Conceptual Design for the Construction of a Biorobotic AUV Based on Biological Hydrodynamics

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Abstract— **The incorporation of novel structures and mechanisms from nature into the design and function of machines is being attempted through biomimetics. The goal of biomimetics in the field of robotics is to use biological inspiration to engineer machines that emulate the performance of animals, particularly in instances where the animal's performance exceeds current mechanical technology. Animals are capable of turning within confined spaces that are considerably smaller than those for engineered devices. The development of a conceptual design for a biomimetic autonomous underwater vehicle (AUV) using pectoral fins to effect high maneuverability was considered by a team of biologists and engineers. The maneuvering capabilities of the biorobotic AUV were to be superior to present technologies currently in use. The biorobotic AUV was to be capable of low-speed control, with abilities to translate sideways, up and down, and forward and backward. The design of the AUV also was to permit hovering and to maneuver with very small radius turns. To accomplish these goals, the biorobotic AUV was to be relatively small in size and utilize pectoral fin-like propulsive and control surfaces. The design of the biorobotic AUV incorporated elements distilled from the biological and engineering literature with regard to hydrodynamics. The body of the AUV would be rigid. Control surfaces/propulsors would comprise two sets of four mobile, articulated fins which would be actuated by artificial muscles. Propulsion would be produced by set a fins located on the posterior of the body just anterior to the tapering end. The fins will be arranged in a cruciform pattern with fins in the vertical and horizontal planes. These fins will have a high aspect ratio with a design similar to penguin or marine mammal flippers. The fins will be rigid. Movement of the fins will be controlled at a single joint, allowing for simultaneous heave and pitch. These movements will provide propulsion by a lift-based mechanism. The second set of fins will be based on the low-AR pectoral fins of fishes that use the labriform mode of swimming. The pectoral fins will be located around the center of gravity. These fins will be composed of a flexible membrane. Movement patterns of the pectoral fins will encompass oscillatory paddling and undulation. The position, orientation and movement of these fins will allow for low-speed swimming and maneuverability and allow for station-holding. Paddling movements can be used for maneuvers in conditions where the velocity of the AUV is zero. Activation of individual fins and combinations of fins will permit translational and rotational movements about the three orthogonal axes of the body. Co-ordination of the fin movements could stabilize the body and thereby compensate for external perturbations in the environment (i.e., waves, currents) that generally destabilize a body. The capabilities of the biorobotic AUV fit in well with Naval objectives. Undersea search operations, such as search and recovery and hunting mines, could be performed by the biorobotic AUV.**

***Index Terms*—AUV, biomimetic, biorobot, control surface, hydrodynamics**

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The immense diversity of animals with their particular morphological features presents a rich resource of novel designs that may be incorporated into advanced technologies. The technology associated with the development of robots is becoming more dependent on biomimetics and biologically-inspired designs. The morphology of animals have been copied for development of various technologies [1], [2]. Both machines and animals must contend with the same physical laws that regulate their design and behavior. These behaviors (i.e., maneuverability, acceleration) can be superior to the performance of machines [3].

Animal systems hold the promise of acting as models for robotic systems with improved performance in the aquatic realm [4]-[7]. As matters of energy economy and greater locomotor performance are desired in engineered systems, imaginative solutions from nature may serve as the inspiration for new technologies. The potential benefits from biological innovations applied to manufactured systems operating in water are high speeds, vorticity control, reduced detection, energy economy, and enhanced maneuverability.

In January 2002, an ONR workshop was held to consider the status of the maturity of the science and technology of biology-inspired high-lift devices. One example of such devices was the pectoral fins of aquatic animals like fish. Biorobots incorporating pectoral fins were considered to have potential application as low-speed vehicles that could precisely maneuver and hold station in the high-energy littoral zone. Animals from small fish to large whales regularly operate in the littoral zone. It was proposed that a biorobot had application as a sensor platform, for underwater inspection, for torpedo countermeasures, and in the evolution of naval ship design. To facilitate designing a biorobot as an Unmanned Untethered Vehicle (UUV) and Autonomous Underwater Vehicle (AUV) with biomimetic control surfaces, it was suggested that a team of biologists and engineers review the use and hydrodynamics of pectoral fins in biological systems. Their review would be the basis for the design of a biomimetic UUV.

A description of the morphological variation and maneuvering performance of the control surfaces of nektonic organisms would be beneficial to both biologist and engineers. As maneuvering performance by animals can be superior to human designed technologies, analysis of biological control surface design, composition, and capabilities potentially could be applied to nautical vessels to enhance performance. Nektonic animals have rapid swimming and maneuvering capabilities and can station-hold in turbulent conditions. These characteristics allow these animals to serve as model systems in the development of nautical technologies by avoiding scaling issues. As with ships, UUVs and AUVs, animals swim at high Reynolds numbers (inertial dominated). In addition, significant progress had been made in understanding some of the basic mechanisms of force production and flow manipulation in steadily operating and oscillating foils, for underwater use (Fig. 1); yet a mapping out of all pertinent principles has not been achieved. Conditions for achieving high lift-to-drag ratio have only partially been established, while the issue of cavitation is largely unknown. Biomimetic observations show that there is a lot more to be learned, since many of the functions and details of biological control surfaces, including fish fins and dolphin flippers, remain unexplored.

The control surfaces of animals have different functions including propulsion, maneuverability, braking, trim control, hovering, reverse swimming, and stability [8], [9]. In nature, the control surfaces are used for prey capture, prey acquisition, escape maneuvers, obstacle avoidance, turning in restricted spaces, surfacing, diving, and control of rapid accelerations. Stealth may be an important characteristic of maneuvering with pectoral fins as prey acquisition by a predator often requires approach without detection [10]. Various morphologies within aquatic animal lineages have evolved which foster maneuverability [8], [9], [11]-[14]. Turning performance can be affected by morphology with respect to rigidity of the body, and mobility and position of the control surfaces (e.g., fins, paddles, flippers) determining the level of performance [3], [8], [11], [14]-[16].

Despite the importance of the control surfaces, there has been no comprehensive review of the structure, function, and hydrodynamic analysis of aquatic biological control surfaces. This project teamed biologists and engineers to review the structural design, function, and hydrodynamics of various control surfaces from a variety of nektonic organisms. The review presented data from descriptive, experimental and theoretical studies from the literature. The review attempted to illustrate how engineering techniques can be applied to the study of biological systems [6], [17]-[21]. The review performed a critical analysis of maneuvering systems whether considered valid, fallacious or speculative. Based on the science presented in the review, a conceptual design wais envisioned for an AUV incorporating biological control surfaces for high maneuverability.

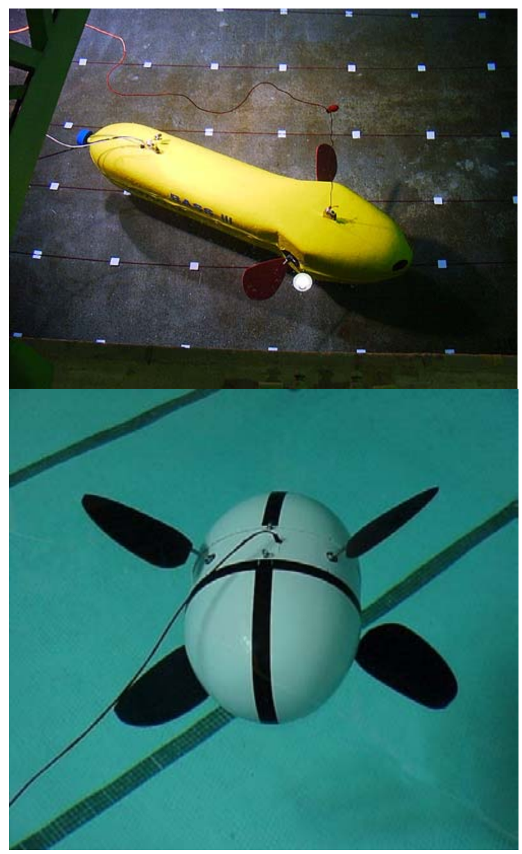

Fig. 1. Biomimetic robots Bass3 (above) and PilotFish (below). Image of Bass3 was provided courtesy of N. Kato and image of PilotFish was courtesy of Nekton Research, LLC.

The goal of this project to design a biomimetic AUV required consideration of the limitations of biology with respect to engineering applications, as well as the advantages.

1. Biological constraints that do not apply to human engineered systems: pros and cons of technology integration

The incorporation of novel structures and mechanisms from nature into the design and function of machines is being attempted through biomimetics. Biomimetics, or what was previously called bionics, attempts to produce engineered systems that possess characteristics, resemble, or function like living systems [22]. The goal of biomimetics in the field of robotics is to use biological inspiration to engineer machines that emulate the performance of animals [7], particularly in instances where the animal's performance exceeds current mechanical technology.

It has been a long standing idea that new technologies can be developed from nature [1], [22]. Because biological designs resulted from the evolutionary Darwinian process of "natural selection", it is considered that animals have already performed the "cost-benefit-analysis", optimizing particular designs for specific functions [2]. Animals have served as the inspiration for various technological developments. Copying animals by the biomimetic approach attempts to seek common solutions from engineering and biology for increased efficiency and specialization [23]. From an engineering perspective, an animal can be described as a mobile vehicle with multimodal sensors tuned to its environment [24]. The diverse morphological specializations exhibited by animals may be targeted by engineers for technology transfer and effectively reduce the time of development of innovative technological solutions.

In aquatic systems, the emphasis on the biomimetic approach has been directed toward the use of locomotor specializations in animals associated with a reduction in energy input while swimming. For over 500 million years, fish and other animals have been able to function and adapt to a fluid environment that is 800 times denser and has 60 times higher dynamic viscosity than air. Machines that are required to work in the aquatic realm encounter the same physical forces of aquatic animals. Both natural and manufactured bodies are subjected to an environment where Archimedes Principle dominates and drag is a major hindrance to movement. Novel developments in engineered systems for operation in the aquatic environment have been produced by both directly copying nature and by insight into independent convergence with animal designs [25]. By examination of processes by which the design of aquatic animals can be adapted to engineered systems, it may be possible to streamline the development of advanced technologies by biomimetic.

What are the limits to the biomimetic approach? Differences between engineered systems and animal systems are apparent. Engineered systems are relatively large in size, are composed of rigid materials, use rotation motors, and are controlled by computational systems that have limited sensory feedback; whereas, animals are generally small in size, are composed of compliant materials, use translational movements produced by muscles, and are controlled by complex neural networks with multiple sensory inputs. In addition, animals are functionally multifaceted (i.e., they move, feed, and reproduce) and must compromise optimal solutions for specialized functions to perform adequately rather than maximally [9], [26].

The potential for the development of new and superior technological designs for enhanced performance based on animal systems has been tantalizing, although elusive [1], [22]. Strict adherence to biological designs is considered to rarely produce any practical results and in some cases can impede the development of engineered systems [1], [22], [27]. For example, airplanes do not flap their wings like birds to simultaneously produce lift and thrust. Such a mechanism is impractical in modern aircraft due to limitations from scaling phenomena and the high speeds attained by commercial and military jets. As a result, the design of aircraft has advanced beyond the size and capabilities of birds for level flight. However, birds did serve as the inspiration for flight and the early development of wing design [28]. Today, interest has focused on the agility of birds to perform complex aerial maneuvers. We cannot fly with the agility of birds because we do not have the brains of birds to control the complex mechanical linkages, while appropriately sensing and regulating the airflow over the propulsor/control surfaces. In this regard, birds demonstrate superior performance to manufactured aircraft.

The laws of physics and the physical properties of structural materials available to biological forms impose constraints on the design of animals [29]. Possible structures and processes that potentially could benefit an organism are not all available. Wheels are not found in animals, despite their ubiquity in manufactured devices and their obvious benefit to energy economy in locomotion. Animals move through forceful contraction of the muscles transmitted to a jointed skeleton by tendonous connections. Therefore, biological systems suffer lower efficiency due to periodic accelerations over a propulsive cycle. Large animals are unable to produce high rates of acceleration, because as size increases the ability of the muscles to generate stresses relative to inertial forces decreases [30].

Animals are multitasking entities. While machines can be designed for a single function, animals must endure compromises in their designs to perform multiple and sometimes antithetical functions. Increased performance by one feature that benefits an organism for a particular function may handicap the organism with respect to another function. Depending on the local environment and immediate selection forces, genetic linkages between traits and pleiotrophic effects can produce changes in one characteristic that produce a correlated effect in other characteristics [31]. In total, the organism as a mosaic of integrated structures and functions may achieve evolutionary success (i.e., survive and reproduce), but not perform optimally for any specific function.

Evolution is not conscious or predictive. Evolution by the theory of natural selection is a response to changing environments. The biotic and abiotic environments of the time that a new design evolves dictate its selection without anticipation for potential future purpose and effectiveness. Indeed, it is difficult if not impossible for any design to be optimized. The environment is nearly always changing producing a non-equilibrium state which places design criteria in a state of constant flux [31]. Both superior and poor designs with respect to present time may be lost if they did not function adequately in past environments or if they were accidentally lost due to chance events. Use of the term 'design' in a biological sense is simply an indication of the linkage between the structure and function of a characteristic possessed by an organism. For biologists, design does not infer construction or organization of an organism's feature toward a specific goal [32].

Another restriction to design is that animals have evolved along lines of common descent with shared developmental patterns. Radical redesigns are not permitted to expedite enhancing performance; instead, it is existing designs that are modified [22]. Within a given lineage, phenotypic change is expressed as variation on theme. Design is constrained by the evolutionary history of an organism. Swimming in whales would be more efficient if these animals remained submerged like fish, because drag increases due to the formation of waves as a body moves in close proximity to the water surface; however, their common evolutionary history with other air-breathing mammals requires that they periodically return to the water surface to fill their lungs despite increased energy cost.

2. Comparison of biological performance with human engineered systems

Animals are capable of turning within confined spaces. Expressed as a proportion of body length (*L*), the minimum turning radius is 0.00-0.47*L* for fish, 0.24*L* for penguins, 0.11-0.17*L* for cetaceans, and 0.09-0.16*L* for sea lions [13], [14], [16], [33]-[36]. The higher minimum turning radius for fish (0.47*L*) was found for the tuna [18]. These fish are thick-bodied and relatively stiff, having specialized for rapid cruising [11]. Squids, that keep the mantle stiff, cannot produce turns of less than 0.5*L* [37]. The shelled *Nautilus* can at best negotiate a turn of 2*L* (Chamberlain, 1990). Encased by a carapace of thickened, suture bony plates, the boxfish *Ostracion* is not limited by stiffness. Boxfish display a minimum *R* of 0.0005*L* [16], which is due largely to rotation. The ability to rotate or spin is dependent on the position of multiple propulsors located about the center of mass.

Animals turn in spaces considerably smaller than those for engineered devices [3], [33], [34], [39]. Submarines with inflexible hulls have turning radii of 2-3*L* [40]. Current operational AUVs display poorer turning performance compared to animals. The REMUS robot has a two-dimensional, minimum turning radius of 3.83 m, which corresponds to a length-specific turning radius of 2.9*L* (http://adcp.whoi.edu/REMUS/docking.html).

In addition to the turning performance expressed as minimum turning radius, animals demonstrate high levels of performance with respect to rate of turn. The maximum turning rate of the sea lion was 690^{o} s^{-1} with a maximum centripetal acceleration of 5.13 *g* (i.e., 5.13 times the gravitational acceleration) [41]. Most turning maneuvers by cetaceans are performed at < 200^{o} s^{-1} and < 1.5 *g*, although turns of 453.3^{o}/s and 3.56 *g* have been measured in fast-swimming *Lagenorhynchus obliquidens* [14]. Penguins have turn rate equivalent to sea lions at 575.8^{o}/s [33]. Fish are capable of higher levels of agility compared to marine mammals. Data from Webb [39], [42], Blake et al. [36], and Gerstner [13] indicate that fish ranging in size from 0.04 m to 0.39 m could turn at rates of 425.6-7300.6^{o}/s. Such performance is extraordinary when it is considered that certain species (e.g., *Salmo gairdneri*, *Micropterus dolomieu*) were able to accelerate to 8.2 and 11.2 times the gravitational acceleration [39]. The experimental submarine USS Albacore was comparatively limited with a turning rate of only 3.2^{o}/s [43].

3. Design specifications of Biorobotic AUV with enhanced maneuvering capabilities

The development of a conceptual design for a biomimetic autonomous underwater vehicle (AUV) using pectoral fins to effect high maneuverability was considered at an all-day meeting held at the Massachusetts Institute of Technology (MIT) on December 19, 2002. The participants in attendance were Dr. Frank Fish (West Chester University), Dr. George Lauder (Harvard University) Dr. Rajat Mittal (George Washington University), Dr. Alexandra Trechet (MIT), Dr. Michael Triantafyllou (MIT), and Dr. Jeffery Walker (Southern Maine University).

In the morning session, participants at the meeting, gave brief presentations outlining information supplied in a review of the literature tasked by the Office of Naval Research. In the afternoon session, the participants were to collectively design a biorobotic AUV based on the available science. Besides basic reviews of biological designs, animal maneuvering performance, hydrodynamics and computational models, the performance and design of currently active AUVs were reviewed (Specification 9, see below).

The design specifications and capabilities suggested for the conceptual design included:

1. An AUV vehicle that can be handled by one or two men.
2. Maneuverability: Low-speed control authority better than that of REMUS; Backout; Translate Sideways, Up and Down, Hover; and very short radius turn.
3. Weight: Lighter
4. Volume: Increase
5. Vibration: Lower
6. Drive: Two options – conventional and unconventional; In Unconventional, replace conventional drives (motors, gears and shafts) by Artificial Muscle.
7. PROPULSOR: Use 4 – 6 or as many prop foils/blades as needed. Each prop foil independently operable to vector thrust to vehicle axis for maneuverability. Foils may be biorobotic penguin wings. If so, make use of MIT Tow Tank data for design.

8. PECTORAL FINS: Use minimal number of independently operable pectoral fins for maneuverability. May use NRL CFD data on Wrasse or such pectoral fins, for design.
9. VEHICLE DATABASE: May consult the following database for vehicles with Pect Fins: Nekton Pilot Fish: US-Japan NICOP Bass Vehicle. CETUS II, which is a non-biorobotic 2 Prop AUV may be consulted, because that vehicle attempts to achieve biorobotic capabilities via 2 props that provide thrust in axes non-parallel to vehicle axis.

Based on the above specifications (1, 3, 4), the biorobotic AUV will be designed around an inflexible, cylindrical body of 0.91 m (36 inches) length and 0.20 m (7.9 inches) diameter with a fineness ratio (FR) of 4.5 (Fig. 1). This FR provides a configuration that gives the minimum drag with maximum body volume [44]. The nose of the AUV will be of conical design, which will allow reduced drag and placement of sensors. The tail will have an elongate conical configuration tapering to a point to reduce drag and wake size. To reduce visible detection, the body should be counter-shaded.

The AUV should be neutrally buoyant at operational depth. Center of buoyancy and center of gravity should coincide at a position located at 50% of body length to enhance maneuvering capabilities [8], [41].

Control surfaces/propulsors will comprise two sets of four mobile, articulated fins actuated by artificial muscles (Fig. 1; Specifications 5-8). This approach of using multiple control surfaces is viewed as important in providing enhanced maneuverability as demonstrated by fishes. Propulsion will be produced by set a fins located on the posterior of the body just anterior to the tapering end. The fins will be arranged in a cruciform pattern with two fins in the vertical plane (0^o, 180^o) and two fins oriented in the horizontal plane (90^o, 270^o) (Fig. 3). The fins will have a high aspect ratio (AR ~ 4) with a design similar to penguin or marine mammal flippers. The planform will be elongate, taping to a point and with modest sweepback toward the fin tip. The fins will be rigid without chordwise or spanwise flexibility. Movement of the fins will be controlled at a single joint, allowing for simultaneous heave and pitch. These movements will provide propulsion by a lift-based mechanism. Such propulsion has beneficial attributes for the AUV of high propulsive efficiency and rapid speed performance. In addition, the aft position of the high AR fins would function in stabilizing the trajectory of the AUV and producing small (< 1 body length) orbital turns (i.e, circular trajectory), particularly around the pitch and yaw axes. The combination of four high-AR fins for turning will permit maintenance of thrust production by two of the fins in the same plane as the other two fins in the orthogonal plane generate the centripetal force to effect the turn. This fin use would give the AUV the capability to maintain small-radius, rapid turns without loss of momentum for extended periods of time.

The other set of fins will be based on the low-AR, broad-based pectoral or dorsal fins of fishes (Fig. 1). The fins will be used similar to the labriform mode of swimming in fishes. The pectoral fins of the AUV will be located around the center of gravity. This placement permits translational movements in three orthogonal planes for station-holding and low-speed precision maneuverability (Specification 3). An AR of one will be used for the pectoral fins. The original design of the pectoral fins would be a square planform, but the fins could be modified with an asymmetrical planform and/or larger size in future designs. The fins will be supported by four rigid rods with each extending from the base at the body to the lateral margin of the fins. The rods will placed at equal distances from each other. The rods will be joined by a flexible membrane to compose the fin surface. The base of each rod will have a spherical end that will fit into a ball-and-socket joint (Fig. 3). The movements of each rod will be controlled by artificial muscles connected to the base of the rod. In order to prevent interference between the wake of the pectoral fins and the aft high-AR fins, the pectoral fins will be arranged around the mid-circumference of the body at 45^o, 135^o, 225^o, and 315^o (Fig. 4). To function like the pectoral fins of fishes, the AUV pectoral fins will be situated with an angle bias of 20^o-45^o (Fig. 2). Fins located at 45^o and 225^o will have a upward-directed bias angle and fins located at 135^o and 315^o will have a downward-directed bias angle. This pattern will prevent unwanted pitching moments. The base of each fin will be enclosed in a narrow groove. The groove will permit the fin to be folded back when not in use to reduce drag during transit. In addition, the flexibility of the fins can be employed to orient much of the fin parallel to the long axis of the AUV to reduce drag during transit. The ability to modify fin geometry by use of a flexible membrane provides a mechanism to pass undulatory waves along the fin or use it as a more rigid surface for wing-like movements.

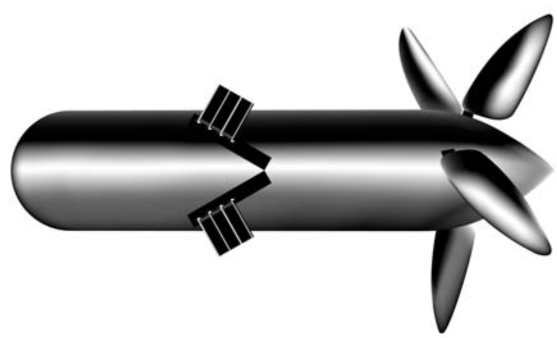

Fig. 2. Biomimetic robot with high-aspect ratio and low-aspect ratio fins for propulsion and maneuvering. The high-aspect ratio fins located posteriorly are based on the flipper designs of penguins and marine mammals. The low-aspect ratio fins are located around the center of gravity. These fins are based on the pectoral fins of fishes. The low-aspect ratio fins are oriented at an angle. These fins may be folded into slots to reduce drag.

Movement patterns of the pectoral fins will encompass oscillatory paddling and undulation. The position, orientation and movement of these fins will allow for low-speed swimming and maneuverability and allow for station-holding (Specification 2). Paddling movements can be used for maneuvers in conditions where the velocity of the AUV is zero. Activation of individual fins and combinations of fins will permit translational and rotational movements about the three orthogonal axes of the body. Co-ordination of the fin movements could stabilize the body and thereby compensate for external perturbations in the environment (i.e., waves, currents) that generally destabilize a body. The oblique orientation and number of the anterior pectoral fins suggests that turning moments could be induced passively by erecting various combinations of fins. The projected fin area in flow would generate drag, which could be utilized for steering and braking.

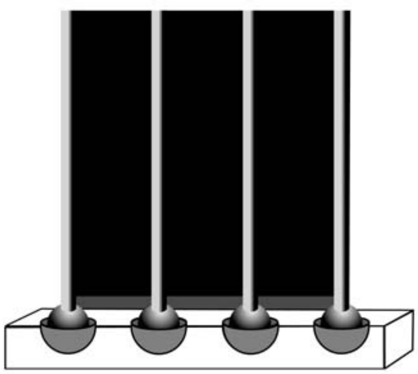

Fig. 3. Close-up of low-aspect ratio pectoral fin for biomimetic robot. The fin is composed of a flexible membrane supported by four rigid rods. The base of each rod has a spherical end to form a ball-and-socket joint for multi-axial movement. Artificial muscles inserting at the base of the rods will control the movements in a coordinated manner.

CONCLUSIONS

The technology associated with the development of robots is becoming more dependent on biomimetics and biologically-inspired designs. As engineers move from the world of large, stiff, right-angled pieces of metal to one of small, compliant, curved-surface pieces of heterogeneous parts, nature will become a more influential teacher. Animal systems hold the promise for improving performance by machines in the aquatic realm [1], [5], [45], [46]. As matters of energy economy and greater locomotor performance are desired in engineered systems, imaginative solutions from nature may serve as the inspiration for new technologies. Enhanced propulsion for engineered systems may be possible by biomimetic mechanisms. In addition, natural propulsive systems can be self-stabilizing and self-correcting. The potential benefits from biological innovations applied to manufactured systems operating in water are high speeds, reduced detection, energy economy, and enhanced maneuverability.

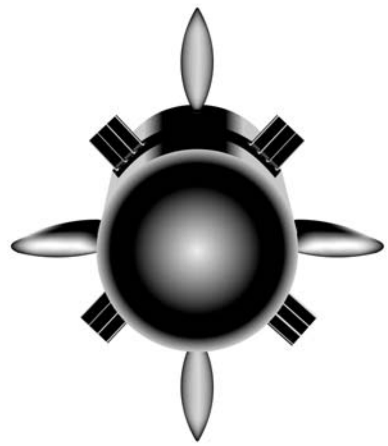

Fig. 4. Front view of biomimetic robot showing position of the control surfaces. The high-aspect ratio fins are located at positions 0^o, 90^o, 180^o and 270^o and small-aspect ratio fins are located at positions 45^o, 135^o, 225^o, and 315^o.

The design of the biorobotic AUV incorporates elements distilled from the biological and engineering literature. The number, design, movement and position of the control surface fins will permit effective propulsive and maneuvering capabilities. The AUV outlined above is anticipated to out-perform current AUV technologies, particularly REMUS. Operational capabilities of the proposed biorobotic AUV, based on hydrodynamics, would include translational and rotational movements about all major axes, continuous small radius turning, precision maneuverability, station-holding, and stability in high energy environments. In addition, the multiple number of fins controlling the movement of the AUV allows for a degree of redundancy, so that if any fins become damaged or inoperable, the AUV may still function. The ability to control and co-ordinate the movements of the fins is dependent on neural control systems. Such systems must be fast enough to reduce reaction times for actuation of the fins due to rapid destabilizing forces, but prevent over-compensation resulting in further instability. The movements of the fins actuated by artificial muscles provides a novel mechanism to reduce the number of moving parts of the system and decrease radiated noise. Thus, the proposed AUV would have increased stealth capabilities. The incorporation of multiple fin-based swimming, neural control systems, and artificial muscles into AUV design has distinct advantages over current AUV designs. The capabilities of the biorobotic AUV fit in well with Naval objectives.

Undersea search operations, such as hunting mines, could be performed by the biorobotic AUV. Previously, trained animals, dolphins and sea lions, have been used for mine-hunting, search and recovery, and anti-intruder missions. Because of their high-speed swimming, maneuvering capabilities, prolonged use time, and sophisticated sensory systems, these animals have proven more reliable than unmanned robots. However, the animal systems have a number of limitations that makes use of a biorobotic AUV more desirable. These limitations include (1) costs resulting from training personnel, deployment, and maintenance facilities, (2) acclimation period for local environments, (3) few available animals, (4) training time with constant revalidation of training, and (5) a political environment that discourages military use of animals. The Biorobotic AUV could be manufactured in large numbers and would not require dedicated personnel. Both of these factors would help to minimize costs. In addition, the AUV could be programmed quickly to meet specific operational objectives and respond to local conditions. As the AUV is designed to be relatively small, it can be rapidly deployed or stored on-site.

A major issue in the construction of a biorobot is the limitation in technology [24]. While the hydrodynamic features of the Biorobotic AUV indicate desirable capabilities for Naval use, its successful construction is dependent on integration of developments in artificial muscle technology and neural control systems. Developments in these areas are necessary to produce systems for operation of the complex movements of the fins with a minimum of noise production. In addition, full operational use will be highly dependent on advancements in power control systems and battery technology. Extended usage of an AUV with a fin propulsor/control surface, especially in a high energy environment, will necessitate large power requirements. The small size of the Biorobotic AUV places constraints on battery size that potentially limit operation time.

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