A Fuzzy Rule Based Docking Procedure for Autonomous Underwater Vehicles

G.J.S. Rae, S.M. Smith
Advanced Marine Systems Group
Department of Ocean Engineering
Florida Atlantic University
Boca Raton
Fl 33431
(407) 367-3804
e-mail : graeme@transquest.oe.fau.edu

Abstract - A fuzzy logic control system is described which allows an Autonomous Underwater Vehicle (AUV) to safely dock with another underwater vehicle The fuzzy logic controller's rulebase recursively drives the docking vehicle towards intermediate fuzzy targets that will put the vehicle in a increasingly better position from which docking is increasingly more achievable . The initial rule base was created from trial runs performed by human operators driving a highly accurate simulation of the docking vehicle behavior.
A six degree of freedom non-linear model of the Ocean Voyager dynamics is used to test the performance of an AUV under fuzzy control. The imaginary docking collar is fixed to a simple, stationary model of a 688 Los Angeles Class submarine. Docking is then attempted from any position around the submarine.

Keywords - AUV, Docking, Fuzzy Goal Seeking, Cell Mapping, Non-Linear Simulation

INTRODUCTION

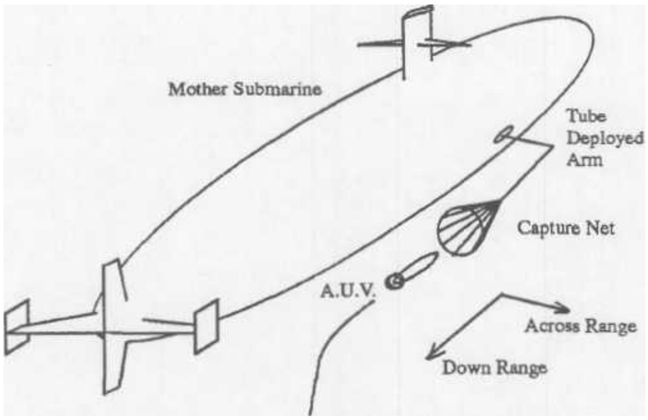
The increasing interest in AUVs with longer mission durations makes appealing the concept of vehicles docking to a submerged 'hitching post' and either resting , refueling or transferring data [13]. The concept of covertly deploying and recovering an A UV from a submarine also has great appeal [151. In this manner, the AUV can be carried to site inside the mother submarine, launched to carry out a mission, and unlike a regular torpedo (the original AUV), return to its launch tube for further missions. One such mission might be the deployment of remote sensor arrays in shallow water. The availability of torpedos that can return home after an unsuccessful mission would mean a significant increase in the effective payload (i. e. the payload that is successfully used) carried by the submarine. Decoy torpedos can also be launched and recovered when the threat has been successfully countered. This will negate the problem of excessive cost of this type of system currently available.

The problem to be addressed here is the algorithm required to autonomously dock a submarine in a confined space. One boundary being a wall or another vehicle, the lower boundary being the sea bed. This arrangement is shown in figure 1. It is assumed that the vehicle has an accurate position sensing ability relative to the ring. No assumptions are made about the presence, strength or direction of currents.

The problem is, in many ways, similar to the problem of parking a robot car [2,12]. A problem that has been solved successfully using fuzzy methods. It was felt that the most suitable solution for our problem would also be a fuzzy algorithm [4,14].
In other similar problems, path planners have computed the entire trajectory for the docking maneuver. This would require very accurate information about the dynamics of the AUV, and the present environment. Information that is largely unavailable. The fuzzy goal approach, does not rely on specific waypoints, orhigh accuracy maneuvers. Target points change as the vehicle moves, two or more goal cells can combine to produce a goal somewhere 'in between'. Accuracy also changes as the vehicle approaches the target. At long ranges the vehicle can be way off course, but as long as it remains within the funnel it *will* dock. The required accuracy increases as thevehiclenears the target.

GENERAL APPROACH

The approach to be used is a goal based fuzzy algorithm. This method allows the vehicle to recursively aim for a target closer and closer to the final docking ring. Theoretically, once the vehicle has found its way to its first goal it should always manage to dock. However, the presence of uncertainties in position sensing and a current, means this may not always be the case. The fact that the algorithm is recursive should deal with



Figural: General layout of the problem

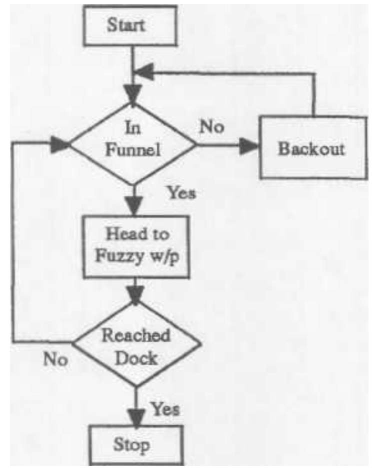


Figure 2 : Flow Chart of Solution

this problem, as the goals are constantly redefined and the ability of the vehicle to successfully complete docking is re-assessed.

There are three distinct problems to be solved

1) Determining if docking is directly possible from the initial location

2) Maneuvering to a position from which docking can be achieved

3) The final docking procedure.

While all these procedures are being carried out, a watch dog set of rules will be preventing the vehicle from colliding with the sea floor or the other vehicle.

INITIAL DOCKING PROCEDURE

Docking can be achieved from anywhere within a 'funnel' around the target ring, depending on the initial orientation of the AUV This funnel is delimited by the minimum turning radius and climb/dive abilities of the AUV The funnel configuration and its derivation is discussed later.

With reference to Figure 1, 'Down Range' refers to the horizontal distance to the docking collar measured along the major axis of the mother submarine, positive heading aft. 'Across Range' refers to the horizontal distance to the docking collar, measured perpendicular to downrange. 'Range is the 'line-of-sight' distance to the collar, also measured in the horizontal plane.

The initial test to check if docking is possible is fairly simple and is as follows

If the vehicle is within the defined funnel initially then it is simply a matter proceeding with the docking routine.

If the vehicle is not in the defined region (i.e. down range or across range are larger than 'very big') then it is assumed that enough maneuvering room exists. A goal for all the positions not defined in the space is the same as the backout target, (some point well downrange and acrossrange from the mother submarine.) If the AUV finds itself on the wrong side or ahead of the target, the first rule to be followed is the 'backout'command. This ensures that the AUV will maneuver to a position from which docking is achievable. On approach from either of these positions, the AUV will avoid the mother submarine using a simple two--whisker obstacle avoidance sonar.

MANEUVERING TO DOCKING POSITION

The general flowchart is shown in figure 2 Successful docking requires that the speed, depth, position and orientation of the vehicle are all driven to the final goal state. The orientation of the vehicle is left uncontrolled. It is felt that the explicit control of the position of the AUV should also implicitly accomplish orientation control, as each successfully reached fuzzy waypoint ensures that the vehicle orientation is also driven towards the goal state.

Speed Control

The speed of the vehicle is governed directly by the range to the docking ring, i.e. the further away from the ring, the faster the vehicle can travel. The only exception to this is when the vehicle is close to the wall or floor, in this case the speed is set to 'slow' in order to minimize damage in the event of a collision.

One of the major problems in controlling a vehicle such as the Ocean Voyager is the very sluggish response it has to speed commands. This is due to its extremely large inertia, a low power motor, and no reverse thrust capability. For example coasting to a slow crawl (say 0.2 Kts) takes around 600 feet from 3 kts and up to 950 feet from 10 kts. As the turning ability of the AUV is a function of forward speed, the algorithm must ensure that the AUV has the correct 'head-on' orientation at a considerable distance from the docking point. This is because the vehicle will lose the ability to turn as it approaches the target and slows down. This required orientation. is provided by ensuring that each subsequent fuzzy waypoint provided by the algorithm is well within the maneuvering ability of the AUV at its present speed, and that each fuzzy waypoint drives the orientation of the vehicle towards the goal orientation (i.e. head-on into the dock).

A set of fuzzy rules are specified to determine vehicle speed, depending on the various ranges, these are

If the range is large and distance to wall/floor is not close then the speed is large
If the range is medium and distance to wall/floor is not close then speed is medium
If the range is small and distance to wall/floor is not close then the speed is small
If the distance to the wall/floor is close then the speed is small.

The precise definitions of these variables are shown in figure 12. In fact the rules do not govern the speed of the vehicle, but the *requested RPM.* A full speed controller is not available, as the AUV currently under consideration has no reverse thrust capabilities and is, therefore, unable to brake.

Position Control.

A set of goals for each of the position cells is shown in figure 4. Once the AUV is in one of these cells and able to achieve the next, docking should be completed. The only case where this may fail (and intentionally so) is near the left hand wall. Here the goals are intentionally set to drive the AUV towards a'backout' cell. This is to minimize the possibility of a collision. As no other cell designates these wall cells as a target, the only time the vehicle should enter these cells is if it pushed there by a current or pulled there by the suction force of a moving submarine. If this were to happen, the avoidance of a collision is far more important than achieving docking. The reason the wall cells drive the vehicle to a another cell which contains a backout command rather than initiate a backout maneuver themselves is to ensure the vehicle is in a better orientation from which to initiate a backout. Once a backout maneuver has been initiated, it cannot be stopped, even if the AUV enters a cell from where docking is achievable. This is to ensure that the AUV will not get trapped in a situation where it is alternately backing out and docking.

Fuzzy Variable Definitions for Position

The definitions of these variables are described in full in figure 10. The minimum turning radius of the AUV is approximately 75 feet and that the docking ring is 30 feet from the centerline of the Target Submarine. After examining the results of trial runs carried out by human operators the fuzzy goal cell definitions were generated. These are summarized in tables 1 and 2.

TABLE 1
Down Range Position Definitions

Negative	*< Oft*
Zero	*< ±2200ft*
Very *small*	*< 200ft*
Small	*100 ->300ft*
Medium	*100 - 500ft*
Big	*450 -4 800ft*
Very *Big*	*>600ft*

TABLE 2
Across Range Position Definitions

Negative big	*-30 -a -22 ft*
Negative medium	*-22 -a -7 ft*
Negative small	*-15->Oft*
zero	*-7 -4+7ft*
Positive small	*0 - -90ft*
Positive medium	*40 -4 160ft*
Positive big	*> 120 ft*

Depth Control

Depth Control is handled in much the same way as heading control. The arrangement of the cells for depth control are shown in figure 5. Each range cell has a defmed and achievable goal depth. Once the vehicle is within the depth funnel, achieving the correct docking depth should be assured. In this case the range is the absolute range to the target, measured along the direct path from the present position of the AUV to the docking collar.

Definitions of these fuzzy variables is based on the performance of the AUV For example a 20 feet depth change can be achieved in 70 feet down. range with the application of a 10s stemplane signal of +10°, followed by a 10s signal of -10°. A suitable set of definitions are shown in tables 3 and 4.

TABLE 3
Range Position Definitions (Azimuth)

Very Small	< 1253
Small	0 -+ 250ft
Medium	125 -4 500ft
Big	250 -> 750ft
Very Big	> 500 ft

TABLE 4
Depth Error Definitions

Negative big	-30 -+-15 ft
Negative medium	-25 - -12 ft
Negative small	-15--0ft
zero	-5 -a +5ft
Positive small	0 -4+15ft
Positive medium	+12 - +25ft
Positive big	> +15 ft

These variables are more accurately described in figure 12. The range allowed for depth control is quite large, even though the vehicle responds well to depth commands. This is due to the loss of depth control at low speeds. An updated depth controller is currently under development at FAU that will lessen this problem [1].

FINAL APPROACH

The algorithm attempts to drive the vehicle to a point just in front of the docking ring. From this point the vehicle must coast, unpowered, with diminished heading control to the final target.

OBSTACLE AVOIDANCE AND BACKING OUT

Assuming the vehicle has successfully entered the funnel, then obstacle avoidance is an inherent part of the goal seeking algorithms. Obstacle avoidance is handled by another part of the Navigation and path planning software. It is a simple two whisker reactive system, with no memory. The response to problems with the approach to target is handled by the 'backout' procedure.

If, during the approach , the vehicle finds itself in a situation from which it cannot directly reach the next target and hence the docking ring, it must perform a backing out maneuver. This is carried out in two steps, the first is to determine if there is sufficient room to turn around and if not, to maneuver until there is. The second rule is to reach a distant objective from which docking is known to be achievable.

This backout point must be somewhere from where it can be guaranteed that the AUV will be able to achieve the goal for that cell, irrespective of the orientation or depth at that time. This is presently set to be downrange: very big, across range: positive big.

IMPLEMENTATION

The algorithm was tested by performing docking runs using the 6 degree of Freedom Non-Linear Simulation developed at FAU [9].The Simulation accurately models the behavior of a real vehicle. The fuzzy rules were generated using Rockwells 'InControl' Software. The generated waypoints were passed to a navigation program which monitored the AUVs position and updated targets based on the present location. Flight Control for the vehicle is provided by a Fuzzy Logic Controller [1,11]. A 3D real-time graphical output of the path of the Vehicle was created using the 'Hoops' graphical interface package.

RESULTS

The results of several simulated docking runs are shown in figures 6 through 11. It can be seen that the AUV successfully navigates to aposition off the starboard quarter of the target. (the 'backout' point) It then approaches the target, decreasing its speed as the ranges to the wall and floor decrease. This speed change is shown in figure 3 below.

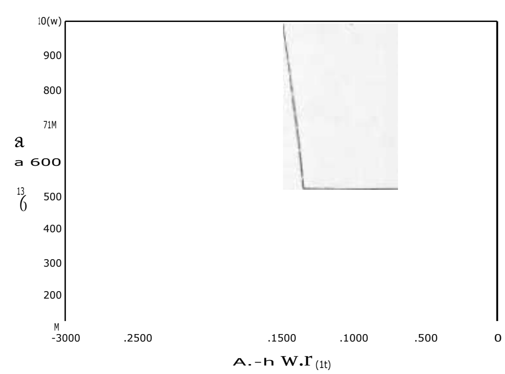


Figure 3 : Speed Decrease as AUV approaches target

The first four examples (figures 6,7,8 & 9) show the AUV approaching the target from each of the four quadrants. The last

0

two images (figures 9 & 10) are snapshots of 3D views to show the AUV achieving the goal depth.

CONCLUSIONS

The application of a goal based fuzzy algorithm for docking an AUV seems extremely promising. Once in the funnel docking should be fast and predictable. This is shown from thew examples, the final approach (the last 100 ft) follow almost identical trajectories. Problems may occur due to the speed control situation, and further investigation into the ability of the vehicle to operate while under reverse thrust, and even in reverse motion is needed.

Initial tests driving the AUV into the docking ring defined in the simulation indicate that the down range scales may have to be tweaked in order to remove the 'wiggle' present in most approaches caused by some roughness in the fuzzy variable definitions. These modifications are not necessary, but may prove useful if no speed control is available in the final vehicle implementation. Across range maneuvering seems simple, with very few control actions required. Depth control is covered well by the defined fuzzy bands. The Quick response of the AUV to depth commands,and almost no overshoot, aids this maneuvering considerably.
Convergence to the dock can be assumed, if no external factors such as current or suction forces act on the vehicle, as every starting cell will eventually map into the dock.

Although the system presented works extremely well for the examples shown, several problems still remain to be addressed. These include

1) Changing the target to *a moving* submarine
This should improve the algorithm, as the AUV will have better heading control due to the higher docking speeds possible.

2) Modelling currents, hull suction effects and other sources of uncertainty in the approach.

3) Simulating docking with the mother submarine at different headings. This was aproblem with the graphical simulation, not by any shortcomings in the docking algorithm.

4)Backout initiation if vehicle speed is too high. At present, the cell sizes are all large enough that speed commands always reach the goal speed for that cell. If the target is moving, this may not be the case.

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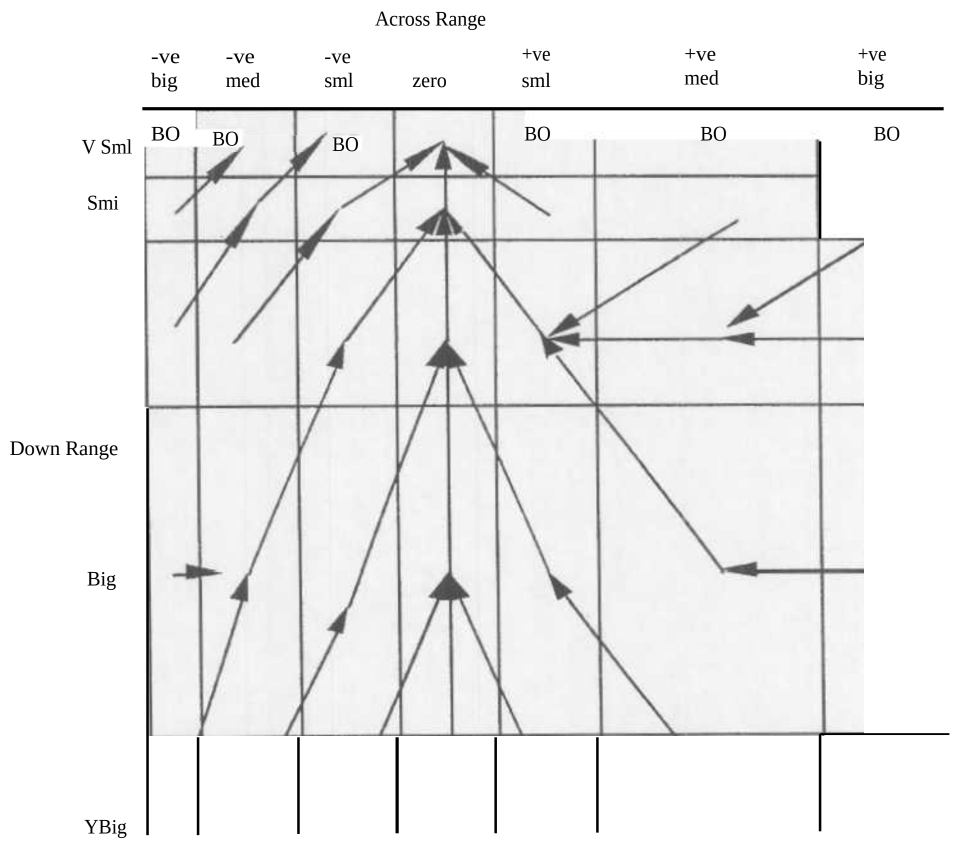

Figure 4 : Goal Cells for Position Control

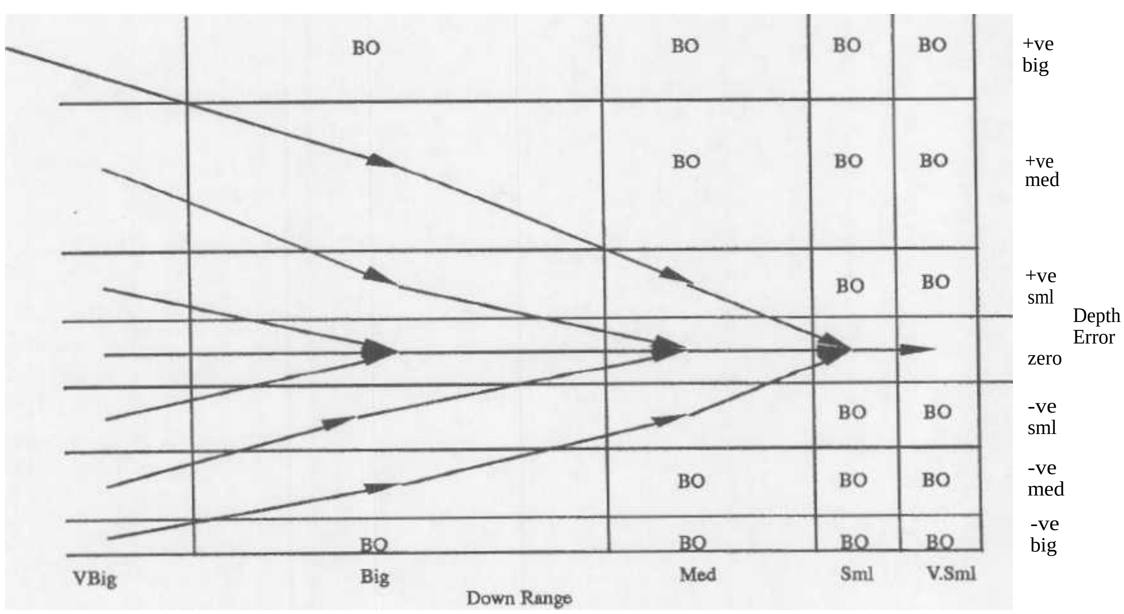

Figure 5 : Goal Cells for Depth Control

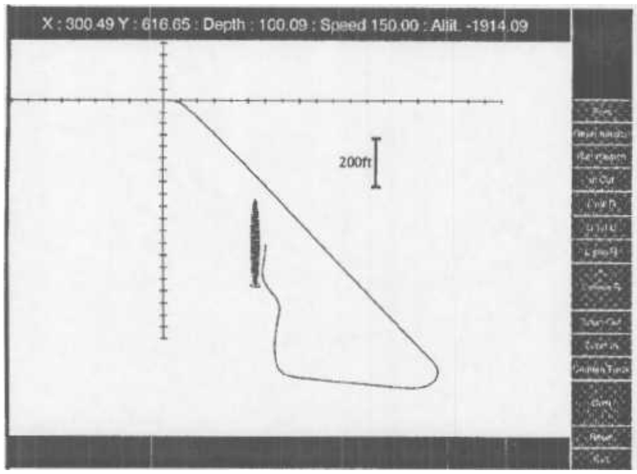

Figure 6 : Docking in Quadrant 1

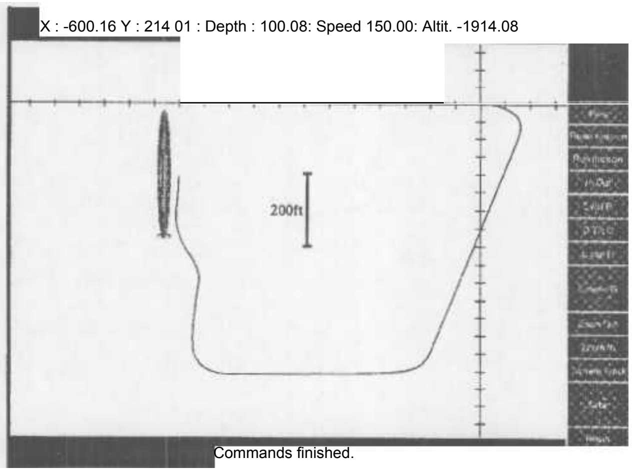

Figure 7 : Docking in Quadrant 2

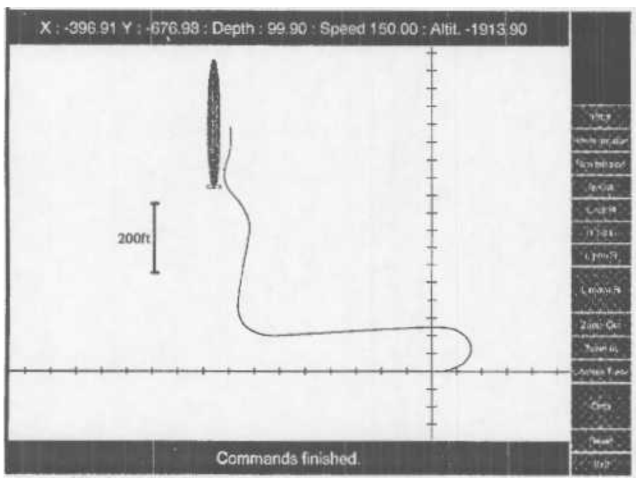

Figure 8 : Docking in Quadrant 3

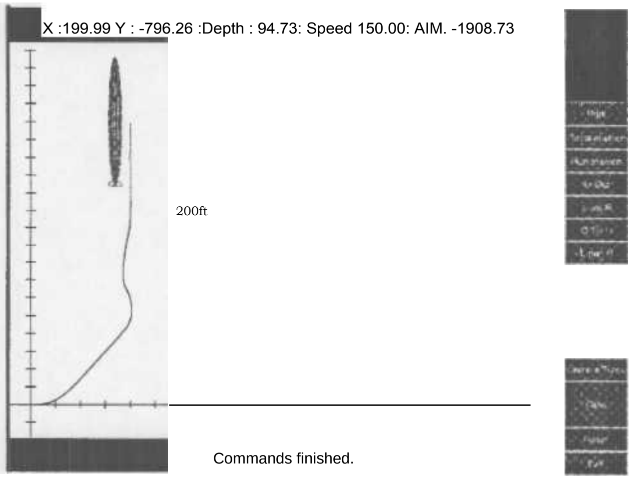

Figure 9 : Docking in Quadrant 4

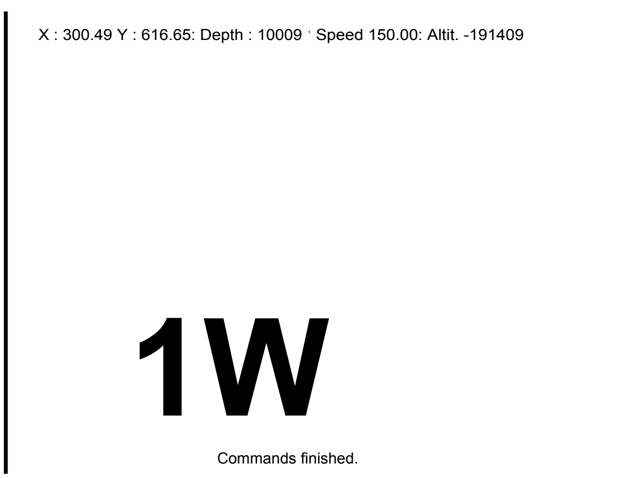

Figure 10: 3D View of Docking in Quadrant 2

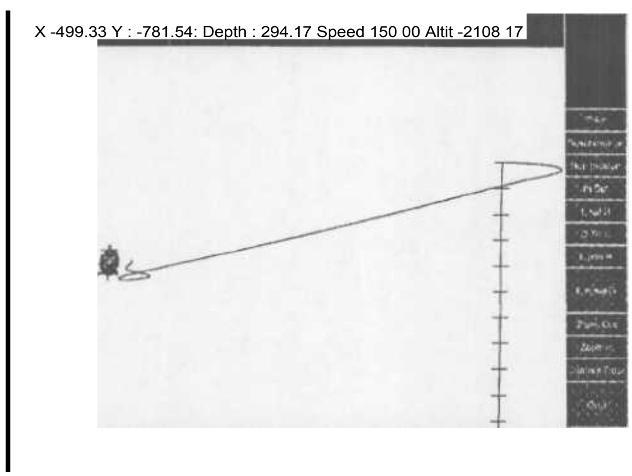

Figure 11 :3D View of Docking in Quadrant 2

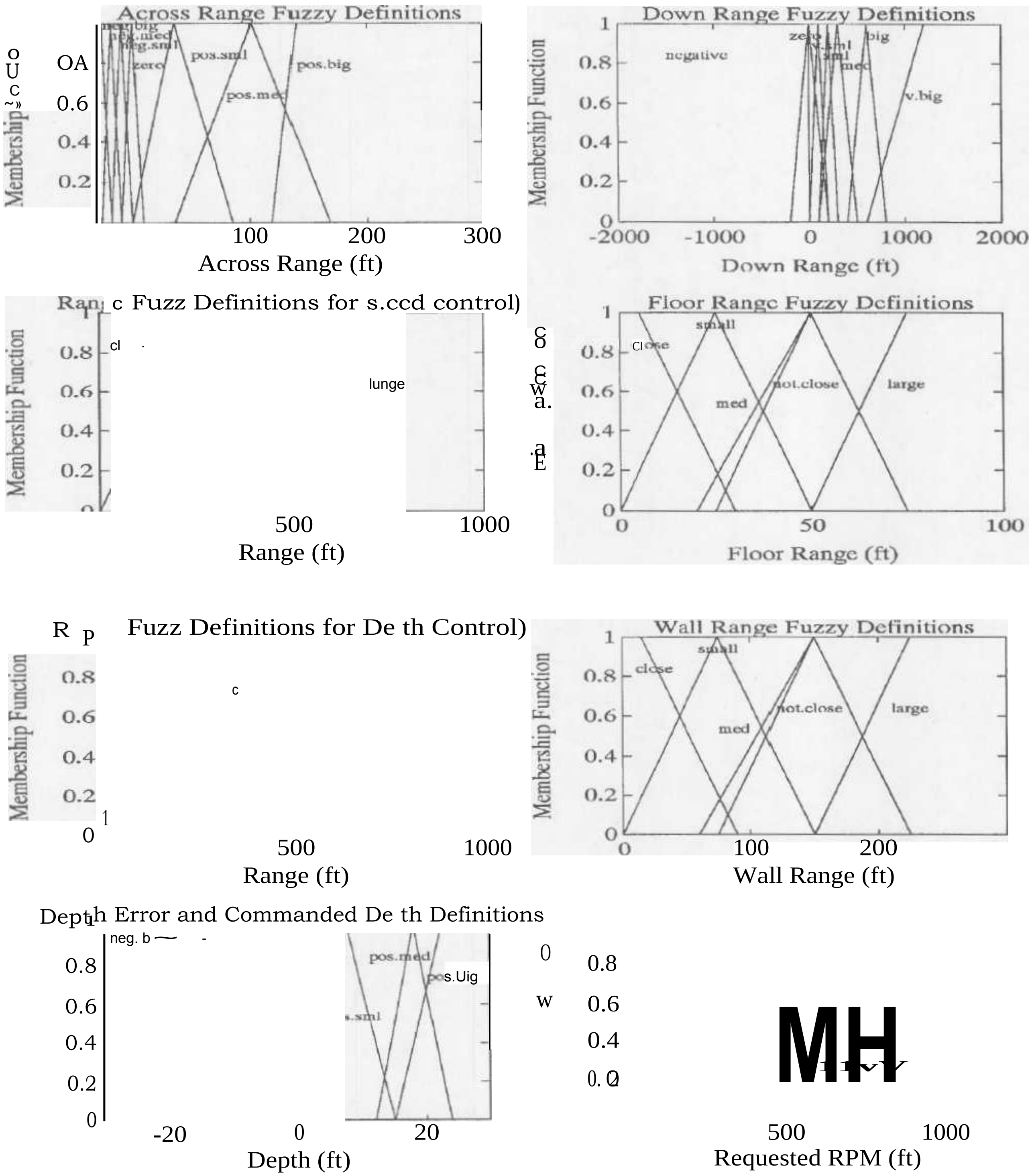

Figure 11: Fuzzy Variable Definitions