The Shrimpfish as a Model for a Novel, Highly Maneuverable AUV

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Abstract – The shrimpfish, Aeoliscus strigatus, is an Indo-Pacific marine fish with a highly unusual posture – vertical with its head down – and remarkable maneuvering capabilities. It can translate straight up and down, turn in place and hover. These capabilities enable the shrimpfish to maneuver through complex tropical marine environments such as coral reefs and eel grass beds, and insert itself between the spines of sea urchins. Shrimpfish also use their maneuverability to track and capture tiny mobile crustaceans within the water column. An autonomous underwater vehicle (AUV) with such capabilities would have a number of interesting and potentially important applications in underwater inspection, sensing and sensor deployment. It will also serve to push the field of marine robotics into a challenging new area. We present the first results of a two-pronged biology and engineering research effort with the ultimate goal of developing an AUV with shrimpfish-like maneuverability. Biological measurements on real shrimpfish were performed to determine its hydrostatic stability. On the engineering side, a simple shrimpfish-inspired vehicle was developed as a testbed to study how fin motion can generate the different swimming behaviors seen in living Aeoliscus.

Keywords – Shrimpfish; Aeoliscus strigatus; biomimetic robot; pectoral fin swimming; AUV

I. INTRODUCTION

The shrimpfish, *Aeoliscus strigatus* (order Syngnathiformes), is an Indo-Pacific marine fish [1] with a highly unusual posture – vertical with the head down – and remarkable maneuvering capabilities. It can translate straight up and down, turn in place and hover [2, 3]. These capabilities enable the shrimpfish to maneuver through complex tropical marine environments such as coral reefs and eel grass beds, and insert itself between the spines of sea urchins. Shrimpfish also use their maneuverability to track and snatch tiny mobile crustaceans out of the water column. This is an impressive example of coordination of visual perception, eye tracking, and body motion in 3-dimensions to grab a free-swimming object less than 1/100 the length of the animal within fraction of a second. Yet another remarkable aspect of shrimpfish is their ability to form schools that exhibit tightly coordinated motion. When startled they can move and rotate in synchrony [3, 4] apparently in an attempt effort to keep their thin sides oriented toward a potential predator rendering them less visible.

Aeoliscus strigatus (Fig. 1) reaches an adult length of 20 cm, its blade-like rigid body is only few mm's wide on the dorsal side tapering to almost nothing on the ventral side, hence its other popular name "razorfish." *Aeoliscus's* normal posture is head down and when it is translating forward the dorsal side leads. Anterior-most on the fish is a long tube-shaped snout terminated with a small trap-door mouth similar to that of the seahorse (its phylogenetic cousin). Posterior to the mouth, moving upwards, are a pair of large eyes, the gills and a pair of large and very active pectoral fins (Fig. 1). These fins are in constant in motion and seem to be the major propulsors of *Aeoliscus*. They often move in antiphase, biasing the fins downward causes the fish to move upward, and in forward motion they can behave like typical flapping fins [5]. Moving further posterior are the slender ventral fins which possess few fin rays. Near the posterior-most end of the fish is a remarkable cluster of all the median fins: anal, caudal and dorsal, grouped together in a posterior-ventral orientation. This group appears to act together as a rudder for turning. The median fins also display complex motions both individually and in coordination with each other. Their role in propulsion and maneuvering is unknown and is a ripe area for study. *Aeoliscus* can turn on single axis that we have observed to correspond roughly to the dorsally-positioned spinal column. The posterior-most tip of the fish, the highest point, is terminated with a hinged spike whose function is unknown. The dorsal side of the fish is devoid of fins, the dorsal having migrated posterior and ventral. *Aeoliscus* has an elongated swim bladder in the dorsal side of its body.

A fish, like any vehicle moving in a fluid, represents a compromise between stability and maneuverability [6] [7]. A hydrostatically stable vehicle will, by virtue of its geometry and mass distribution, automatically generate forces to counteract a perturbing force in order to return it to its original orientation. A hydrostatically unstable vehicle will fall out of its original orientation in response to an external force and needs to expend energy to maintain a particular, fixed orientation. Hydrostatic stability is advantageous if the stable orientation is the desired state, as in a buoy. Hydrostatic stability is not desirable, however, if the vehicle needs to quickly maneuver in an energy efficient way. Hydrostatic stability depends on the relative positions of the center of gravity (CG) and the center of buoyancy (CB). Many fish are unstable along one or more axes and use forces generated by their fins to maintain posture for functions such as sensing, feeding and for stealth [7]. Knowledge of the hydrostatic stability of the shrimpfish is a key element to the design of a

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bio-inspired vehicle and is the topic of the biological side of this paper.

Biomimetic robots have dual functions that cross engineering and biology [8]. They serve as platforms to assess the utility of biological mechanisms (e.g. flapping fin propulsion) in artificial systems such as robots. They can also serve as hyper-instrumented surrogate animals to test hypotheses for advanced biological investigations. We are developing a biomimetic robot to study how the many unusual aspects of the shrimpfish (body shape, posture, fin configuration and fin kinematics) all contribute to the fish's high maneuverability. Flapping fin (aka foil) robots of similar design to ours have been developed by others e.g. [9] [10], however, they mimicked more typical, horizontally oriented fish. Our vehicle will enable the exploration of slender vertically oriented flapping fin robots.

II. Biological Measurements

A. Biological Measurements

1) Materials and Methods

Wild-caught shrimpfish were obtained from a commercial supplier. The fish were maintained in a 110 liter recirculating aquarium containing artificial seawater at a salinity of 1.025 a temperature of 25° C, a pH of 8.3 and a 10/12 light/dark cycle. They were fed twice daily on juvenile Artemia enriched with marine microalgae and a fatty acid and vitamin supplement.

For anatomical and hydrostatic measurements the shrimpfish were euthanized by immersion in a solution of tricaine methanesulfonate (MS222) at a concentration of .5g per liter of seawater from the colony tank. For all of the following procedures a euthanized shrimpfish was kept immersed in seawater between measurements to maintain its state of hydration. The seawater in which the measurements were made was taken from the shrimpfish colony tank.

The standard length (Table 1) of the shrimpfish was measured from the tip of the mouth to the joint of the tail spike. This measurement was chosen because the tail spike was frequently broken or in various states of regeneration. The distance from the tip of the mouth to the base of the pectoral fin was also measured (Pec Fin Base, Table 1). The maximum dorsal to ventral depth (Depth, Table 1) of the fish was measured at the level of the pectoral fins. The maximum width of the fish (left to right dimension, Width, Table 1) was measured at the level of the gills (the widest part of the fish). Linear measurements were made with a digital caliper.

Mass (M_g) was defined to be the mass of the fish out of water with external water removed but with its internal water retained (Wet Mass, Table 1). Internal water included the water in the tubular mouth and the gills. To measure mass a euthanized shrimpfish was held by the thumb and forefinger and shaken 3 times to remove the external water. It was then placed in a dry, tared weighting boat and weighed on a digital balance with a resolution of .001g and a linearity of .002g.

The mass of the water displaced by the shrimpfish, M_d (Displacement, Table 1) was measured as follows. A vertically-mounted glass tube with a fine horizontal line was filled with seawater to the level of the line The line and water level were observed with a low-power, horizontally mounted microscope. The euthanized fish was placed in the tube, raising the water level by the volume of the fish, and the water was carefully removed to reduce the level back to the horizontal line. The removed (displaced) water was weighed on the same digital scale as was used for the wet mass measurement. This method automatically accounts for the density of the seawater. Since acceleration due to gravity (g) is constant we found it convenient to use mass (in grams) as a surrogate for force, thus the "force of gravity" corresponds to M_g and the "buoyant force" corresponds to M_d. The net buoyancy (M_{bnet}) is simply the difference between the mass (M_g) of the fish and the water displacement mass (M_d).

$$M_{bnet} = M_g – M_d \qquad \text{(eq. 1)}$$

Buoyancy was also expressed as a percent of the wet mass (last column, Table 1):

$$\% \text{ Buoyancy} = (M_{bnet} / M_g) \times 100 \qquad \text{(eq. 2)}$$

The center of gravity (CG) location measurement method was based on the fact that an object in air that can freely rotate about a single point comes to rest with its center of gravity directly below the suspension point. This is known as the plumb line method for 2-D CG location [11]. A shrimpfish was suspended in air by impaling it on a horizontally mounted insect pin. The fish was rotated about the pin until it swung freely. It was then allowed to come to rest. Near the fish was a plumb line consisting of a thread held vertical with a small weight. An image of the fish was taken with a 1 megapixel digital video camera coupled to a 35 mm f3.5 lens. The camera was controlled using LabView Vision Assistant software (National Instruments, Austin TX, USA) running on a PC and the images were stored as JPEG files. Illumination was provided by a DC-powered flood lamp. This procedure was repeated two more time for a total of three different suspension points. The third suspension point, though not absolutely necessary, was used to increase the accuracy of the measurement. The three measurements were taken in rapid succession to prevent loss of water from the body. Adobe Photoshop (Adobe, San Jose, CA, USA) was used to transfer each plumb line to the body of the fish by drawing a line over the image of a plumb line and shifting the line (with no rotation) over the fish until it intersected the suspension point. The new image of the fish plus plumb line was saved and the procedure was repeated for the images with the other two suspension points. The three images were then overlaid and the images of the fish bodies aligned. This resulted in a single image of the shrimpfish with three intersecting plumb lines indicating the position of the CG. This procedure determined the location of the center of gravity in the antero-posterior direction from the tip of the mouth (CG, A-P, Table 2) and dorsal-ventral direction from the dorsal side (CG, D-V, Table 2). These distances were normalized to the standard length (Norm. CG, A-P), and to the maximum depth of the fish (Norm. CG, D-V, Table 2). The 3-dimensional location of the

CG was assumed to be on the midplane of the body due to its left-right symmetry.

The location of the center of buoyancy was determined by slowly immersing a fish into a tank of seawater until its weight was reduced by ½ of the buoyant force. The CB is along the line on the body at the air-water interface. A euthanized shrimpfish was glued to a white plastic plate with cyanoacrylate glue. We glued the snout (anterior) end to the plastic plate thus keeping the head out of water to prevent air bubbles or addition/loss of water through the mouth and gills from affecting the measurement. The plate was bolted to an aluminum strut that was attached to the below weighing point of the digital balance. The fish plus mount was tared and the fish slowly lowered into a tank of seawater. The negative weight of the fish slowly increased until it was equal to ½ of the buoyant force. A digital image was taken of the fish and the procedure was repeated two more times with the fish in different orientations. For each image the line corresponding to the air-water interface was drawn across the body using Adobe Photoshop. The three fish images were then overlaid and aligned resulting in a single fish image with three lines intersecting at the center of buoyancy. Between each measurement the fish was kept wet by pipetting with seawater. As with CG, this procedure determined the location of the center of buoyancy in the antero-posterior direction from the tip of the mouth (CB, A-P, Table 2) and dorsal-ventral direction from the dorsal side (CB, D-V, Table 2). These measurements were normalized to the standard length (Norm. CB, A-P, Table 2), and to the maximum depth of the fish (Norm. CB, D-V, Table 2). The 3-dimensional location of the CB was assumed to be on the midplane of the body point due to its left-right symmetry.

The surface tension of the water added a bias to the CB measurement by introducing a small downward force on the fish. This problem was overcome in two ways. First only larger shrimpfish were used for these measurements reducing the size of the surface tension force compared to the buoyant force. Second, a surfactant was added to the water to reduce the surface tension force. BRIJ 35 Wetting Agent (Ricca Chemical Co., Arlington, TX, USA) was added at a concentration of approximately .25 ml in 3 liters of seawater. The surfactant was mixed thoroughly and bubbles removed from the surface prior to the CB measurement. To test the validity of our measurement techniques a control consisting of a negatively buoyant solid rectangular bar of PVC (76.2 mm x 12.3 mm x 6.3 mm) with known, coincident CB and CG. Suspension measurements for CG and CB were performed in the same way as were done on the shrimpfish. CB measurements were made in seawater and in seawater plus surfactant.

2) Results

The measurements of 5 fish are presented (fish 7 – 11 in Tables 1 and 2). Fish 1 – 6 were used to perfect the techniques of CB measurement. *Aeoliscus* is negatively buoyant with a net buoyancy ranging from about 4.49 to 15.23 percent of the wet mass. The CG and CB results were normalized to the standard length and maximum depth of the fish to allow for inter-fish comparisons. The control results are presented in Table 3.

III. The Shrimpfish robot

Our current Model 1 shrimpfish robot (Fig. 2) consists of two pectoral fins each actuated by two waterproof RC servos allowing two degrees of freedom per fin. The proximal servo adducts and abducts the fin in relation to the body. Orthogonal to the proximal servo is the distal servo which pitches or feathers the fin (Fig. 2 inset). The fin assemblies are attached to a horizontal aluminum U beam that is coupled to a vertical aluminum tube that serves as the rigid spine of the robot.

An RC servo is a position-controlled device, the commanded position is represented by the pulse width of the PWM control signal sent to the servo. By transmitting a rapid succession of position commands the servo can be made to rotate through a specific trajectory. For the fins on our robot a sinusoidal trajectory was generated on each servo. The combined action of the two servos on a fin generated thrust for a specific maneuver: forward translation, vertical translation and turning. An Arduino Mega microcontroller (www.arduino.cc) generated four PWM signals to control each axis of the fins simultaneously. The Arduino was tethered to the robot by a cable containing the control lines plus power lines for the servos. Power was supplied externally. Different movements and movement parameters were selected by a user interface consisting of a number of potentiometers and switches read by the Arduino. Control programs were written in the Arduino programming language.

Experiments with the tethered robot were performed in a 1000 gal. tank. For some experiments, the robot was tethered but unconstrained. In other experiments we limited motion to the horizontal plane by extending robot's spine and coupling it to a horizontal rail (mounted across the top of the tank) with a Tee fitting that slid along the rail. We have demonstrated horizontal translation and turning with the two fins moving in phase and in anti-phase for both constrained and unconstrained experiments. The anti-phase motion mimicked the natural motion of *Aeoliscus's* pectoral fins. Substantial side to side rolling was observed in these experiments. Vertical translation was demonstrated in experiments with the unconstrained robot in which the pectoral fins operated in phase but with a downward bias to create a net upward thrust.

IV. Discussion and Conclusions

When examining the center of buoyancy, our method showed that surface tension had a significant effect on our measurements. When the tip of the fish would break the water's surface, the apparent weight of the fish increased due to the surface tension "pulling down" on the fish. To attempt to minimize the effect of the surface tension a surfactant was introduced into the seawater. The validity of this method was tested using a PVC bar of uniform density and a known CG and CB.

The results of our experiment show that the surfactant altered our normalized experimental results by about 1% (Table 3), increasing the accuracy of the method. However the surfactant did not completely neutralize the effect of surface tension on our measurements; there still existed an approximately 0.7% error between the known CB and the normalized experimentally measured CB. A 0.7% change applied to the averaged CB leads to an averaged normalized CB position that is less than 1% different from the averaged normalized CG position in the anterior-posterior direction (Fig. 1). With this correction, our results show that the CG and CB are at the approximately same position along the long axis of the fish. Our results also show that the CG is dorsal to the CB by about 8.7% along the dorsal to ventral axis. We don't know if the dorsal to ventral separation of the CG and CB pitches the fish forward (counterclockwise in Fig. 1) to a passively stable orientation. Alternatively, given the small and difficult to measure forces involved and the potential errors in our measurements, the CG and CB may be essentially coincident and *Aeoliscus* is neutrally stable. Careful studies of the posture of live and freely-sinking euthanized fish are needed to resolve this issue.

Our Model 1 shrimpfish biomimetic robot shows the feasibility of generating shrimpfish-like motion with a simple, low-cost system. Horizontal translation, turning in place and vertical translation were demonstrated. The side to side rolling was likely due to the absence of stabilizers present in the real fish in the form of its relatively broad body and the posterior cluster of median fins. We are currently developing a Model 2 shrimpfish robot with an actuated posterior fin to mimic the rudder-like aspects of the median fin cluster of the real fish. The new robot's relative CG and CB locations will match that of the real fish. Parallel studies on the fin kinematics of real shrimpfish will yield parameters that will enable the programming of fin actuation patterns with greater biological fidelity.

Shrimpfish-inspired vertically oriented hovering AUVs may have important applications in underwater inspection, exploration and object retrieval, for example: (i), a slender, stick-like, underwater robot that can smoothly maneuver in between the twisted wreckage of a downed airplane or collapsed bridge to take images and to sense contaminants emanating from the wreck; (ii) a similar robot making micro-scale chemical measurements within the nooks and crannies of a coral reef for a high spatial resolution study of reef damage due to ocean acidification; (iii) a slender robot that can be inserted into a well hole or a crack in a fuel tank for close-up visual inspection while simultaneously taking samples and making chemical/physical measurements; and (iv) a vertically oriented hovering AUV that can serve as a midwater "virtual buoy" to position a vertical array of acoustic transducers. From a research point of view, a shrimpfish-like robot will serve as a testbed for the study of sensory-motor coordination in fish and for the development of advanced sensory-motor coordination algorithms in marine robots. *Aeoliscus's* food catching system mentioned in the introduction, for example, would be a great model for such work.

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Fish	Standard Length (mm)	Pec Fin Base (mm)	Depth (mm)	Width (mm)	Wet Mass (g)	Displacement (g seawater)	Net Buoyancy (g)	Buoyancy as % of mass
7	116.9	48.4	13.4	3.7	1.582	1.514	-0.068	-4.49
8	117.7	50.1	12.8	3.3	1.543	1.484	-0.059	-3.98
9	127.8	52.8	13.7	4	2.178	2.037	-0.141	-6.92
10	125.8	52.2	13.4	3.7	1.995	1.885	-0.11	-5.84
11	114.4	49.5	12.8	3.8	1.528	1.326	-0.202	-15.23

Table 1 Dimensions, mass and buoyancy measurements of five shrimpfish, *Aeoliscus strigatus*. See *Materials and Methods* section for explanation of the measurements.

Fish	Std. Length (mm)	Depth (mm)	CG, A-P (mm)	Norm. CG, A-P	CG, D-V (mm)	Norm. CG, D-V	CB, A-P (mm)	Norm. CB, A-P	CB, D-V (mm)	Norm. CB, D-V
7	116.9	13.4	51.3	0.439	4.51	0.337	49.9	0.427	5.33	0.398
8	117.7	12.8	55.6	0.472	4.21	0.329	53.2	0.452	5.52	0.431
9	127.8	13.7	59	0.462	4.94	0.361	57	0.446	5.76	0.420
10	125.8	13.4	58.7	0.467	4.65	0.347	56.7	0.451	5.73	0.428
11	114.4	12.8	54.3	0.475	4.45	0.348	53.2	0.465	6.12	0.478
Ave.				0.463		0.344		0.448		0.431

Table 2. Locations of the center of gravity (CG) and center of buoyancy (CB). See *Materials and Methods* section for explanation of the measurements. Normalized dimensions were averaged across all fish studied (Ave.).

	CG, A-P (mm)	Norm. CG, A-P	CG, D-V (mm)	Norm. CG, D-V	CB, A-P (mm)	Norm. CB, A-P	CB, D-V (mm)	Norm. CB, D-V
Actual	38.1	0.5	6.147	0.5	38.1	0.5	6.147	0.5
w/ Surf.	37.950	0.498	6.11	0.497	37.600	0.493	6.13	0.499
w/o Surf.					36.770	0.483	6.13	0.499

Table 3. Data from control, a rectangular PCV bar with known, coincident CB and CG. Actual measurements made with a digital caliper. Center of gravity measurements were made in air, surfactant not relevant. Center of buoyancy measurements were made with and without surfactant (surf.).

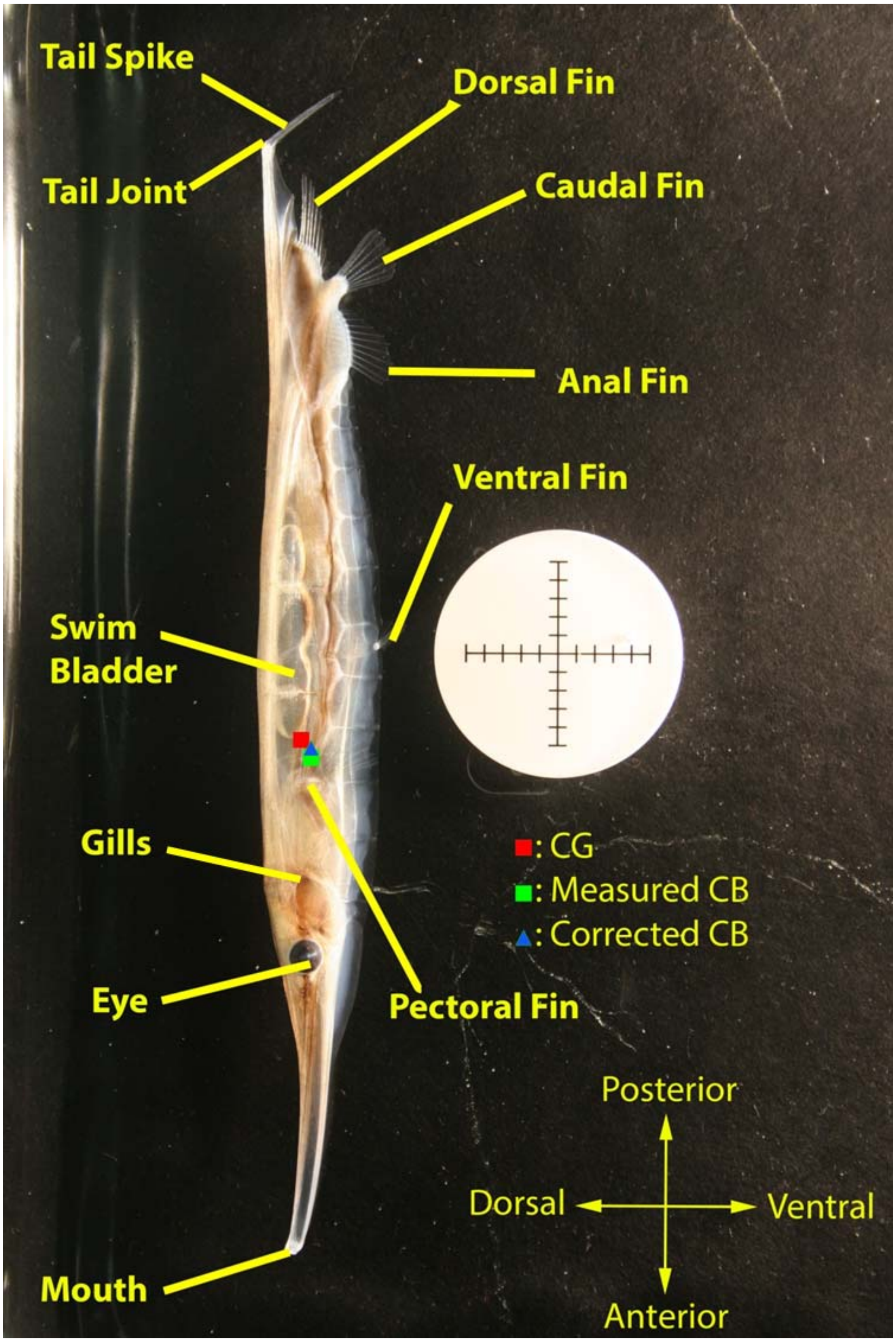

Figure 1. The shrimpfish, *Aeoliscus strigatus* in its normal head-down swimming posture. Scale is 2 cm in both directions. The swim bladder has become distorted due to the preservation of this specimen in 10% neutral buffered formalin. CG (red square), center of gravity; CB (green square), center of buoyancy; corrected CB (blue triangle) takes into account the effects of surface tension on the measurement, see text.

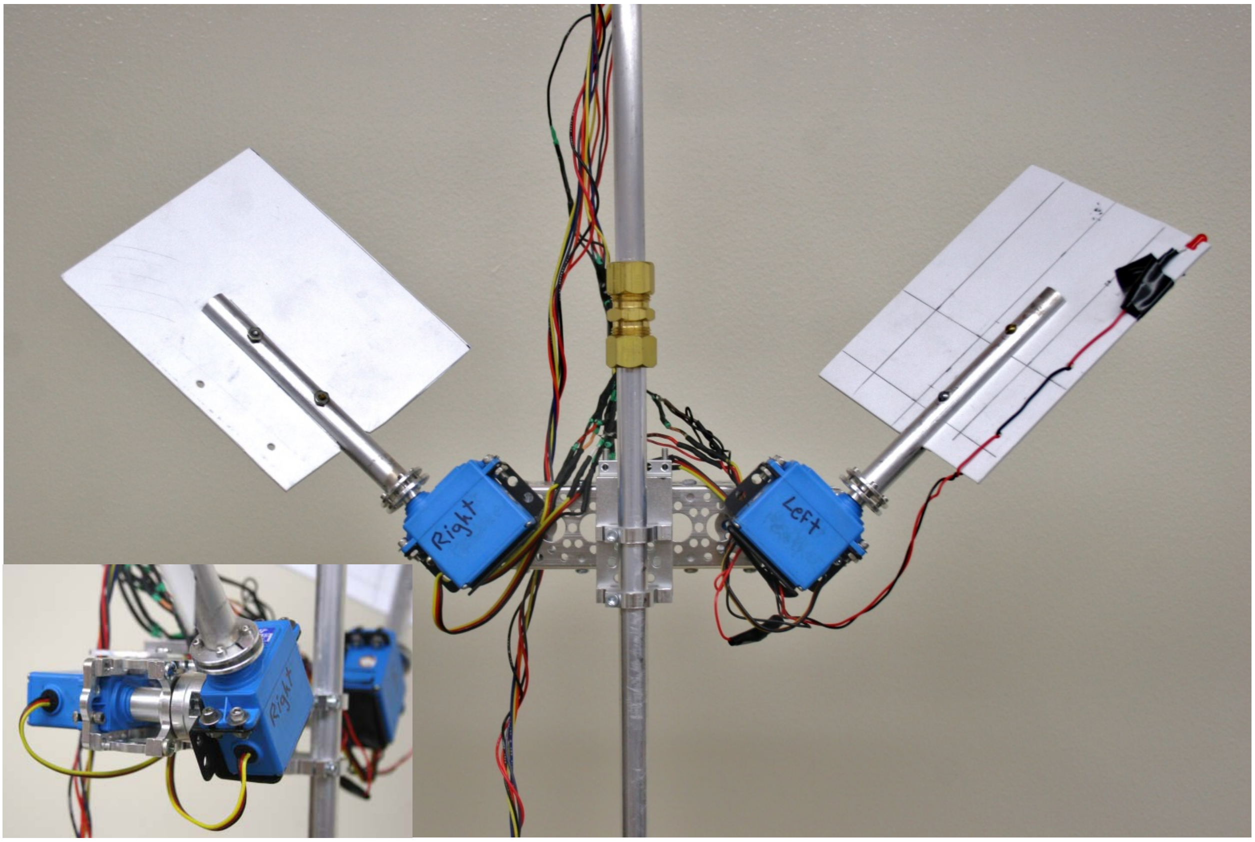

Figure 2. Model 1 Shrimpfish Robot, dorsal view. Two styrene pectoral fin plates are each driven by two RC servo motors. Inset shows the proximal adduction/abduction servo (left) coupled to the distal pitch or feathering servo (right). Fin dimensions: 135mm x 115mm