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A Biorobotic Pectoral Fin for Autonomous Undersea Vehicles

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Abstract - **A biorobotic fin for autonomous undersea vehicles (AUVs) was developed based on studies of the anatomy, kinematics, and hydrodynamics of the bluegill sunfish pectoral fin. The biorobotic fin was able to produce many of the complex fin motions used by the sunfish during steady swimming and was used to investigate mechanisms of thrust production and control. This biorobotic fin is an excellent experimental tool and is an important first step towards developing propulsive devices that give AUVs maneuvering characteristics that match and exceed those of highly maneuverable fish.**

I. INTRODUCTION

We have undertaken a research program designed to develop a propulsor for autonomous undersea vehicles (AUVs) that is based on the pectoral fin of the bluegill sunfish (*Lepomis macrochirus*). Fish represent a category of biological systems that have performance characteristics which have not been achieved using traditional engineering approaches [1]. Many species of fish are highly maneuverable and have remarkable control over their body position even in turbulent flows. These abilities are the direct result of their fins being highly conformable control surfaces that can produce and vector thrust in three dimensions. The paired pectoral fins, in particular, are important for executing high and low speed maneuvers and for enhancing high speed stability. By using only the pectoral fins, bluegill sunfish are able to able to hover, conduct yaw turns, roll about their long axis, and translate backwards and forwards at low speeds [2, 3]. It is believed that by studying the movements of the pectoral fins and borrowing appropriately from their design, that a human engineered propulsor can be developed to give AUVs superior levels of control and maneuverability.

Based on studies of the anatomy, kinematics, and hydrodynamics of the sunfish pectoral fin [3, 4] we have developed a biorobotic fin that borrows from the biological fin's design and that can reproduce closely the biological fin's movements. The motions of the sunfish pectoral fin during swimming are highly complex and involve the fin being cupped about its spanwise axis, a sweep of the fin away and towards the fish's body, changes in the fin's shape and area, the reorientation of the fin about its base, and a dynamic interaction between the flexible fin and the water. These types of movements are common among many bony fishes, but are not modeled well by the "rowing" and "flapping" kinematics that have traditionally been used to describe the motions of fish fins and the wings of insects [5, 6] and that have been used previously to guide the design of robotic pectoral fins [7, 8, 9]. As a result of these complex motions, the bluegill pectoral fin is able to produce relatively high levels of thrust and low lateral and lift forces. Tests conducted with the biorobotic fin in a water tank have shown how the fundamental movements of the fin contribute to the production and control of thrust.

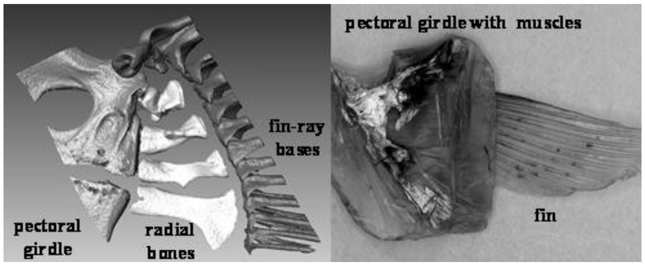

Figure 1: Bluegill sunfish pectoral fin (right) and micro-tomography images of the pectoral girdle (left).

II. DESIGN OF THE ROBOTIC FIN

The design of the biorobotic fin was based heavily on the anatomy of the sunfish pectoral fin (Figure 1). The sunfish pectoral fin is comprised of 14 fin rays that are sandwiched between two layers of a thin, flexible membrane. The fin rays are made of two segmented bony halves called hemitrichs. The base of each hemitrich is attached to a cartilage pad which sits on top of the radial bones and scapula of the pectoral fin girdle. The girdle resides just within the body of the fish. The arrangement of the fin rays and bones in the pectoral fin girdle has obvious similarities to the fingers and metacarpals of the human hand [10], and allows the base of the fin to be twisted and reoriented and the fin rays to still be swept forward and back. Each fin ray is actuated by two pairs of abductor and adductor muscles

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that attach to the fin ray base. There are no tendon attachments within the webbing of the fin. The two most dorsal fin ray fins are fused and have three extra muscles, presumably to provide additional control over the movement of these rays [3]. The fin is naturally very flexible, but its stiffness and shape can be controlled by manipulating the fin ray elements. The fin rays behave much like bilaminar strips such that the curvature of each fin ray can be controlled by contracting the abductor/abductor muscle pairs and displacing the base of one hemitrich relative to the other.

The basic design of our biorobotic fin uses five fin rays embedded in a flexible urethane webbing (Smooth-On Inc., Easton PA) (Figures 2 and 3). The webbing is pleated so that it can be expanded easily. Its linear measurements are 2 to 3 times that of the biological fin. The bases of the fin rays are attached to a compliant base mechanism that serves a similar purpose as the radial bones and cartilage pad in the sunfish – it supports the fin rays, but is flexible and allows the base of the fin to move and be reoriented. The compliant base is mounted to a rigid foundation plate which connects to an array of servomotors (Hitec RSD Inc., model 645 MG). The servomotors control the fin rays via nylon tendons which pass through channels in the foundation plate and tie to the base of the fin rays. This design is a simplification of the sunfish anatomy, but the components retain similar functionality to their biological counterparts.

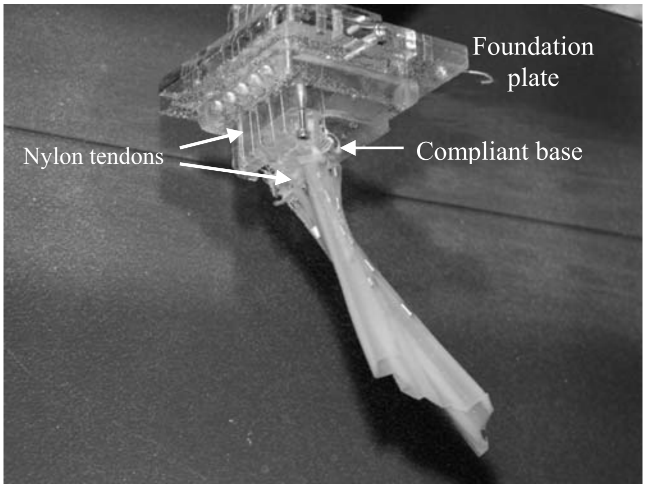

Figure 2: A five fin ray biorobotic fin moving in flow tank.

The fin rays were built using stereo-lithography so that they could be designed and constructed easily with fine details and individual mechanical characteristics. The fin rays have two hemitrichs that lead into a single notched element (Figure 3). The lengths and taper of the hemitrichs and the lengths of the notched elements were manipulated to adjust the fin ray's passive stiffness and its ability to curl when the bases of the hemitrichs were displaced. Like the biological fin ray, small displacements at the base cause there to be a large displacement at the tip of the fin ray. Thin copper strips are wrapped around the hemitrichs to prevent the hemitrichs from bowing when the fin rays are curled. These are equivalent to transverse fibers in the biological fin rays. At the base of the hemitrichs are holes to which the tendons are attached.

The compliant base mechanism supports the fin rays and serves as a compliant joint about which the fin rays are moved (Figure 3). The compliant base was cast using a liquid urethane with a modulus of elasticity of approximately 1.2 MPa. The bases of the fin rays sit atop head and neck structures in the compliant base and are held in place by the tension of the tendons. The compliant base is segmented to allow it to bend. Its shape is designed to provide support primarily in the X direction, but to allow the fin to be cupped by flexing around the Z axis, expanded in area by bowing about the X axis, and despite these changes for the fin rays to still be swept forward and back about their Y axes. The degrees of freedom provided by this compliant design would have been much more difficult to achieve with a rigid hinged mechanism. Its flexibility also allowed the fin to be manipulated and moved in manners that were not originally intended.

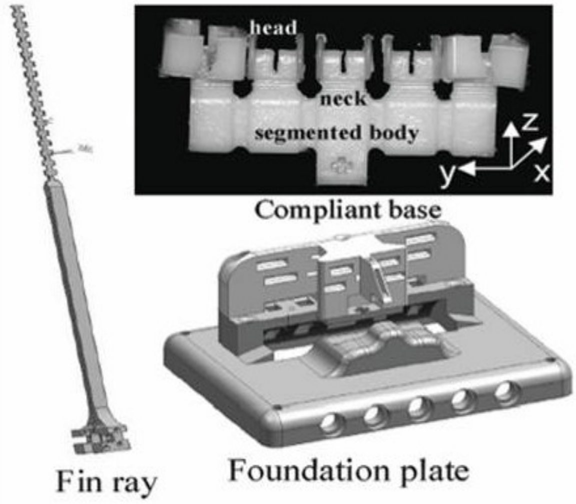

Figure 3: Component parts of the biorobotic fin.

The compliant base mounts to a rigid foundation plate (Figure 3) which connects the fin to the actuator module and contains the channels through which the tendons pass. The positions of the channels defined the paths through which the tendons moved the fin ray bases. How well the fin was able perform certain movements was therefore very sensitive to the placement of these channels. The best positions and channel angles were found through trial and error. The plate was built using stereo-lithography which greatly enhanced the speed at which design changes could be made and implemented.

The actuation of the fin rays was designed to enable the fin to execute four motions that had been identified as fundamental to the biological fin's movement. These component motions were identified by applying proper orthogonal decomposition (POD) to the fin's displacements during steady swimming [11]. The fundamental motions were 1) a sweep of the fin forward and back, 2) a cupping of the fin about its spanwise axis, 3) an expansion of the fin's area in the plane of the fin, and 4) a curl of the distal end of the fin towards the fin's base. The tendon arrangement is shown in Figure 4. Sweep was executed simply by pulling on the front or back of the fin ray base. For expansion, tendons were attached lateral to the midline of each fin base so that the fin was opened like a hand fan. Curl was accomplished using a single tendon that pulled the two bases of a fin ray tightly against the head of the compliant base, and then by pulling the back base up and the forward base down. The cupping motion was created by pulling the most lateral fin rays of the fin forward and towards the midline of the fin.

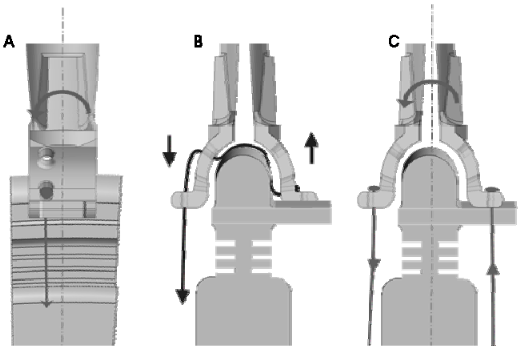

Figure 4: Tendon attachments for expansion (A), curl (B), and sweep (C).

III. PERFORMANCE OF THE FIN

The prototype biorobotic fin created each of the four component motions very well (Figure 5) and was able to combine the component motions to create fin movements that combined gross displacements of the fin with actively controlled conformations of the fin's surface. The fins produced motions that appeared very similar to those used by the bluegill sunfish, and as well were able to create movements such as rowing (feathering plus paddling) [5] that may not be associated with bluegill sunfish, but that might, under certain conditions, be effective for propelling or maneuvering an AUV. The ability to create a rich spectrum of movements enables this biorobotic fin to be used to discover the most optimal fin movements for an AUV. The biorobotic fin's ability to create such a range of motions was due to the many degrees of freedom and level of control that was provided by actuating individual fin rays with multiple actuators, rather than actuating the fin as a single entity with individual pitch, flapping, and rowing motors [7, 9].

One minor problem with the biorobotic fin's design was that the component motions were not completely decoupled from each another. The activation of the curl component caused the fin to move as if sweep was also being activated, and the cupping motion interfered with expanding the area of the fin. Because of this coupling, one could not attribute with complete confidence changes in the fin's motion or thrust production to one particular component motion. However, slight changes in how the component motions were combined, such as by reducing the magnitude of the sweep motors when sweep and curl were used together, made the relation between a particular motion and the forces produced by the fin more clear.

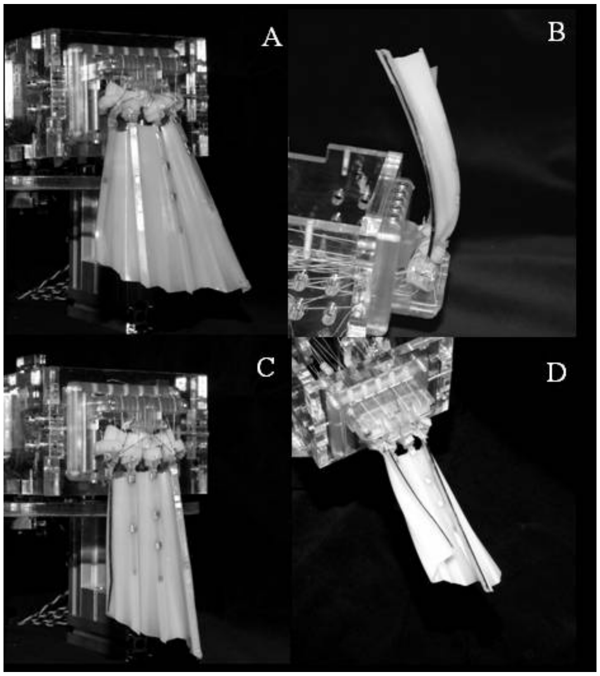

Figure 5: Component motions: expansion (A), curl (B), relaxed (C), and cupping (D).

The thrust produced by the fin was measured by mounting the fin to a carriage that rode on air bearings (New Way, Aston PA) and pushed against a load cell (Futek L2357, Irvine CA). The fin was lowered into a water tank and its motion was cycled between the vertical (90 deg to water's surface) and horizontal using simple sinusoids to drive the sweep, curl, and expansion components. Cupping was driven using a square wave so that cupping was either on fully or off. Sinusoidal velocity profiles are not optimal for producing thrust and reducing drag, but their simple profile allowed for the changes in force to be more easily attributed to changes in the fin's shape or movement rather than to differences in the fin's velocity when being swept forward or back.

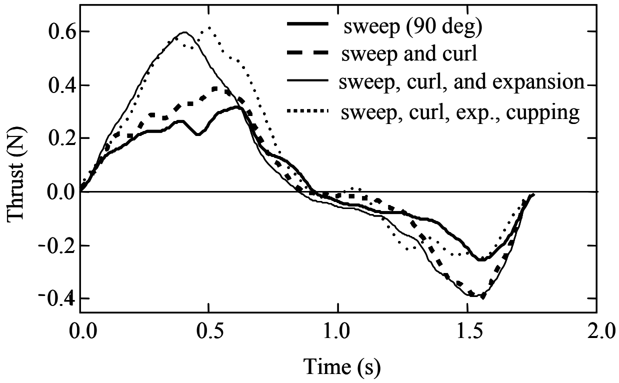

Figure 6: Thrust and drag from different combinations of component motions. The instroke begins at t = 0, and is followed by the outstroke.

	Peak force (N)		Impulse (kg m s^{-1})		
Fin motion	**Thrust**	**Drag**	**Thrust**	**Drag**	**Net**
sweep (90 deg)	0.33	-0.28	0.17	-0.10	0.07
sweep and curl	0.39	-0.40	0.20	-0.13	0.07
sweep, curl, and expansion	0.60	-0.39	0.26	-0.16	0.10
sweep, curl, exp., and cup	0.62	-0.25	0.31	-0.11	0.20
rowing (feather and paddle)	0.48	-0.12	0.19	-0.06	0.13

Table 1: Peak forces and total impulse created by fin.

Representative measures of the thrust and drag forces produced when using combinations of the component motions are shown in Figure 6 and in Table 1. When moved using sweep alone the fin appeared very pliant, and tended to bend at the distal end and along its edges. The fin generated higher levels of thrust than drag and created a net positive impulse, which represents the change in momentum of the water that would act to propel an AUV forward. The addition of curl to the sweep motion made the fin visibly more rigid and increased the magnitude of the thrust and drag. Curl was not activated such that it changed the curvature of the fin, but was used specifically to increase the stiffness of the fin. It did so by pulling the fin ray bases tightly against the head of the compliant base which made each fin ray a more rigid structure. Because both thrust and drag were increased, the net impulse imparted to the water by the fin was not improved by the addition of curl. However, the changes in force demonstrated that the force produced by the fin can be modulated by actively controlling the fin's stiffness. This would provide a means for an AUV to modulate quickly the force produced by the fin without having to alter how the fin is being moved through the water. The activation of the expansion component increased the area of the fin as it was being swept back towards the body (instroke, adduction) by approximately 30%. This had an enormous impact on the fin's thrust, but little on the fin's drag. In the example shown in Figure 6, expansion increased the peak by 54% and the net impulse imparted to the water by 43%. The cupping component, which cups the fin about its spanwise axis during the fin's outstroke (abduction), affected mainly the drag force and altered the duration of the thrust. The peak drag and its impulse were lowered significantly, mainly because the fin was in a more hydrodynamic shape when cupped than when moved through the water as a flat fin. Although the cupping was beneficial to the fin's net impulse, it did not create the hydrodynamic results that were hoped. Experimental and numerical analysis of the cupping motion of the fish fin showed that the cupping motion may enable the fin to produce positive thrust, rather than drag, during the outstroke. This phenomenon was not seen with this biorobotic fin, but will be investigated further using the next biorobotic fin prototype.

IV. CONCLUSION

By taking key design cues from the anatomy of the bluegill sunfish, a biorobotic pectoral fin was developed that could produce motions that resembled closely the complex movements of the sunfish pectoral fin. Because of its many degrees of freedom and high level of control, the biorobotic fin was capable of producing a rich spectrum of motions and was an effective experimental tool for understanding how hydrodynamic force could be produced and modulated. The curl, area, and cupping of the fin's surface were all shown to be effective means of modulating the force produced by a basic sweep of the fin away and back towards the fish, or AUV, body. The development of this biorobotic fin is an important step towards developing propulsive devices that can produce and vector thrust in three dimension and give AUVs superior levels of maneuverability.

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