International Conference on Control, Automation and Systems 2008
Oct. 14-17, 2008 in COEX, Seoul, Korea

Fuzzy Logic PID Based Control Design and Performance for a Pectoral Fin Propelled Unmanned Underwater Vehicle

Jason D. Geder[1], John Palmisano[2], Ravi Ramamurti[1], William C. Sandberg[1*], and Banahalli Ratna[2]

[1] Laboratory for Computational Physics and Fluid Dynamics, U.S. Naval Research Laboratory, Washington, DC
(Tel : +1-202-767-1975; E-mail: jgeder@lcp.nrl.navy.mil)
[2] Center for Bio-molecular Science and Engineering , U.S. Naval Research Laboratory, Washington, DC
(Tel : +1-202-404-6061; E-mail: banahalli.ratna@nrl.navy.mil)
[*] (Current Address) Modeling and Analysis Division, Science Applications International Corporation, McLean, VA
(Tel : +1-703-676-8010; E-mail: william.c.sandberg@saic.com)

Abstract: This paper describes the modeling, simulation, and control of a UUV in six degree-of-freedom (6-DOF) motion using two NRL actively controlled-curvature fins. Computational fluid dynamic (CFD) analysis and experimental results are used in modeling the fin as part of the 6-DOF vehicle model. A fuzzy logic proportional-integral-derivative (PID) based control system has been developed to smoothly transition between preprogrammed sets of fin kinematics in order to create a stable and highly maneuverable UUV. Two different approaches to a fuzzy logic PID controller are analyzed: weighted gait combination (WGC), and modification of mean bulk angle bias (MBAB). Advantages and disadvantages of both methods at the vehicle level are discussed. Simulation results show desirable system performance over a wide range of maneuvers.

Keywords: Biomimetic pectoral fin, UUV, unsteady CFD, fuzzy logic, PID, adaptive curvature, weighted gait combination

1. INTRODUCTION

Low-speed and high-maneuverability performance, required in near-shore and littoral zone missions, is a major weakness of current unmanned underwater vehicle (UUV) technology. To address this issue, flapping fin mechanisms have been studied to understand how certain aquatic organisms achieve their high levels of controllability and how these mechanisms can be adapted to UUVs [1].

In our previous work, we concluded that flapping pectoral fins were the solution for low-speed, high-maneuverability operation [2]. We designed a biomimetic fin propulsor with actively controlled-curvature [3], and have designed a test vehicle that utilizes two of these fins for propulsion and control [4].

Because vehicle simulation results show a need for more than bang-bang (or case-based) control, a fuzzy logic proportional-integral-derivative (PID) based control system is developed. This novel controller commands changes in fin kinematics for vectoring control forces necessary to enable a stable and highly maneuverable UUV.

This paper studies two such non-finite pectoral fin UUV control methods. The first method is weighted gait combination (WGC) [5]. WGC is a control method that takes several preprogrammed fin gait motions and recombines them in real-time to form intermediate hybrid motions.

The second UUV control method studied is mean bulk angle biasing (MBAB). When a pectoral fin flaps, it produces both lift and thrust forces. By modifying the mean angle of the flapping fin, the lift force can be controlled without affecting forward thrust.

2. VEHICLE DESIGN AND MODELING

2.1 Vehicle design

Our team has completed the design and construction of a biomimetic controlled-curvature robotic pectoral fin [3]. A test vehicle (Fig. 1) has been designed to demonstrate the speed and maneuverability enabled by a pair of these pectoral fins [4]. The hull measures 1.3″ high, 13″ long, and 7″ wide, and has a dry weight of 2.6 pounds making it slightly negatively buoyant.

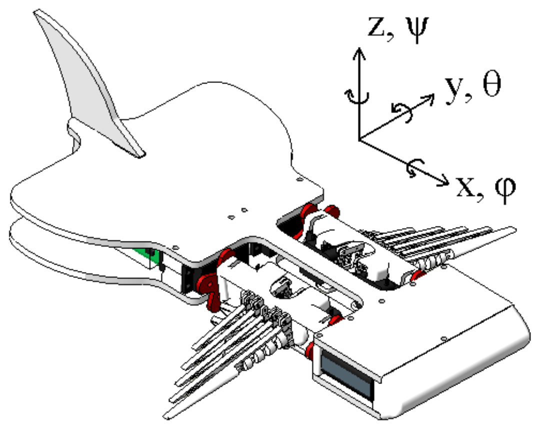


Fig. 1 Test vehicle carrying two NRL fins.

The vehicle has been integrated with onboard sensors and a custom designed microcontroller [5]. Angular rate gyroscopes and linear accelerometers are attached to three independent axes, and a pressure sensor for depth measurement is mounted onboard as well. Combined with signal amplifiers for high resolution data collection, this system provides all necessary onboard hardware for testing fin force production and vehicle maneuverability.

2.2 Equations of motion

A model of the physical system is formulated to aid in control system development and vehicle performance studies. Our unique UUV propulsion system makes use of actively controlled elastic fin deformations that produce forces at any desired vector [5, 6]. The rest of the vehicle is rigid and can thus be defined by standard rigid body equations of motion [7],

$$\vec{f}_0 = m\left(\left(\frac{\partial \vec{v}_0}{\partial t}\right)_r + \vec{\omega}\times\vec{v}_0 + \dot{\vec{\omega}}\times\vec{r}_G + \vec{\omega}\times\left(\vec{\omega}\times\vec{r}_G\right)\right) , \tag{1}$$

$$\vec{m}_0 = \tilde{I}_0\dot{\vec{\omega}} + \vec{\omega}\times\left(\tilde{I}_0\vec{\omega}\right) + m\vec{r}_G \times\left(\left(\frac{\partial \vec{v}_0}{\partial t}\right)_r + \vec{\omega}\times\vec{v}_0\right) , \tag{2}$$

where m is mass, v_0 is the translational state vector, ω is the rotational state vector, r_G is the center of gravity location, I_0 is the inertia tensor, f_0 is the external forces vector, and m_0 is external moments vector.

From Eqs. (1)~(2) we have derived the complete equations of motion and computed the prototype vehicle coefficients from CFD analysis, vehicle geometry, and mass placement [4].

2.3 Fin Forces

The external forces and moments on the vehicle, f_0 and m_0, from Eqs. (1)~(2) include those generated by the NRL fins. A combination of 3-D unsteady CFD computations [2] and experimental measurements [6] are used to determine force time-histories generated by the fins for a range of fin kinematics.

Initial computational studies to optimize the performance of the NRL fin [3, 8] provided a basis for determining which fin parameters to analyze as potential control variables. These controllable fin parameters include bulk fin stroke amplitude (Φ), fin mean stroke position (Φ_{mean}), deflection of each of the four actuated fin ribs ($\Gamma_{1\text{-}4}$), and flapping frequency.

Unsteady CFD simulations were completed across a wide span of fin motions across all controllable parameters [2]. Non-dimensional scale factors, k_Φ and k_Γ, were used to define the values of the controllable parameters, Φ and Γ, as,

$$\Phi \text{ (radians)} = 1.2514\cdot k_\Phi , \tag{3}$$
$$\Gamma \text{ (radians)} = \Gamma_1 = 0.1152\cdot k_\Gamma , \tag{4}$$

where Γ is a measure of the fin curvature from leading to trailing edge, and is defined by the maximum tip deflection of the leading edge rib.

To evaluate UUV controller performance in simulation, a full range of fin forces need to be known. Therefore, curve-fitting equations were derived to map fin kinematics to stroke averaged forces (Figs. 2~3).

After validating the experimental force measurement accuracy [3, 5], a library relating force data to specific fin gaits has been built [6]. These experimental results provide a more accurate representation of the forces generated by the fin because the parameters used in CFD simulation do not take into account fluid-structure interaction.

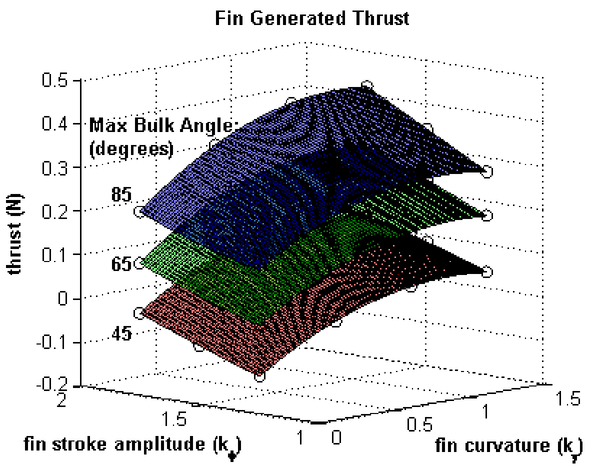


Fig. 2 Mean fin generated thrust as a function of the controllable parameters, bulk fin stroke amplitude and fin curvature, both non-dimensional. Max. bulk angle: 85° (blue) – biased by +0.1N, 65° (green), 45° (red) – biased by -0.1N.

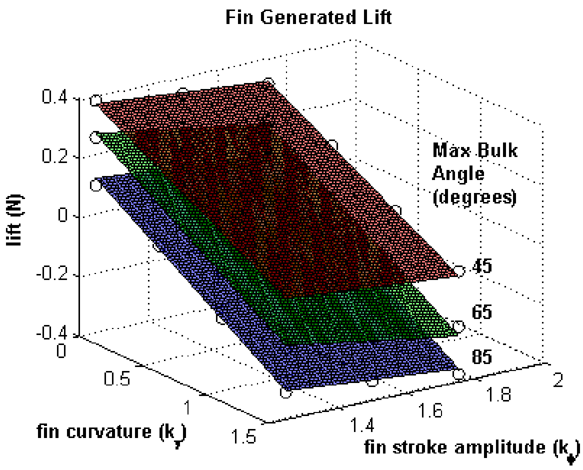


Fig. 3 Mean fin generated lift as a function of the controllable parameters, bulk fin stroke amplitude and fin curvature, both non-dimensional. Max. bulk angle: 85° (blue) – biased by +0.1N, 65° (green), 45° (red) – biased by -0.1N.

2.4 Preprogrammed Gaits

A specific set of fin kinematics is called a gait, and ideally, an infinite number of these gaits would be programmed onto the onboard vehicle microcontroller. This would ensure an exact gait to match any force vector commanded by the vehicle controller. However, this being infeasible, instead we must carefully choose only a few preprogrammed gaits that the vehicle navigation control system can draw from [5]. Therefore, the control system uses combinations of this limited set of gaits to generate the infinite number of fin force vectors needed to perform six degree-of-freedom (6-DOF) maneuvers. The results from Figs. 2~3 identify trends in force output which help determine the preprogrammed gaits.

Four gaits have been chosen, including a maximum forward thrust gait (K_f), a maximum reverse thrust gait (K_r), and maximum upward and downward thrust gaits (K_u and K_d, respectively) (Fig. 4). Any desired force vector (K_c) for each fin can be achieved through weighted combinations of preprogrammed gaits [5], and then maps of these combinations to forces through the equation,

$$K_c = f\left(K_f, K_r, K_u, K_d\right) \quad . \tag{5}$$

Note that all gaits are chosen to be entirely uncoupled allowing each gait to be independently optimized and studied to improve the overall controller. Extensive experimental testing has been carried out to determine optimum gaits for generating maximum forward and reverse thrust, and maximum positive and negative lift [6].

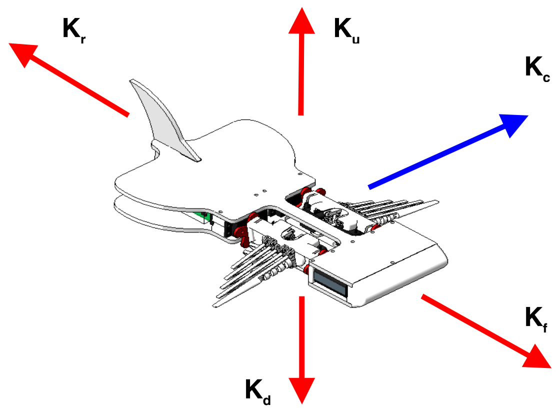


Fig. 4 Preprogrammed gait forces (red vectors) used to achieve desired force vectors (blue vectors).

3. VEHICLE CONTROL

3.1 Bang-bang (or case-based) control

Before designing the fuzzy logic PID based control algorithm for the vehicle, we first analyzed the performance of a simple bang-bang control algorithm. This algorithm limits the fins to switching discretely between only the four preprogrammed gaits (Figs. 6, 8). Vehicle simulations employing the bang-bang control approach exhibit undesirable highly oscillatory motions dictating the need for development of a more sophisticated control technique.

The four experimentally selected gaits, previously mentioned for producing each of the major thrust and lift vectors, have been modeled as baseline sets for both of the NRL fins.

We can see in the z-position response (Fig. 5) that the vehicle exhibits undamped oscillatory behavior with bang-bang control. This is also apparent in the pitch angle (θ) (as defined in Fig. 1) response which is marked by 60 degree peak-to-peak oscillations. This high magnitude oscillation would preclude the use of certain onboard sensors, such as video cameras for object imaging, blurring low-light imaging and adding significant noise to the inertial measurement unit.

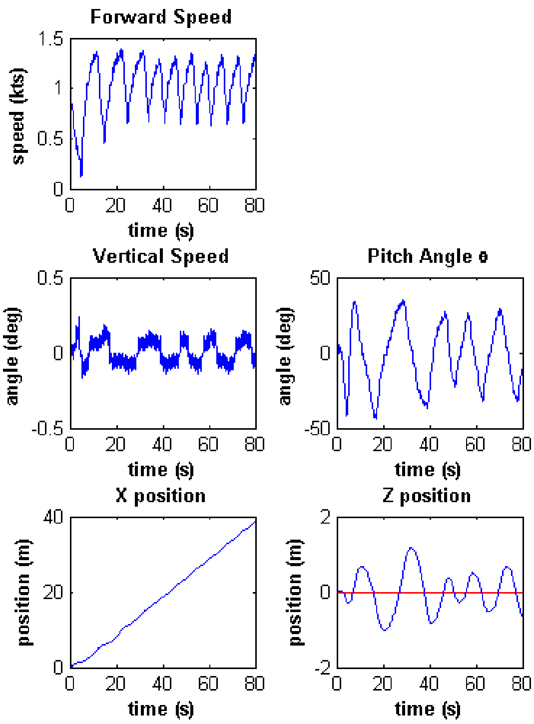


Fig. 5 Vehicle response to steady level flight command with bang-bang control

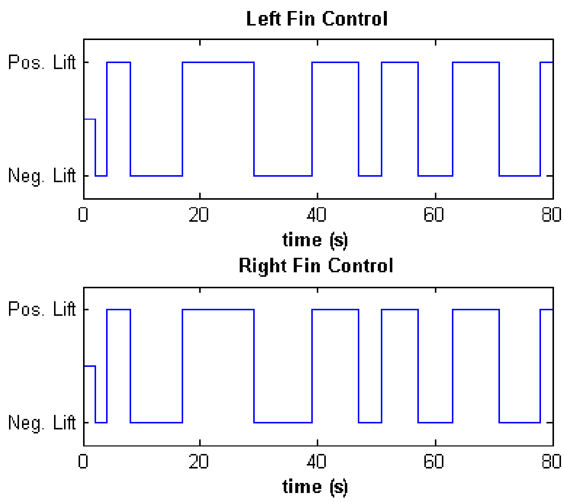


Fig. 6 Control response to steady level flight command with bang-bang control

The limitations of bang-bang control are displayed on a broader scale in lateral turning maneuvers (Fig. 7) where we see vehicle roll (φ), pitch (θ), and yaw (ψ) (as defined in Fig. 1) oscillate with peak-to-peak excursions in excess of 60 degrees. These results show that bang-bang control is unable to provide the precise maneuvering required of the UUV.

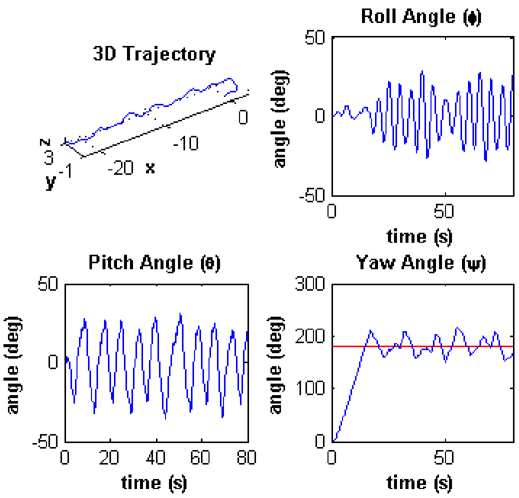


Fig. 7 Vehicle response to yaw command with bang-bang control

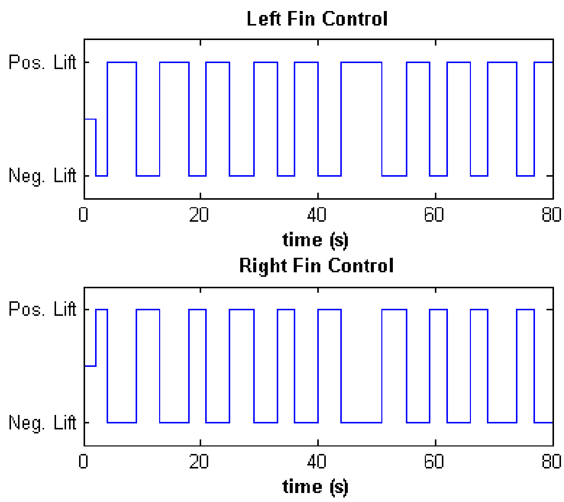


Fig. 8 Vehicle response to yaw command with bang-bang control

3.2 Fuzzy Logic PID Based Control

To improve stability and damp the oscillatory behavior of the vehicle, a continuous transition between the four preprogrammed gaits is necessary. One way to program this type of control is using a fuzzy logic system in which two or more preprogrammed fin gaits, each optimized for producing a desired force vector, are combined to create an intermediate gait. Fig. 9 outlines the design steps necessary to the creation of a controller for the NRL test vehicle.

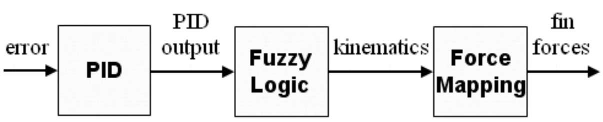


Fig. 9 Representative control block diagram.

Linearized equations of motion were computed from the 6-DOF vehicle model to determine control gains for various maneuvers using classical control techniques [4]. For example, we linearize about steady level flight at a constant forward speed and determine control gains for depth response using the algorithm,

$$u_z = K_{zp} e_z + K_w w + K_{zi} \int e_z \,, \tag{6}$$

where u_z is the control output, K_{zp} is the proportional gain, K_w is the derivative gain, K_{zi} is the integral gain, e_z is the vertical position error, and w is the vertical velocity. Similar control outputs are found for the other states in the forms,

$$\begin{aligned} u_x &= K_{xp} e_x + K_u u + K_{xi} \int e_x \\ u_y &= K_{yp} e_y + K_v v + K_{yi} \int e_y \\ u_\theta &= K_{\theta p} e_\theta + K_q q + K_{\theta i} \int e_\theta \\ u_\psi &= K_{\psi p} e_\psi + K_r r + K_{\psi i} \int e_\psi \end{aligned} \tag{7}$$

3.2.1 Weighted Gait Combination (WGC) Method

The individual PID control outputs for various vehicle states, Eqs. (6)~(7), are then combined to compute the total control value for each of the fins. In the WGC method, these control values are computed as shown in Eq. (8).

$$\begin{aligned} u_{LEFT\_FIN} &= u_x + u_y + u_z + u_\theta + u_\psi \\ u_{RIGHT\_FIN} &= u_x - u_y + u_z + u_\theta - u_\psi \end{aligned} \tag{8}$$

In this weighted gait method, the output control values for the left and right fins are then mapped to percentages of the four preprogrammed gaits using a membership function. Using vertical position control in forward flight as an example (Fig. 10), the membership function determines weighting of three of the sets of preprogrammed gaits that contribute to the control output kinematics for each fin.

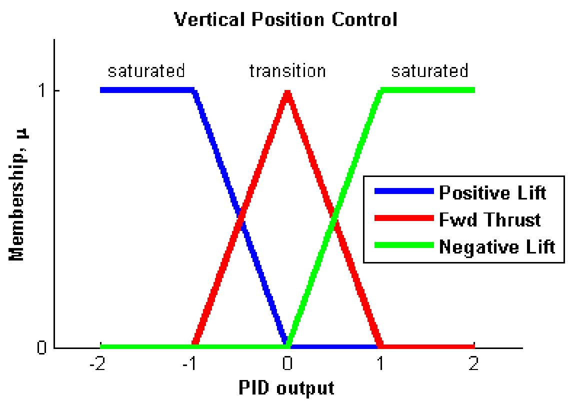
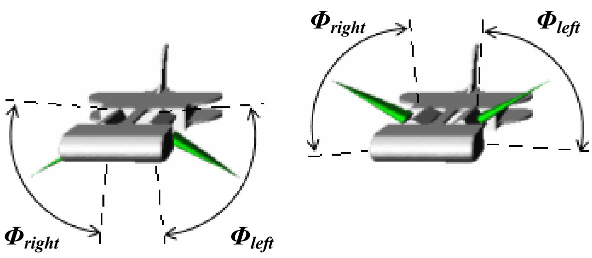


Fig. 10 Membership function for vertical position controller in forward flight.

If the vehicle is very far below desired depth, the maximum positive lift gait is 100% used for both fins, thereby saturating the controller. Similarly, if the vehicle is very far above desired depth, the maximum negative lift gait is 100% used for both fins. And if the vehicle is within some predetermined range of desired depth the output kinematics is calculated as a combination of the optimal positive lift, forward thrust, and negative lift gaits.

3.2.2 Mean Bulk Angle Bias (MBAB) Method

An alternate to the WGC method of fuzzy logic PID control has also been investigated in which control over fin lift force is achieved through biasing the fin mean bulk rotation position (Φ_{mean}) up or down (Fig. 11). This propulsion control method entirely decouples lift from thrust, simplifying the controller design.



(a) (b)

Fig. 11 NRL two fin vehicle showing wing mean position at, (a) -30° which produces a positive lift force, and (b) +30° which produces a negative lift force.

The effectiveness of this MBAB method was suggested by the results of the CFD studies [2] illustrated in Fig. 3 where we see lift increase as the fin stroke is biased downwards. Control over horizontal plane motion is still achieved through combining the preprogrammed forward and reverse gaits for the left and right fins as in Eq. (9).

$$\begin{aligned} u_{LEFT\_HORIZ} &= u_x + u_y + u_\psi \\ u_{RIGHT\_HORIZ} &= u_x - u_y - u_\psi \\ u_{BULK\_BIAS} &= u_z + u_\theta \end{aligned} \tag{9}$$

The final step in modeling the vehicle control law progression, for both the WGC and MBAB methods, is determining how each gait or combination of gaits maps to a force vector generated by each fin. Based on CFD and experimental testing, a mapping from membership in the various gaits to these fin generated force vectors is made as discussed in section 2.3 [2, 6].

4. SIMULATION RESULTS

Simulation was highly effective for investigating stability and maneuverability performance of the UUV using the WGC and MBAB control methods.

The fuzzy PID controller using the WGC method was tested first in simulation on the 6-DOF model previously developed [4], producing predictable results. Vehicle response to a climb maneuver (Fig. 12) displays a much smoother transition to steady state compared with bang-bang control response (Fig. 5). During the maneuver, the full weight percentage is on the positive lift gait briefly, and then smoothly levels out to a full forward thrust gait weighting (Fig. 13).

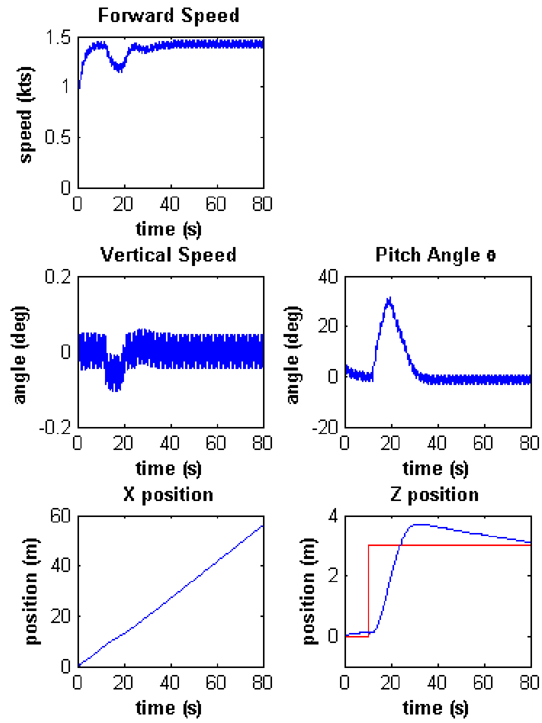


Fig. 12 Vehicle response to step command in vertical position with fuzzy logic PID control using WGC.

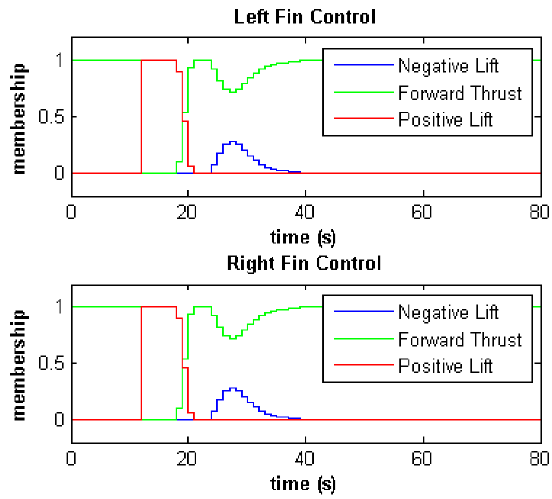


Fig. 13 Control response to step command in vertical position with fuzzy logic PID control using WGC.

One concern with the WGC method is the difficulty in controlling multiple vehicle states independently. In the climb maneuver response, we see z-position controlled, but this is at the expense of an accurate forward speed control (Fig. 12). We can correct for this by scaling down the overall weight on the gait combinations, but this would reduce the envelope in which the vehicle can operate. More specifically, we cannot obtain maximum lift simultaneously with maximum thrust.

The MBAB method solves this problem. By using this method, we are almost completely decoupling lift forces from thrust forces when we combine gaits. This allows us to more easily create a linear map from control output to fin force.

Vehicle response to a climb maneuver (Fig. 14) is analyzed using the MBAB method, but in this case vehicle speed is held constant at 0.5 m/s. During the maneuver the mean bulk rotation position (Φ_{mean}) is at maximum position briefly, and then slowly returns to its level cruise position for a smooth transition in the z-response. Meanwhile, a combination of the forward and reverse gaits is achieved to maintain desired forward speed (Fig. 15).

Vehicle response to a yaw maneuver (Fig. 16) using mean stroke bias for lift control also displays a much smoother transition to steady state, and less oscillation in steady state than bang-bang control response. Roll and pitch (θ and φ) are limited to 3-4 degrees of steady state oscillation, while yaw (ψ) displays even less at ~1-2 degrees. Rise time is also not adversely affected, as the control limits are saturated throughout 80% of the yaw angle change (Fig. 17), just as they are using the WGC method.

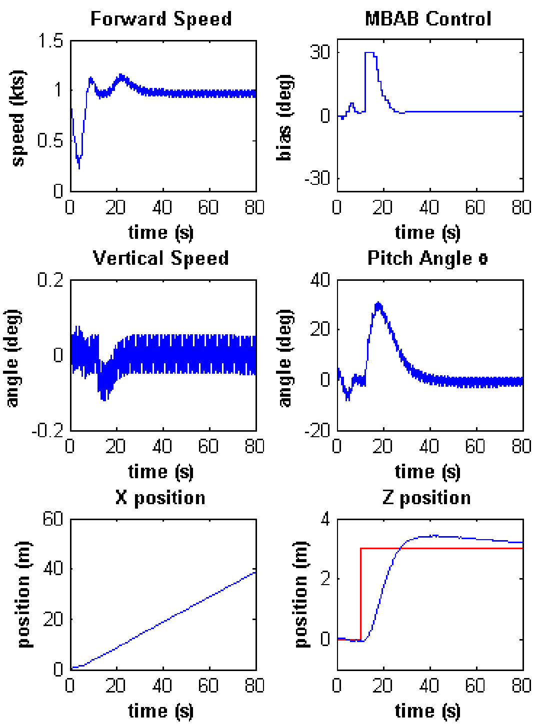


Fig. 14 Vehicle response to step command in vertical position with fuzzy logic PID control using MBAB.

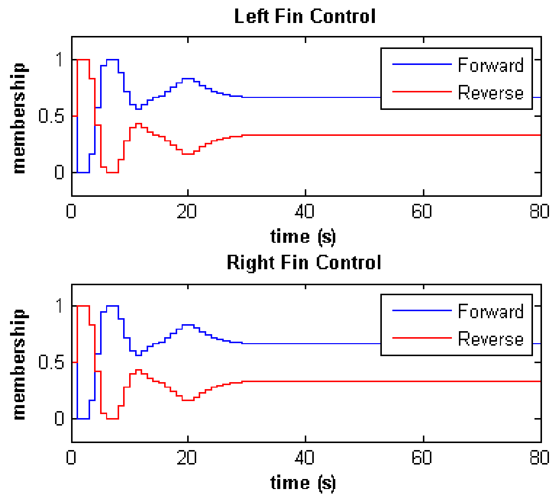


Fig. 15 Control response to step command in vertical position with fuzzy logic PID control using MBAB.

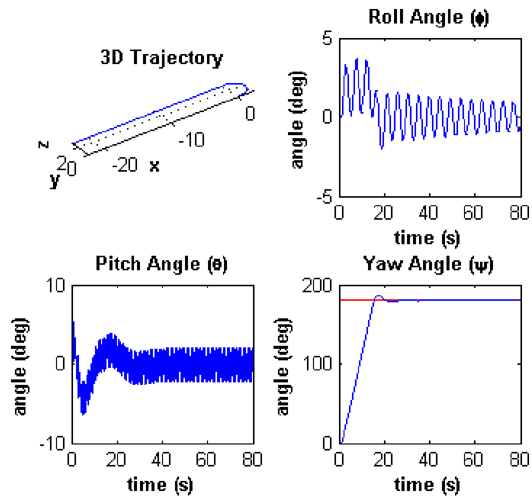


Fig. 16 Vehicle response to yaw maneuver with fuzzy logic PID control using MBAB.

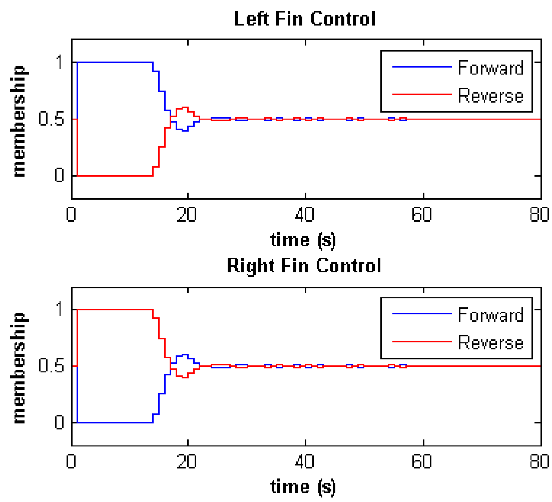


Fig. 17 Control response to yaw maneuver with fuzzy logic PID control using MBAB.

4. DISCUSSION

While the benefit of decoupling lift from thrust is seen in vehicle results using the MBAB controller, this advantage only applies when the fin is at or near a zero degree angle of attack with respect to the incoming flow. At higher magnitude angles, the lift and thrust are no longer decoupled when we bias the fin mean bulk angle up or down. This becomes an important issue as we look forward to redesigning the UUV.

Other results indicate that turning radius and speed can be improved by one or a combination of several methods. These methods include improving the negative thrust gait, changing the vehicle geometry (ie. decreasing the size of the vertical tail would facilitate faster yaw maneuvers), and investigating the advantages of non-linear gait weighting.

Since an extensive search for reverse thrust kinematics has already been conducted [6], a mix of changing the vertical tail and investigating non-linear control weighting need to be considered for future generations of the vehicle. Since vehicle pitch oscillations are relatively small (~3-4 degrees), adjusting the hull geometry to increase the pitch moment of inertia would decrease these excursions even more. However, this would be at the expense of decreasing the maximum attainable vehicle pitch angle with current fin gaits, thereby slowing vertical position response. A fine balance needs to be found.

5. CONCLUSIONS

A prototype vehicle to demonstrate the propulsion and maneuvering performance of its actively controlled surface curvature deforming pectoral fins has been developed. Three control techniques were quantitatively compared for their ability to enable hovering and maneuvering of our UUV using two NRL flapping fins. We have described the mathematical development and maneuvering performance obtained using this controller. Experimentally and computationally demonstrated fin performance provided adequate force production for vehicle propulsion and control, as shown in simulation results.

While bang-bang control yielded poor results in simulation, algorithms for combining preprogrammed fin gaits using both WGC and MBAB methods were successful in controlling vehicle speed, position and orientation.

REFERENCES

[1] J. E. Colgate and K. M. Lynch, "Mechanics and Control of Swimming: A Review," *IEEE Journal of Oceanic Engineering*, vol. 29, pp. 660-673, July 2004.

[2] R. Ramamurti and W. C. Sandberg, "Computational Fluid Dynamics Study for Optimization of a Fin Design," In *Proc. of the 24th AIAA Applied Aerodynamics Conference*, AIAA-2006-3658, San Francisco, CA, 2006.

[3] J. Palmisano, R. Ramamurti, K. Lu, J. Cohen, W. Sandberg and B. Ratna, "Design of a Biomimetic Controlled-Curvature Robotic Pectoral Fin", In *Proc. of the IEEE International Conference on Robotics and Automation*, Rome, IT, 2007.

[4] J. D. Geder, J. Palmisano, R. Ramamurti, W. C. Sandberg and B. Ratna, "A New Hybrid Approach to Dynamic Modeling and Control Design for a Pectoral Fin Propelled Unmanned Underwater Vehicle," In *Proc. of the Fifteenth International Symposium on Unmanned Untethered Submersible Technology*, Durham, NH, 2007.

[5] J. S. Palmisano, J. Geder, R. Ramamurti, W. Sandberg, B. Ratna, "Real-Time Robotic Pectoral Fin CPG Using Weighted Gait Combinations," submitted to *IEEE Transactions on Robotics*, 2008.

[6] J. S. Palmisano, J. Geder, R. Ramamurti, W. Sandberg, B. Ratna, "How to Optimize Efficiency and Propulsion of a Controlled-Curvature Robotic Pectoral Fin," to be submitted for publication in October 2008.

[7] T. I. Fossen, *Guidance and Control of Ocean Vehicles*, John Wiley & Sons, New York, 1994.

[8] R. Ramamurti, W. Sandberg, J. Geder, "Computations of Flapping Fin Propulsion for UUV Design," submitted to *47th AIAA Aerospace Sciences Conference*, January 2009.