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Comparison of Fuzzy and Crisp Controllers Applied to Navigation of a Sailboat

P. Tsubaki* S. Miyamoto**

*Nippon Motorola Ltd.
3-20-1 Minami-Azabu, Minato-ku Tokyo 106, Japan

**Department of Information Science and Intelligent Systems
Faculty of Engineering, University of Tokushima
Tokushima 770, Japan

Abstract

This paper describes simulation of navigating a sailboat around obstacles to a goal as quickly and safely as possible. Navigation strategies using concepts from fuzzy control are compared with more conventional ones through application at the levels of choosing an optimal heading and steering the sailboat towards that heading.

1 Introduction

A system can often be classified as one more suited to application of fuzzy control, or one in which traditional methods are adequate. Among users of fuzzy control, those regarding traditional or crisp methods to be of limited use and fuzzy methods appropriate in all cases would apply it to either system type without discrimination. The remainder would use fuzzy methods only when traditional methods fail, such as in the first type. For example, the former group would use fuzzy control in the case of the inverted pendulem, while the latter would use traditional methods. As the system discussed in this paper is one not easily classified into either system type, it is used as a basis to compare the performances of fuzzy and crisp methods on such systems.

The navigation of a sailboat is similar to the problems of robot, automobile, and motorized-boat guidance [1][2], which have been applications of fuzzy control in the past, but includes constraints introduced by the vehicle's dependence on the speed and direction of wind. The sailboat navigation problem becomes challenging when trying to reach an upwind goal in the presence of obstacles. A sailor can describe how he navigates in such a situation, but the strategy is difficult to express in the form of equations. Using a simulation, four control methods using different degrees of fuzzy logic are applied to this problem of sailboat navigation and compared on the basis of speed in reaching a goal and safety in steering around obstacles.

2 System Model

The simulated sailboat dynamics are based on equations of motion derived using parameters of a 4.23-meter, single-mast, single-sail Laser-class sailboat [3] (equations of motion are omitted here).

3 Navigation System

PID control and simple fuzzy control algorithms are sufficient for making adjustments in the rudder and sail and guiding the sailboat to a goal as quickly as possible under simple conditions. Given the added constraints of a headwind and obstacles, however, the sailboat can no longer simply steer directly towards the goal in order to reach it safely. Intermediate goals become necessary as heading directly for the final goal under such conditions would lead to stalling in the case of a headwind and a collision in the presence of obstacles. Therefore, a two-layer strategy becomes more appropriate, with the top *planning system* using goal bearing, wind bearing, and bearings and distances to visible obstacles to recommend an intermediate heading to the bottom *control system*. The control system would then do the actual steering, accordingly setting the rudder angle and adjusting the length of the sheet, the rope which limits the sail angle.

3.1 Fuzzy Planning System

For the purposes of comparison, both fuzzy and crisp path-planning systems are implemented, using mem-

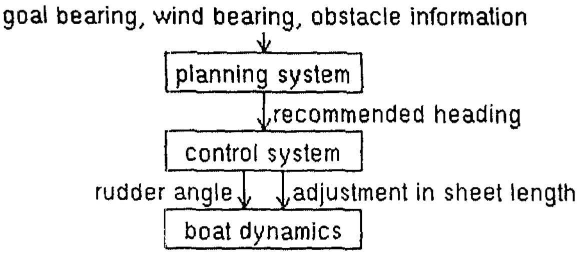

Figure 1: Navigation System Block Diagram

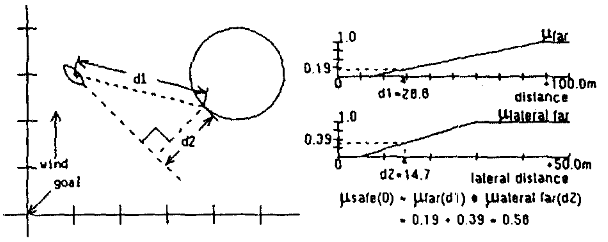

Figure 2: Evaluation of *safe* membership function for direction 0°

bership and indicator functions, respectively. In the fuzzy system, a value from 0 to 1 is assigned to each direction from −180° to 180°, at 1° intervals, with 0° representing the boat's bow. The number between 0 and 1 represents a rating of how desirable or *passable* the corresponding direction is. For example, if there is a nearby obstacle in direction 10°, then 10° is not a desirable direction, corresponding to a low value such as *0.0 passable* or *0.01 passable*. A direction directly opposite the final goal is also given a low value, as it would lead the boat further away from the goal. On the other hand, a direction which is clear of obstacles, downwind, and in the general direction of the final goal would correspond to a relatively high value, such as *0.8 passable* or even *1.0 passable*. Once all directions are assigned such values, we have a discrete membership function for the fuzzy set *passable* for the arguments ranging from direction −180° to 180°.

The qualities which make a direction *passable* are that the direction is not upwind, close to the heading recommended by the planning system during the previous iteration, in the general direction of the final goal, close to the present direction of the bow, and clear of obstacles. The direction best possessing these qualities is recommended by the planning system to the control system. The fuzzy sets corresponding to each of these qualities are given the names *not upwind, heading, goal, least change* and *safe*, respectively. These fuzzy sets are of standard trapezoidal and triangular shapes with the exception of *safe*. The computation of the *safe* membership function involves the use of two other fuzzy sets, *far* and *lateral far*. If there is an obstacle in a certain direction, as long as it is *far*, that direction is *safe*. Even a direction in which there are no obstacles at all is not always *1.0 safe*. In figure 2, direction 0° is *safe* only if the nearest point of the obstacle to the path in direction 0° is either *far* from the boat or *laterally far* from the path. More simply, if $d1$ is *far* or $d2$ is *laterally far*, direction 0° is *safe*. It turns out that the direction is only *0.58 safe*, although no obstacles actually lie in direction 0°. How *far* the sailboat is to an obstacle is proportional to the speed of the boat; the faster one travels, the closer it seems. Therefore the width of the membership function of *far* contracts as the boat's speed increases. The *far* membership function in figure 2 is for velocity $1m/s$.

If a direction is *not upwind, heading, goal, least change* and *safe*, then it is *passable*. All five sets are combined with *and*, the first three with minimum and the last two with algebraic product. Combining all sets with only minimum would minimize or even nullify the effect of *least change* and *safe* sets. The argument corresponding to the maximum value of the resulting membership function of *passable* is the heading recommended by the planning system.

3.2 Crisp Planning System

The crisp planning system resembles its fuzzy counterpart, but it uses indicator instead of membership functions. All directions are assigned a 1 or 0 value, indicating whether they are *passable* or not, respectively. If the direction is not upwind in a crisp sense, in the direction of the goal in a crisp sense, can be reached on a starboard (port) tack, and is safe in a crisp sense, it is classified as *1.0 passable*. These qualities are given the names *crisp upwind, crisp goal, starboard (port) tack* and *crisp safe*. *Crisp safe* is a non-fuzzy version of safe, where a direction is considered *safe* as long as any obstacle in that direction is *crisp far* (farther than $50m$).

Unlike the fuzzy system which will almost always have a maximum point, when these indicator functions are combined by *logical and* they produce the *passable* indicator function which will usually have more than one direction with a 1 value, leaving doubt as to which is the most desirable direction. In this case it is the direction which is closest to the final goal bearing. If there is no direction having these four qualities, i.e., *passable* is 0 for all directions, then the tack is switched to port (starboard).

3.3 Fuzzy Control System

3.3.1 Sheet Rules

In order for the sailboat to reach its goal as quickly as possible, the sail should always be kept at an optimal angle $\theta_{sail_{optimal}}$ for the current wind conditions.

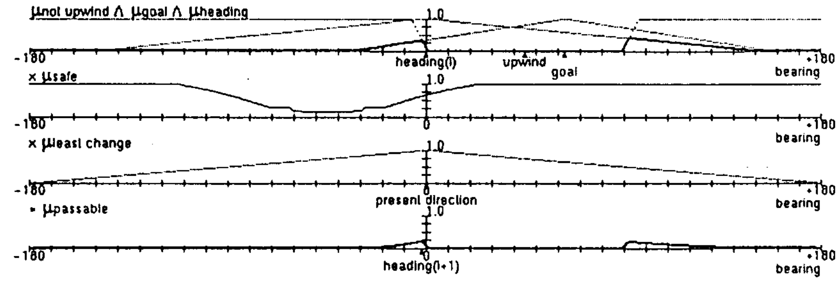

Figure 3: Fuzzy planning system's evaluation of *passable* membership function and recommended heading for situation in figure 2

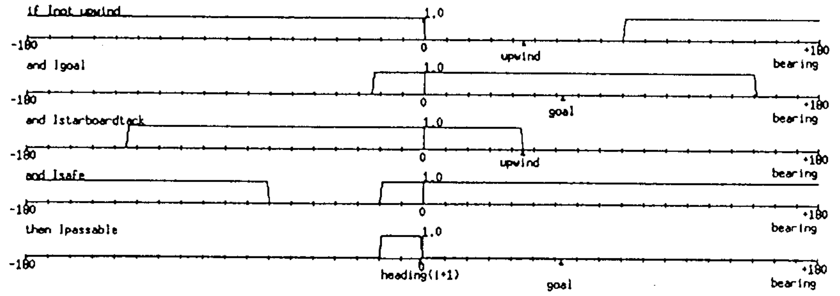

Figure 4: Crisp planning system's evaluation of *passable* indicator function and recommended heading for situation in figure 2

This angle maximizes the force accelerating the boat forward, which is proportional to the following expression:

$$F_{forward} \;\alpha\; \sin^2(\theta_{wind} + \theta_{sail} - \theta_{bow}) \sin\theta_{sail}$$

θ_{wind} represents the wind direction, θ_{sail} the angle of the sail relative to the boat, and θ_{bow} the boat's direction. A look-up table is computed which gives a $\theta_{sail_{optimal}}$ for each wind bearing at 1° increments. The same table is used for the PID control system. The fuzzy control sytem uses the above information and the difference between this reference value and the actual value $\theta_{sail_{error}}$ to compute an appropriate change in sheet length Δl_{sheet}.

if $\theta_{sail_{optimal}} =$	*and* $\theta_{sail} =$	*then* $\Delta l_{sheet} =$
starboard	*port*	*bigshorten*
port	*starboard*	*bigshorten*
if $\theta_{sail_{optimal}} =$	*and* $\theta_{sail_{error}}$	*then* $\Delta l_{sheet} =$
starboard	*plus*	*shorten*
starboard	*optimal*	*same*
starboard	*minus*	*lengthen*
port	*plus*	*lengthen*
port	*optimal*	*same*
port	*minus*	*shorten*

3.3.2 Rudder Rules

The rudder angle is set according to the goal bearing θ_{goal} and the change in goal bearing since the last iteration $\Delta\theta_{goal}$:

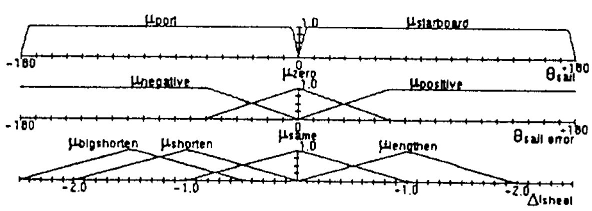

Figure 5: Membership functions for sheet rules

if $\theta_{goal} =$	*and* $\Delta\theta_{goal} =$	*then* $\theta_{rudder} =$
bow	*positive*	*ps*
bow	*zero*	*z*
bow	*negative*	*ns*
portbow	*positive*	*z*
portbow	*zero*	*ns*
portbow	*negative*	*nb*
portbeam		*nb*
starboardbeam		*pb*
starboardbow	*positive*	*pb*
starboardbow	*zero*	*ps*
starboardbow	*negative*	*z*

3.4 PID Control System

This system is slightly nonlinear due to trigonometric and saturation functions in the plant dynamics and has two inputs and multiple outputs. To apply PID control to such a plant, it needs to be analyzed as a single input-single output linear system. To create a linear

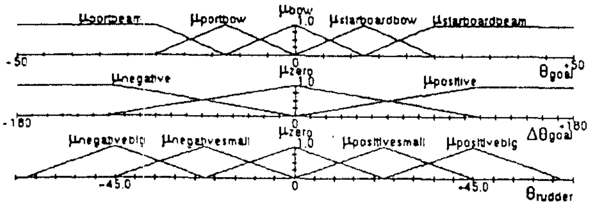

Figure 6: Membership functions for rudder rules

SISO version of this plant, the system's dynamics are separated into two parts, producing two isolated SISO systems for the purpose of calculating gains for a PID controller. The two parts, a system with input rudder angle and output goal bearing, and a system with input adjustment in sheet length and output sail angle, are actually interdependent, sheet length and sail angle affecting velocity and therefore the boat's heading. They are modelled as SISO second- and first-order lag plants, respectively. Since the sheet system is just an integrator, proportional feedback is adequate. For the rudder system, a PD controller is sufficient to pull the pole on the origin into the left-half plane. $k_p = 1.83$ and $k_d = 0.3$ provide adequate response without severe saturation of the rudder input, which is constrained between −45° and +45°.

4 Simulation

Under a light breeze of $3m/s$, the sailboat was required to travel $600m$ to an upwind goal and arrive within $10m$ of it. Ten round obstacles of radii from 1.0 to $41.0m$ were located randomly throughout each course. Four navigation strategies were tested, each using different combinations of the fuzzy and crisp planning systems and the fuzzy and PID control systems. Each strategy was tested for 50 different courses.

5 Performance Evaluation

The results of the simulation are displayed in the following table. Wins indicates the number of times the navigation strategy completed a course with the fastest time:

strategy (planning/control):	*wins:*	*collisions:*
fuzzy/fuzzy	8 (16%)	0
crisp/fuzzy	5 (10%)	7 (14%)
fuzzy/PID	3 (6%)	2 (4%)
crisp/PID	34 (68%)	7 (14%)

6 Conclusion

Crisp planning and PID control was the quickest to finish an upwind course clear of obstacles, and usually completed the courses with obstacles more quickly than did their fuzzy counterparts. The strategies using more elements of fuzzy theory were less prone to collisions than the ones without. Using fuzzy methods, it is possible to grade the danger of collision, making it possible to choose less dangerous directions, whereas in the crisp case there is no distinction between a slightly dangerous path and a very dangerous one. A slightly dangerous situation might go unnoticed by the crisp system, but the fuzzy system would take this into account well ahead of time, giving it advance warning. Fuzzy methods are apparently more suitable for the path-planning aspect of the problem, as it is one which requires human-like evaluation and decision ability.

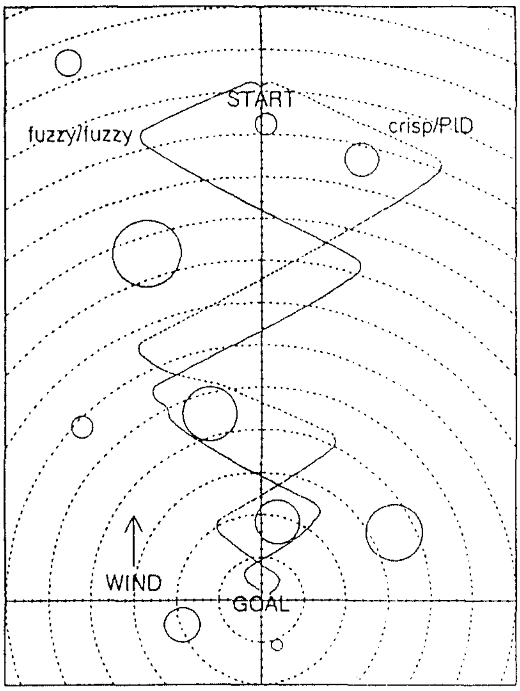

Figure 7: A course navigated by fuzzy/fuzzy and crisp/PID systems

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[3] B. Bond. *Complete Book of Sailing*, Hamlyn publishing, London, 1990.