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DESIGN AND DEVELOPMENT OF AN UNMANNED UNDERWATER VEHICLE (UUV) IN THE FORM OF A CUTTLEFISH

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ABSTRACT

Current methods of unmanned underwater locomotion do not meet stealth, robustness and efficiency. This work discuses about designing a Bioinspired UUV or Unmanned Underwater Vehicle that uses an undulating fin approximating to that of a cuttlefish fin locomotion. This propulsion method has higher maneuverability and ability to navigate while leaving its surroundings relatively undisturbed as compared to other propeller based systems. Mathematical models and control algorithms describing the complicated locomotion have been developed, and a simulation model is used to verify the theoretical results. This design of UUV can be utilized for underwater data collection and military applications without hampering the underwater wildlife.

INTRODUCTION

Although the concept has been around for decades, the role of Unmanned Underwater Vehicles (UUV) have become more significant, especially in the military and defense areas. Recently, many researchers have focused on developing a bio-inspired UUV that is robust, efficient and harmless to the underwater wildlife. The researchers in the this field, support the locomotion using the undulating fin as opposed to a propeller type design, due to its higher maneuverability and ability to navigate while leaving its surroundings relatively undisturbed [1],[2]. As stated by K. Low et al, "The need for higher efficiency, maneuverability and propulsive performance essentially requires fish-like performance [12]."

The most common locomotion of a fish is called Body-Caudal Fin (BCF) locomotion, where the thrust is generated by a wave propagated through their body and/or caudal fin. But few species, such as cuttlefish and knifefish, makes use of Median and/or Pectoral Fins (MPF) for generating forward thrust [2]. An experiment performed with a robot fish with single-face and silicon skin has proved that biomimetic fin produces less noise for the underwater propulsion system [3]. An underwater propulsion system developed at Nanyang Technological University was constructed using several linkages that consist of fin rays to mimic the rays and fins of cuttlefish [4]. The control of each fin ray was independent, which not only made the mechanism more flexible but also allowed the robot to generate sinusoidal function as well as other time-dependent functions [5]. Another similar underwater robot with two undulating side fin was developed at Osaka University [6]. For the ensuring the omni directionality of the UUV, another design named Sepios evolved, which had four undulating fins arranged symmetrically around a central cylinder [7]. Whereas few researchers used a single set of undulating fins, below the body, for propulsion as inspired from knifefish, using MPF locomotion [8],[9].

Some studies employed a depth control mechanism, using the principles of buoyancy, along with the undulating fins[10],[11] and later incorporated modularity and improved control systems [12],[13] in the Nanyang design. Other similar mechanisms were also built to study the effect of fin's principal dimensions on the swimming motion of UUV [14]. Some researchers also modelled the hydrodynamics of the undulating fin and used CFD to study the pressure and velocity distributions on fin surfaces [15], [16] and studied effect of propagating wave motions on the fin surfaces [17].

In the field of underwater robotics, researchers and scientists have worked on many other bioinspired UUV designs such as Cownose Ray inspired design [18], Boxfish inspired design

[19], Salmon inspired tendon drive fishtail design [20] and many more. Based on previous research, the cuttlefish-like mechanism has been proven to make the UUV more flexible, maneuverable, and quieter. However, the main concern with this mechanism is its high energy consumption and less efficiency.

The purpose for this project is to develop a mathematical model, design, and simulate a UUV, in the form of a cuttlefish, that has an improved energy efficiency and better control. Some of the proposed approaches to solve this challenge are: developing a better mathematical model to define the kinematics of UUV and dynamics involved in the complicated locomotion, implementing low-power consumption servomotors, optimizing the number of servomotors involved and redesigning the control algorithm according to account for the changes. The nonlinearity associated with the undulated fin locomotion needs to be studied comprehensively and to be considered for improvements

NOMENCLATURE

x represent the horizontal motion of the UUV
y represents the displacements of the fin elements in the vertical direction.
M represents the mass of the UUV

ASSUMPTIONS

The UUV is analyzed based on the following assumptions: the fluid is incompressible, the cuttlefish body is symmetric and neutrally buoyant, and the UUV moves in the horizontal direction, and the disturbance flow is negligible. The two undulating fins of the cuttlefish operates under the sinusoidal waveform. The inputs of the systems are amplitude and frequency of the wave and the input power for the servo motors. The output considered are the velocity of the UUV, from which the output power and the efficiency of the system can be determined.

PROJECT OVERVIEW

Earlier studies used individual servo motors to control each fin ray independently. This method did provide the flexibility to control and vary the amplitude of each fin ray. But at the same time each of the servo consumed a lot of electric power that in turn reduced the efficiently of the UUV.

This study hopes to concentrate on increasing the efficiency by incorporating a crankshaft mechanism for each of the two fins that will drive any array of fin rays with a phase difference. This configuration requires only 2 servo motors to drive the crankshaft. The speed of the UUV will then be controlled through varying the speed of the crankshaft. The direction of the UUV in the axial plane can also be controlled through independently varying the speed of the two crankshafts. The fin rays are connected to each other using a flexible membrane that could aid in providing a smooth sinusoidal waveform.

Some of the potential challenges for the project are the system cannot be linearized and the mathematical models not representing the actual performance of the UUV. The system can be analyzed using some numerical methods such as CFD for integrating the nonlinear effects. Also, in order to evaluate the accuracy of the mathematical model, the UUV is simulated with the boundary conditions as close to the actual experiment as possible.

MATHEMATICAL MODEL

A mathematical model has been developed to study the dynamics of the UUV. The model is based on the continuous time varying system of the fin motion shown in Equation (1) and Figure (1) below.

$$y = A \sin(kx - \omega t) \tag{1}$$

where A is the amplitude, k is the angular spatial frequency, and ω is the angular temporal frequency of the sinusoidal fin motion.
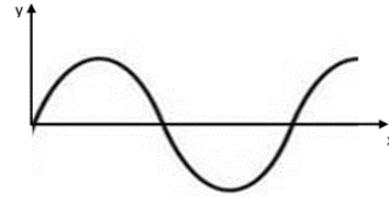
Figure 1: Sinusoidal Waveform

Based on Lighthill's *Note on the Swimming of Slender Fish* [22], the mean thrust generated by the fin motion can be expressed as follows:

$$F_t = \frac{1}{2} m \left[\left(\overline{\frac{\partial y}{\partial t}} \right)^2 - U^2 \left(\overline{\frac{\partial y}{\partial x}} \right)^2 \right] \tag{2}$$

where m is the mass of water per unit length and U is the free-stream velocity of the water. The mass of water per unit length can be approximated by the equation below:

$$m = \frac{1}{L} \rho \int_0^L \frac{1}{2} |y_0| b \cos \theta \, dx \tag{3}$$

where L is the total length of the fin, b is the width of the fin, y_0 is the fin motion in the y-direction evaluated at $t=0$, and θ is the angle between the fin ray and the z-direction. By assuming θ is very small and using symmetry to evaluate the integral, the mass of water per unit length can be obtained in term of the amplitude (A), water density (ρ), number of waves (n), and the dimensions and characteristics of the fin as shown below:

$$m \approx \frac{2\rho A b n}{kL} \tag{4}$$

From Equation (1), the following expressions can also be obtained:

$$\left(\overline{\frac{\partial y}{\partial t}}\right)^2 = \frac{1}{T}\int_0^T A^2\omega^2\cos^2(kx-\omega t)\,dt = \frac{A^2\omega^2}{2} \tag{5}$$

$$\left(\overline{\frac{\partial y}{\partial x}}\right)^2 = \frac{1}{T}\int_0^T A^2 k\cos^2(kx-\omega t)\,dt = \frac{A^2 k^2}{2} \tag{6}$$

Substituting Equations (4), (5), and (6), into (2) gives:

$$F_t = \frac{\rho A b n}{kL}\left(\frac{A^2\omega^2}{2} - U^2\frac{A^2 k^2}{2}\right) \tag{7}$$

The overall drag force on the body are given as:

$$D = \frac{1}{2}C_D\rho S\dot{x}^2 \tag{8}$$

where C_D is the drag coefficient, and S is the area of the UUV projected onto the yz-plane. Resolving the forces in the free body diagram of the UUV gives the following expressions:

$$M\ddot{x} = F_t - D \tag{9}$$

$$M\ddot{x} = \frac{\rho A b n}{kL}\left(\frac{A^2\omega^2}{2} - U^2\frac{A^2 k^2}{2}\right) - \frac{1}{2}C_D\rho S\dot{x}^2 \tag{10}$$

Let $(x_1, x_2) = (x, \dot{x})$, and x_2^* be an equilibrium point, where $x_2 = x_2^* + \delta$. By linearization, a system of first-order differential can be derived:

$$\begin{cases} \dot{x}_1 = \delta + \sqrt{\dfrac{2\rho A b n}{kLC_D\rho S}\left(\dfrac{A^2\omega^2}{2} - U^2\dfrac{A^2 k^2}{2}\right)} \\[4mm] \dot{\delta} = -\dfrac{2}{M}\sqrt{\dfrac{2\rho A b n C_D\rho S}{kL}\left(\dfrac{A^2\omega^2}{2} - U^2\dfrac{A^2 k^2}{2}\right)}\,\delta \end{cases} \tag{11}$$

EXPERIMENTAL SETUP

The study was intended to be based on simulations of the dynamics of the system. A prototype model was built to the test the undulating fin mechanism and also to validate the results from simulations. The specifications of the UUV built are indicated in Table 1. The image of the UUV built is shown in Figure 2.

The nonlinear mathematical model was evaluated using linearization of the dynamical equations. The stability study was performed using MATLAB and simulations of the system was generated using SIMULINK.

Sr. No	Parameter	Symbol	Value
1	Maximum amplitude of fin motion	A	0.114m
2	Wavelength of undulating wave	λ	0.254m
3	Fin width	b	0.254m
4	Length of fin segment	L	0.254m
5	Mass of the UUV	m	4.55 kg
6	Critical free stream velocity	U_C	0.25m/s
7	Cross sectional area of UUV	S	0.039m^2
8	Drag coefficient	C_D	0.82
9	Density of water	ρ	1000kg/m^3
10	Number of waves	n	1

Table 1: Experimental Setup parameters
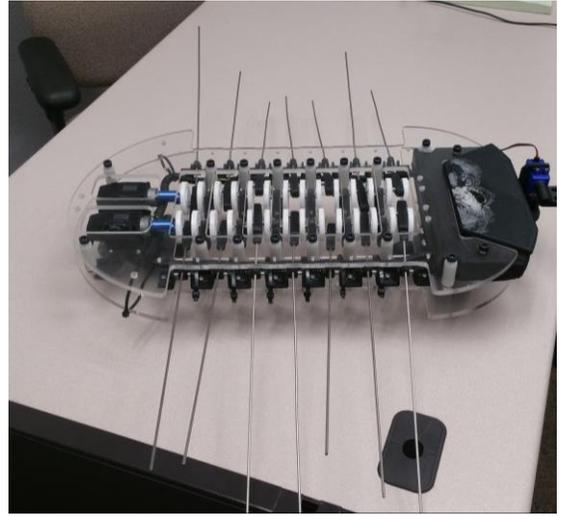
Figure 2: Experimental UUV

OBSERVATIONS

The mathematical model was further simplified to study the dynamical behavior of the UUV. The linearized equations were written in a much simpler form as shown below in Equation (12)

$$\dot{\delta} + 2\sqrt{C_1 C_2}\,\delta = 0 \Rightarrow \dot{\delta} = -2\sqrt{C_1 C_2}\,\delta \tag{12}$$

where

$$C_1 = \frac{\rho A b n}{MkL}\left(\frac{A^2\omega^2}{2} - U^2\frac{A^2 k^2}{2}\right)$$

and

$$C_2 = \frac{1}{2M}C_D\rho S$$

The given Equation (12) can be considered to have real roots only if C_1 and C_2 are greater than 0. C_2 consists of all positive terms. But C_1 gives negative values, if the free stream velocity of water is so significant that the UUV is not able to overcome it with the thrust produced (i.e. negative thrust when $U > U_c$). So as long as the UUV travels in a water body with a very low free stream velocity ($U \ll 0.25$ m/sec), the system

converges to be stable. It is observed that the positive thrust is generated for all values of omega, as shown in Figure 3 & 4.
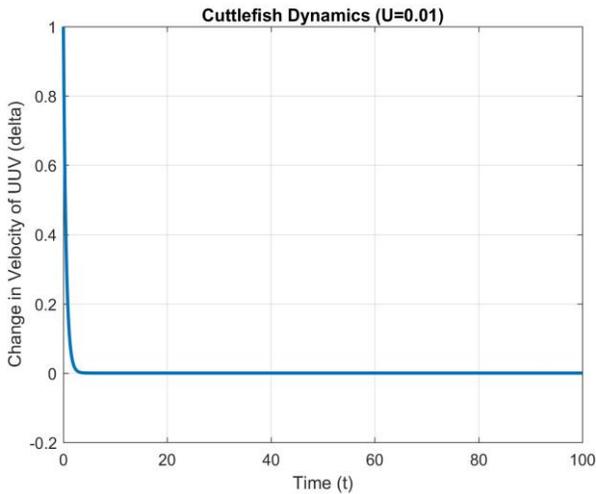
Figure 3: Variation of velocity of UUV at U=0.01m/s
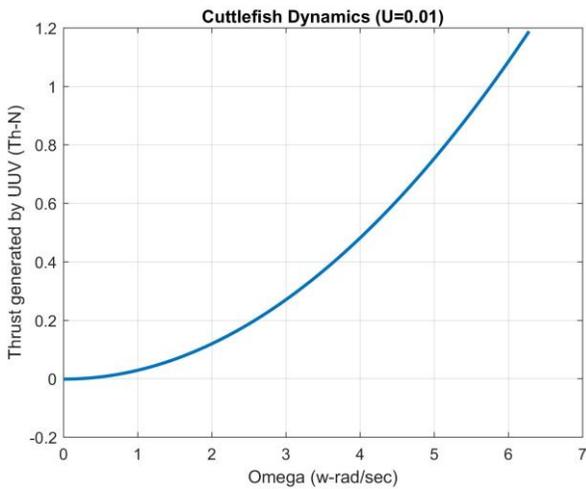
Figure 4: Variation of thrust by UUV at U=0.01m/s

For the condition of free stream velocity (U=0.25 m/sec), it is observed that even though the velocity indicates stable system, it is observed to have negative thrust. As indicated in Figure 5, the UUV takes some more time to converge to a stable operation. As the velocity is increased, the UUV just produces enough thrust to become positive, as shown in Figure 6. The thrust generated is utilized mostly in overcoming the free stream velocity.

As the free stream velocity (U>0.25 m/sec) goes beyond the critical value, the UUV is observed to have both unstable motions and also negative thrust, as shown in Figure 7 & 8. Hence the system behavior can be assumed to be just simply stable without any control input. Though the system is observed to have the instability bounded, the free stream velocity is considered to be a constant value. In real application they

would vary and we would like to increase the limits of operating range of stream velocity, in which the UUV can perform stable operation. Hence it would require a control input to achieve the same.
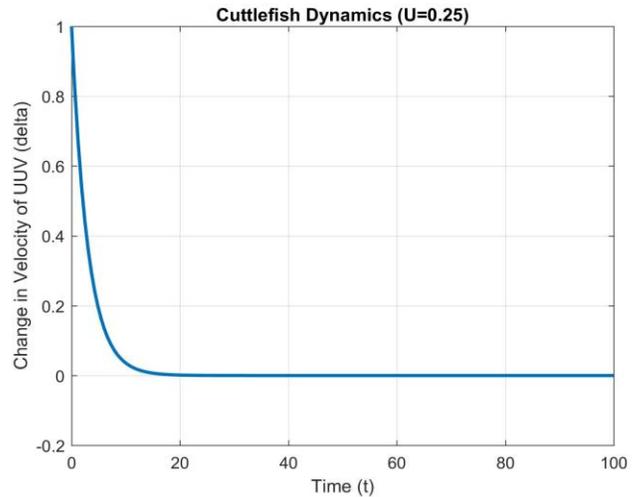
Figure 5: Variation of velocity of UUV at U=0.25m/s
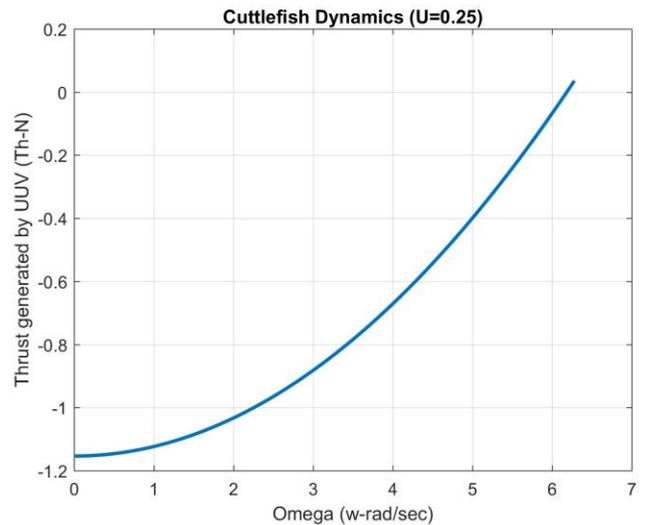
Figure 6: Variation of thrust by UUV at U=0.01m/s
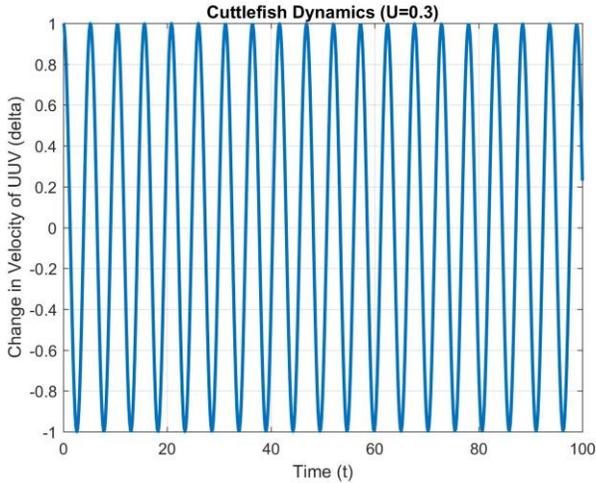
Figure 7: Variation of velocity of UUV at U=0.3m/s
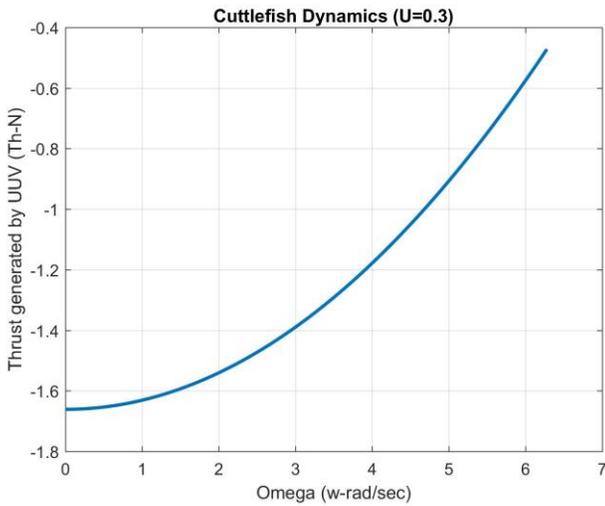
Figure 8: Variation of thrust by UUV at U=0.3m/s

The assumptions indicated above can also be verified mathematically, using the eigenvalues of the system matrix. By substituting Equation (12) in Equation (11) and updating the constants we get the following state space form of the model which can be observed as Equation (13)

$$\frac{d}{dt}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -2\sqrt{C_1C_2} \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 2C_1 \end{bmatrix} \qquad (13)$$

The eigenvalues of the system matrix for different values of free stream velocity (U) are evaluated. It is evident from these eigenvalues that the system is simply stable at lower values of U and becomes simply stable due to zero real parts of eigenvalues. The system can be made stable by introducing a proportional control (negative feedback) over the velocity of UUV as indicated in Equation (14)

$$\dot{\delta} = -2\sqrt{C_1C_2}\delta - K\delta \qquad (14)$$

The state space model (Equation 13) gets updated as follows in Equation 15

$$\frac{d}{dt}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -2\sqrt{C_1C_2} - K \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 2C_1 + K \end{bmatrix} \qquad (15)$$

Considering a proportional gain value of K=5, we get the eigenvalues of the system matrix having negative real parts, hence the systems is asymptotically stable. The dynamics of the UUV model was also simulated using SIMULINK in accordance with the state space models, as shown in Figure 9.
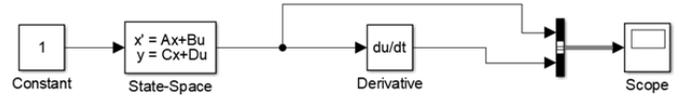
Figure 9: SIMULINK model of UUV

As mentioned above the output from the Simulink model also indicated similar trends for the forward moving velocity of UUV, as indicated in Figure 8.
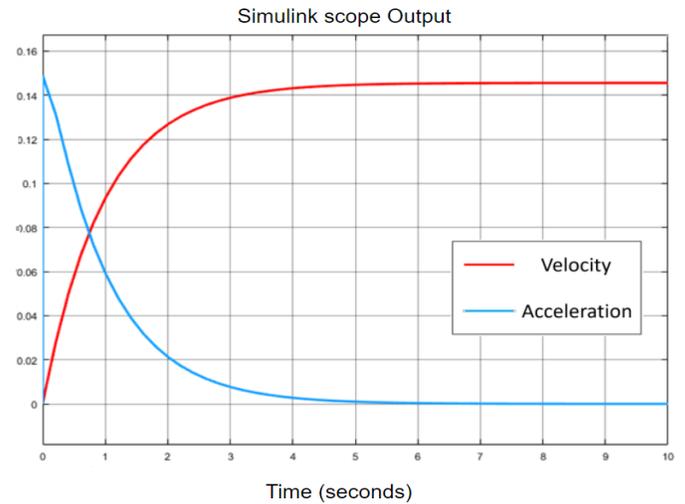
Figure 10: Variation of velocity (blue) and acceleration (red) of UUV at U=0.01m/s

The plot in Figure 10 shows how the velocity of the system reaches its steady state value after approximately 5 seconds. This time can be reduced through tweaking system parameters. Multiple iterations were run and the system outputs recorded for each run. The UUV performance was seen to be highly enhanced at the ideal mechanism scenarios as evident from Figure 11. The maximum velocity increases along with a decrease in settling time. This scenario lets the UUV maneuver at a free stream velocity of 0.25 m/s.
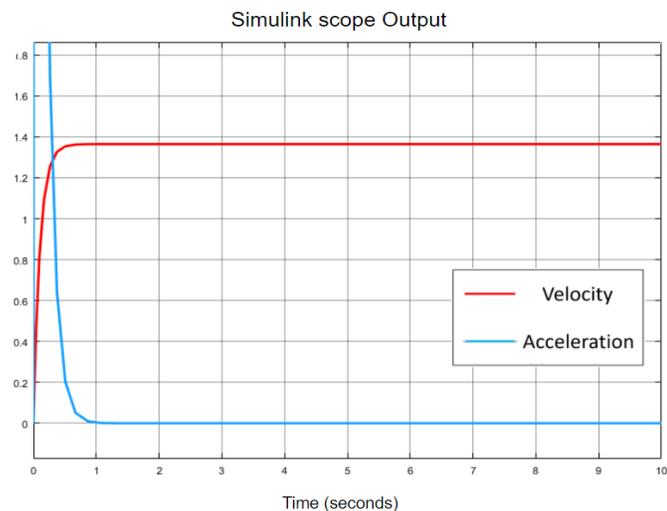
Figure 11: Variation of velocity (blue) and acceleration (red) of UUV at U=0.25m/s

At U = 0.3 m/s the system behavior changes. The system starts behaving erratically. After normalization, the system output is as in Figure 12. The UUV starts going along the stream which is undesirable. This demands the addition of a control system. As mentioned earlier, a proportional control system was added. After the addition of a proportional control of K = 5 (as seen in equation 15), the system behavior is as in Figure 13. The system attains steady state quicker than the uncontrolled system. Also, the simulated UUV moves ahead opposing the stream velocity. Hence, the simulated UUV shows desirable behavior.

Figure 12: Response of the UUV simulation at U = 0.3m/s without a proportional controller.

Figure 13: Response of the UUV simulation at U = 0.3m/s with a proportional controller.

CONCLUSIONS

The results of the analysis suggest that the maximum propulsive force largely depended upon the frequency of the traveling wave. For the demo and testing model that was created, the amplitude was a fixed quantity due to design constraints.

The system behavior after adding the proportional gain values, seems to have made the system stable, but it still lacks enough thrust to overcome the free stream velocity. As the current design is only capable to reach a maximum speed of 3.04 rad/sec for the fin rays undulating motion and maximum amplitude of 0.114 m, we restrict the application of the UUV to the steady water or in water flow with low free stream velocity.

Figure 14: Assembled prototype

Future plans include studying the nonlinearity associated with the undulated fin locomotion comprehensively along with the stability margins of operation. This includes time varying factor of mass of water displaced, accounting for the nonlinear factors in the UUV motion. Also revising the crankshaft that drives the rays such that they rotate efficiently and minimize the

drivetrain energy loss due to friction and performing extensive tests underwater with the experimental UUV model. The data collected will be used to validate the simulation results with the empirical data. Additionally, a sliding mode controller will be implemented after testing the mechanical behavior of the UUV. Controllability and maneuverability will be improved with feedback provided by adding onboard accelerometers and gyroscopes in the future.

ACKNOWLEDGMENTS

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