Performance Results of a Fuzzy Behavioral Altitude Flight Controller and Rendezvous & Docking of an Autonomous Underwater Vehicles with Fuzzy Control

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ABSTRACT

This paper describes the performance of the Fuzzy Behavioral Decision Based Controller (FBDC) approach used to control the bottom altitude flight controller of the Ocean Voyager II (OVII) and Ocean Explorer (OEX) AUVs. This paper also describes the approach planned for implementing rendezvous and docking capability on the OEXs. This approach is based on an inexpensive short base-line navigation system and a fuzzy docking controller.

Keywords: - Autonomous Underwater Vehicles, AUV, Bottom Altitude Control, rendezvous and Docking, Fuzzy Control, Fuzzy Behavioral Decision Controller, Fuzzy Waypoints.

INTRODUCTION

The Ocean Voyager II (OVII) and Ocean Explorer (OEX) AUVs are tasked with a variety of 3D water column and near bottom coastal search and survey tasks for various sensor system payloads. Of particular importance are the Bottom Classification Albedo Package (BCAP) developed at USF for calibration of satellite spectrometry and the Chirp Side-scan Sub-bottom (CSSB) sonar developed at FAU for surface and sub-bottom profiling [1,2]. Both payloads require that the AUV maintain level flight at a constant altitude over the bottom to achieve accurate measurements. In addition, the AUV must maintain a minimum safe distance above the bottom to avoid collision with rocks, reefs, and other obstacles. Even in missions where the AUV tracks depth, an altitude follower is needed prevent collision with the sea floor when the commanded depth is greater than the water columns height. Because the AUVs are optimized for long range surveys they use a minimum of control effectors. Depth/Altitude control is achieved by controlling the pitch of the vehicle with a stern plane. Hence, when the bottom is not flat, level flight, constant altitude, and bottom avoidance may be conflicting objectives. Therefore, a mission's success requires the simultaneous satisfaction of multiple criteria; the ability to keep the vehicle safe while ensuring quality data recording. The primary sensor used for altitude tracking is a downward looking sonar. This provides accurate altitude data but no preview of the oncoming sea floor topology. Because of the need for the altitude controller to satisfy multiple competing objectives with little or no preview, a reactive fuzzy behavioral architecture was selected as a promising approach to solving the problem. Fuzzy decision making provides a formalism for interpolative reasoning and the simultaneous satisfaction of multiple constraints.

In our approach, the two main tasks of safety and data recording are broken down into five behaviors: abort mission, avoid bottom, track bottom, stabilize platform, and maintain current behavior. Each of these behaviors output a desired pitch angle and speed that best satisfies that behavior's objective. A supervisor assigns weights to the various outputs based on the current state of the current vehicle and environment. A fuzzy aggregation operator is used to combine the outputs of the different behaviors using a weighted average that results in a final control pitch and speed. The primary advantage of this approach is the interpolative nature of the fuzzy combination of behaviors. The fuzzy combination ensures smooth transitions between behaviors that prevents chattering or persistence. We call this hybrid approach a Fuzzy Behavioral Decision Controller (FBDC).

The controllers within each of the behaviors as well as the supervisor are expressed as fuzzy rules. Conventional controllers could have been used for some of the behaviors but fuzzy controllers were used primarily bccause an accurate analytical model of vehicle was not available. Moreover the combination of controllers could be viewed as a non-linear multi-constraint optimal control problem. Finding a solution to this type of problem is difficult with a good model and problematic without one. Instead we chose to use a combination of qualitative information, experimental data, along with computer simulation based on an approximate model to determine the fuzzy control rules. Based on our past experience, a "model-free" approach that relies on the robust non-linear nature of the fuzzy controllers can be successful.

Algorithm

There are two main tasks associated with the USF ground - truthing mission: *Vehicle Safety Task* and *Data Recording Task*.

There could be others such as way point navigation, mine hunting, docking, etc. each having their own set of subtasks. For the purposes of testing the controller, only the above two were used. The FBDC determines the commanded pitch and forward water speed needed to satisfy mission constraints on vehicle altitude and motion. The commanded pitch ad speed are then input as references to the pitch and water speed controllers.

Vehicle. Safety Task - The vehicle safety task is comprised of two subtasks: Abort Mode and Bottom Avoidance Mode.

The Abort Mode is a fail safe behavior that ensures the safety of the vehicle in a no-win situation. It has two outputs: a range of pitches that will steer the AUV to the surface and a range of speeds. The speed ranges are based on maximum stopping distance if the motor was to be shut off, given the altitude. The idea is that the vehicle should be moving with as little momentum as possible if a collision is eminent.

The Bottom Avoidance Mode, however, assumes that a collision can be avoided. It has the same two outputs as the Abort Mode. The pitch ranges also tend to steer away from the bottom but not necessarily at the maximum pitch angle. The speed range is based on the controllability of the vehicle. The OVII is most controllable between 3 and 4 knots. However, the vehicle can be controlled somewhat below 2 knots, and not at all for speeds under I knot.

Data Recording Task - The Data Recording Task is much more complicated. It involves three subtasks: Bottom Following Mode, Stable Platform Mode, and No Operation Mode.

Bottom Following Mode is based on the constraint imposed by the fact that the illuminated strength of the lights for camera recording on the BCAP payload has a maximum range of around 5 meters. While the minimum height desired for safety reasons is 3 meters. This controller, therefore, outputs a range of control pitches to keep the vehicle in the 3 to 5 meter range.

Stable Platform Mode is based on the requirement that the recorded image from the camera is allowed to only have a single pixel blur. Equations were derived that, based on the AUV's altitude and state, would calculate the maximum speed, pitch rate, roll rate, and yaw rate allowed to stay in the 1 pixel window. Assuming the vehicle is maintaining this criteria, the output of "pitch ranges" is centered about the vehicle's current pitch with limits based on the calculated values. Similarly, the "speed range" is based on those calculations.

The No Operation Mode is active when the vehicle motion satisfies all the other constraints and hence little adjustment is needed. The outputs of the subtask are small ranges centered about each of the current state values of the AUV

Figure 1 depicts the logical flow chart for the implementation of FBDC in the OVII. The evaluation functions are small fuzzy algorithms that calculate the performance of a given subtask. Using the Safety Evaluation as an example, assume the vehicle is determined to be safe to a degree of 0.8. Therefore, the degree to which the vehicle is less safe is 0.2. These values are then applied to the outputs given by the Tracking Evaluation and Avoidance Evaluation. This method of propagating the gains down leads to the normalization of the outputs.

Decision Aggregator/Arbiter- The aggregation is based on thresholds and criteria. A decision rule base is arranged such that aggregation of the modes is based on a pass / fail system of criteria. i.e. IF criteria "A" is passed as ok then do a weighted average calculation between modes 1,2, and 4, ELSE do the calculation on modes 3 and 4. Although currently the aggregation is based on a weighted average other more complex aggregation methods are possible and will be investigated in the future.

Space restrictions prevent a more detailed description of algorithm. Although one can be found in [3,4].

Prior to the development of the multi-behavior controller a simplistic altitude control based on the existing depth autopilot was used io track altitude. In the simplistic controller, the difference between the desired altitude and the current altitude is added to the current depth thereby producing a depth error for input to the depth controller. Although, this simple controller has been used extensively in at sea runs of the AUVs and tracks the bottom satisfactorily, it does not guarantee satisfaction of the pixel blur constraint.

Graphs of preliminary results of the FBDC controller's performance are shown in the appendix for two at-sea test runs. The primary objective of the first run was to observe how well the controller satisfied the pixel

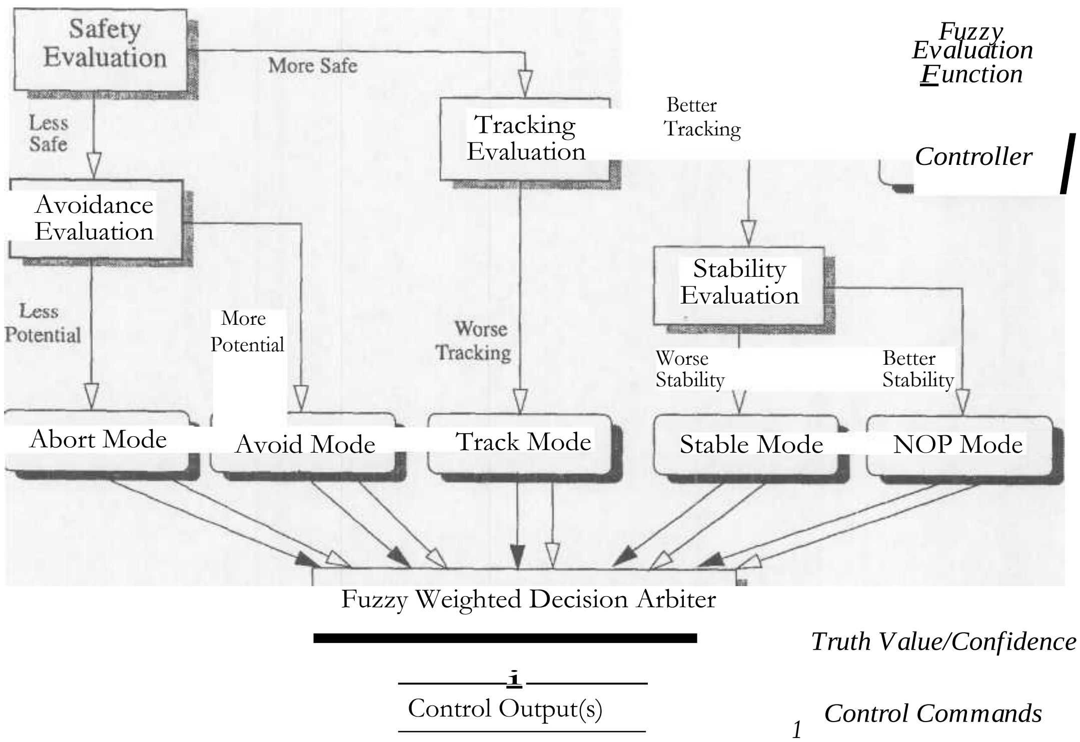


Figure 1: Altitude Controller Behavior Decision Flowchart

blur constraint. Consequently a sandy sloping bottom was chosen. The pixel blur is below 1 throughout the run. In run #2 a slightly more hazardous bottom was chosen with reefs 1-2 ft. high along the bottom. The vehicle ran a "lawnmower" pattern over the reefs. The weights on the evaluation functions were also adjusted to place more importance on tracking. The primary objective in this run was to observe how well the vehicle tracked the bottom without violating the pixel blur and safety constraints. As is shown in the graphs the pitch control is more active than run #1 with slightly more pixel blur (although still close to 1).

FUZZY WAYPOINTS AND DOCKING CONTROL

This section describes the test set up and implementation of a rendezvous and docking approach for the Ocean Explorer series vehicles based on an inexpensive SBL navigation system and a fuzzy docking controller. The docking controller is a special case of a navigation scheme based on fuzzy waypoints A fuzzy waypoint not only defines a location in space but uses fuzzy rules to express a vector flow field of desired trajectories to that waypoint. This approach to waypoint navigation uses the interpolative properties of fuzzy decision making to combine rules for various goals for vehicle behavior into a unified expression of desired vehicle motion.

The fuzzy waypoint rule base expresses a desired trajectory segment for any location relative to the waypoint/trackline. This greatly simplifies the expression of more complex behavior in the vicinity of the waypoint, For example, a fuzzy waypoint can express a preferred approach direction to the waypoint as well as the desired path of the vehicle in the event of a missed waypoint. Furthermore, a nonsymmetric and location dependent response to cross track error along the track between two waypoints may be expressed to account for non-symmetric physical constraints on maneuvering space (such as the sea floor or mid-water objects). By appropriately varying the gradient of trajectory segments as a function of distance and direction to the waypoint and current velocity, the vehicle can automatically assume a varying crab angle in response to currents or be less (more) responsive to disturbances far away (close) from the waypoint. In addition, the outputs of conventional trackline and waypoint homing controllers can be fuzzily integrated into this approach.

The concept of a fuzzy waypoint is a generalization of the fuzzy docking controller idea developed at FAU/FIT in that each waypoint is treated as a "docking target" [5,6,7,8]. Alternatively, (locking can be viewed as just another type of fuzzy waypoint navigation where perhaps the constraints on navigational accuracy are more restrictive. This provides a unified approach and simplified expression. The vector flow field defined by the fuzzy rules is analogous to that produced by the well known potential field approach to robot navigation. However, the fuzzy approach has some notable advantages. Since the trajectory segments are expressed directly as fuzzy rules, local minima do not arise and vehicle maneuvering constraints such as turning radius, predetermined obstacles, etc. can be explicitly handled. The fuzzy rule base also requires less computation than a potential field and the computation does not increase exponentially with the number of obstacles.

Docking Algorithm

The basic approach is a goal based fuzzy algorithm. This method allows the vehicle to recursively aim for a target closer and closer to the final docking target. The set of fuzzy goals defines a docking funnel. Theoretically, once the vehicle has found its way to its first goal it should always manage to dock. The recursive nature of the algorithm compensates for uncertainties in position sensing and current, as the goals are constantly redefined and the ability of the vehicle to successfully complete docking is re-assessed. The fuzzy goal approach does not rely on specific waypoints, or high accuracy maneuvers. Target points change as the vehicle moves, two or more goal cells can combine to produce a goal somewhere 'in between'. Essentially, the fuzzy rules define a vector flow field for vehicle motion. Precision increases as the vehicle approaches the target. At long ranges the vehicle can be way off course, but will eventually dock as long as it remains within the funnel. Successful docking requires that the speed, depth, position and orientation of the vehicle are all driven to the final goal state. The succession of fuzzy goals indirectly control the orientation of the vehicle as it is driven to the target.

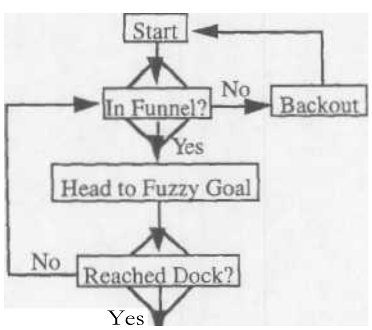


Figure 2: Fuzzy Docking Algorithm.

At each invocation of the docking algorithm the system must determine if the AUV is in a state from which docking is directly possible. Based on that assessment one of two actions is taken [1] Maneuver to a position from which docking can be achieved. [2] Move to the next fuzzy goal. The general flowchart is shown in Figure 2

The docking strategy is to dock reliably with minimal demands on vehicle maneuverability. This is done by defining a funnel shaped region where docking can proceed safely. To insure that the vehicle stays in the funnel, the boundary surrounding the funnel should be "thick" relative to uncertainties in vehicle position and "stiff" relative to vehicle dynamics and environmental disturbances. That is, safe docking will ensue as long as the maximum position errors will not place the vehicle outside the boundary and as the vehicle gets closer to the edge of the funnel, the commanded maneuvers should point, with greater ' thrust, the vehicle more towards the center of the funnel (orthogonal to the boundary) and less towards the target. Thus as the vehicle is pushed nearer the boundary of the funnel, the docking algorithm will direct the vehicle back into the center of the funnel where safe docking can proceed.

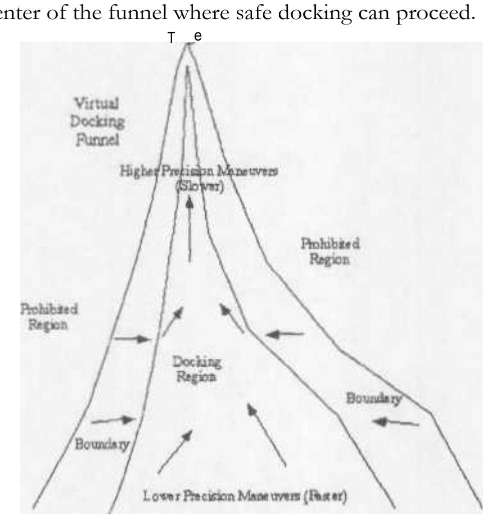


Figure 3: Virtual Docking Funnel.

The shape of the funnel is determined by the minimum turning radius and climb/dive abilities of the AUV. Near the mouth of the funnel, the vehicle is relatively unconstrained and low-precision high-speed maneuvers are allowed. As the vehicle proceeds down the funnel towards the target, increasingly precise maneuvers are required. However, by then the vehicle is more lined-up with the target so only minor adjustments in direction are required. This strategy is illustrated in Figure 3.

After examining the results of trial runs carried out by human operators the fuzzy goal cell definitions were generated. Interestingly, human operators of the docking simulation could rarely achieve successful docking while the computer implementation of the fuzzy algorithm always docked successfully.

Both the extent of the funnel and the desired intermediate goals for any location in the funnel are represented by three sets of fuzzy rules. One set defines the desired XY behavior with rules of the form,

IF x is A and y is B THEN

Goto x is A' and y is B'

where x is down range, y is across range, and A,B,A',I3' are fuzzy sets that define various locations of the AUV relative to the target. Figure 4 is a graphical illustration of the rule base for the XY positioning of the AUV during docking. Each box represents the antecedent of a rule. The arrow leaving each box indicates the consequent goal of that rule.

Similarly, another set of rules defines the XZ docking behavior. The overlap between the antecedents of neighboring rules means that several rules may be partially satisfied for a given state of the vehicle. The automatic interpolative effect of the fuzzy rule combination is to define a smooth set of docking commands that "averages" the goals of neighboring regions. This is in contrast to conventional navigation approaches that rely on discrete way-points.

In a non-fuzzy way-point based approach, the vehicle repeatedly homes in on each subsequent way-point. The commanded heading is a function of the next way-point location and how close the vehicle came to the last way-point. Sharper turning angles are required whenever the AUV misses a way-point. Moreover, if the vehicle gets off course, a "go/no-go" decision must be made between going on to the next waypoint or going back to the previous one. In contrast with fuzzy rules (way-points), neighboring rules influence the commanded heading also.The fuzzy waypoint approach has been tested under simulation with good result. See [5,6,7,8] for detailed descriptions of the results.

Implementation Design for Docking Tests

Currently the approach is being implemented on the Ocean Explorer Series vehicles. The major assumption made by the controller simulation is that the vehicle have reliable information about its position relative to the docking target. Navigation information for the fuzzy docking algorithm will be provided by an inexpensive SBL navigation system from Desert Star called the DiveTrackerTM SBL System.

The specific package we will use is specialized for applications involving ROV's or AUV's (DTI-PD12A). The package consists of a surface station (DTI-DRY), a bare electronics module (DT1-MOD), three 40khz transducers for use as a baseline, two 40khz transducers used on the vehicle, data exchange cables for the dry station to a PC and for the bare module to the vehicle host computer, along with software for both the PC and the bare module.

The accuracy of the system is dependent upon many variables, such as ambient noise, thermoclines, physical objects, and length of baseline. Most factors influencing the accuracy of the system are uncontrollable, however the length of the baseline can be designed to maximize accuracy at a given range. The DiveTrackerTM system has a rated accuracy within +/- 6" depending upon location, range and length of baseline.

The basic arrangement of the DiveTrackerTM system will use a three-transducer baseline array in a triangular pattern. The use of three transducers instead of two as a baseline eliminates the ambiguity as to which side of the baseline the vehicle is operating. The three

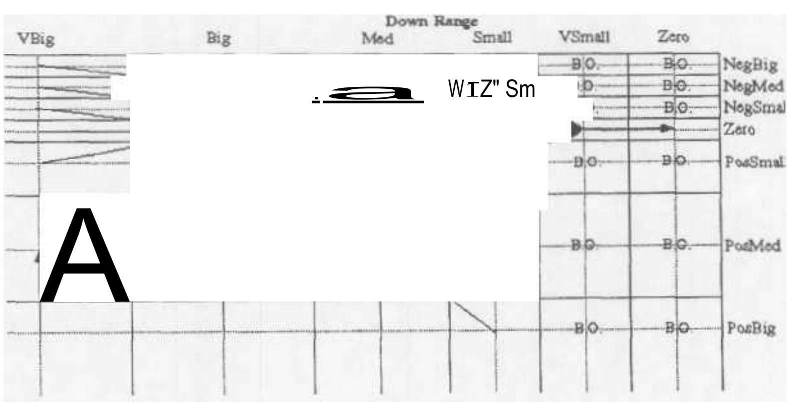


Figure 4: Across/Down Range Rule Grid.

transducers are connected to the surface station which is monitored by a PC as a tracking station. Two transducers will be used on the vehicle, one mounted forward and the other mounted aft. This will ensure that the vehicle orientation with respect to the dock can be determined. The transducer data is processed by the bare module within its pressure vessel and communicated to the host computer over the LonTalk network. The physical layout of the baseline array is designed for a three-phase progression over the duration of the two year project. Each phase will provide more accurate results by employing a more stable and longer platform as a baseline. The following is a detailed description of the layouts for the three phases of the project.

Phase 1: The initial baseline sonar arrangement will be fixed to FAU's research vessel, Oceaneer IV. The transducers will be mounted to the ship using rods and extended into the water as shown in figure 1. This configuration will he used to ensure that the data received is correct and all communications are being carried out properly. Once this format has been established and satisfactory results verified by the Trackpoint in current use, the next phase will begin. A diagram of this arrangement is shown in Figure 5.

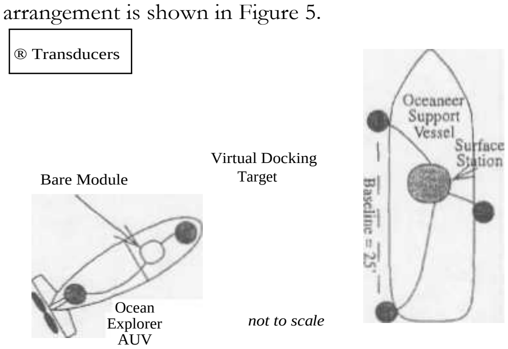


Figure 5: Oceaneer Mounted

Phase 2: This phase will incorporate a ship deployable portable structure to be used as a baseline array. The baseline of this arrangement will be larger than that of the ship to attain better accuracy and will be more stable due to reduced wave interaction. Three poles connected to a locking hinge will form the based of the structure. When opened the poles will form a "T". The structure will be anchored to the bottom and have the transducers upright on adjustable length posts attached to the end of the poles. The arrangement is designed for quick assembly/disassembly under water. Figure 6, shows the phase 2 orientation. Also in this phase, the vehicle will be navigated using the SBL to waypoints defined by the DiveTrackerTM system. Since the orientation of the baseline array will be fixed by the structure, there will be no need to accurately survey the deployment area. Rather, just allow the system to come to rest in an environmentally safe, sandy bottom.

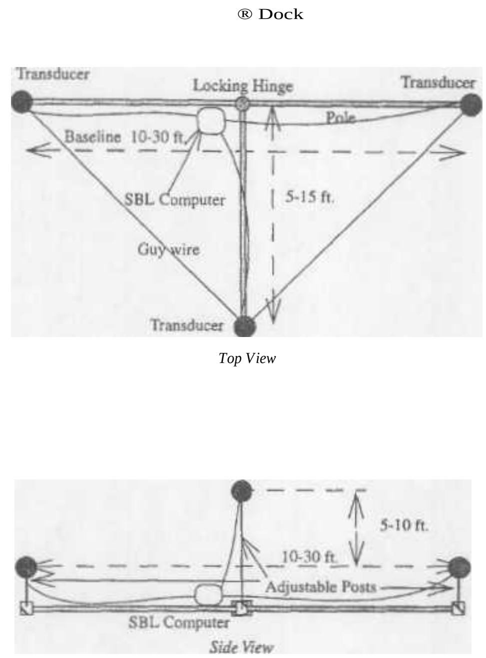


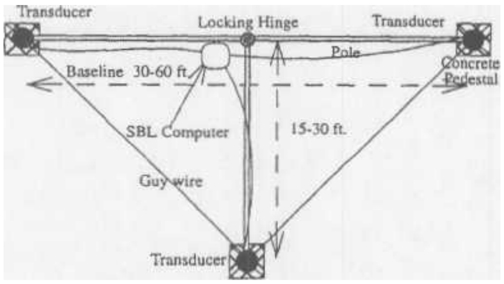
Figure 6: Phase 2 arrangement.

Phase 3: The final phase will use a semi-permanent bottom-mounted arrangement with an even longer baseline. This arrangement is designed for extended operations including inclement weather. Figure 6 shows this semi-permanent system. Phase 3 will also involve a docking structure fixed to the bottom in a known location with respect to the baseline array. This docking structure will then be defined as a waypoint. As in phase 2, the vehicle will be navigated by the DiveTrackerTM SBL to the waypoint. Visual inspection of the proximity of the vehicle to the docking structure by a diver will aid in the tuning of the system.

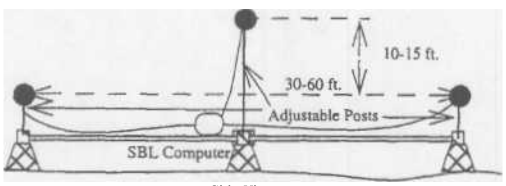
CONCLUSIONS

Preliminary results from at sea trials show the FBDC approach to perform very well. The method enables the satisfaction of various constraints on vehicle behavior to be easily integrated into a control scheme without explicit models of vehicle motion. Successful demonstration of the fuzzy docking approach combined with an inexpensive navigation system should make it possible to extend mission lifetimes for AUVs while reducing the level of human supervision and support.

RS Dock



Trip View



Side View

Figure 7: Phase 3 Arrangement.

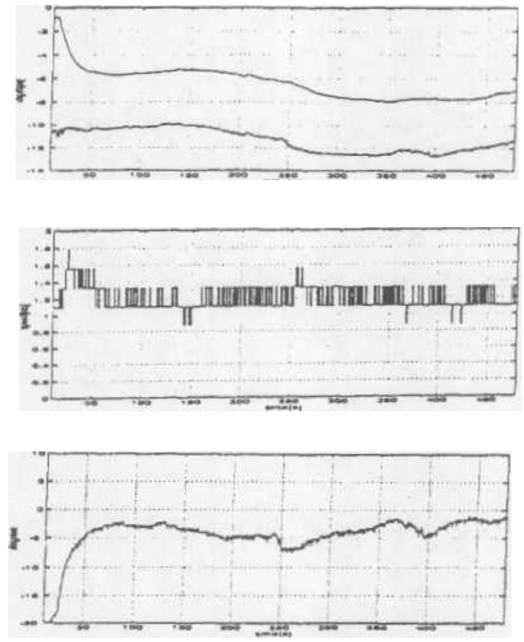


Figure 8: Run #1 (a) altitude (b) speed (c) commanded pitch.

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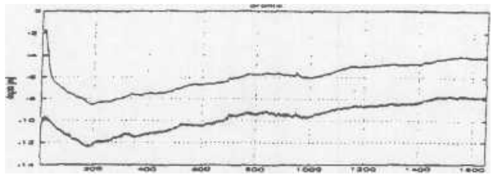

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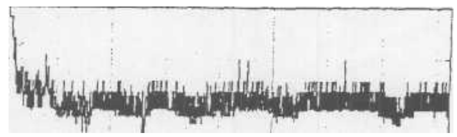

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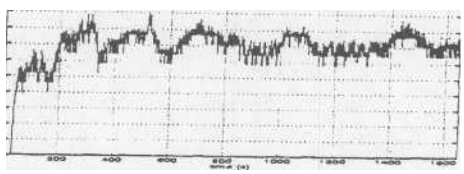

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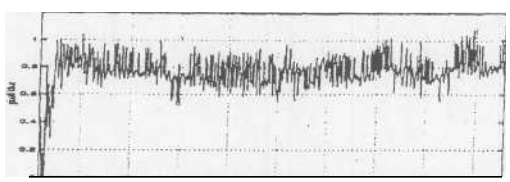
Figure 9: Run #2 (a) altitude (b) speed (c) commanded pitch.



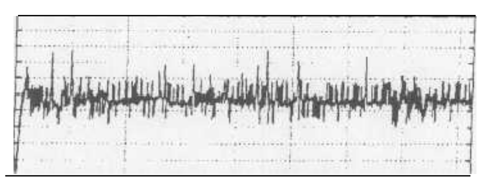


Figure 10: Pixel blur (a) run #1 (b) run #2