

**FUZZY LOGIC APPLICATIONS TO EXPERT SYSTEMS  
AND CONTROL**

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**Dr. Robert N. Lea  
Software Technology Branch/PT4  
NASA Johnson Space Center  
Houston, TX 77058  
Phone: 713/483-8085  
Email: rlea@nasamail.nasa.gov**

**Yashvant Jani, Ph.D.  
Technology Systems Division  
Togai InfraLogic Inc.  
Houston, TX 77058  
Phone: 713/480-8904  
Fax: 713/480-8906**

**ABSTRACT**

A considerable amount of work on the development of fuzzy logic algorithms and application to space related control problems has been done at the JSC over the last few years. Particularly, guidance control systems for space vehicles during proximity operations, learning systems utilizing neural networks, control of data processing during rendezvous navigation, collision avoidance algorithms, camera tracking controllers, and tether controllers have been developed utilizing fuzzy logic technology. These systems have given very good results, and in some areas such as fuel and power usage they have shown superior performance to shuttle systems. Several other areas in which fuzzy sets and related concepts are being considered at the JSC are to diagnostic systems, control of robotic arms, pattern recognition and image processing.

It has become evident, based on the commercial applications of fuzzy technology in Japan and China during the last few years, that this technology should be exploited by the government as well as private industry for energy savings, reducing human involvement in industrial processes, and for many complex control problems where precise mathematical modeling is either practically impossible or very costly.

**1. INTRODUCTION**

In his article "Fuzzy Sets", Prof. Zadeh [1] first developed the concepts of fuzzy logic in 1965 and established these concepts firmly during the 70's [2] with other pioneers [3,4,5,6,7]. Contrary to its name, it is a precise subdiscipline in mathematics that enables mathematicians and engineers to utilize human like thinking in decision making processes. Handling imprecise information is much easier in the architecture provided by fuzzy logic compared to conventional logic. However, it was not accepted by the U.S. community for a long time simply because the word 'fuzzy' has negative connotations. It was felt that fuzzy logic based decision making processes involved fuzzy reasoning rather than human like common sense reasoning that must sometimes be based on information that is inherently not crisp. In fact, fuzzy logic is a method based on sound mathematical principles that enables one to model natural language rules and to make common sense evaluations of the degree to which non-crisp conditions such as low temperature, fast speeds, or sharp turns are satisfied. Control engineers made arguments that desired control can be achieved using existing control theory principles until the triple inverted pendulum was balanced using fuzzy logic principles. This task could not be performed adequately using conventional logic. The real utility of this logic was shown by the Japanese [8,9,10] when they applied the principles to subway control, automatic transmission control, camera focusing, and many other problems. Recently U.S. business people have taken an interest in this field [11,12,13] as the Japanese applications have shown that this logic can save developmental time and costs.

Investigations in the areas of fuzzy logic and neural networks have been underway since 1984-1985 [14] in the Software Technology Laboratory (STL) at the Johnson Space Center (JSC). The utility of this logic in several autonomous space operations applications have been demonstrated utilizing high fidelity orbital operations simulations [15]. Our objectives in the STL are to investigate new technologies for control and decision making processes. We are evaluating fuzzy logic techniques, neural network methods, genetic algorithms, and learning techniques based on fuzzy sets and neural networks for building expert systems and robust controllers. We are

particularly investigating the feasibility of applying these technologies to space operations to achieve desired operational efficiency and reduce overall life cycle costs.

In this paper, we describe the fuzzy logic applications achieved at JSC in section 2. Our current activities in the areas of fuzzy learning systems and neural networks are described and potential results are discussed in section 3. Several commercial applications mainly from Japan are described in section 4 and a summary and discussion of advantages and disadvantages of fuzzy logic is given in section 5.

## **2. FUZZY LOGIC APPLICATIONS AT JSC**

As reported earlier [14,15], several fuzzy logic and neural networks applications are underway at JSC. In this section we will summarize results of only three because of space limitations: the six degree-of-freedom (6DOF) controller, the collision avoidance, and the camera tracking control.

### **2.1 Proximity Operations And Results**

The 6 DOF controller for a spacecraft has been designed and tested [16,17] in a shuttle simulation for proximity operations. The 6 DOF controller uses sensor measurements of range, elevation and azimuth angle directly as input and generates the commands for the jet select routine to null out the errors. For a given mission profile, it maintains a proper range and range rate. The elevation and azimuth angle measurements are used in conjunction with the angular rates to generate jet firing commands required to follow a desired trajectory such as shown in fig. 1. For example, during the v-bar approach, the controller maintains elevation and azimuth angles close to zero and range and range rate close to their desired values. If the range is smaller than the desired range, the controller will slow down accordingly. If the range rate is slower than the desired rate then the controller will increase the speed. In keeping the elevation and azimuth angles close to zero, the controller adjusts its actions based on the angle errors, rate errors as well as current pitch rate and roll rate. While the vehicle is translating its attitude is being maintained by the rotational part of the controller.

Our approach of correcting the elevation and azimuth errors and range rate error in conjunction with maintaining orientation and body rate errors has given good results and shown significant savings in fuel (Table I). The performance of our 6 DOF controller based on simultaneous relative trajectory and attitude control is very good and robust. The controller is responsive and maintains the flight profiles within the expected range. The controller holds proper elevation and azimuth angles during all proximity operations test cases, and performs proper range and range rate control. It transitions along the v-bar or r-bar from approach to station keeping in a way very consistent with profiles flown by pilots. It also performs fly-around maneuvers very well and continuously maintains proper range deadband and attitude while transitioning to the required station keeping position.

We plan to continue to test this 6 DOF controller further and compare its performance with mission planning data, the manual crew procedure test cases flown in mission simulator, and possibly flight data. Our preliminary test data shows that the correlation between the translational and rotational rates can be handled easily by the fuzzy controller. We also plan to modify the 6 DOF controller such a way that it can be easily adapted by other spacecraft.

### **2.2 Collision Avoidance**

Future unmanned missions to Mars will investigate the terrain and collect soil samples in advance of manned missions [18]. Path planning is a crucial element in the activities to be undertaken by an autonomous rover. As an initial effort to address this problem a fuzzy control system for maneuvering a four wheel vehicle with front wheel steering from one position to another and requiring a particular attitude at the terminal point was developed in the STL [19,20]. Since obstacles such as boulders or troughs may block the shortest path from the current position to the target position for the next sample acquisition, collision avoidance algorithms were later developed [21,22] that takes sensor data giving range to obstacle, current velocity and orientation of the vehicle and processes it through fuzzy rules to generate steering commands to avoid obstacles as they are encountered. Simulation testing has been performed for a set of representative test cases, and performance of the guidance algorithms have been evaluated for a variety of obstacle scenarios. It was found that a higher-level path planner is needed to handle situations when the vehicle is caught in a back-off setting, that is, when it is not possible for the vehicle to pursue a "forward" path. It is significant to note that the method employed does not depend on object identification, but rather, detection of the degree to which an object (where present) or (more generally) an angular sector represents an obstacle. This is a significant relaxation over most collision avoidance schemes. Our simulation results and planned enhancements for

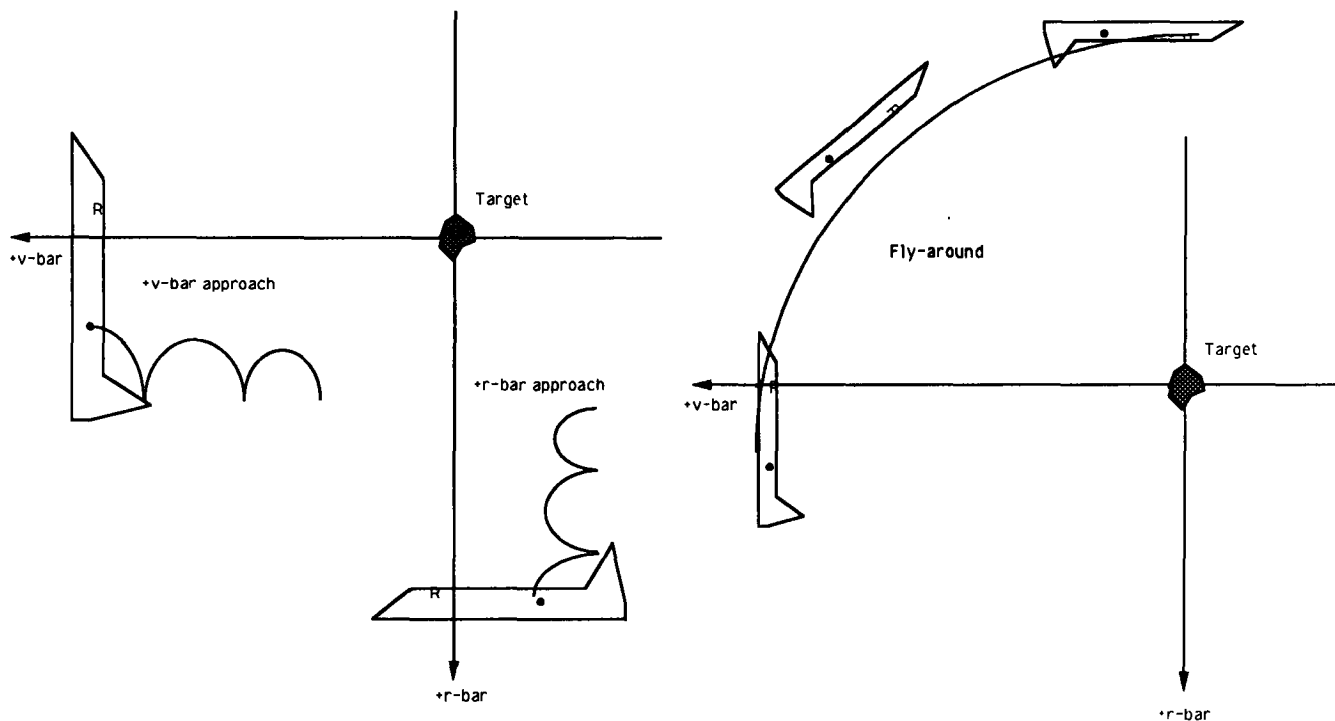


Fig. 1a Proximity Operations v-bar and r-bar Approaches Fig. 1b Proximity Operations fly-around Segment

**Table Ia . Fuel Usage Comparison between conventional and fuzzy attitude controllers**

Run #	Fuel Usage (kg)		Savings %
	Conventional	Fuzzy	
5	18.40	18.44	-0.22
6	8.88	9.45	-6.42
7	26.27	20.58	21.66
8	159.91	122.26	23.54
13	24.22	23.31	3.76

**Table Ib. fuel usage, arrival times and mission segment information for the 6 DOF testcases**

RUN #	Maneuver	Distance	Rates	Arrival Time	Fuel Used
1	V bar approach	400 ft-50 ft	zero rates	1450 sec	33 lbs
2	R bar approach	400 ft-50 ft	zero rates	1720 sec	61 lbs
3	1/4 Fly Around	@200 ft	0.2 rate	1800 sec	48 lbs
4	Station Keeping	@200 ft	zero rates	1800 sec	12 lbs

the future point to refinements in the algorithm, the possibility of adaptive tuning of the system and, as expected, the need for a higher-level path planner to handle cases that involve backoff, sensor fusion, positioning of the vehicle at the destination, moving obstacles, and other situations that involve radically changing environments of operation.

Five test cases were designed to test the capabilities of the collision avoidance system. The first and second test cases were designed to test avoidance of a single obstacle with varying size. The third and fourth test cases show that obstacles can be successfully avoided one by one as the rover reaches the desired destination. The fifth test case shows that the rover can avoid many obstacles even if they are lined up, leaving only a small opening. The five test cases described above are given in Fig. 2, which was taken from the summary piece for each run from a graphical simulation developed on an IRIS workstation.

Some important points of these results are as follows: a) trajectory control [19,20] includes not only position control but also orientation control. When collision avoidance algorithms are integrated with the trajectory control [21,22], the orientation control can not be managed properly without major modification to the system. Proper orientation can be achieved only if there is sufficient distance between the last obstacle avoided and the target point so that the rover can turn itself. Since this distance can not be guaranteed, the desired orientation of the rover at arrival was not addressed with the collision avoidance problem; b) the back-off situation requires some knowledge about the obstacles just avoided, or some information about the obstacles in the path. Since our cameras were looking forward, we postponed the 'back-off' situation study; and, c) when the rover is going forward, and it encounters an obstacle that can be avoided only by going back, it must remember that the distance it must go back is a factor. Otherwise, it can get into a situation where it continues to go back and forth when the critical distance for collision avoidance is not altered. Thus, the transition from forward to backward requires special care.

Fuzzy logic control together with straightforward algorithms yield an effective system for autonomous collision avoidance in an environment of uncertain information. The technique is robust and avoids complexity in initial stages where simple obstacle avoidance is a key element rather than involved object identification or mapping of a complete world model. This technique could be integrated with fast and sophisticated object identification algorithms if desired. Future developments would include a plan for backoff situations where a forward path is not possible, fusion of information from several sensors of various types with differing degrees of uncertainty to be managed, adaptive tuning of fuzzy components, avoidance of moving obstacles, and a higher level path planner for optimization of operation in regional or global environments.

### 2.3 Camera Tracking Controllers

The concept of a camera tracking controller that generates the necessary pan and tilt motors commands to keep an object as close to the center of the field of view of the camera as possible has been developed at the JSC [23,24]. This concept has been developed further and currently software simulations have been built that are allowing limited performance testing. This Camera Tracking System (CTS) is a good example of one where a fuzzy control system is much better suited to the problem than conventional control methods. Clearly since one does not know ahead of time what object will be tracked or what it will do once the camera is trained on it. The fuzzy controller generates rate commands based on the required angle change, available camera rates, and the estimate of range to the object.

Seven test cases have been designed to provide representative trajectories during proximity operations like the V-bar approach, R-bar approach, station-keeping and fly around for the CTS performance evaluation. Since the object in our simulation does not have active control, its trajectory is purely based on the forces of the orbital environment. To give an example of results, the plots of the sixth test case which represents a Passing Orbit are discussed. In this test, the object is translating in all three direction as shown in fig. 3a, 3b, and 3c, where the LVLH x, y, and z position are given as functions of time. The out-of-plane and in-plane LVLH trajectories are shown in fig. 3h, and 3i. Because of this motion, the controller must use pan and tilt angles to track the object. The pixel-x, pan angle, pixel-y and tilt angle are shown in fig. 3d, 3e, 3f, and 3g respectively.

Initially, the camera is pointed along the LVLH x-axis. The pixel-x and pixel-y measurements are 240 and 280 respectively due to the position of the object in the LVLH frame. Thus, the controller commands pan left and tilt down. Pan left implies negative pan angle and therefore pan angle continuously decreases from a small negative value to a large one as shown in fig. 3e. The trajectory of the object is such that the pan angle continuously increases in the left direction making a full circle. In fig. 3e, the pan angle is nearly  $2\pi$  at the end of the test. This behavior is completely expected for the Passing Orbit case.



Fig. 2a Collision Avoidance for an object

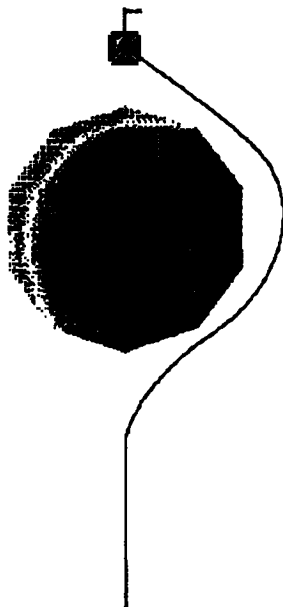


Fig. 2b Collision Avoidance for a large object

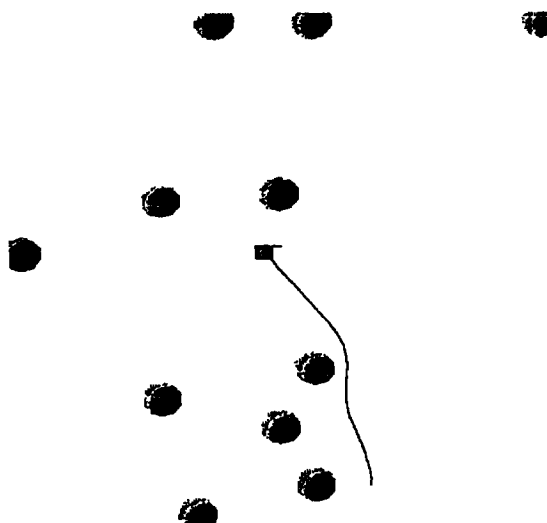


Fig. 2c Collision Avoidance for a set of objects (easy)

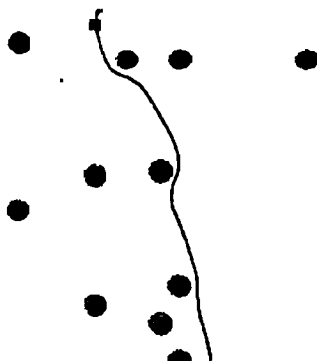


Fig. 2d Collision Avoidance for a set of objects (hard)

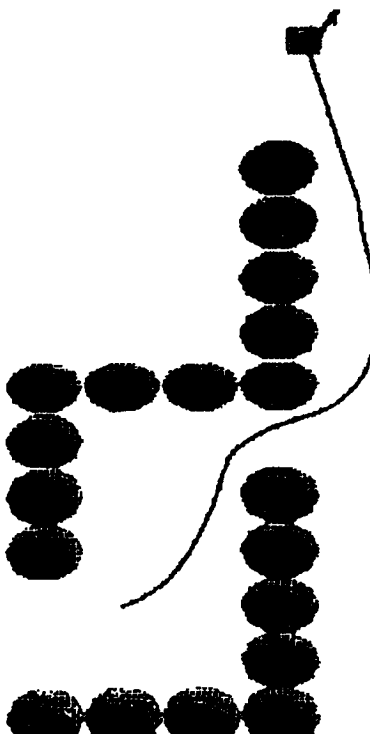


Fig. 2e Collision Avoidance for a simple maze

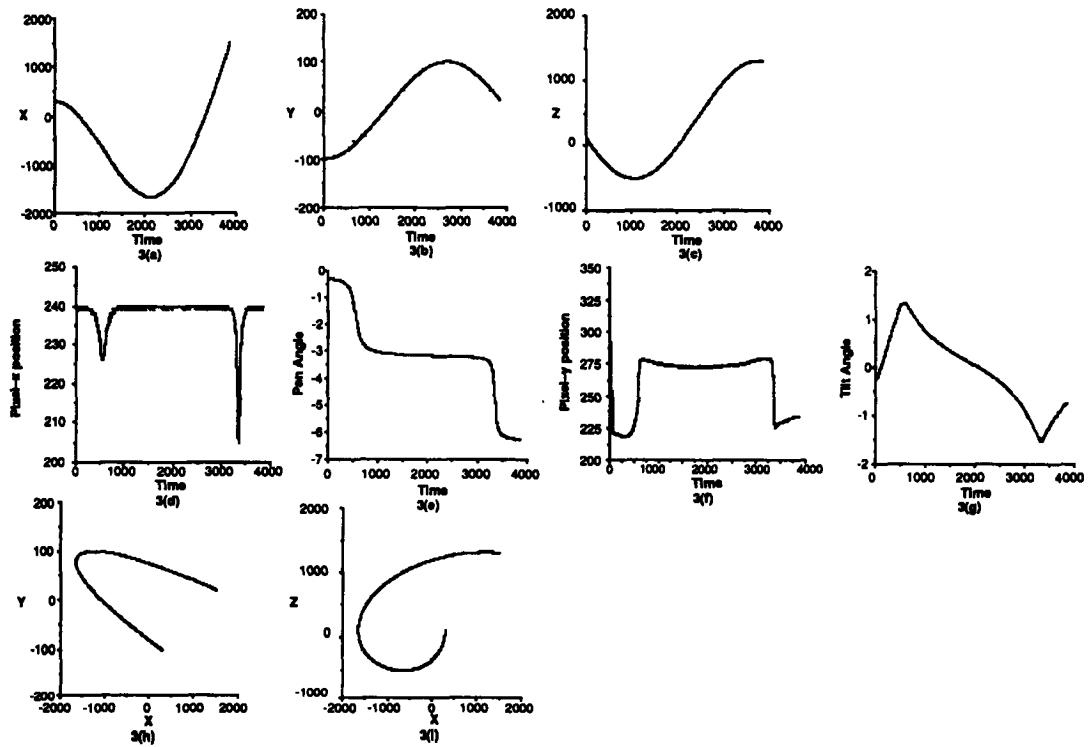


Fig. 3(a)-3(c) motion of the object in terms of X, Y, and Z vs. time in the LVLH coordinate system.  
 Fig. 3(d) correlates with 3(e), as the pixel-x position changes, the camera will pan right or left.  
 Fig. 3(f) correlates with 3(g), as the pixel-y position changes, the camera will tilt up or down.  
 Fig. 3(h) motion of the object in the X-Y plane in the LVLH coordinate system.  
 Fig. 3(i) motion of the object in the X-Z plane in the LVLH coordinate system.

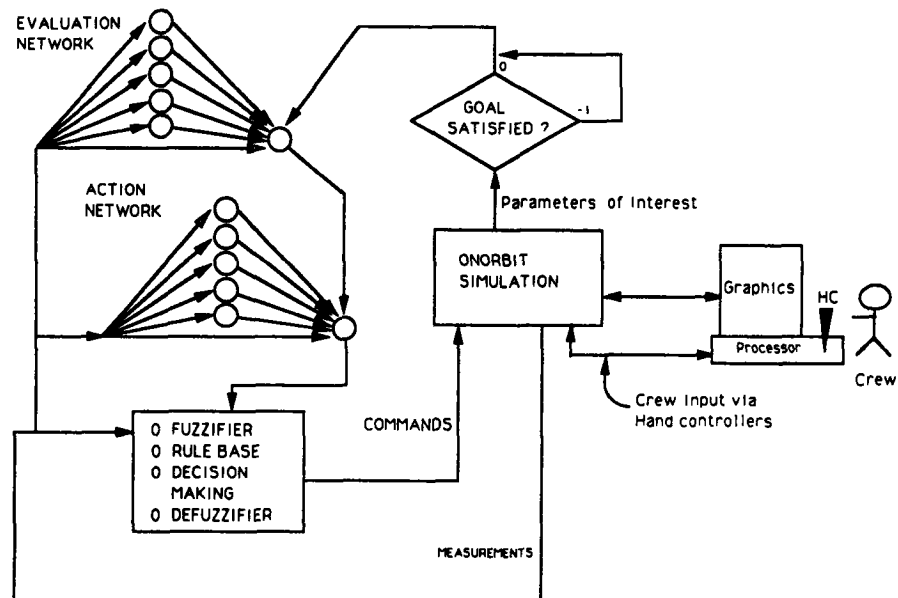


Fig. 4 FUZZY LEARNING SYSTEM FOR DOCKING OPERATIONS

The Tilt down command corresponds to a positive rate in the gimble frame, but results in a total negative tilt angle with respect to LVLH due to the mounting of gimble drive. The tilt angle decreases for only a couple of seconds. (Since the output data is every 10 seconds, tilt down is not visible in the plot.) As the pixel-y position drops below 270, the tilt rate command stops. The controller begins commanding tilt up, when the pixel-y position has a value less than 240. As the controller commands tilt up rate, the tilt angle increases in the positive direction as shown in fig. 3g. (Tilt up is negative rate in gimble frame, but results in positive rate with respect to LVLH frame and hence the positive tilt angle.) The tilt angle does not change during the time pixel-y position reverses from 224 to 275. However, when pixel-y is pegged at 275, the tilt angle changes from 1.5 to -1.5 radians.

In summary our test results show that : 1) the x-position and y-position of the object in the camera FOV are maintained in the zero-zone (pixel range 240 to 270) most of the time, confirming that the controller is capable of keeping the object in the camera's FOV, 2) pan and tilt angles were adjusted to reposition the object in the center (see definition of CENTER in ref. 24) when it went outside of the zero zone, 3) in one case, response of the controller was slower in comparison to the object's motion, however, the object never went out of the range of the CENTER membership function. Performance of the fuzzy tracking controller is very good and the object is maintained properly in the center of the FOV.

Our future activities for the CTS are focused on several tasks : 1) Modify the membership functions to maintain the object in a narrow range, 2) Utilize the range directly into the rules rather than the intermediate scale factor, and if possible reduce the number of rules, 3) implement the estimated angular velocity rules and provide a controller with a dynamic response, 4) implement the centroid calculations algorithms to handle the image in the pixel form, and 5) implement the rule set in a fuzzy chip that can directly interface with the gimble drives and camera digitizer.

### 3. CURRENT ACTIVITIES

Reinforcement learning techniques based on fuzzy control and multi-layer neural networks have been successfully demonstrated at the Ames Research Center (ARC) using the inverted pendulum as an example [25,26]. As a joint project between JSC and ARC, a concept has been put together for applying this technique to spacecraft docking operations [27]. Fuzzy controllers developed at JSC will be implemented in the Approximate Reasoning Intelligent Control (ARIC) architecture, fig. 4, and test cases will be performed using high fidelity simulation of shuttle docking scenarios. As a first part of this project the attitude controller developed for the shuttle has been implemented in the ARIC architecture and a test case for attitude hold has been performed. Our preliminary results are very promising [28], and shows that the fuzzy learning technique has no problem in controlling the angular rates. We are further investigating how to control angles and plan to expand the control to translational parameters such as range and elevation angle. Failure criteria has been developed for the attitude hold, and the fuel usage criteria will be developed as we further learn to utilize this technique for all attitude maneuvers.

The Tethered Satellite System (TSS) mission [29] planned for August 1992 involves the upward deployment of the Italian satellite on a 20 km. conducting tether. Electric current will be induced as the tether is dragged through the magnetic field of the Earth. Because of interaction between the orbital environment and tether dynamics, there are several oscillations in the tethered system. Particularly of interest are the "skip rope" oscillations resulting from the interaction of the Earth's magnetic field with the current pulsing through the tether. Identification and control of the skip rope oscillations is very important. Mission success is dependent on how successfully these oscillations can be damped during the satellite retrieval. Because of this situation, the mission profile has a very special Onstation-2 phase where the tether is not retrieved unless the skip rope magnitude is smaller than a critical value. Since the skip rope oscillations excite very peculiar attitude oscillations for the satellite, the magnitude and phase of the skip rope can be detected using the satellite rates and angle data. The coupling between the attitude oscillations and the skip rope behavior is complex and very non-linear.

The Space Time Neural Network (STNN) developed at JSC [30] provides the capability to learn the time variations as well as spatial variations using digital filters before the data is provided to hidden layers as well as the output layer. A concept under consideration is to apply the STNN to learn the coupling between satellite attitude oscillations and the tether skip rope behavior. Input to the network will be satellite rates, tether length, tension and other relevant parameters. Output should be the skip rope magnitude and phase. Using a 2.4 km. Onstation-2 test case, simulation data has been generated that can be used for training as well as testing. Several STNN's have been configured to identify the skip rope magnitude and phase. Twenty and thirty hidden nodes in two different layers have been used, and ten, twenty, and forty zeros for the digital filters have been used between the input and hidden layers. Preliminary results suggest that the STNN may require a long learning time. This is consistent with the

understanding that the coupling between the skip rope and the satellite oscillation is very complex and non-linear. Additional data may need to be generated for training. Data will be generated using tests like retrieval from 20 to 2.4 km., and Onstation-1 segment.

Other problems being considered in the STL are the use of fuzzy robot arm positioning control to relieve the difficulty of solving the inverse kinematics problem, diagnostics systems to help identify faults in a timely manner, Rotary Fluid Management Device pump control to conserve energy aboard the Space Station Freedom, and Station re-boost thrust and fuel management. Projects to study the use of fuzzy logic to conserve energy through efficient control of heating, ventilation, and air conditioning systems will be started this next year. These types of applications will be beneficial to many industrial operations.

#### 4. COMMERCIAL APPLICATIONS OF FUZZY LOGIC

Applications described in this section are primarily based on information received from Dr. Masaki Togai of Togai InfraLogic in his presentation at a workshop in Nov. 1990 [31].

The fuzzy autofocus system developed by Cannon and Togai InfraLogic and the image stabilization system for the Panasonic video camera recorder have been successfully implemented into their respective products. The objectives of the autofocus were to improve the quality of focus and reduce the focusing time. The technique is based on generating the approximate measure of sharpness and utilizing it in connection with the motor speed using fuzzy rules. There are 13 simple rules such as "If the sharpness is high and its differential is low then the focus motor speed is low". Results were very satisfying. The quality of focus was improved in terms of sharpness, the focusing time was reduced by 20 %, and the hunting was reduced resulting in power savings and motor wear and tear. The fuzzy logic based code is smaller in size than standard focusing systems and execution time is less. The Panasonic image stabilization system successfully eliminates unwanted movement in video recordings such as that caused by the camera being bumped or bouncing caused by unstable platforms such as would result if one were filming from a moving vehicle.

The concept and first design for the Mitsubishi Heavy Air Conditioner system was conceived in April 1988. The fuzzy inverter air conditioner system is based on 50 fuzzy rules and uses the max-product inferencing method and centroid defuzzification method. A temperature sensor provides the measurement and commands are generated for the inverter, compressor valve and fan motor in terms of inverter frequency, compressor pressure and fan speed. Simulation was completed by the summer of 1988 and production began in October 1989. The results are very encouraging. Room heating and cooling times were reduced to one-fifth, temperature stability increased by a factor of 2, there was an overall power savings of 24%, and a reduced number of sensors was required for the entire operation of system.

The objective of the Nissan Automotive Transmission application was to provide a "smoother ride", reduce wear on the transmission and provide a more "human" like shifting pattern. This fuzzy transmission controller utilizing a rule base replaces conventional control in one of Nissan's models. Testing and evaluation is not complete but initial results show a distinct reduction in the frequency of shift in a varied terrain.

Developed by Bunji Kaneko, manager of systems development at Yamaichi Securities, and Michio Sugeno, professor at Tokyo Institute of Technology, the Yamaichi Fuzzy Fund is a premiere application for trading systems. It handles 65 industries and a majority of the stocks listed on Nikkei Dow and consists of approximately 800 fuzzy rules. Rules for the system are determined by a committee that meets monthly. Additional changes are made by senior analysts as deemed necessary. The three major categories of rules are Macro rules, Micro rules and Industrial rules. The system was tested for two years, and its performance exceeds the Nikkei Average by over 20 %. While in testing, the system recommended "sell" 18 days before Black Monday. Analysts will agree that the rules for trading are all "fuzzy".

#### 5. SUMMARY

Fuzzy logic is simple, easy to understand and reflects human type thinking. Its architecture is very well suited for implementing heuristic knowledge or the knowledge gained through experience. For example, control of a processing plant typically performed by human operator can be easily automated using this framework in software. Several applications have shown that the fuzzy logic based control is usually robust, non-linear and comparatively stable. It



provides an ability to combine seemingly non-related parameters for higher order reasoning. Control of systems that are non-linear and difficult to model is easily achieved using fuzzy logic principles.

Hardware and Software tools are now available such that systems can be implemented from concept to software simulation and then to hardware prototype in a very short time. Tools like the TIL-shell [32] and fuzzy-C compilers [33] provide capabilities to enter the fuzzy algorithms in graphical forms and generate error free source code for simulation as well as hardware chip. In our experience, fuzzy controllers can be easily designed using heuristics and experiential knowledge. Tuning of membership functions and modifications to the rule base is also simplified at a point where rapid implementation and testing is possible. Maintenance of the algorithms is minimal. Since the algorithms are in a graphical form, the knowledge transfer from one generation to another generation is very easy. Applications like Cannon Auto-focusing Systems have shown that the fuzzy algorithms require small memory and process the data in faster in comparison with other algorithms.

In U.S., the word "fuzzy" has a bad connotation, and therefore, the industry is afraid that if their appliances are based on fuzzy logic, nobody will buy or use them. The market share will be lost resulting in less profit. Even though fuzzy logic is based on the well defined notion of a fuzzy set, confusion still exists because the word "fuzzy" does not seem to fit with words like logic or focusing. Since fuzzy logic allows modelling of human like thinking, control of processes begin to look very easy, and thus the engineers feel that since much of the complexity is lost something of importance must be missing. However, it should be emphasized that to build fuzzy control systems that work efficiently a through engineering understanding of the problem is required. The advantage is that very complex and ill-defined plants do not need to be modeled. It is true that for fuzzy control criteria such as stability, controllability and observability are not yet clearly defined. Work in this field is in progress and the community expects new results in a short time. Control criterion such as the Lyapunov criterion have been developed for fuzzy control and have been applied to aircraft systems. The utility of such criteria is being investigated for other applications and decision making processes.

Based on the many successes of this technology, for the most part by the Japanese, it appears to be about time to exploit this field for decision making and expert system applications and enjoy advantages offered by this logic and its architecture for efficiency, and cost savings. In space operations, autonomy at a higher level will be easier to achieve using this technology and the result will be a major contribution to cost effective operational efficiency.

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