2007 IEEE International Conference on
Robotics and Automation
Roma, Italy, 10-14 April 2007

Micro Autonomous Robotic Ostraciiform (MARCO): Design and Fabrication

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Abstract— **This paper presents the design and fabrication of a robotic Ostraciiform. The robot's design is inspired by the highly stable and fairly maneuverable boxfish. Boxfish with its multiple fins can maneuver in confined spaces with a near zero turning radius and it has been found that its unusual boxy shape is responsible for a self correcting mechanism that makes its trajectories immune to water disturbances. The Micro Autonomous Robotic Ostraciiform (MARCO) project aims to apply these features in a novel underwater vehicle design. Miniature underwater vehicles with these characteristics have a variety of applications, such as environmental monitoring, ship wreck exploration, inline pipe inspection, forming sensor networks, etc.**

Tail fin hydrodynamics have been investigated experimentally using robotic flapper mechanisms to arrive at a caudal fin shape with optimal shape induced flexibility. Fluid simulation studies were utilized to arrive at the body shape that can result in self correcting vorticity generation. The robotic ostraciiform prototype was designed based on the above results. Ostracifform locomotion is implemented with a pair of 2-DOF pectoral fins and a single DOF tail fin. The finalized body shape of the robot is produced by 3d prototyping two separate halves.

I. INTRODUCTION

Autonomous Underwater Vehicles (AUVs) are being used extensively for a variety of applications ranging from environmental monitoring to oil and gas exploration [1]. However, these AUVs are not suitable for applications where the vehicle has to explore confined spaces like ship wrecks or oil pipe lines, where maneuverability and stability are more important than speed. Tasks such as these call for designs that are small, maneuverable and precisely controlled. The present work is a step towards realizing such Micro Underwater Vehicles(MUVs). In this paper, the design and fabrication of Micro Autonomous Robotic Ostraciiform (MARCO), a biologically inspired MUV design, is presented. The design is based on experimental flapping fin hydrodynamic results [2] and simulation studies conducted to arrive at a self stabilizing body shape [3](See Fig. 1, Bio-inspired design process).

A. *Overview of Biomimetic Underwater Robots/Vehicles*

In order to improve the performance of AUVs in terms of efficiency and maneuverability, many researchers have proposed biomimetic propulsion systems that swim using flapping fins rather than rotary thrusters. The effort to exploit unique locomotion characteristics found in a variety of fish for use in underwater robots includes understanding the physics of flapping fin propulsion, designing electro-mechanical architecture (motors and mechanisms) that can mimic the motion of the appendages, and formulating the control structure so the robot can effectively "swim". In the following paragraphs, the authors present a brief outline of the main swimming styles found in fish and their robotic counterparts. Sfakiotakis et. al. [4] present a good review of fish swimming modes targeted at roboticists interested in aquatic locomotion.

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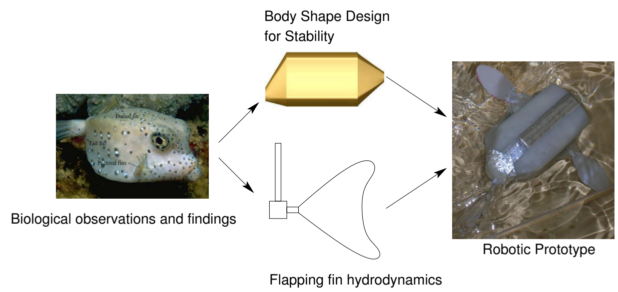

Fig. 1. Bio-inspired design process.

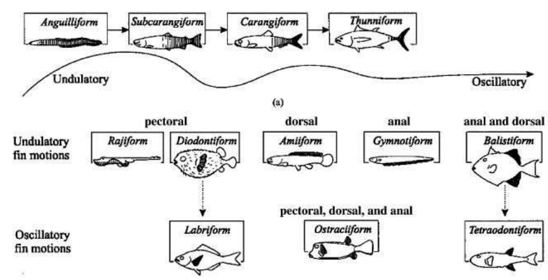

Fig. 2. Fish classification based on swimming styles originally appeared in [5] and modified in [6]

Fig. 2 shows a classification scheme of fish locomotion mechanisms. It was originally presented in [5] and was modified in [6]. The three main swimming styles are characterized by undulatory body motion, undulatory fin motion, and oscillatory fin motion. A more traditional classification is one proposed by Breder [7] that broadly identifies two styles of swimming: one is Body and/or Caudal Fin (BCF) locomotion, and the other is Median and/or Paired Fin (BMP) locomotion. Fish classes that use varying degrees of body undulation and/or caudal fin oscillations for thrust generation are examples of BCF swimming, and fish that use paired fins like the left and right pectoral fins, dorsal, and ventral pelvic fins for thrust generation are classified under the MPF

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swimming style.

The undulatory to oscillatory motion continuum (see the first row of fish in Fig. 2) has been the primary focus of fish-robot design. Anguilliform has the maximum undulatory motion, and can be characterized by a transverse wave traveling through the length of the entire body. In Carangiform through Thunniform, the body undulatory motion is confined only to the posterior third. Ostraciiform was initially believed to be at the oscillatory end with an oscillating tail fin for propulsion. However, recent biological observations indicate that Ostraciiform's multiple fin structure does much more than "sculling the tail" [8]: boxfish use a variety of fins in different gaits depending on the propulsion speed, a behavior that enables them to minimize recoil movement (unwanted deviation that results from flapping) and maintain more constant energy usage. Most recently, Bartol et. al. [9], [10] have found that a body shape with keel structures plays an important role in correcting body orientation in the presence of disturbances by shedding counter rotating vortices.

MIT's Robotuna, built by Triantafyllou's group [11], marked the beginning of the biomimetic approach in underwater vehicles. The design is based on carangiform locomotion. Barrett et. al. [12] demonstrated that the highly articulated robotic fish experienced less drag with undulatory motion than that seen without body undulation. Zhu et. al. [13] from the same group also identified a vorticity control phenomenon, which explains the interaction of the vortices shed by the undulating body and the ones in the wake shed by the tail fin. Such interaction of the body with the wake was also shown to reduce the muscle activity in fish [14].

Anguilliform requires a greater amount of body undulation and thus more degrees of freedom must be connected in series to form a robot design of this type. McIsaac and Ostrowski [15] studied motion planning and control of a serial chain robotic eel, REEL. They have generated gaits (time functions of the joint angles) for the straight and turning motions of 3-link and 5-link robots. MacIver et al. in [16] presented some aspects of underwater vehicle design in the areas of sensing and motion mechanisms of a knifefish in [17].

The Biologically Inspired Robotics Group (BIRG) at EPFL presented a swimming and crawling robot, BoxyBot [18] that is "loosely inspired by the boxfish". The focus there was to mimic boxfish-like switching of swimming modes under different speed ranges. Prior to this work was Berkeley's centimeter Micro Swimming Robot, which realized three flapping fins using piezoelectric actuation.

Currently, a new class of "biorobotic" underwater vehicles based on the biomimetic principles of flapping foils are being designed. These platforms do not necessarily mimic the locomotion style of a particular fish class, but employ fin designs and motion kinematics that are the result of experimental and computational fluid mechanics work. Licht et. al. [19] presented the design of a vehicle platform with four heaving and pitching foils. A team of ocean engineers, fluid mechanists, and biologists proposed a concept vehicle taking advantage of high efficiency foils in combination with articulated pectoral fins with rays for enhanced maneuverability [20]. Pulsatile jet formation loosely inspired by squid is presented in [21]. Kato's Bass III [22] is the latest 3 DOF pectoral fin based vehicle designed for low speed precise maneuvering.

Bandyopadhyay [23] presented a comprehensive review of approaches on various fronts of biomimetic underwater vehicle technology like high lift generating fin hydrodynamics, vehicle maneuverability using pectoral fins, muscle-like actuators and neuroscience based control.

In the MARCO project, the authors are building palm sized, maneuverable, multiple fin underwater robotic prototypes. The outer shape that encloses the multiple fin mounted chassis is designed like the shape of the spotted boxfish to mimic the inherent self correcting mechanism. Earlier studies on optimal fin design and body shape can be found in [2] and [3] respectively. In this paper, the design and fabrication of the robotic prototype that incorporates these findings is presented.

II. Design Of Boxfish-like MUVs: Hydrodynamics And Stability

Boxfish found in tropical coral reefs is an elegant swimmer with a rigid box-like shape and multiple oscillating fins to cruise and maneuver. It is known for its ability to swim smoothly through turbulent waters of coral reefs and exhibit excellent maneuverability[24], characteristics desirable in an underwater vehicle[25]. Bartol et. al., in their breakthrough article [9] explained that the bony shape (with dorsal and ventral keels) of Smooth trunkfish (*Lactophrys triqueter*) enables it to generate self-correcting forces to keep its trajectory immune to instabilities in water. In a more recent paper [10], they have found similar "body induced vortical flow" mechanism in other classes of tropical boxfish with different carapace shapes. Thus, in case of boxfish inspired underwater vehicles the design problem of bio-mimicry comprises of both the body shape and coordinated fin motion.

A. Flapping Fin Hydrodynamics

This study has two objectives: to arrive at the best experimental fin shape and motion parameters for implementing flapping fin based motion in the MUV, and to model the hydrodynamics forces, to the required complexity, for use in the controller design and system simulation. Towards this end an experimental setup consisting of a robotic flapper and a mini tow tank facility has been created. Optimal fin shape-flexibility has been investigated using different fin shapes and material [2]. A summary of the results is presented here for completeness.

The shapes considered have a systematic progression of flexibility due to change in geometric parameters. The boxfish like fin shape (see Fig. 3) was used as the template to vary the fin geometry. To change the chordwise flexibility, the dimensions c_1 and c_2 have been varied while fixing the aspect ratio (h_2/h_1) and the total area of the fin. This kind of parametric variation displaces the center of pressure of the fin, thus varying the degree of flexing.

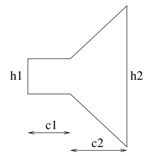

Fig. 3. Shape template used to vary the tail fin shape. See TableI for the values of c_1 and c_2 for the shapes considered.

TABLE I

SHAPE PARAMETERS OF THE TEMPLATE (SEE FIG. 3) FOR SHAPES S1 TO S4.

shape	c_1(in cm)	c_2(in cm)
S1	4.00	4.11
S2	3.01	4.57
S3	2.02	5.02
S4	1.00	5.50

Four shapes (labeled S1 to S4) from this continuum have been considered experimentally. Table I gives the geometric dimensions. The shapes were cut from 0.6mm thick Delrin, 0.1mm thick Polyimide, and 0.6mm thick Polyethylene in order to look at them over a range of material stiffness. In fact, from a flexibility point of view all twelve shapes (four profiles, three materials) form a continuum of EI values, which have a strong correlation to the amount of flexing [26]. Each shape/material combination (with the exception of shape S1 of Polyethylene) has been flapped harmonically at frequencies ranging (in 0.1 Hz intervals) from 0.3Hz to 0.8 Hz, while being towed at a speed of 0.08 m/s. The Strouhal number is a non-dimensional number that relates the forward velocity, U to the flapping frequency, f as:

$$St = \frac{fw}{U} \tag{1}$$

where w is the wake width. In our case, w was treated as the width of a single fin stroke, or

$$w = 2l \sin \theta_0 \tag{2}$$

where l is the total length of the fin and sensor (which is placed in between the fin and the base of rotation), and θ_0 is the angular amplitude. We define the non-dimensional thrust and drag coefficients as:

$$C_T = \frac{2F_x}{\rho A U^2} \tag{3}$$

and

$$C_D = \frac{2F_y}{\rho A U^2} \tag{4}$$

where F_x and F_y are forward thrust and side way components of the force vector in the horizontal plane, ρ is the density of the fluid and A is the fin area. η is defined as a measure of forward propulsive efficiency:

$$\eta = \kappa \frac{F_x U}{M_z \omega} \tag{5}$$

The denominator in Eq. 5 is taken as a measure of the torsional power required to drive the fin where M_z is the moment measured by the force sensor and $\omega(= 2\pi f)$ is the circular frequency of flapping. κ is a non-dimensional scaling constant.

Fig. 4 and 5 shows the variation of C_T and η over the four fin shapes of different materials (Delrin, Polyimide, and Polyethylene). The criteria for fin selection should be high values for C_T and η over a range of frequencies. Caudal fin flapping frequency is one of the key parameters that has to be changed to control the speed of the MUV. Thus, having good thrust production and high efficiency over a range of frequencies is desirable. Shape S3 of Polyimide clearly is the best choice as indicated by the C_T and η values. The choice was based on the above parameters and not compared to that of a real boxfish.

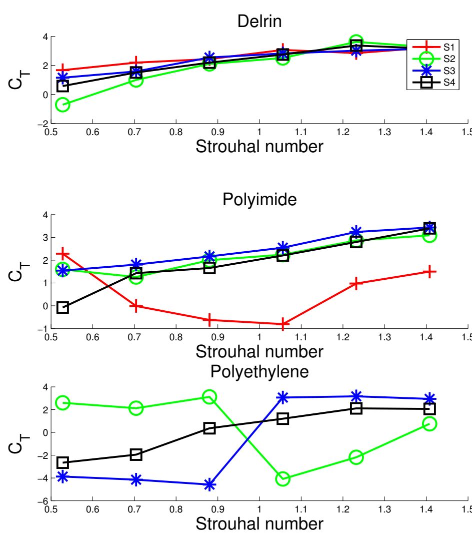

Fig. 4. Variation of C_T with Strouhal number for the fin shapes considered.

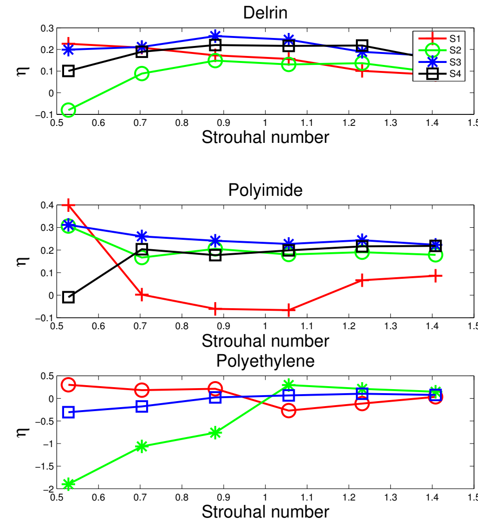

Fig. 5. Variation of η with Strouhal number for the fin shapes considered.

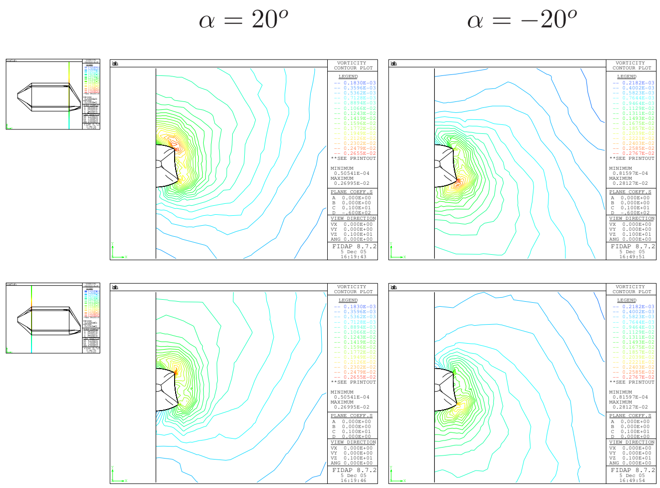

Fig. 6. Vorticity contour maps at various cross sections (as seen from the rear of boxfish) of the spotted boxfish for pitch angles of attack $\alpha = 20, -20$

B. Body Shape Design for Self Stability

As a part of MUV design fluid flow simulations on boxfish like shapes are used to determine the morphological features responsible for the counter rotating vortices responsible for the self stability[10]. Design guidelines for engineering the outer shape of the MUV are derived from this study [3]. The main morphological features of the boxfish shapes are captured in the solid models at various cross sections like the mouth, eye-ridge, peduncle etc., and extrusion and loft features are used to join them in a way the overall shape resembles that of the boxfish. The solid models were then exported in IGES format into the mesh generation software, GAMBIT. The model is kept in a brick volume. The volume of the brick (minus the boxfish volume) is meshed using random tetrahedral elements. Shape functions were defined to make the mesh more refine on the surface of the boxfish. A laminar steady state flow was solved in FIDAP. Flow at different pitch and yaw angles were used to study the vorticity generated around the boxfish body. The Reynolds number (Re) used was based on the total body length as the characteristic and varied from 100-1000. Here are some key findings:

- Results of Spotted Boxfish and the Buffalo Trunkfish indicated that the regions of concentrated vorticity for pitch and yaw disturbances were similar to those reported in Bartol et. al.
- The variation of the cross section along the length of the body determined, for pitching in particular, the regions of concentrated vorticity. Whereas the keel sharpness had a more pronounced effect on the yaw stability.

Fig. 6 shows sample vorticity contours for flow disturbances at 20 and -20 degrees of pitch angles. Concentrated vorticity can be clearly seen near the regions of sudden change in cross section. Detailed results for different shapes and angles of attack can be found in [27].

III. Robotic Prototype

Following sections describe the various elements of the robotic prototype design. The robotic prototype of the boxfish consists of a chassis with flapping units for the pectoral and caudal fins. The outer body shape is rapid prototyped and assembled on the chassis in left and right halves.

A. Fin Placement and Degrees of Freedom

The boxfish employs a total of five fins to effectively maneuver. Biologists have observed three main swimming gaits employed at three different speed levels[8]. The design issue is how many of these fins can be practically implemented in a small underwater vehicle and how many degrees of freedom are used for each fin motion. For effective planar maneuverability, the degrees of freedom have to be distributed around the body. Our present design incorporates a single DOF flexible tail fin for propulsion and a pair of 2 DOF pectoral fins for steering (yawing) and diving (pitching). Although the dorsal and anal fins of boxfish are believed to play a role in generating low recoil movement [8] (by canceling the moments induced by other fins), they are not included in the design due to size constraints. The shape of the pectoral fins was based on the actual shape of the boxfish. The caudal fin flexility and shape were determined through the hydrodynamic experiments.

The 2DOF pectoral fins use flapping and rotational motion in the so-called rowing mode. Rowing mode is a drag based thrust generation stroke with a full cycle of the fins. The power stroke is a quick backward push of the oil with the chord length perpendicular to the flow. A recovery stroke invovles bringing back the fin with the chord length parallel to the flow. The rotation DOF is used to change the orientation of the fin at stroke reversals. This type of system can generate substantial turning movements about the body center of mass for sharp turn boxfish[24]. The pectoral fins can also be used effectively as lifting surfaces by holding them at a suitable angle of attack to an oncoming flow.

B. Mechanisms for Fin Motion

A coaxial wrist mechanism that is similar to the robotic flapper design presented in [2] for fin hydrodynamics experiment. The difference is that there is no deviation DOF and the gearbox size has been downsized to a 2 cm $\times$ 2cm $\times$ 2cm volume using the smallest off-the-shelf miter gears available. The tail fin mechanism consists of a gear stage between the tail fin shaft and the motor shaft.

The fin kinematics of the robotic boxfish can be described by relations between the actuator rotation angle and the corresponding fin DOF rotation. The side fin flapping and rotation angles are coupled due to the no-slip condition of the wrist bevel gear contact. Forward kinematics of the pectoral fin are given by:

$$\theta = G_t^{\theta} \cdot G_w^{\theta} \cdot \theta_m \quad (6)$$

$$\phi = G_t^{\phi} \cdot G_w^{\phi} \cdot \phi_m - G_w^{\phi} \cdot \theta \quad (7)$$

and that of the tail fin simply by:

$$\psi = G^{\psi} \cdot \psi_m \quad (8)$$

TABLE II
ROBOT PARAMETERS

Size and weight			
Length	Width	Height	Weight
15cm	9.2cm	8.5cm	490gm
Fin transmission gear ratios			
G_t^θ	G_t^ϕ	G_w^ϕ	G^ψ
0.75	1.33	1	0.75

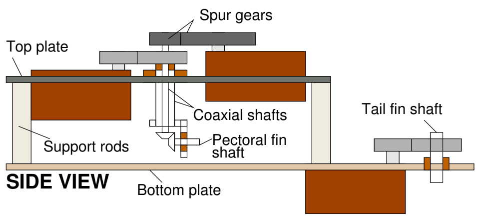

Fig. 7. MUV chassis

where Gs are appropriate gear ratios. The robot size parameters and the gear ratios can be found in Table II. Subscripts t and w indicate the top plate and the wrist mechanism and super scripts indicate the DOF angle.

C. Chassis Design

The pectoral fin mechanism requires the motors driving it to be placed above the wrist mechanism. A parallel plate structure has been used to place the pectoral fin motors in front and above the wrist gear box. The electronic chips were placed on the top plate along with the pectoral fin motors and transmission mechanism. The battery pack, tail fin motor and transmission are mounted on the bottom plate. The plates are made out of 0.125 inch thick Delrin sheet. A CNC mill was programmed to machine all the features on the plates.

D. Actuators and electronics

Actuator selection is one of the most important factors governing the size of the MUV. Accurate positioning of the fin flapping angles is required to control the force generation for turning and cruising. Servo motors with built in feedback are used in place of a DC motor and encoder combination. All the servos are daisy-chained to a servo controller that drives them to the position commanded by the processor.

The onboard electronics include a Javelin-Stamp$^{\text{TM}}$microprocessor module by Parallax Inc. and a serial motor controller PCB unit by Pololu Inc. The power supply for the motors, motor controller, and processor is provided by a pack of five 1.2V NiMH batteries. The microprocessor can be programmed using an embedded Java version. A Java class routine is used to command the motor controller in serial communication mode using a built in UART object. Object class files for different sensors can be easily incorporated into the program.

E. Outer Shape

The outer shape of the MUV was rapid prototyped using the stereolithograhy (3D printing) technique. Features for assembly and fin placement have been incorporated onto the shape. To seal the robot, we used layers of adhesive tape and oil resistant film along the dividing line. The fin extensions were covered with latex sheet and attached to the shaft with a plastic O-ring. The latest configuration of the robot is one in which the body shape is assembled in diagonal halves as shown in Fig. 8. This makes the sealing the tail fin easier as compared to the earlier version where the tail fin sealing and the robot body sealing has to be done at the same area. Fig. 9 shows the swimming prototype.

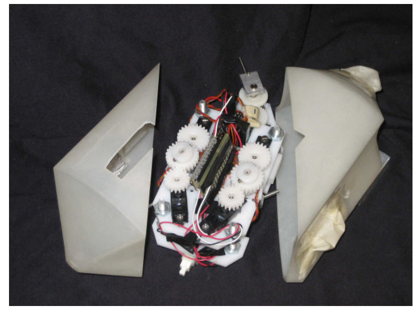

Fig. 8. Latest MARCO configuration with body shape mounted using diagonal halves for better sealing of the tail fin, which is now entirely covered with the right half.

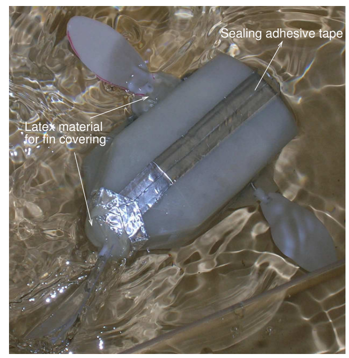

Fig. 9. Swimming prototype

F. Buoyancy and Center of Mass

For the robot to be neutrally buoyant, the weight force must be equal to the buoyancy force. The buoyancy is determined by the volume of oil (experimental trials were conducted in a low viscosity, clear oil to avoid electrical shorting) displaced by the solid model. Copper bars, machined to fit underneath the chassis plates, were used to balance the buoyancy force and the weight force. The heaviest parts, such as the batteries and large copper plate, were designed to fit in the lower region of MARCO. The robot was designed to have inherent stability by having the center of mass below the center of buoyancy. The location of the center of mass was found by hanging the boxfish from a string at different points and taking an image. Each image was overlaid on top of one another and a line drawn to extend the string. The approximate point of intersection of the lines was the experimental center of mass.

G. Experimental Trials

The current robotic prototype can be programmed to use different gait styles. The gait for the trials was a constant forward propulsive force that was alternatively applied by the caudal and pectoral fins. A CCD camera, by Allied Vision Technology, operating at 30 fps was used to record swimming trials and determine speed, recoil movement, and turning radius. The robot was run under the field of view of the camera and each image was saved in National Instrument's Vision Assistant for LabVIEW. A Virtual Instrument (VI) was created to calibrate the pixels to real world units of inches. Each image was then sequentially analyzed for the speed, recoil, and turning radius. The speed and turning radius were measured by the change in position of a point on the robot and a constant point in the field of view. The average speed obtained was 0.0411 m/s with an almost zero turning radius. The recoil can be measured by the deviation in each frame from the straight line between the beginning and end points. The average recoil was found to be 0.826 cm.

IV. Conclusions and Future Work

In this paper, the design and fabrication of a biomimetic micro underwater vehicle, MARCO has been presented. The design attempts to achieve the maneuverability of a small scale, multiple fin underwater system like that of the boxfish, while incorporating a body with a self correcting mechanism. Our ongoing work on flapping fin hydrodynamics supports the fin shape selection for optimal thrust generation, and simulation studies on body shapes were used to prototype the outer shape of the robot. One of the immediate goals is to use the prototype to evaluate the efficiency of various gait patterns involving fin coordination for a given set of flow conditions. Sensors and command architecture will also be used in future generations to give the robot greater autonomy. Currently, new mechanical sealing techniques and more processing power are being incorporated into the next generation of the prototype to facilitate longer trial runs and effective control of the robot.

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