A Micro-UUV Testbed for Bio-Inspired Motion Coordination

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The goal of this micro-UUV research is to create a system of underwater vehicles that can interact with little or no human intervention. In nature, these systems are commonly seen, such as schools of fish or flocks of birds. The Collective Dynamics and Control Lab at the University of Maryland (UMD) is constructing an underwater-vehicle system with biologically inspired sensors to test and evaluate motion coordination algorithms. The test facility is the Neutral Buoyancy Research Facility (NBRF) at UMD. We have created a fleet of submarines that interact with their surroundings using a visual-imaging system, which identifies other submarines. The visual sensors feed image data to the autopilot unit, which uses an image-processing algorithm to compute the relative position and orientation. These data are fed into a set of prescribed behaviors to accomplish motion coordination. To verify the results of testing, an external camera system in the NBRF is used to track the submarines. Preliminary results show that using bio-inspired sensors is a viable way to create an underwater system capable of motion coordination.

1. Introduction

A collective of autonomous vehicles capable of coordinated data collection would be a useful addition to underwater research. Such collectives could be used for oceanographic mapping, port monitoring and anti-submarine warfare. Systems like this are commonly seen in nature, such as flocks of starlings or schools of fish. The intricate motion coordination of such systems is a capability that autonomous underwater vehicles have not displayed to date without significant operator intervention.

The Collective Dynamics and Control Lab (CDCL) at the University of Maryland is in the process of creating a motion-coordination tesbed. This system is presently comprised of six autonomous micro-scale (< 1 m) submarines tested at the University of Maryland Neutral Buoyancy Research Facility. The research being conducted at the CDCL is inspired by the idea of biological control, which entails a decentralized control strategy based completely *passive* sensing capabilities. By using a behavior-based control strategy, the CDCL hopes to create a fleet that is capable of autonomous motion coordination.

This paper describes the micro-UUV testbed being developed at the CDCL. Section 2 provides background information, including a description of the submarine fleet hardware and the NBRF. Section 3 gives an overview of the testbed, including the autopilot design, the onboard visual sensing, the image processing algorithms, the planned collision detection sensor array, the behavior-based control, and how the submarines are tracked.

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2. Background

The testbed is composed of two separate parts. First, there is the fleet of six identical submarines. These submarines each have an autopilot unit attached to them in which the control algorithms are computed and relayed to the submarine for execution. The second part is the testing facility, the NBRF, which is a 367,000 gallon underwater environment. Tests are conducted at the NBRF on a regular basis and have given an abundance of experimental data.

2.1 Submarine Hardware

The micro-UUV testbed presently utilizes RC submarine kits purchased from Mike's Sub Works, LLC. Each submarine is a 1/60 scale model of the USS Albacore. It has one 6 volt motor which drives a propeller shaft, and two servos that operate the ailerons and elevators. The kit comes with a two-part, molded plastic pressure hull, rated to six feet. These pressure hulls are replaced with a plastic cylinder with removable end-caps. The kit includes a battery compartment similar to the pressure hull used for the electronics. The electronics included in the kits are a Viper 10 speed controller, a NMH27 battery, and a HITEC Laser4 radio control system. We also use a voltage regulator because the radio receiver required a lower voltage.

To construct the kit, the outer hull is trimmed down to fit. Then the tail cones are assembled with the ailerons and elevators attached. The tail cone is glued to the bottom half of the outer hull. We assemble all of the electronics, fit them inside the pressure hull, and conduct tests to make sure that the pressure hull does not leak. It is then mounted inside the outer hull on pieces of ABS plastic and strapped down with cable ties. The battery hull is tested in the same manner and then attached to the outer hull with Velcro so that it is easily removable. Once everything is strapped down, we submerge the whole assembly and test all of the moving parts. Once we confirm that everything is working properly, we ballast the sub so that it is neutrally buoyant. Tests are conducted in the NBRF, first on a tether to make sure that it does not sink and, finally, untethered.

2.2 Neutral Buoyancy Research Facility

The NBRF is located at the University of Maryland. The facility contains a 50-foot diameter and 25-foot deep water tank that contains 367,000 gallons of clear, filtered water. The CDCL uses the NBRF as a dive tank in which to collect data on the submarines and their interactions.

Since the submarines have minimal data storage capabilities and no means of data transmission, an external, off-board system is used to collect tracking data. The NBRF has six underwater video cameras mounted inside the tank which are used for this purpose. These cameras collect live video imagery that is used to track the 3D position and pose of the submarines.

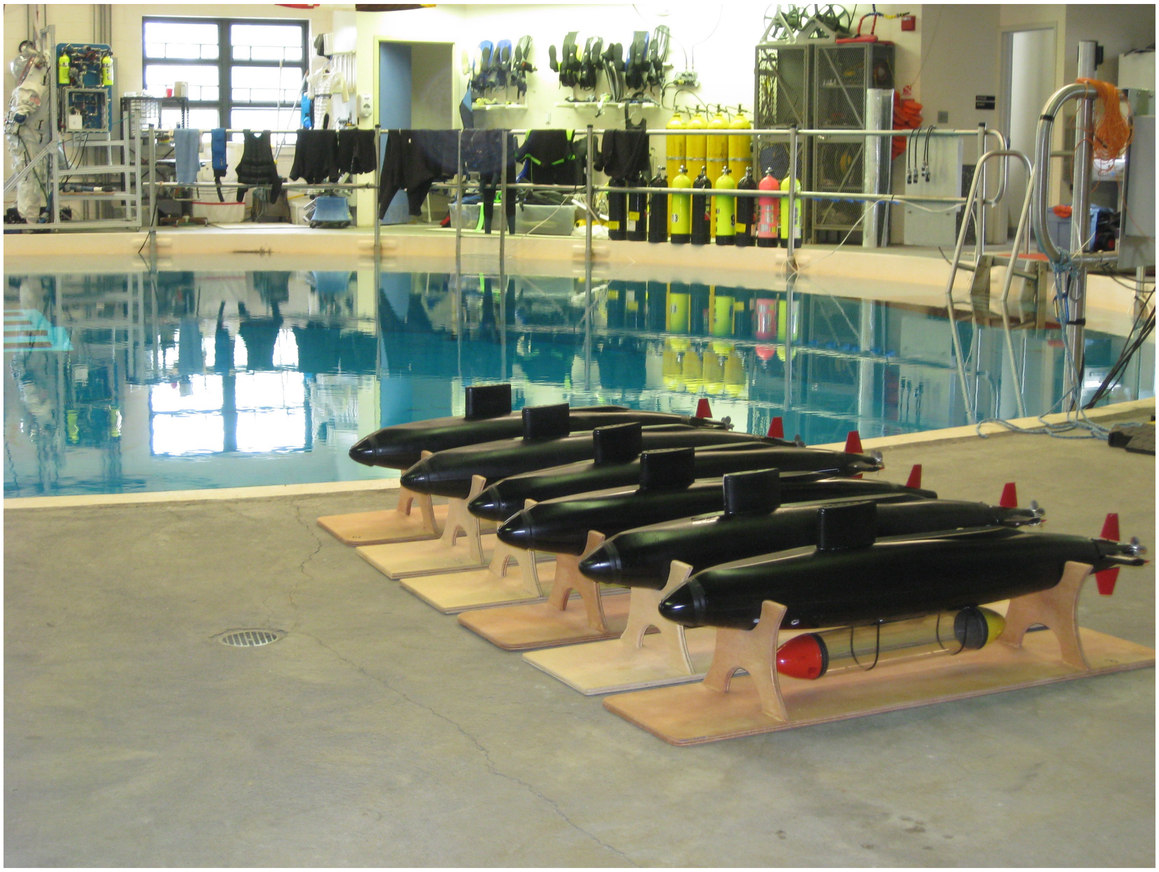

Figure 1. Submarine fleet and the NBRF

3. Testbed Overview

A behavior-based control system is an intricate architecture to put into place. The testbed is designed so that each submarine is completely self-sufficient, except for a shutdown command that can be sent from the shore. The submarines contain a number of sensors to interpret their surroundings. Each submarine has an autopilot unit which contains these sensors. The sensors onboard the submarine include a rate gyroscope and two cameras, which act as the eyes of the submarine. The submarines do not use any form of active communication, such as RF or acoustics, to communicate with one another. Information flows through the submarine network through vision-based motion coordination.

3.1 Autopilot Design

The autopilot module is a capsule designed to provide onboard feedback control to the submarine’s rudder using a wireless signal. The module is positioned underneath each submarine, which allows for minimal modifications to the kits and also ensures a well-established wireless communication link between the components.

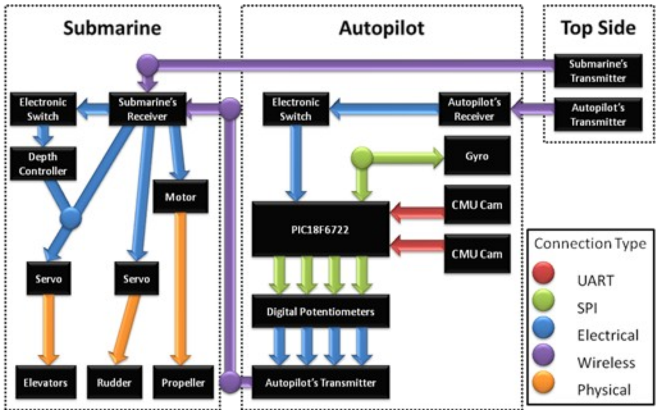

Figure 2: Functional Block Diagram of the Autonomous Rudder Control System.

The module itself consists of the following three subassemblies: the turning rate sensor, vision sensors, and wireless communication system. The turning rate sensor is a one-axis gyroscope mounted perpendicular to the rudder. It is controlled by a PIC microchip through an SPI connection and continually provides a turning rate within ±300 degrees per second. The camera system passes information about other submarines in the vicinity through a UART connection. This information is used to determine a desired course heading. Finally, the wireless system consists of a modified handheld transmitter and four digital potentiometers. The original potentiometers on the transmitter were replaced with digital versions. This substitution allows the microchip to control the channels of the transmitter which, in turn, controls the submarine.

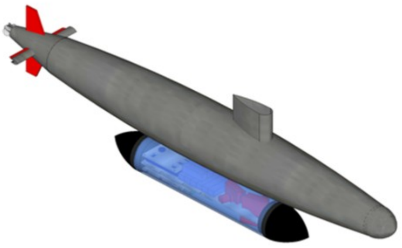

Figure 3: Autopilot System Integration

All three systems are linked together and a PID controller has been implemented onboard the microcontroller. This union effectively allows the module to determine a desired course heading using the camera information, and compares that heading to the actual course heading of the gyroscope. The controller then drives this difference to zero by turning the rudder though the use of the digital potentiometers.

Figure 8 shows a plot of time against error in the turning rate of an impulse response. The plot begins at zero with a little fluctuation due to jitter. Then, an mpulse was applied to the system by striking the table and causing it to rotate. The PID was set to eliminate this spinning motion and settled the system in about 1 second.

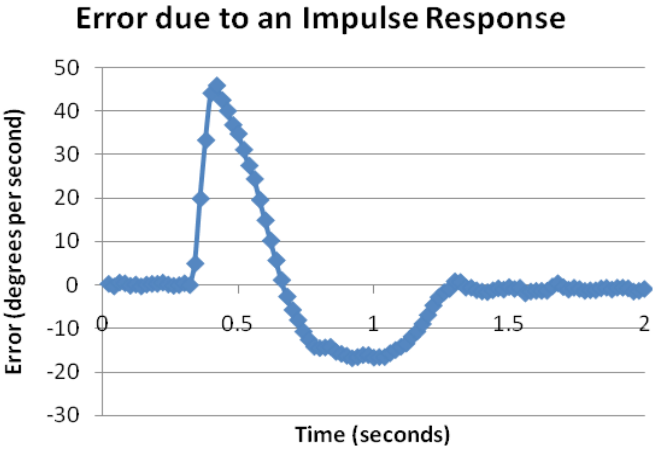

Figure 4. Impulse Response.

3.2 Onboard Visual Sensing

To locate the other subs in the tank, we decided to use an integrated computer vision platform, the CMUcam3. The CMUcam3 consists of an Omnivision CMOS camera and a 60 MHz ARM7 processor with 64 kB of ram, with a full open source API, and capable of running custom C code. The software on the CMUcam identifies subs in each image frame and returns a bounding box surrounding each sub.

Due to the limited memory of the CMUcam, we use a custom blob detection algorithm, dubbed Multitrack2. Since the subs are painted black, and testing occurs in a well-lit white tank, this approach is remarkably successful. To conserve memory, the algorithm assembles the bounding boxes in a *scanline* process, discarding the details of individual pixels, retaining only the information needed to display the bounding box.

The first step of the Multitrack2 algorithm is to compute a binary image from a standard 3-color RGB image, based on a defined threshold from previous images. The algorithm then proceeds through the image scanlines, recording each pixel coordinate that indicates an entrance (in) or an exit (out) of a black region, assembling a list for each. It then compares the ins and outs of the current and previous line, looking to see where they overlap in the horizontal axis. If they do overlap, it adds the pixels of the current line to the previous lines' blob. If an in/out pair has no overlap, it forms a new blob entity. If multiple blobs have become connected via the ins and outs of the new scanline, it merges all the blobs together into a new, larger entity. Blobs that have no continuation in the current line are pushed to a finalized state. Finally, the ins and outs of the previous line are discarded, a new scanline is processed, and the loop continues. Once the image is fully processed, small blobs below a certain threshold are filtered out, and the bounding boxes of each sub are sent to the control system.

If the sub is rotated in the image frame, it can significantly throw off bounding boxes. To compensate, we draw a vertical line at the expected location of the mast to record the maximum height of the sub at one point. This is the narrow pink line in Fig. 5.

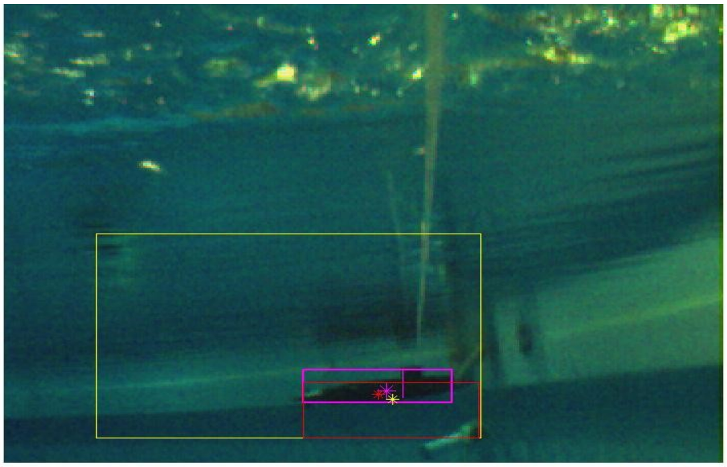

Figure 5. Bounding box creation using the CMU Cam's

3.3 Image Processing to Extract Relative Position and Orientation

The image processing portion of the autopilot depends on capturing and processing images with a CMU camera in real time in order to output the relative position and orientation of observed submarines. The main considerations in the design of the autopilot were to get an accurate location and orientation of the submarine, while maintaining fast processing speed and minimal data storage. The image processing was meant to mimic the visual communication in the aquatic environment, which is essential to the survival and proliferation of a species.

The determination of the relative position and orientation of submarines within the field of view of the CMU cameras requires an input of the horizontal projection of the second submarine on the image plane of the camera to output the desired quantities. These quantities are ρ, the distance between the camera lens and the center of mass of the second vehicle; ψ, the angle the second vehicle makes with the horizontal plane of the observing vehicle; and θ, the heading of the second vehicle, as seen in Fig 6. The angle ψ is derived using four quantities: the horizontal angle of view (α_h), the perpendicular distance to the underwater vehicle (z), the length of the image (h), and the distance from the center of the image to the center of mass of the submarine (d), as can be seen in Eq 1. ψ is given by

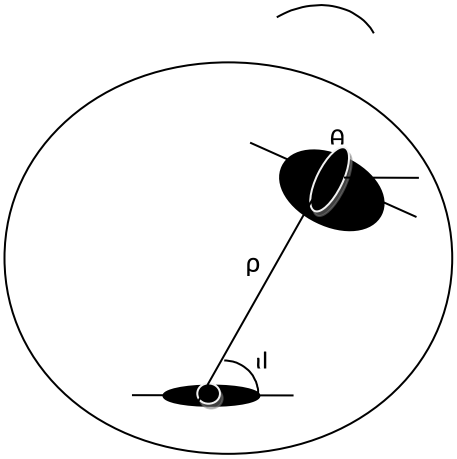

Figure 6. Top View of Two Submarines with Orientation Quantities Labeled.

$$\psi = \tan^{-1}\left(\frac{h}{2\mathrm{d}}\tan(\alpha_h)\right) \qquad (1)$$

The second derived quantity is ρ, which depends on two constants, the focal length (f) and the height of the underwater vehicle at the center of mass (H_s) and two varying quantities (ψ) and the height of the bounding box (H_{bb}). P is given by

$$\rho = \frac{fH_s}{H_{bb}\cos(\psi - \frac{\pi}{2})} \qquad (2)$$

The final derived quantity is θ, which is dependent on both ψ and ρ. The final equation depends on the width of the bounding box (W_{bb}), the length of the submarine (L), the focal length (f), the distance from the center of the image to the center of mass of the submarine (d), and the width of the projection of the submarine on the horizontal plane of the camera (W_b). Θ is given by

$$\theta = \sin^{-1}\left(\frac{W_b \sin(\frac{\pi}{2} + \beta)}{L}\right) + \tan^{-1}\left(\frac{2\mathrm{d} + W_{bb}}{2\mathrm{f}}\right) + \frac{\pi}{2} \qquad (3)$$

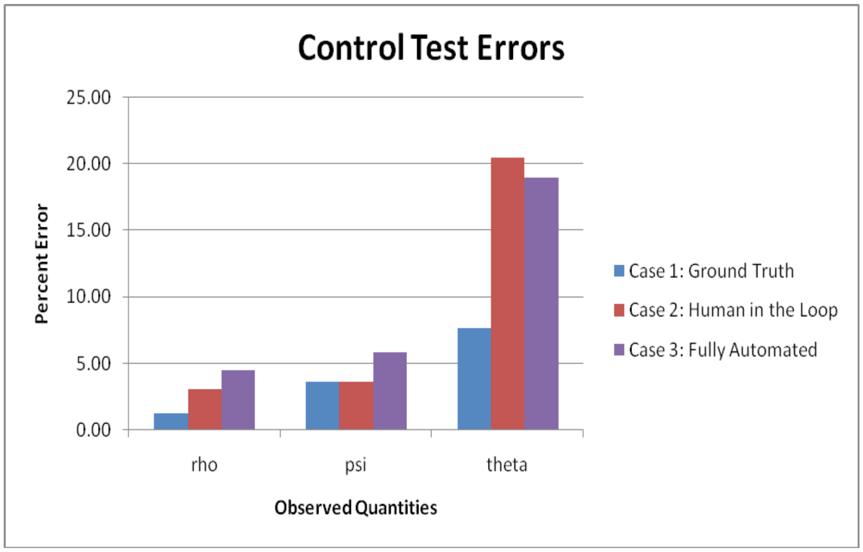

Figure 7. Errors in the derived quantities of the Control Tests.

The error associated with the derivation of the relative position and orientation of observed submarines was analyzed using a series of control tests. These tests were broken down into three data reduction methods. The first was a ground-truth experiment where the bounding boxes were selected by hand and the dependency the derived quantities had on one another was eliminated by using the known values (Case 1). The second analysis was the "human in the loop" analysis where the bounding boxes were selected by hand and the dependencies were incorporated (Case 2). The final analysis was the fully autonomous model where the bounding boxes were selected by the program and the dependencies were incorporated (Case 3).

As expected, the ground truth had the least error, as can be seen in Fig. 7– below 10% for θ, ρ and ψ. The addition of dependencies added 1.8% error to ρ, due to its dependency on ψ, and 12.8% to θ due to its dependency on both ρ and ψ. The value of ψ remained constant due to its lack of dependency on either value. The addition of a fully autonomous model increased error in ρ and ψ, and decreased error in θ. It added 1.39% error to ρ, 2.23% error to ψ, and decreased the error in θ by 1.49%. Thus, in full autonomous operation, we expect the sub to be able to measure relative position and orientation within 20% .

3.4 Collision Detection

To enable the UUV platform to detect the occurrence of a collision with a wall or other submerged obstacle and adjust its orientation in the event of a collision, we are developing a passive, self-powered piezoelectric collision sensor. We use a passive sensor because of the parallel to passive biological sensors found in fish. Piezoelectric film, produces a substantial voltage, up to 100V [i], when agitated and has been proven to work in other impact sensors.

We have designed an RLC circuit configuration that temporally extends the voltage spike from a collision to a duration that the PIC can detect. The model for the RLC circuit, where q is the charge over the capacitor, is described by:

$$L\frac{d^2q}{dt^2}+R\frac{dq}{dt}+\frac{q}{c}=V$$

When agitated, the film produces V = 40 to 80 volts. Assuming this, and that it fully charges the capacitor, the model predicts that with a 10K resistor, a 2 μH inductor, and a 4μF capacitor, the output voltage duration will last more than 0.2s; a sufficient amount of time to register on the PIC using an analog input that is being monitored at ~10 Hz. This can be seen in the graph below.

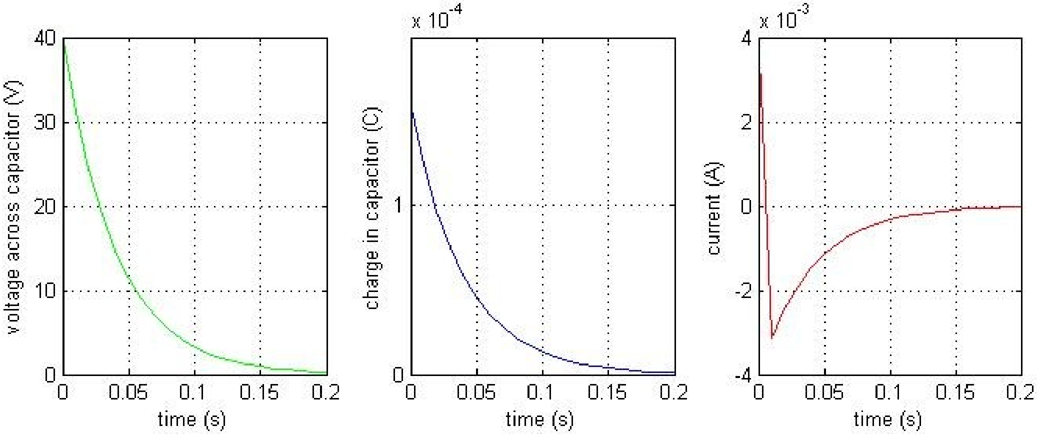

Figure 8. Voltage Duration of Piezoelectric Sensor

The sensor will be placed on the nose of the UUV, as shown in the diagram below. In order to maximize the voltage produced on impact, the piezoelectric film will be pre-bent so that an impact will force the top of the piezoelectric "arc" inwards, which produces a greater voltage than an impact on flat piezoelectric film. This is because voltage produced is proportional to the deformation of the film. In ongoing work, we are designing an array of piezoelectric sensors to detect the location of impact on the UUV.

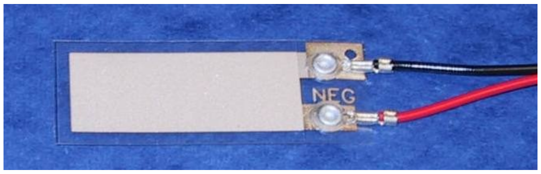

Figure 9. Measurement Specialties- piezoelectric film

3.5 Behavior-Based Control

The primary inspiration for the control of the submarine collective is a school of fish. These are nature's "autonomous" collectives. They respond to outside disturbances and perform complex motion coordination with only passive sensing, such as, visual and hydrodynamic imaging. This is the type of behavior that the CDCL aims to implement in our submarines. Each behavior is given a priority corresponding to its importance for a given mission. For example, a *mission-timeout* behavior, which stops all control after a given amount of time, is given the highest priority in the stack of behaviors[ii]. A sample behavior stack is shown in the diagram below:

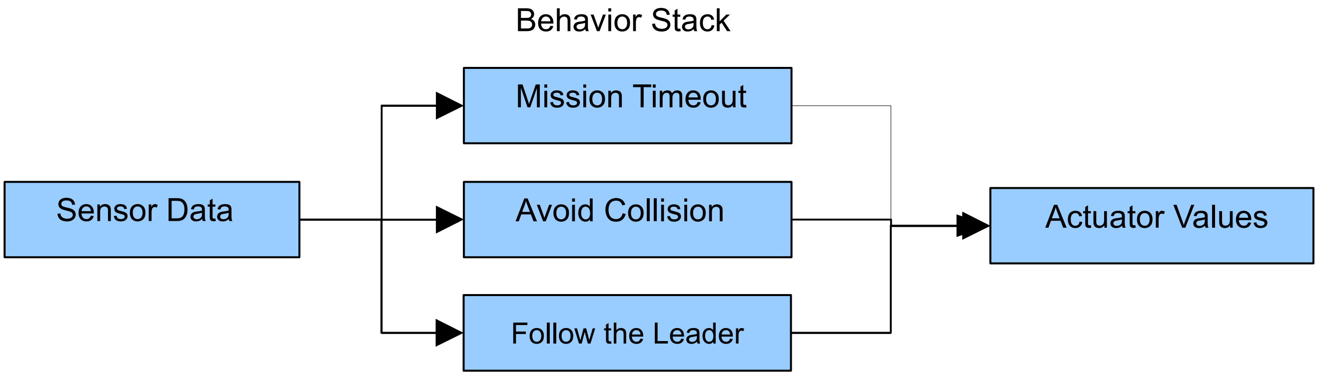

Figure 10. Behavior modeling

The autopilot unit controls two degrees of freedom: speed (forward motion) and rudder (horizontal motion). The speed is open-loop controlled, and the rudder is closed-loop. The vertical motion is controlled by an off-the-shelf depth controller .

The sensor data, described below, goes into different behavior functions that are stacked in order of priority, and the output is the desired turning rate of the sub, and the desired speed of the propeller. Fig. 7 shows three different behaviors: mission timeout, avoid collision, and follow the leader.

The sensor data is read once every iteration of the autopilot code. The behavior modules process this data and output the desired values depending on which behavior has the current priority. For example, a sample iteration is as follows: if the mission has timed out, then cue the mission timeout behavior, which has priority over the others. If the mission has not timed out, try to avoid collisions. If there are no collisions to avoid, then try to follow the desired coordination behavior, such as follow the leader. Shown below is a pseudo code version of the software implementation:

```
void main(){

      startup(*data); // startup sequence that sets the gyro and cameras
      runMissions(*data);
         –  contains different mission profiles, such as Dive, and any
            behaviors
         –  Each profile has the following flow:
                  readSensors(data);      // reads the cameras and gyro
                  CooperativeControl(data)// contains behavior laws
      runPID(data)                        // implements the PID

      return;
}
```

Figure 11. Software Implementation

This paradigm emulates the behavior of a school of fish. A fish attempts to avoid collisions with the fish surrounding it and tries to follow the fish in front of it. There are many other behaviors that can be incorporated. For example, parallel swimming could model schooling, or swimming in a circle to simulate whales herding krill.

3.6 Probabilistic Tracking

The micro-UUVs design lacks the ability to record absolute position in three dimensions. It is therefore important that an external system be utilized to track each UUV. The measurements of a vehicle's position in 3D and orientation are then used to quantify the performance of control algorithms.

For measurements, we use the existing multi-view camera system within the facility that comprises five high-resolution ZC-YH701N GANZ cameras. The cameras are mounted on the inside wall of the tank with three cameras at mid-level depth of 3.81 m spaced at 90 degree intervals looking straight into the center of the tank. The remaining two cameras are at a 45 degree interval to the mid-level ones just below the surface of the water at 0.61 m looking down at an angle of approximately 15 degrees.

Two challenges in vision-based tracking of underwater vehicles are target maneuverability and nonlinear measurement models. In order to capture the nonlinearities of both dynamics and measurements in our tracking algorithm we use a nonlinear estimation technique called particle filtering[iii] to estimate position, velocity and orientation of the vehicles.

A model-based estimation technique consists of two steps: predict and update. The predict stage uses dynamics of target motion to propagate the estimate in time, while the update stage uses measurements to revise the estimate. In a probabilistic framework that we use for tracking the nonlinearities in both these steps are preserved. A motion model for a steered vehicle[iv] is used to approximate target motion, and perspective projection relates 3D position to a 2D point on the image plane[v]. In addition, other information such as boundaries of the test environment, absence of a target in a camera frame, and the target geometry itself is used to estimate position and pose information of the target.

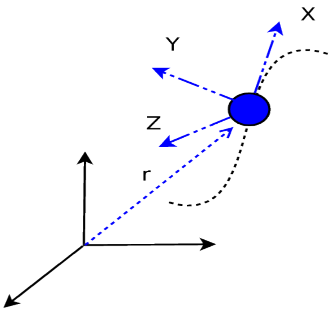

Figure 12 Body-fixed and inertial coordinate systems

If ***r*** denotes the position of a target in the inertial frame, and ***x, y, z*** are a set of orthonormal vectors attached to the target body such that ***x*** is in the direction of velocity (see Fig. 12), the motion model can be represented as[vi]

$$\begin{aligned}\dot{r} &= sx\\ \dot{x} &= yq+zh\\ \dot{y} &= -xq+zw\\ \dot{z} &= -xh-yw\end{aligned} \qquad (4)$$

where q and h are the curvature controls on the target and w is the control on roll motion.

Measurements are used to update estimates in the form of likelihood functions. These functions (conditional probability of measurement given a state) use prior knowledge of test environment and target geometry to predict the position and pose of a target.

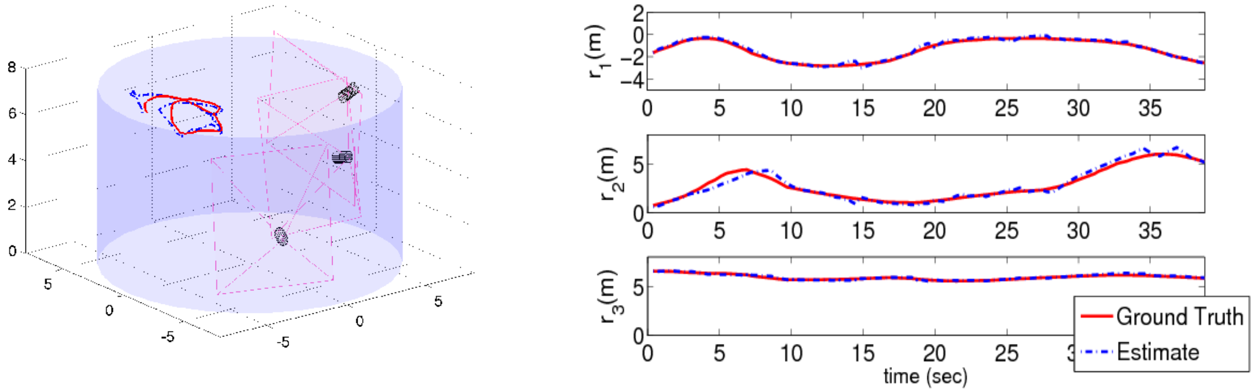

Figure 13: Track estimation in 3D. Position estimates from three cameras are compared to ground truth obtained from four cameras using least squares.

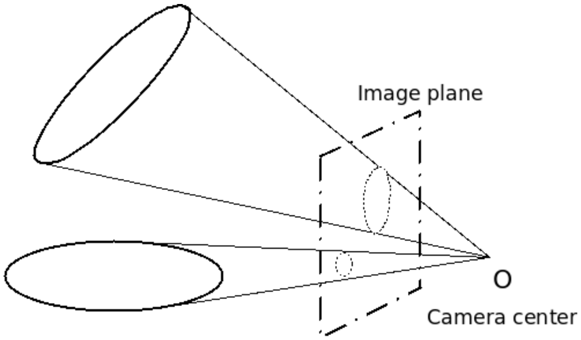

Figure 14: Two different orientations of the same object project different contours on an image plane.

In order to estimate pose of a target, we model target shape as an ellipsoid. As shown in Fig. 14, the orientation and eccentricity of the bounding elliptical contour around the submarine image are dependent on both camera and target position. These measurements are used to predict pose of the sub.

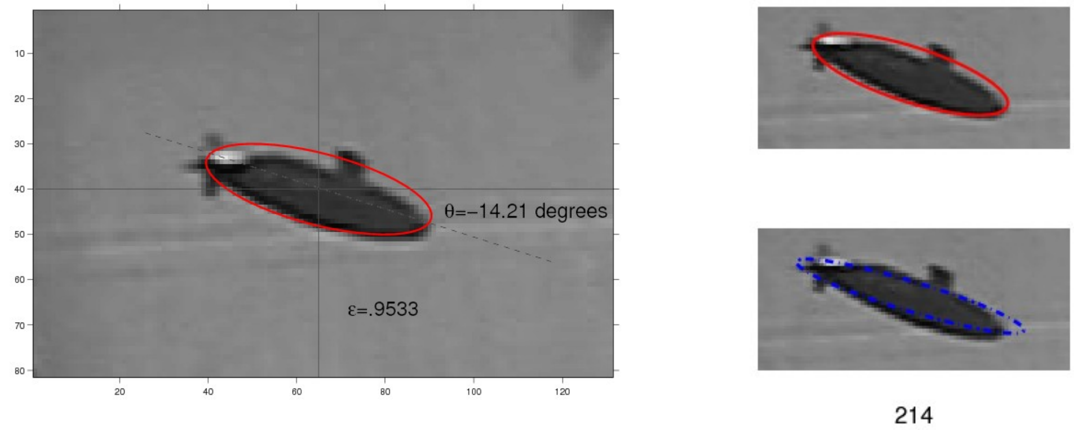

Figure 15: Measurements and estimates for target pose. A single frame is shown on the right with the measurement and the corresponding pose estimate projected back on to the same image

A sampling importance resampling (SIR) particle filter is used to fuse the vision-based likelihood function with the self-propelled motion model (Eq. 4). The tracking algorithm is tested on one and two targets in the NBRF and is shown to be accurate within one body length of the target (~1 m). To address clutter and changing lighting conditions, the background is updated as a running average[vii] before subtraction from the current image frame.

4. Conclusion

This paper describes a bio-inspired fleet of micro-UUVs capable of motion coordination. The subs are tested in a 367,000 water tank. The visual-sensing capability of each submarine is completely passive, so there is no need for RF or acoustic communication. The control is decentralized and is based on a behavior model. The control is accomplished on an onboard autopilot unit. The autopilot unit uses cameras to create bounding boxes around any other subs in the water, which is then processed to produce their position and orientation. This data is fed into a set of behavior-based cooperative control laws that dictate the motion coordination that is desired. The output of the control laws is sent to a PID controller , which computes and wirelessly the servo commands to the submarine. We use underwater video cameras to collect tracking data.

While the research has not been completed, the preliminary results are promising. Of the six submarines that will be in the final fleet, three are fully operational with three more on the way, and open-loop control of the completed submarine fleet has been proven. Initial steps to completing closed-loop control have been taken; the cameras have the capability of creating accurate bounding boxes around the subs and provide valuable position and orientation data for the autopilot units. An addition collision sensor using piezoelectric film is also being developed. Further research is needed to show that the submarines can follow cooperative control laws based on predetermined behaviors. The next step is to integrate the cooperative control laws with the data being provided by the cameras to output actuator values to create a closed loop control system on board each submarine. In addition to this, we hope to add the collision sensing capability, increasing the bio-inspired sensor capability of the fleet.

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