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Artificial Muscle Actuators in Biorobotic Fish Fins

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***Abstract*— Artificial muscle technologies offer the possibility of designing robotic systems that take full advantage of biological architectures. Of current artificial muscle technologies, nickel titanium (Ni-Ti) shape memory alloys are among a few that are readily usable by engineering labs without specialized skills in material science and/or chemistry. Ni-Ti actuators are now being used to replace servomotors in biorobotic fins. This has significantly reduced the volume that is required for actuators, and will enable several fins to be integrated into a multi finned, flexible bodied, biorobotic fish.**

I. Introduction

Artificial muscle technologies are being explored as a means to actuate and control the motions of biorobotic fins. Although traditional servomotors have been used successfully to develop biorobotic fins and fish [1],[2],[3],[4],[5],[6],[7] they are less than ideal for advanced designs that exploit the anatomy and mechanical characteristics of the biological fish. In particular, the size and rigid structure of servomotors make it difficult for them to be integrated into thin, small, flexible bodied fish robots in sufficient quantity to generate all the fin and body motions that are used by fish for steady swimming and maneuvers. Additionally, their rotary motion, which is most efficient at high speeds, must be transformed to produce linear motions at the low speeds and frequencies required by fins. Furthermore, the noise created by these reduction gears is undesirable in naval and research applications. Scalability, flexible packaging, and direct linear motion are just a few of the many advantages that the current generation of artificial muscle technologies offers for advanced robotic designs.

Fin based propulsors have been developed in our laboratory that generate biologically relevant forces and flows by recreating, to the first order, the kinematics and structural properties of biological fins (Fig. 1) [2],[4],[7] ,[8]. These fins have been used primarily as experimental tools to investigate biological hypotheses about fin swimming and its implementation in structurally tuned robotic systems. The biorobotic fins are now being applied to an autonomously swimming fish to investigate propulsion and control using multiple, heterogeneous, interacting fins.

Although these robots have a much simpler architecture than the biological fish, they are rather complex and have tens of actuated degrees of freedom. To reasonably execute the movements and structural control that is exhibited by the bluegill sunfish (*Lepomis macrochirus*) during steady swimming and turn maneuvers, a biorobotic fish which uses our current generation fin propulsors would require a total of 38, push-pull actuators – each pectoral fin requires ten actuators, the caudal fin requires eight, the dorsal and anal fins are expected to use four each, and the tail another two. The sheer number of actuators makes for a very difficult packaging problem and prevents a widespread use of servomotors. In terms of performance, the actuators must be capable of producing, in general, 1-5 N force, several mm displacement, bandwidths from 0.5 to 2.0 Hz, and be controlled for position and velocity. Actuators that are used in research and development robots should be capable of tens of thousand of cycles, while those that are eventually applied to commercial vehicles should be capable of hundreds of thousands of cycles and must have low energy consumption. To address these design, packaging, and performance challenges, we are developing systems that use a combination of traditional motors and shape memory alloy actuators.

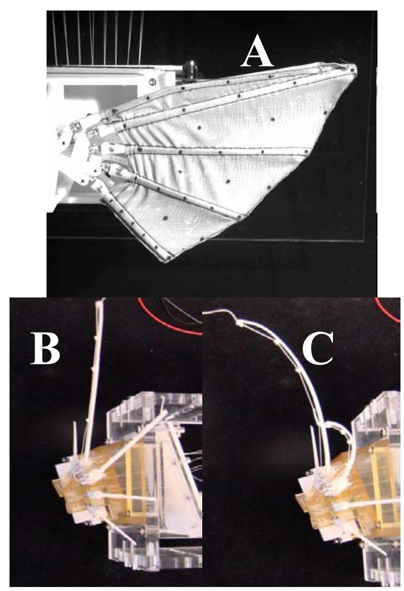

Fig 1. Biorobotic pectoral fin (A). Fin ray with active curvature control (B, C).

In the remainder of this paper we will discuss several research efforts that have used artificial muscles in fish robotics, the rationale for selecting shape memory alloy actuators for our implementation, and designs which incorporate NiTi shape memory alloy actuators to control the motion of structural fin rays in biorobotic fins.

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II. Artificial Muscle Actuated Fish Robots

Numerous artificial muscle technologies have been applied to fin-based robotic propulsors with varying degrees of success. Although none drive the motion of the fins with as much force and level of control as might a servomotor, the artificial muscle actuators enable designs that would simply not be possible using traditional servomotors. For example, polypyrrole (Ppy) based conducting polymers have been configured as linear actuators to drive the sweeping motions of pectoral and caudal fins, and as well were configured as large, bending sheets to create the 3D curvatures exhibited by the fins [9].The motions and shapes of these fins were visually impressive, but the fins did not move with sufficient speed to create significant hydrodynamic forces. Single ionic polymer metal composite (IPMC) actuators have been used as rectangularly shaped caudal fins that propel entire fish-like bodies [10], and multiple IPMC actuators have been used in a side by side configuration to create fins that exhibit the undulatory motions of ray-like fins [11]. Very recently, flexible matrix composite actuators have been incorporated into a robotic system that creates the oscillatory motions of a fish tail. These devices generated sufficient force to propel a fish-like body at speeds of up to approximately 1 L/s, and have the potential to exhibit controllable mechanical properties (Michael Philen, Virginia Tech, unpublished data). Of all the fish-like robots that have been driven with artificial muscles, the most functional have used shape memory alloy (SMA) actuators. SMAs are arguably the most mature of the artificial muscle technologies, and have been incorporated in fully capable, multiple segmented robots that swim and maneuver like lampreys [12].

Artificial muscle technologies have obvious advantages over traditional servomotors, especially when properties such as the manner in which they can be incorporated into a design, their high force densities, and relatively high active strain are considered together [13]. However, a distinct disadvantage of most of these technologies is that they are not, at the present time, readily usable by engineering labs which do not have specialized skills and resources. As with conducting polymers [9], artificial muscle technologies often exhibit excellent stress, strain, and strain rate properties when evaluated at a small scale, but few of the materials are able to achieve simultaneously the forces, displacements, bandwidth and lifecycle that are required by a typical, full scale robotic device. Additionally, in the majority of applications in literature, the laboratory in which the artificial muscle technology has been used was very skilled in material science and/or chemistry, and relied heavily on those skills to facilitate the use of the actuator. Most artificial muscle technologies, therefore, are still best suited for specialized research applications, and cannot be considered off the shelf devices that can be implemented with ease.

The lone exception to this may be actuators using shape memory alloys. SMAs are readily purchased and require little beyond basic mechanical and electrical engineering skills to prepare, connect, and power with proper electronics. SMAs may not have the research potential of electro-active polymers in terms of, for example, being grown into 3D structures with combined sensing, logic, and actuation properties, but regardless are quite capable actuators.

Multiple alloys, such as Cu-Zn-Al, Cu-Al-Ni, and Ni-Ti, exhibit the shape memory effect with the most utilized being Ni-Ti (nitinol). Flexinol, a commercial Ni-Ti wire that is processed specifically for actuator applications, is capable of producing up to 8% strain and 345 MPa of stress in a single pull (Dynalloy, Inc., Costa Mesa CA). Cyclical loading of the alloy requires these properties to be reduced to approximately 4% strain and 138 MPa of stress, but hundreds of thousands of cycles are achievable in this range. This translates into significant forces and displacements for small wires: a single wire with a diameter of 0.214mm diameter and a length of 250mm, has a mass of 0.057 grams, and is capable of 10 mm of displacement while supporting in excess of a 5N load. Nitinol actuators are not yet an off-the-shelf substitution for servomotors, though. Nitinol cycle times can be long, which decreases the available bandwidth, but studies have shown that annealing techniques, water cooling, and pulse width modulation can all improve cycling frequency [14]. Furthermore, control over the nitinol actuator length is not inherent to the alloy, but techniques such as pulse width modulation, external length sensing, and resistive feedback have all been used to give SMA wires a level of position control [15], [16], [17], [18].

III. Implementation of SMA in Fish robot

A. Implementation

Nitinol-based actuators are being used to replace the servomotors that are used currently to control the motions of the fin rays of biorobotic fins. The primary design objectives are: to reduce the volume required by the actuators; to locate the actuators adjacent to the bases of the fins rays (as in the biological pectoral fin girdle); and to make the manner in which the actuators attach to and modulate the fin rays more effective. These must be achieved without degrading significantly the ability of the robotic fin to produce the complex movements used by the fish for swimming.

As described in [2], [4], our fin designs use independently controlled fin rays that are mounted within a hinged base and are covered in a thin, elastic webbing (Fig. 1). The robotic fin rays are very flexible, and are shaped to have structural properties that are similar to those for the biological fish. Each fin ray may require up to three degrees of actuation to produce the fin motions used by the fish for steady swimming, hovers, and turn maneuvers. The speed, amplitude and phase relation of the sweep (adduction and abduction for pectoral fins, and back and forth oscillations for caudal, dorsal and anal fins) of each fin ray dictates, largely, the base motion used by the fin. Lateral rotations of each fin ray contour the shape and size of the fin and help control the direction of the fin's forces. The curvature of each fin ray has a large effect on the fin's stiffness which is critical to the fin's dynamic interaction with the fluid. Although fins have been developed using conducting polymers as actuators and as structural members [9], all the fins that have been used for experimentation have had their fin rays driven by servomotors via low stretch, polyethylene tendons.

Two actuator arrangements are being implemented in biorobotic fins; one used to control the curvature of a fin ray and one that is used to actuate the sweep and lateral movements of each fin ray. The curvature control is a straightforward application of an SMA wire; each end of the actuator is connected to the base or tip of the fin ray and the actuator passes through eyelets along the length of the ray (Fig. 2). Attachment loops at either end of the actuator are formed and crimped back to the nitinol wire using stainless steel tubing. The nitinol wire is electrically insulated from the water environment in which the fin operates with a Teflon sleeve that terminates at the crimps. Electrical connection is made through wires that are soldered to the stainless crimps. The length of the actuator is set such that there is enough slack in the wire to allow the fin ray to bend back when it is moved through the water, but that when actuated the wire becomes taut and the fin ray pulled straight and stiffened. In preliminary testing, the forces exerted on the nitinol by the fin when moved through the water are sufficient to return the nitinol to its relaxed length. Therefore, it does not appear necessary to use antagonist actuator wire to elongate the agonist wire after actuation.

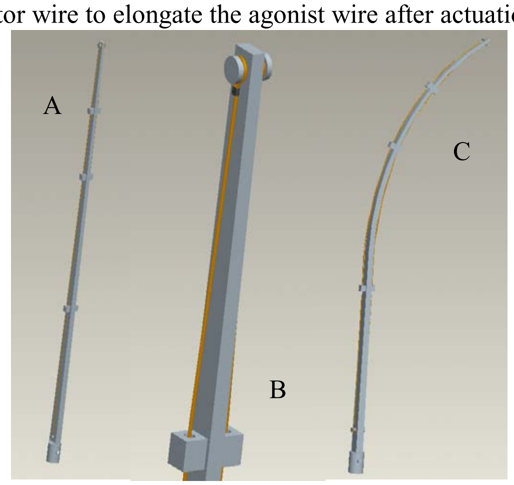

Fig 2. Robotic fin ray with relaxed nitinol actuators (A), Close up of nitinol actuator attachment to the fin ray (B), Curvature of fin ray with one actuator contracted (C)

To achieve the displacements required to sweep the fin rays through a full motion, an agonist-antagonist pair of nitinol wires, each up to 300 mm long, is required. These wires are wound around 6 mm Teflon posts with embedded conducting bars (Fig. 3), so that electrical contact is made along every length of the wire in each loop. This compact arrangement produces nearly the full contraction length of a non-wound wire, while increasing the speed at which the wire contracts since current is passed through shorter lengths of wire. This configuration presents challenges in a wet environment as it is difficult to insulate the posts while maintaining good electrical contact with the sections of the nitinol. The actuator has been be implemented in a dry configuration, and prototypes are being investigated for a wet configuration. The advantage of the wet configuration is that the water cools the nitinol quickly and therefore speeds relaxation after contraction. However, the wet configuration requires a greater energy consumption since heat is transferred from the wires more quickly than in air.

B. Some challenges

Nitinol-based actuators are readily usable, but multiple engineering challenges must be overcome for a nitinol-based actuator to approach the capabilities of a standard servomotor. The stresses, strains, and power density of a nitinol wire are more than satisfactory, but cycle time, lack of position control, and power efficiency must be addressed as part of its implementation in a biorobotic fin design.

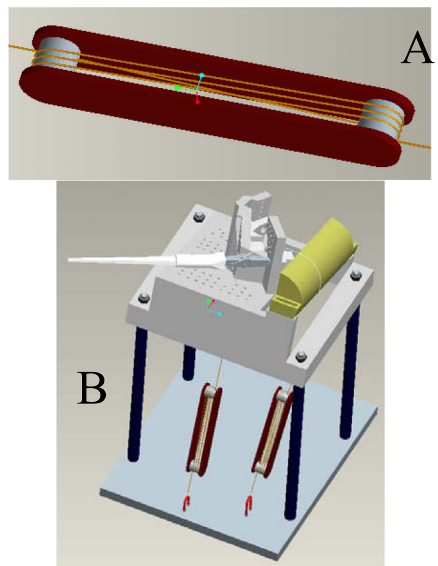

Fig 3. Compact nitinol actuator (A). Implementation of compact actuators to drive one biorobotic fin ray using an existing experimental base (B) as in Fig. 1.

Actuation speed can be increased through the use of appropriate pulse width modulation (PWM) of the input current instead of a dc signal. Research has shown that a large initial current spike drives nitinol to contract quickly and that only a reduced amplitude pulse train is necessary to maintain the actuator position [17]. An additional benefit of PWM is that the actuator can be more easily maintained at a temperature only slightly above phase transition, thereby reducing the amount of heat it must shed before returning to its relaxed state. Further improvements in relaxation speed have been gained through an annealing process of the nitinol wire itself; large current spikes applied to a pre-stressed nitinol wire result in over a three-fold reduction in contraction time [19]. Also, relaxation speed is increased by submerging the actuator in a cold liquid. Finally, studies have shown that both coiled and pre-stressed straight nitinol are capable of achieving a 1.5Hz bandwidth which is acceptable for fin implementations [20], [12].

Nitinol is inherently a binary actuator, in that once heated past its transition temperature, it contracts to a length dependent on the load it is supporting. Thus, position and velocity control, which are required to create the motions used by the fish, are challenges that need to be overcome. These difficulties are compounded by nitinol's temperature dependence; the amount of current that is required for joule heating to cause the wire to exceed its transition temperature is greater when the environment is colder. A few methods have been implemented to gain better control over the contraction length of a nitinol actuator. Simple displacement sensors made using sliding potentiometer are a simple manner in which to implement position feedback, but the implementation of one mechanical sensor per actuator does not appear to be an elegant solution. PWM, along with rigorous characterization of a nitinol actuator, has been used to modulate the amount of the alloy that passes the transition temperature, thereby producing open loop control over the contraction length [12]. Feedback of the resistance of the actuator itself appears to be a promising control solution; resistance of the actuator can be a controller input considering that it varies with actuator length [16],[17],[18].

A popular criticism of nitinol is its efficiency, which is on the order of a few percent (manufacturer's report 5%). This is certainly a concern when developing an autonomous vehicle that must operate for long periods on stored energy. It is difficult to quantify the power demands of a biorobotic AUV utilizing the existing fin propulsors, as energy consumption of these units is still being evaluated. It is promising, however, that a nitinol actuator which supported a load 25 times as large as required by a robotic fin ray, required approximately 4.3W to operate in 15°C water [12]. Based on this, we estimate that a single pectoral fin will require approximately 7.0 W during continuous operation. In one hour of operation, this equates to less energy than is stored in two, 9 volt, lithium-ion batteries.

IV. CONCLUSIONS

Actuators that can be arranged, scaled, and have stress and strain properties similar to skeletal muscle are requirements if robots are to be developed that take full advantage of biological architectures. Although artificial muscle actuator technology has improved rapidly over the years, few artificial muscles are mature enough to be implemented easily by engineering laboratories which do not have the expertise in material science and chemistry to support and implement these actuators in full scale robotic designs. Among artificial muscles, shape memory alloys are perhaps the most viable, and can be implemented readily into designs as simple actuators. The use of SMAs still pose challenges – position control, strain, energy consumption – but these challenges seem to be surmountable. We have shown in initial designs that SMAs are suited for use as actuators in biorobotic fins, and are taking advantage of these actuators to develop underwater robots that employ multiple fins that recreate movement used by the biological fish for steady swimming and maneuvers.

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