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Contributed Paper

Fuzzy Control of a Hovercraft Platform

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A great majority of current applications of fuzzy logic are in fuzzy expert control systems. The candidate systems for fuzzy expert control can be characterized as systems that possess complex or unmodeled dynamics, high dimensionality, many interacting variables, system perturbations, or a combination of any of these. The hovercraft is one such system. The complexities that exist in hovercraft control arise because of the dual requirements of maintaining lift and maneuverability, as well as stability. Using fuzzy logic, the difficulties in both the design and the application of the control process are well managed. This paper demonstrates this through the implementation of the design and application of a fuzzy controller for stabilizing the response of a simple hovercraft platform. The physical platform constructed as a testbed is described, along with the associated control hardware. This is followed by a discussion of the fuzzy rule-based system development which resulted in a fuzzy controller using a total of twelve rules for achieving platform stability.

Keywords: Fuzzy control, hovercraft platform, hardware implementation, stabilization, real-time.

1. INTRODUCTION

Achieving control and stability of any craft can be a difficult accomplishment. For hovercraft, the requirements of control and stability are closely interrelated, and designs are often influenced by handling needs. As a result, it is difficult to establish specific criteria for hovercraft control systems. Typically, the control of hovercraft is achieved through a combination of active and/or passive mechanical control devices such as motors, rudders, fins, etc. This work concentrates on active automatic control using fuzzy logic. The difficulties in the control of hovercraft arise mainly because of their unique necessity to maintain both maneuverability and relative freedom from the surface over which they operate.[1] With fuzzy logic, however, the difficulties are well managed, both in the design and in the application of the control process.

Fuzzy logic controllers provide a means of transforming a linguistic control strategy based on expert knowledge into an automatic control strategy.[2] These controllers can be viewed as expert control systems that smoothly interpolate between rules. Rules fire to continuous degrees and the multiple resultant actions are combined into an interpolated result. The processing of uncertain information and saving of energy using common-sense rules and natural-language statements are the basis for fuzzy logic control. The use of sensor data in practical control systems involves several tasks that are usually done by a human in the loop, e.g. an astronaut adjusting the position of a satellite or putting it in the proper orbit, a helicopter pilot adjusting the throttle to achieve level flight, etc. All such tasks must be performed based on the evaluation of the sensor data according to a set of rules/heuristics that the human expert has learned from experience or training. Often, if not most of the time, these rules are not crisp (based on binary logic), i.e. some common-sense or judgemental-type decisions are needed. The class of such problems can be addressed by a set of fuzzy

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variables and rules which, if done properly, can make expert decisions.[3] The hovercraft control and stability problem falls into this class, and this paper demonstrates the applicability of fuzzy logic as an approach to its solution. In particular, both the design and application of a fuzzy controller for actively stabilizing the unstable response of a simple hovercraft platform are implemented.

2. SYSTEM DEFINITION

The entire system includes the hovercraft platform, attitude sensors, the PC-based controller and other necessary interface hardware. The overall concept of the approach is to take sensor readings from the hovercraft, send the results to the computer, compare the results to a level and/or stable situation and finally compensate for the difference by adjusting individual motor inputs to the hovercraft. If the craft is already stable, then the controller will maintain the operation of the motors until the craft becomes unstable. The process would then repeat itself. This then represents a closed-loop system with feedback, as shown in Fig. 1. In Fig. 1 the block labeled "Hovercraft Platform" represents the actual *physical apparatus* and not a mathematical model of the platform dynamics. That is, the controller designed for this system is *model-free*; it represents a non-analytic mapping from inputs to outputs. Although it may be possible to derive an approximate mathematical model for the system and a corresponding conventional control law, this work aims to demonstrate the ease of developing a fuzzy controller for systems with unmodelled dynamics using knowledge and intuition about the actual process being controlled. Moreover, an important goal of investigating such controllers is to prove the applicability of the techniques, as opposed to just determining ways to control systems for which conventional control theory is not suitable.[4] The fuzzy logic inferencing is embodied in the software that controls the system. Conceptually, the controller could be programmed onto a chip and then mounted onboard the hovercraft. This suggests the use of VLSI implementations of fuzzy logic controllers as proposed in Ref. 5. However, this particular objective is not included in this project. The following sections describe the development of the key components of the control system, as well as the interfacing between adjacent components.

3. HOVERCRAFT DEVELOPMENT

A physical model for the hovercraft with a triple-motor configuration is shown in Fig. 2. The hovercraft platform is made up of a triangular Styrofoam frame, three model airplane motors, three light-weight model airplane propellers, two sensors (described in the following section), and interfacing cables. The triangular frame measured about 0.5 m (~20 in.) on a side and was about 2.5 cm (~1 in.) thick. The airplane motors used for lift were relatively heavy compared to the propellers. When power from a d.c. power supply was applied to a single motor with a propeller attached, the motor barely lifted itself. In fact, the motor provided little lift even when the power supply had reached its maximum potential; it was decided to use battery packs to supply the motors with enough current to maximize the motor potential. Given the resource constraints on this project, the battery packs were a logical tradeoff. For obvious stability considerations, it was decided to use three motors mounted in a triangular configuration onto the Styrofoam platform. Styrofoam was the only material available for the frame; it proved to be just barely light enough that the motors chosen could provide sufficient lift. When all three motors were operating at maximum speed, the craft lifted about 1 in. off the ground. Without any control, however, the hovercraft was extremely unstable and the corners of the hovercraft repeatedly hit the ground. This erratic behavior caused severe damage to the hovercraft platform, and as a result, a few trips back to the drawing board. Since the main concern in this study was lift *stability* rather than thrust, propulsion or altitude control, it was decided that the craft would be elevated by suspending it from a tripod. In this manner the stability of the platform about a nominal (level) attitude could still be studied and, at the same time, the physical model would not be damaged during experimentation. The corners of the hovercraft platform were then loosely tethered to the legs of the tripod to avoid

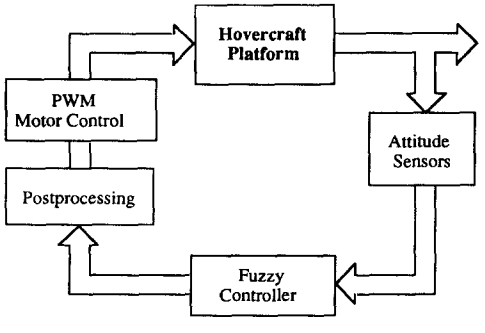

Fig. 1. Hovercraft control system.

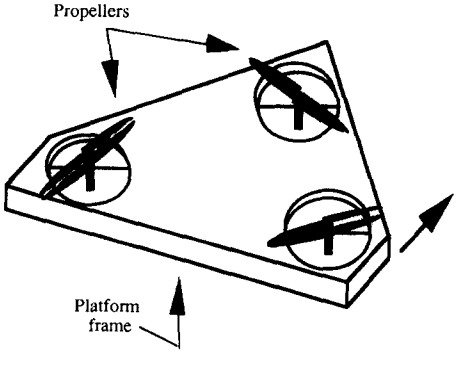

Fig. 2. Physical model of a simple triple-motor hovercraft platform.

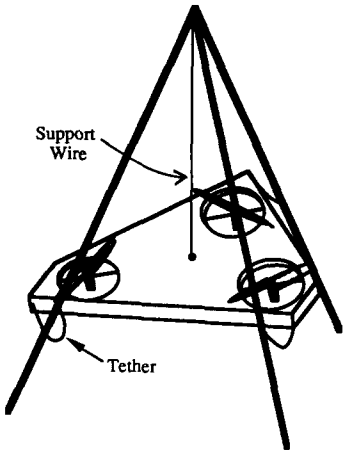

Fig. 3. Tripod-suspended platform.

further damage during testing and operation. This had the effect of restricting the yaw motion of the platform, such that the essential states to observe were reduced to roll and pitch. A diagram of the revised hovercraft system is shown in Fig. 3.

4. SENSING AND ACTUATION

The two attitude sensors for measuring the roll and pitch of the hovercraft were each comprised of a potentiometer with a pendulum attached. A diagram of the sensor with the pendulum in the nominal position is shown in Fig. 4. The nominal position corresponds to zero roll ($\theta_1 = 0$) and zero pitch ($\theta_2 = 0$). Valid measurements were taken from a 90° portion of the full rotational range of the potentiometers. The potentiometers were of a commercial variety; however, the pendulum attachment mechanisms were constructed in the laboratory. The attitude sensors were mounted to the hovercraft such that the pendulums were free to swing a full 90°. As might be expected, the potentiometer shafts had to have a very low resistance to torque in order for the pendulums to swing freely. As the hovercraft tilts, the pendulum remains vertical causing a voltage change on the output of the potentiometer that is proportional to the angle, θ_i. This voltage (0–5 V) is transmitted to the computer, converted to a digital representation and used as the input to the fuzzy controller.

The two sensors were used to give an approximate measure of the rotation about two different axes (pitch and roll) as depicted in Fig. 5. Notice that for θ_2, the

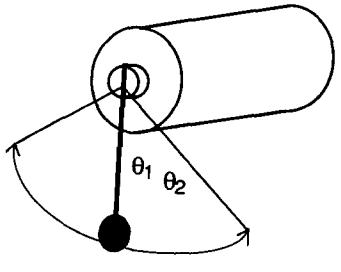

Fig. 4. Attitude sensor for measurement of roll, θ_1 and pitch θ_2.

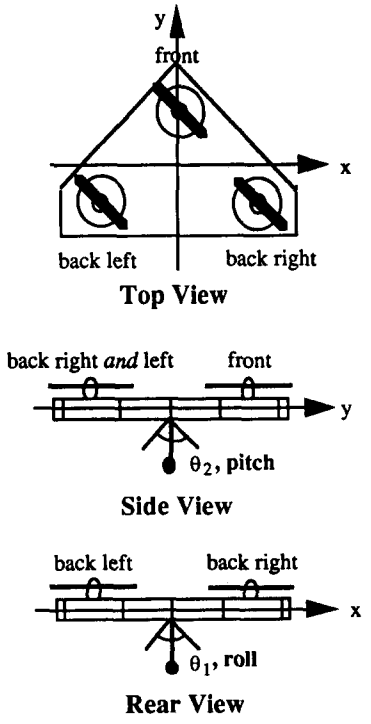

Fig. 5. Some principal views.

side view consists of both the back-right *and* back-left motors. This allows distribution of the motor forces such that only two axes, and therefore two pendulums, are needed for attitude measurement and control. In other words, a resultant of the back-right and back-left motor forces can be used to form a couple with the front motor force to effect hovercraft pitch. Roll can be effected in a similar manner using a couple formed by the back-right motor with the back-left motor (the front motor is not considered to affect platform roll). The control algorithm implements the force distribution necessary for pitching the hovercraft platform by simply dividing the power delivered to each of the rear motors by two so that there is essentially one resultant motor force on the rear and one motor force on the front. If the hovercraft tilts in such a way that both pendulums swing, the controller will compensate for pitch and roll by adjusting the motor inputs appropriately such that the hovercraft restabilizes.

5. FUZZY CONTROL

Fuzzy sets[6] may be represented by a mathematical formulation, often known as the membership function. This function gives a degree or grade of membership within the set. The membership function of a fuzzy set A, denoted by $\mu_{A(X)}$ maps the elements of the universe X into a numerical value within the range [0,1], i.e.

$$\mu_{A(X)}: X \rightarrow [0,1]. \tag{1}$$

In control system applications membership values are actually measures of degree of causality in an input-output mapping. Within this framework, a membership

value of zero corresponds to a value which is definitely not an element of the fuzzy set, while a value of one corresponds to the case where the element is definitely a member of the set.[3] A fuzzy controller typically takes the form of a set of IF-THEN rules whose antecedents and consequents are membership functions. Consequents from different rules are numerically combined (typically union via MAX) and are then collapsed to yield a single real-number output. The hovercraft fuzzy controller accepts two inputs and produces three outputs. The inputs are platform pitch and roll; output is comprised of three motor pulse time durations. The controller fuzzifies (assigns a fuzzy membership grade to) the attitude sensor readings, and motor pulse time durations appropriate for the current instant of control are determined. In order for a fuzzy inference engine to provide approximate reasoning about linguistic attitude variables, rules must be defined for the system.

Fuzzy rules and membership functions are integral parts of the fuzzy logic inferencing process. If an application can be viewed as a system governed by if-then rules, then fuzzy logic is a suitable control tool. Two examples of fuzzy if-then rules used in the hovercraft fuzzy controller are as follows:

IF roll is NL, THEN T_{bl} is SHORT, T_{br} is LONG, T_f is SHORT (2)

IF pitch is PL, THEN T_{bl} is SHORT, T_{br} is SHORT, T_f is LONG.

In this case T_{bl}, T_{br}, and T_f represent the time durations for pulsing of the back-left, back-right, and front motors respectively. The terms SHORT, LONG, MED (medium), PL (positive large) and NL (negative large) are fuzzy sets or linguistic variables defined over input and output universes of discourse. In this work, they are measures of vagueness or uncertainty in time and angular displacement. Linguistic variables are useful in the context of fuzzy membership functions. That is, the membership functions are created by partitioning the universe of discourse of a given state variable (e.g. roll) with overlapping fuzzy sets. The number of fuzzy sets in a given partition dictates the granularity of the decision space, as well as the size of a complete rule base. In this work, the membership functions illustrated in Fig. 6 were specified using an iterative trial-and-tune procedure. An initial intuitive set of membership functions and rules was tested on the system and repeatedly tuned, based on the observed behavior of the system, until satisfactory performance was achieved. This is one of the more-primitive approaches to fuzzy system design; more-systematic approaches exist which are based on the notion of fuzzy identification[7] or structured optimization techniques.[8] In any case, if some knowledge of the system behavior exists, the relative ease of designing fuzzy controllers for stable systems remains when the plant of interest is unstable. When rules of the form given in (2) are used in fuzzy rule-based control the controller can be thought of as a proportional controller since control outputs vary in proportion to the inputs. This is consistent with Ref. 9, where rules for proportional-like fuzzy knowledge-based controllers are specified in the same manner.

The idea behind the fuzzy control process is based upon the sensor readings of the particular system. In this case, the digital voltage representations of the angles for roll and pitch, θ_1 and θ_2, are the inputs to the fuzzy logic controller. The if-then rules are developed such that if the hovercraft is not level, then the motors need to adjust. In fact the rules mimic the specific operations that a human expert might use. For example, at some instant an expert might notice that θ_2 (pitch) is about 36° from being level. He would then adjust the front motor so that it had a shorter-duration pulse of operation and simultaneously adjust the back-right and back-left motors to have a longer pulse of operation. This would result in the rotation of the hovercraft platform about the θ_2-axis. But as the hovercraft approached level, the operator would then have to readjust the motors to maintain the hovercraft's stability. The fuzzy rules attempt to accomplish exactly the same task. Moreover, they consider continuous pitch values between the 36° position and the level position. This then means that the fuzzy rules are firing almost *continuously*, whereas the operator has to adjust as often as possible, which is not necessarily continuous due to human limitations. Another advantage that the fuzzy control has over the human operator is the speed at which the computer changes the control outputs. The human expert has the limitations of his physical body and muscles, whereas the computer can make the changes and implement the infinitely possible situations within micro-seconds.

A particular advantage to using fuzzy control lies in the way that the fuzzy rules interact to perform approximate reasoning about sensor inputs. In a given control cycle more than one rule may fire, thus resulting in several recommendations for the current control ac-

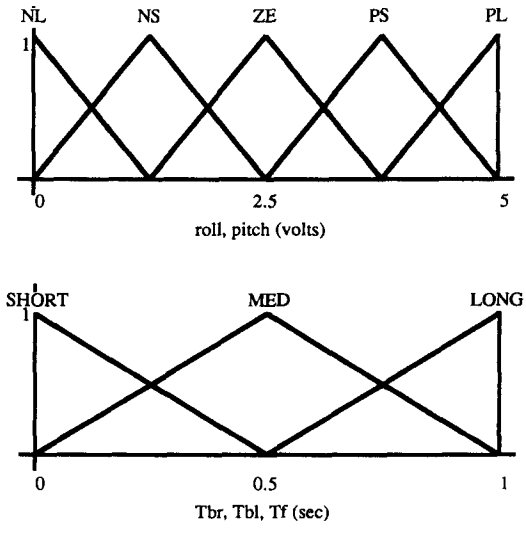

Fig. 6. Fuzzy membership functions

tion. The conflict of recommendations is resolved such that the control action is representative (to a degree) of the recommendations of each individual contributing rule. For instance, if the hovercraft attitude is such that both θ_1 and θ_2 are not at the nominal orientation, then several rules will be executed. This will result in simultaneous control input recommendations for the three motors for each rule. Fuzzy logic inference then maps the recommendations into single control inputs for each motor. This is why fuzzy logic makes the design and implementation of a control system easier for complex plants. For example, in the hovercraft (and other similar dynamic systems) significant coupling exists between motion about the pitch and roll axes. This coupling would complicate the analytical design of a model-based conventional controller. In the fuzzy control system described here, each axis is considered as if it were being controlled individually. Using fuzzy logic the control of the axes is combined into one system and the interactions are handled implicitly.

6. IMPLEMENTATION

The stabilization of the simple hovercraft platform described in Section 3 was achieved in real-time using an AT&T 386-based PC-clone. Some of the hardware and software details of this real-time implementation are discussed in this section. The attitude measurements were fed into an analog-to-digital converter. The voltages were converted to digital signals and made available to the fuzzy control software as inputs to the rule base. The motors were controlled using a technique called Pulse Width Modulation (PWM), which is a process in which the motors are turned on/off for various time durations depending upon the desired effect. For instance, the pulse that controls the motor would be turned on for a certain duration of time, but then turned off for another duration of time, and cycled through this sequence repeatedly. If a motor needed to have more power, the time duration during which it was turned on would be increased. Similarly, if the motor required less power, the time duration for which it was turned on would be decreased. Using fuzzy logic inferencing, three time durations were determined for simultaneous output to the three motors. The control software actually mapped the time durations to 16-bit, binary words. These words were sent via the PC interface card to digital output pins to control the motors as described later. This process allowed the three motors to be controlled simultaneously and continuously.

The actuation bit streams transmitted by the controller were fed into three relays which allowed the motors to be switched on when a logic 1 (high) signal was passed, or switched off if a logic 0 (low) signal was passed. The disadvantage of using relays in the hovercraft control application is that they soon wear out after a finite number of on-off transitions. This relay-motor connection closes the loop (see Fig. 1).

6.1. Software development

Software for the hovercraft control system was written using the C programming language and Togai InfraLogic's Fuzzy-C.[10] Closed-loop software control was achieved by a collection of five principal modules. These modules combine functionally to execute the following control algorithm:

Loop > Acquire hovercraft attitude (roll and pitch) from onboard potentiometers

Loop > Assign a bit stream representing each time duration

Loop > Loop.

The top-level module implements this software control cycle by invoking calls to submodules which perform sensor data acquisition, fuzzy inferencing, post-processing of fuzzy controller output, and hovercraft control input. As mentioned above, data acquisition is performed via the A/D card. The roll and pitch are used by the fuzzy controller module to determine the approximate motor pulse time durations necessary for stabilization. A fuzzy rule base consisting of 12 rules (see Appendix) of the form discussed in Section 5 is used in this implementation.

Once the necessary time durations have been determined they are post-processed by assigning a bit stream representation to each. That is, the code maps a range of time durations (0–1 s) into a set of bit streams (as mentioned earlier) to be used as PWM control inputs. The number of 1 s/0 s in a bit stream is proportional to the amount of time a motor signal should be high/low. The control bits are then sent to the hovercraft motors via a 3-bit control word made up of the least significant bit of each of the three bit streams. The control words are transmitted one word at a time. Each bit individually represents one high/low control bit to be sent to one of the three relays connected to the motors. For example, if the current bit streams are:

front motor	00. . .00100
back-right motor	10. . .01111
back-left motor	11. . .01010

then the sequence of control words would be

×010
×011
×110
×011
×000
. . .
×001
×011

where bit 3 is disregarded, control bit 2 is the front

motor input, control bit 1 is the back-right input, and control bit 0 is the back-left input. Each bit in a control word sets the state of a digital output pin on the A/D card, thus allowing parallel PWM control of the hovercraft motors. Since the fuzzy logic controller output provides crisp time durations, this post-processing is necessary to achieve the PWM control as described earlier.

7. RESULTS AND DISCUSSION

The hovercraft platform was suspended from the tripod in such a way that the wire attachment was not aligned with the platform center of gravity (see Fig. 3). As a result, before the apparatus was turned on, its attitude was significantly offset relative to the desired stable (horizontal) orientation. Since the desired nominal attitude corresponded to zero pitch and roll, all measurements essentially represented the attitude error at each sampling instant. The initial offset represented the initial attitude error state from which the fuzzy controller had to drive the platform to reach the nominal state. In the laboratory the PC-based fuzzy controller was successful at stabilizing the response of the tripod-suspended platform. By "successful" here is meant that the controller accomplished its objective of driving the platform from its initial state to the desired nominal state, maintaining attitude about the nominal state, and eliminating the erratic instability experienced in the early stages of development (Section 3). However, there was room for improvement in the steady-state stabilizing effect. To elaborate, the hovercraft platform was observed to sustain heavily damped oscillations about the nominal state. Attempts to eliminate these oscillations by further tuning of the membership functions were made but to no avail. It is believed that this behavior is due to the fact that the current system does not utilize any process information related to the past or future, i.e. error integral or derivative information. Although the control system described in this work acted as a fuzzy proportional controller, variants to this approach would also be suitable for achieving stability of simple hovercraft platforms. Using alternative software techniques or improved sensing, the availability of the derivatives and integrals of θ_1 and θ_2 would give rise to a fuzzy proportional-integral-derivative (PID) controller. It is expected that a fuzzy PID controller would have the usual effect of improving the stability of the hovercraft platform and both its steady-state and transient response.

7.1. Future plans

In any dynamic system, the question of guaranteed stability and controllability arise. These are structural properties of control systems, the acceptable meanings of which are defined in the mathematical language of analytic control theory. It is not clear whether the analytical tools of conventional control theory are the most suitable for analyzing the structural properties of fuzzy logic or other soft computing systems. As such, many researchers are currently concentrating on developing theoretical approaches to the problem as it relates to fuzzy systems. For example, Mamdani[4] argues that fuzzy control provides an alternative paradigm to the analytic control theory that consists of non-analytic approaches to control and are based on decision-making approaches from artificial intelligence. He goes on to assert that "prototype testing is more important than stability analysis. . .[and that] stability analysis is still an important issue but a different way has to be found to study it".

While the stability of the fuzzy controller presented in this work has been observed but has not been proved here, the authors do have an interest in pursuing suitable techniques for assessing the structural properties of the hovercraft control system. Future research will be directed towards this end. In particular, stability, controllability and robustness to system parameter perturbations need to be addressed. One of the earliest approaches to stability analysis of fuzzy controllers was developed by Braae and Rutherford.[11] The approach is known as the "fuzzy phase plane" approach (or "state space" approach) and is based on the relationship between the phase plane and the fuzzy rule base. It is a graphical approach that is useful for predicting stability as well as other dynamic phenomena. Fuzzy phase plane analysis is limited to two-dimensional systems due to difficulties in the interpretation of higher-dimensional graphical representations of the phase plane.[9] The fact that the hovercraft fuzzy control system does not comply with the restrictions of the approach precluded its use here.

Future plans also include an attempt at the derivation of a mathematical model that adequately describes the dynamics of the hovercraft platform. The availability of a mathematical model will permit the design of conventional controllers that can be compared with the fuzzy controller presented in this article. An assessment of the relative performances can then be made and conclusions can be drawn about the merits of each approach for controlling hovercraft platforms.

8. SUMMARY

A physical model of a simple hovercraft platform constructed in the laboratory has been described. The associated fuzzy logic controller that was designed to stabilize the attitude of the platform in real-time was discussed. Some details regarding the hardware and software implementation of the system were presented, followed by a discussion of the results and plans for further investigation. The aim of this project was to demonstrate the ease of developing a fuzzy controller for systems with unmodelled dynamics using knowledge and intuition about the actual process being controlled. Accordingly, the controller is model-free.

The observed laboratory results demonstrate the potential of a fuzzy logic controller for stabilizing a simple hovercraft platform. The fuzzy system exhibits a control performance comparable to what could be accomplished by a human expert. It has been demonstrated that with the aid of fuzzy logic the stability of a somewhat complex and inherently unstable system can be achieved and maintained. Furthermore, the difficulties in both the design and the application of the control process are well managed.

There are many applications of fuzzy logic and this particular application gives an idea of how to adapt the fuzzy methods to a problem. As a system becomes more complex, an extended sensor suite, additional linguistic variables, and consequently additional rules may be necessary to control the system. In fact, as long as rules can be made about any situation, e.g. the stock market, psychology, law, etc., fuzzy logic can be a part of the controlling process.

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APPENDIX

Fuzzy Rule Base:

Rule 1:	IF roll is PL	THEN T_{bl} = LONG,	T_{br} = SHORT,	T_f = MED
Rule 2:	IF roll is PS	THEN T_{bl} = MED,	T_{br} = SHORT,	T_f = MED
Rule 3:	IF roll is ZE	THEN T_{bl} = MED,	T_{br} = MED,	T_f = LONG
Rule 4:	IF roll is ZE	THEN T_{bl} = SHORT,	T_{br} = SHORT,	T_f = MED
Rule 5:	IF roll is NS	THEN T_{bl} = MED,	T_{br} = LONG,	T_f = MED
Rule 6:	IF roll is NL	THEN T_{bl} = SHORT,	T_{br} = LONG,	T_f = SHORT
Rule 7:	IF pitch is PL	THEN T_{bl} = SHORT,	T_{br} = SHORT,	T_f = LONG
Rule 8:	IF pitch is PS	THEN T_{bl} = MED,	T_{br} = MED,	T_f = MED
Rule 9:	IF pitch is ZE	THEN T_{bl} = MED,	T_{br} = MED,	T_f = LONG
Rule 10:	IF pitch is ZE	THEN T_{bl} = SHORT,	T_{br} = SHORT,	T_f = MED
Rule 11:	IF pitch is NS	THEN T_{bl} = MED,	T_{br} = MED,	T_f = SHORT
Rule 12:	IF pitch is NL	THEN T_{bl} = LONG,	T_{br} = LONG,	T_f = SHORT

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Eddie Tunstel received the B.S. and M.E. degrees in mechanical engineering, with a concentration in robotics, from Howard University, Washington, D.C., in 1986 and 1989 respectively. Since 1989 he has been a Member of Technical Staff of the Robotic Intelligence Group at the Jet Propulsion Laboratory in Pasadena, Calif. As of 1992, he is a JPL Minority Fellow and Ph.D. candidate in electrical engineering at the University of New Mexico, Albuquerque. His general research interests inlcude embedded fuzzy logic control of autonomous mobile robots, soft computing and microrover technology.

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