max}} \right)$$

describes the relationship in a formal way. The desired heeling h is a function of speed v and direction α of the apparent wind (Figure 6). The constants k , h_{\max} , and v_{\max} are boat specific and determined by experiments. h_{\max} describes the maximum desired heeling for apparent wind speed of v_{\max} or above.

The graphical representation of the heeling function is illustrated in Figure 6.

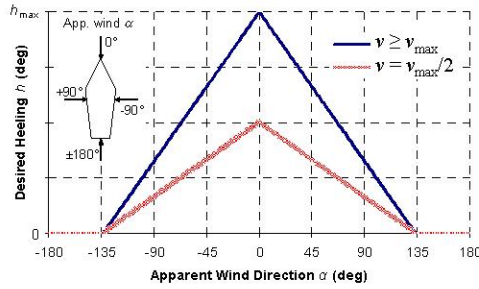


Fig. 6. Desired heeling function

2) *Input Variable*: As input for the sail FIS acts the variable *heeling (deg)*, which is the difference between the desired heeling and the actual heeling of the boat. Three trapezoidal fuzzy sets describe the linguistic terms *too low*, *optimal*, and *too high* (Figure 7).

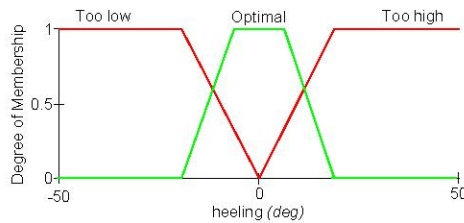


Fig. 7. Fuzzy Sets for "heeling"

3) *Output Variable*: The sail control circuit's output is the change of the sheet winch position, which influences the sail position directly. The fuzzy variable *sail change* (in percent of extreme positions) contains of three singletons representing the linguistic terms *tighten*, *keep*, and *ease off* (Figure 8).

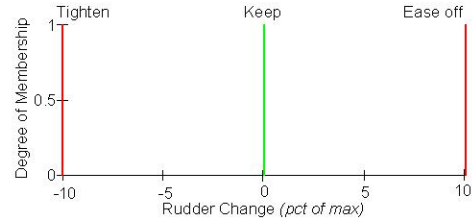


Fig. 8. Fuzzy Sets for "sail change"

4) *Fuzzy Rules*: The rule base of the sail FIS contains the three IF-THEN-rules:

- 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.

III. MANOEUVRES

It is assumed that the weather routing system only provides courses which are navigable efficiently. In order to sail every given course, the system must be able to

- Keep on a given course
- Execute a tack and
- Execute a jibe.

A. Keep on a Given Course

Parallel execution of sail and rudder control circuit guarantees to keep on course by immediately adjusting the rudder in the case of course deviation. The sails are adjusted to keep propulsion.

B. Execute a Tack

If the direction given by the routing system changes significantly a tack may be necessary. The following procedure happens in this case (Figure 9):

1. The sailing boat turns its bow towards the wind. Due to the change in the angle of the apparent wind, heeling decreases. Therefore, the sail control system tightens the sheets.
2. The bow turns through the wind so that the wind changes to the other side of the boat. Heeling increases again. Therefore the sail controller eases off the sheets.
3. The boat reached its new course.

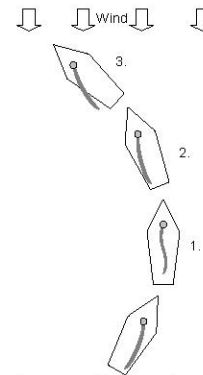


Fig. 9. Tack execution

The tack is implicitly executed by the two fuzzy systems, just by a new given target direction which makes it necessary.

C. Execute a Jibe

As for human sailors the jibe is a bit more difficult than the tack and optimal timing is more important. In addition to the parallel execution of rudder and sail FIS a special rule has to be applied during the jibe (Figure 10).

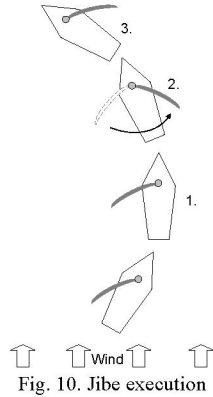


Fig. 10. Jibe execution

1. The sailing boat turns its stern towards the wind. On exact downwind direction the desired heeling is 0. Therefore the sail is completely eased off.
2. Special Rule for the jibe: If the stern has turned through the wind significantly (hysteresis), but the sail is still on windward side, the sail gets tightened temporary in order to move to leeward side. The hysteresis condition avoids permanent changes of sail position on downwind course with minimal changes of wind or boat direction.
3. The boat reached its new course.

IV. SYSTEM ARCHITECTURE

Experiments were carried out on the 1.38 m yacht model “Robbe Atlantis” (Figure 11) under real-world conditions. The boat won in the First Microtransat Challenge for autonomous sailboats in Toulouse, France, June 2006. 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.

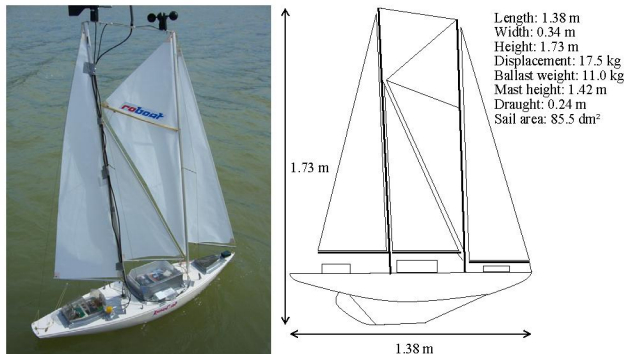


Fig. 11. Robbe Atlantis

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. A computer program called “abstractor” running on the boat gathers sensor data and transforms them into semantically useful information for the routeing software. All necessary data are measured.

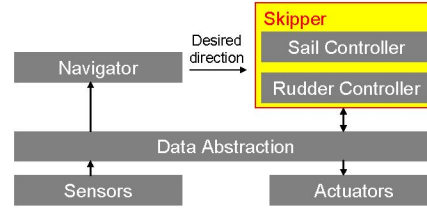


Fig. 12. System Architecture

Figure 12 shows the modular architecture of the entire system. Various sensors deliver data for the routeing system (navigator) and the FIS (skipper) which cover the rudder and sail control circuits. The data abstraction layer transforms the raw data from sensors into semantically useable data for the high level applications. Damping, scaling, unit transformations, or plausibility checks are done at this level. Both control circuits periodically send their results (rudder and sail position) back to the abstraction layer. These position data are then transformed back into a format, which is expected by the hardware controller devices for the actuators.

V. EXPERIMENTS AND RESULTS

Several test runs have been carried out to demonstrate feasibility and suitability of the presented approach. The data refers to the final test run prior to the Microtransat competition in France, where the wind conditions have been within the operation range of the demonstration boat. Tack and jibe are analysed in detail.

Figures 13 and 14 show the process of manoeuvre execution. 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.

A. Tack in Detail

The tack in Figure 13 starts on an initial course of 187 deg and ends on a target direction of 328 deg. The true wind direction is around 328 deg and its average speed is 1.2 m/s. The average boat speed in the beginning and the end of the manoeuvre is about 0.4 m/s and decreases slightly after 10 s, when the boat is pointed directly to the wind. The boat executes the complete tack successfully within 16 s and a trajectory of 6 m. The detailed process flow is described in Table II.

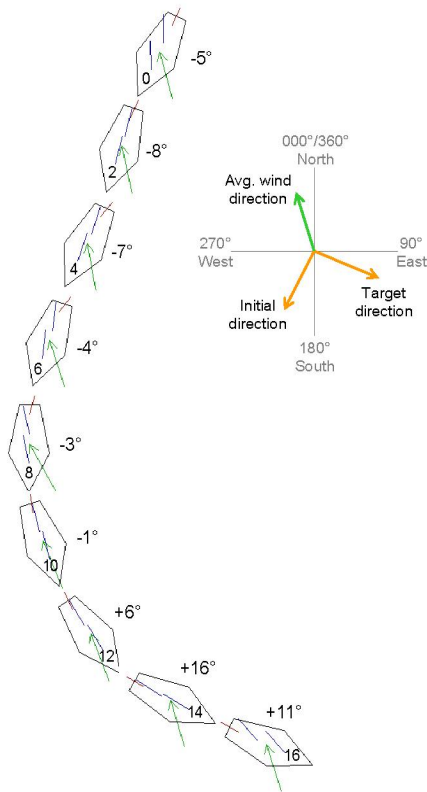


Fig. 13. Tack from test run in 2 s time interval: rudder and sail position, apparent wind direction, heeling in deg, time from beginning in s.

TABLE II
TACKING TIMELINE (ACCORDING TO FIGURE 13)

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 by the routeing system 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 to the wind. Heeling decreases below the desired value due to a lack of lateral wind force. Thus the sail control circuit tightens the sheets as a trial to reach the desired heeling. To avoid over steering the rudder is already in central position again.
12	Due to mass inertia the boat keeps turning towards desired direction.
14	Lateral wind forces increase. Hence heeling increases above desired heeling.
16	New desired direction is reached. Sheets are eased off in order to reach desired heeling.

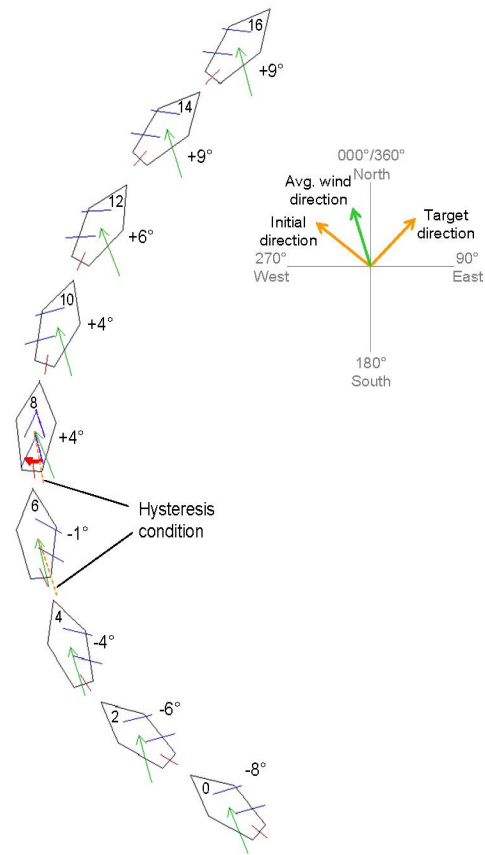


Fig. 14. Jibe from test run in 2 s time interval: rudder and sail position, apparent wind direction, heeling in deg, time from beginning in s.

TABLE III
JIBING TIMELINE (ACCORDING TO FIGURE 14)

Time in s	Process
0	The boat is sailing broad reach on a port tack (initial course).
2	The boat receives a new direction by the routeing system and initiates the tack by moving the rudder.
4	The boat begins to turn and rudder inclination increases.
6	The boats stern has already turned through the wind. Although the sails are still on 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 leeward side.
10	Now the boat is sailing broad reach on starboard side. Sails are eased off completely again, because desired heeling is low on broad reach course. The rudder inclination decreases, because target direction is almost reached.
12, 14	The rudder is back near middle position. Due to mass inertia the boat keeps turning towards desired direction.
16	New desired direction is reached. Sheets are eased off in order to reach desired heeling.

B. Jibe in Detail

The jibe in Figure 14 starts on an initial course of 312 deg and ends on a target direction of 40 deg. The true wind direction is around 326 deg and its average speed is 1.2 m/s. The average boat speed is 0.6 m/s and does not change significantly the entire manoeuvre. The boat executes the complete jibe successfully within 16 s and a trajectory of 10 m. The detailed process flow is described in Table III.

VI. CONCLUSIONS

A sailboat can be effectively controlled by two independent Mamdani type fuzzy inference systems. This reflects common sailing practice where different persons act more or less independently on rudder and sails respectively.

This system basically allows to keep the boat on a predefined course and ensures a suitable sail position. Changes of the desired direction may lead to manoeuvres like tack or jibe. Tacking is executed implicitly by the fuzzy control circuits. Only the jibe requires an additional rule in order to move the sails to leeward side.

Experiments using a 1.38 m yacht model have been carried out to demonstrate feasibility and suitability of the presented approach. Log files from actual sailing trips show a steering behaviour as expected by sailing experts. The boat executes the complete tack or jibe successfully within about 15 s. The test runs did not show any conflicts between the two fuzzy inference systems executed in parallel.

The input parameters of the system are sensor values (wind, boat direction, and heeling) and a navigable desired direction. The desired direction can either be prescribed manually or determined automatically by a weather routing system. Combination of automatic weather routing and the described fuzzy control system allows the sailboat to reach any target completely autonomously.

APPENDIX

TABLE IV
NAUTICAL TERMS AND EXPLANATIONS

Apparent wind	The velocity of air as measured from a moving object, as a ship.
Bow	The front section of a ship or boat.
Heeling	A tilt of a boat, to one side.
Jibe (jib, gybe)	To shift from one side to the other when running before the wind, as a fore-and-aft sail or its boom.
Leeward	The direction in which the wind is blowing.
Points of sail	Direction of a boat with respect to the direction of the wind.
Port	To the left side of a vessel as perceived by a person on board the ship and facing the bow.
Port tack	If the wind is coming from anywhere on the port side, the boat is on port tack.
Sheet	A line (rope or chain) that regulates the angle at which a sail is set in relation to the wind.
Starboard	To the right side of a vessel as perceived by a person on board the ship and facing the bow.

Starboard tack	If the wind is coming from anywhere on the starboard side, the boat is on starboard tack.
Stern	The rear part of a ship or boat.
Tack	To change the course of a sailing vessel by bringing the head into the wind and then causing it to fall off on the other side
True wind	The velocity of air as measured from a platform fixed to the ground, such as an anchored boat.
Windward	The side toward the wind.

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REFERENCES

- [1] R. Stelzer and T. Pröll, "Autonomous sailboat navigation for short course racing," submitted for publication, 2007.
- [2] W. Kumm, K.D. Kurtz, J.F. Muhs, H.A. Pfaff, and M. Sachweh, *Seemannschaft*, Bielefeld: Delius Klasing, pp. 99-101, 2003.
- [3] J. Abril, J. Salom, and O. Calvo, "Fuzzy Control of a Sailboat," *International Journal of Approximate Reasoning*, vol. 16, pp. 359-375, 1997.
- [4] T.W. Vaneck, "Fuzzy Guidance Controller for an Autonomous Boat," *IEEE Control Systems Magazine*, vol. 17, pp. 43-51, 1997.
- [5] W. H. Warden, "A control system model for autonomous sailboat navigation," in *IEEE Proceedings of Southeastcon*, vol. 2, pp. 944-947, School of Industry and System Engineering, Georgia Inst. of Technol., Atlanta, 1991.
- [6] M.L. van Aartrijk, C.P. Taglioloa, and P.W. Adriaans, "AI on the Ocean: the RoboSail Project," in *Proceedings of European Conference on Artificial Intelligence 2002*, pp. 653-657, 2002.
- [7] M.L. van Aartrijk and J. Samoocha, "Learning to sail - knowledge discovery in embedded adaptive systems," in *Proceedings of European Symposium on Intelligent Technologies, Hybrid Systems and their implementation on Smart Adaptive Systems (EUNITE)*, 2003.
- [8] Y. Briere, "First Microtransat Challenge" [online]. Available: www.ensica.fr/microtransat, 2006.
- [9] C. Sauze and M. Neal, "An Autonomous Sailing Robot for Ocean Observation," in *Proceedings of TAROS Conference 2006*. [online] Available: http://taros.mech.surrey.ac.uk/papers/Sauze_Neal.pdf, 2006.
- [10] M. Neal, "A hardware proof of concept of a sailing robot for ocean observation," *IEEE Journal of Ocean Engineering*, vol. 31, pp. 462-469, 2006.
- [11] E.H. Mamdani and S. Assilian, "An Experiment in Linguistic Synthesis with a Fuzzy Logic Controller," *International Journal of Man-Machine Studies*, vol. 7, pp. 1-13, 1974.