

Intelligent control of a highly flexible robotic structure with hundreds of motor elements

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ABSTRACT

As the number of the degrees of motion freedom increase in a robotic system, so grows the difficulty of control. We describe a model of a novel highly flexible robotic architecture composed of hundreds of motor elements, each associated with a unique degree of motion freedom. This new robotic architecture possesses a variably compliant structure that allows for the controlled distribution of loads and forces, and for the maintenance of different conformations. We then suggest two methods of intelligent control to manage the many motor elements. One method derives from neural networks, the other involves algorithms inspired by the biological immune system. Both methods are based on the system's perception of its own kinematics, and later self-prediction of the forces generated by coordinated subsets of motor elements that accomplish robot mobility and other work upon the environment.

Keywords: Robotics, Modeling, Simulation, Intelligent Control, Learning

1. INTRODUCTION

U.S. Armed Forces personnel are beginning to use small mobile robots, such as the iRobot Packbot, the Mesa Associates Matilda, and the Foster-Miller Talon, in explosive ordnance disposal and security operations [1]. Military and civilian teams tested similar small mobile robots for urban search and rescue operations at the World Trade Center site in September of 2001 [2]. While it is far preferred to employ robots rather than humans in dangerous tasks, the use of these robots remains labor intensive and application limited. Operators report that the robots would be more useful if the robots had better mobility in the work environments, decreased energy dependence on the human operators, decreased control dependence on the human operators, and increased survivability in the presence of environmental hazards.

Theory and experience indicate that increased conformational flexibility and decreased weight density contribute to better mobility [3]. Increased conformational flexibility, accompanying increased numbers of degrees of motion freedom can significantly complicate the control problem, and will likely require embedded adaptable controllers to manage the many actuators. New solutions must also be found for the problems of energy and survivability, but there is an indication that these solutions will also depend very much on the control architecture [4].

Robot designs, construction materials, energy processes, and control architectures, should reasonably be tailored to the environmental and mission conditions to which we intend to employ the robot. What makes this reasonable, beyond the face of it, is that we observe this to be the case among natural animate agents. Biological agents across the phylogenetic scale have evolved efficient solutions to most of our robotic technical and operational problems. Our first motivation to produce more useful robots then is to explore new robot designs, materials, and energy and control processes by emulating biological models and processes.

We have previously argued that robots in order to work most efficiently among human collaborators must exhibit, at a minimum, comparable dimensions, and comparable capabilities in mobility, durability, vitality, and adaptability [3]. And yet, we hope to use robots primarily to circumvent the limitations intrinsic to biological species. Such limitations include their physiological vulnerabilities, their long and expensive training requirements, and their propensity to err.

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Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 2005		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE Intelligent Control of a Highly Flexible Robotic Structure With Hundreds of Motor Elements				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) SPAWAR Systems Center 53560 Hull Street San Diego, CA 92152				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES The original document contains color images.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 10	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

How then can we best emulate the natural agent's superlative attributes while avoiding reproducing the natural agent's weaknesses, or worse? An answer to this question is the second motivation of the present work.

2. APPROACH

We begin our effort by considering some potential fundamental building blocks for our artificial agent, just as cytoplasm is the substrate for all of the various components of a natural agent. One likely candidate for a fundamental constituent, following the lead of Yoseph Bar-Cohen [5] of the Jet Propulsion Laboratory, is the electro-active polymer (EAP). Developers of EAP technology have made great progress in the last decade [6-13]. Electroactive polymers are appearing as sensors, actuators, computing elements, and even as batteries and energy transducers [13]. EAP advantages over conventional materials include low cost, light weight, adaptive flexibility, plasticity in molding, multifunction capabilities (sensor and actuator in the same component), and suitability for embeddable logic [11]. EAP limitations include low efficiencies, low sheer strength, low capacities, and slow conducting speeds [11]. All of which may be overcome in the near term with the use of hybrid solutions and of the development and use of appropriate tissue designs, and in subsequent years with anticipated advances in the core polymer technologies. The time is right to start thinking about the new system architectures that roboticists could build using these newly available materials. An EAP-based robot is conceivable, incorporating all of the advantages of the core EAP technologies. An EAP-based robot would thus present with low cost, light weight, increased safety, increased flexibility, increased resilience, and increased compatibility with the human condition.

With the electro-active polymer in various configurations, we might hope to construct an all-plastic robot that has polymer actuators, polymer sensors, polymer computers for information processing, polymer ligaments and coverings, and polymer energy transducers and storage devices. Fortunately, all of these polymer applications are under development at many laboratories, some of which we have referenced above. What we must figure out is how to use them appropriately in a system design, including the strategies for control. Our approach must include the following steps. We must define the specific polymer material requirements for each robot component. We must define a functional architecture for each of the several components (sensors, actuators, linkages, capsules, logic elements, energy transducers and storage devices). For efficiency, we should build a model of the artificial components and submit them to simulations to test design factors, functional dynamics, and determine optimal constituent polymer parameters. We must build prototype components for validation testing and demonstrations. All the while we must consider control strategies for the assemblage of the several polymer components, and the coordination of their many polymer constituents.

2.1 Artificial Muscle

Natural muscles have mechanical properties that conventional actuators do not possess. These natural machines show large strain, moderate stress, high efficiency and stability, fast response time, high power/weight ratio, and long lifetime [17]. In the last years a great interest has arisen to develop materials that mimic natural mechanisms. The resulting electro-active polymers are capable of producing moderate displacements when submitted to electrochemical reactions [9,10]. This property has been used to fabricate actuator devices that imitate and even improve upon the performance of natural muscles. These artificial muscles are lighter and less bulky than conventional robotic actuators. Electro-active polymer-based muscles also require less power than other actuator systems. Recent developments in artificial muscle technology have also resulted in polymers that are stronger and more flexible [8, 12].

One candidate polymer that we are considering is the ion conducting polymer. The ion conducting polymer operates at low voltages (1-6v), and features high tensile strengths, large stresses and stiffness [6,7]. Preliminary analysis and calculations show that, given our energy budgets and force and displacement requirements, the EAP segments should be about 8.9 cm long, 0.4 cm wide, and 0.05 cm thick. Each EAP segment should produce more than 0.2% strain between 2 and 5 V at 0.1 Hz bandwidth in order to achieve acceptable performance from our artificial muscle designs. EAPs with these dimensions and performance characteristics are currently available.

Individual polymer segments must be linked together to develop sufficient forces and moments to achieve useful behaviors in the scale of human activity. The linking process, however, should avoid rigid frames that would add otherwise non-functional weight, decrease flexibility and reduce the desirable degrees of motion freedom, and increase the probability of breakage. To avoid these problems, we developed an artificial muscle design that interlocks strands

of end-wise connected polymer segments into braids. Because all the strands within a braided structure are mechanically interleaved, the braid mechanism evenly distributes load and force throughout the structure, and allows for predictable, consistent lay-up and conformation. Within a braid, each overlaying segment acts as a fulcrum for its neighbor [16].

Braids can take on almost any shape, similar to baskets made of reeds. For example, EAP could be braided to form a flat plain, a sphere, a cone, or a tube. The tube braid pattern, otherwise known as a biaxial braid, is particularly applicable to the present work as it could support an artificial colon, or an artificial snake. Using the biaxial braid an artificial snake could be produced with dimensions comparable to natural species. That is, with a 5 cm resting diameter and 45 cm in resting length, giving a total volume of about 891 cm^3 . To create this biaxial braid we would attach the multiple EAP segments end to end to make strands of approximately 91 cm in length. Forty of these strands would then be braided to form a tube, using a braid pattern similar to the ones shown in Figure 1.



Figure 1: Flexibility of the Biaxial Braid

The biaxial braid will permit the segments, which are free-floating in relationship to their lateral neighbors, to shift spatial relationships to achieve deformations of the global braid, and then to renormalize spatial relationships when forces are removed. The biaxial braid is a natural container, similar to the thorax, in which developers could pack energy storage polymers and computing devices. The biaxial braid could serve as a variably stiffened shock absorber that could minimize body and component damage during impacts and falls. The absence of this ability is a major cause of loss of function in conventional robots. In the initial braid pattern that we have designed, the positions of the EAP segments along the braid will be staggered cyclically to ensure deflections of the structure in any direction. Sinusoidal activations of any neighborhood of segments will contribute to peak deflections anywhere on the tube. Due to the biaxial braid, contractions and dilations of the EAPs will vary the local segment diameters as well. Figure 2 shows a computer generated wire-frame design of braided artificial muscle.

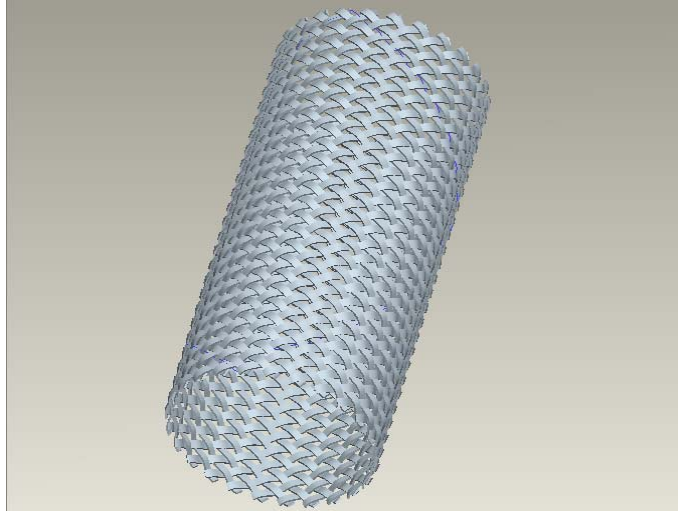


Figure 2: 3D-design of braided EAP structure.

The braid permits cooperative action among the braid segments, increasing the net forces applied, and eliminating the need for a fixed super structure such as a skeleton. Any number and combination of the available polymer segments could be activated in any number of diverse patterns to achieve great spatial and temporal complexity of corporate behavior. The biaxial braided tube should be capable of peristaltic conduction [14] as well as a variety of other wave patterns along the longitudinal axis of the tube, similar to those employed by natural snakes for mobility. Waves of potentials may be distributed across all polymer segments during any movement, differing in place, amplitude, phase, and frequency.

2.2 Sensor-Motor Integration

Sensors for stretch and motion are embedded in the natural muscle. We could accomplish something similar by coupling EAP sensor and actuator segments in the strands. In one instantiation, each actuator segment or each group of segments would be overlaid with a sensor segment. The ratio of sensor segments to actuator segments would depend upon the sensor resolution required by the artificial muscle with the limit approaching 1/1. When the actuator segment changed conformation, the associated sensor segment would uniquely register the change. An actuator segment could also serve as a sensor segment with the appropriate electronic interface, but sensing while activating in this case could be difficult to accomplish with ion-conducting polymers. Using a multi-function polymer would have the advantage of efficiency. The central controller might be able to decide how much sensor resolution and actuator force is required for a particular task, and then allocate a portion of the polymer segments to the sensing task and the remainder to the actuator task. As fine motor control is often associated with low force requirements and high sensor resolution, and conversely, high force requirements with low sensor resolution requirements, such a dynamic redistribution of the polymer assets could double the dynamic range of the artificial muscle.

2.3 Modeling and Simulation

Our modeling and simulation work is progressing along the following steps. First, we are modeling the characteristics and behavior of individual polymers that are candidates for the braid strand segments. The forward kinematics function that defines the deflections and forces produced for any polymer segment, independent of the braid, given its applied voltage, are often available from the polymer developers through their own empirical testing. In those cases where the forward kinematics information is not available from the developers, then physical samples of the developers' products must be acquired and tested for these properties.

We are concurrently building models of the braid architectures using Pro-Engineer. When complete, we will submit these models to simulations to study the behavior of each polymer segment under the constraints of the braid. A competent simulation of segment behavior will, in turn, determine the force dynamics for the braid. With the planned simulations using MSC Marc, a finite element (FE) analysis package suitable for nonlinear flexible systems, we will be able to investigate the behavior (displacements, stresses, strains, friction, etc.) of the entire braid under various external forces and moments. We will repeat the investigation for different types of braid patterns, braid angles, and

polymer segment material properties to determine optimal braid construction.

2.4 Control Architecture

The key question for the operation of the braid in a robotics application is what voltages should be applied to the matrix of polymer segments to achieve any particular conformation and force vector?

Because the braid segments are connected on their longitudinal axes to form strands, and press against each other on their normal axes [18], and because the strands are connected to flexible rings at the braid ends, forces would be distributed throughout the braid with the activation of even one polymer segment. Thus with the activation of many segments, there is a great deal of mutual tugging and pushing. The net result is that the braid changes shape. This change in shape can exert forces on the internal environment of the braid, and on external contact points. The task of the controller is to apply the right potentials to the right segments to achieve the desired change in shape.

It is noted that each polymer segment can be activated independently by a voltage difference and that the general voltage-force relation is known for each type of polymer modeled.

The appropriate adaptive control algorithm for the closed loop control of our artificial muscle must accommodate the following uncertainties:

- Individual polymer force/power relationships will show variations
- Variable relative positions of braid strands that result from conformal changes in the braid
- Variable external forces due to changes in contact points as the braid moves through the environment
- Individual polymer sensor deflection/resistance relationships will show variations

The basic operation of the control architecture is to resist changes in the position and shape of the braid that may be induced by external forces. In this way, the braid would maintain its shape under the force of gravity or acceleration. The easiest way to accomplish this is to link directly the sensor to its underlying actuator. As the sensor is deflected from its resting position, a change in resistance signals the necessary change in potential applied to the associated actuator to restore the sensor to its resting value. By modulating the link between each sensor and actuator, deformations in conformation can be produced without internal resistance. Modulation could be accomplished by applying a DC bias, or by changing the transfer gain, or by adding a persistence factor, or by a combination of these techniques.

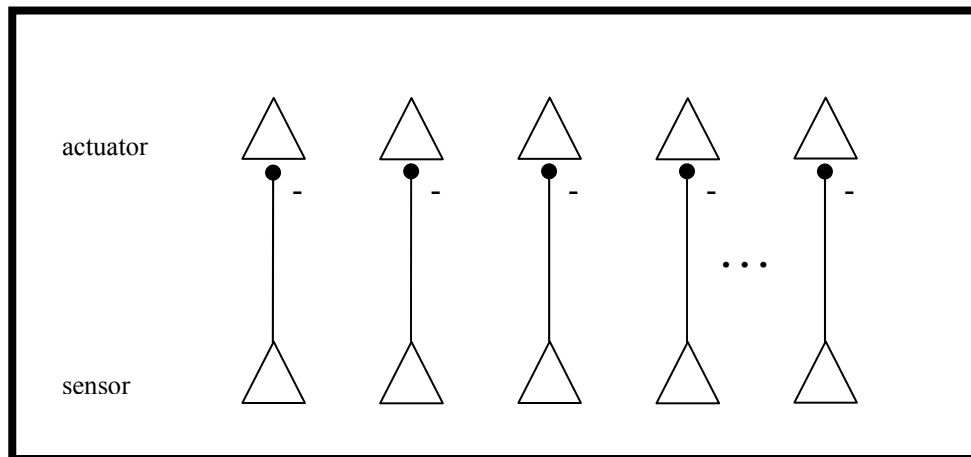


Figure 3: Two-layer sparsely connected neural network.

2.4.1 Neural Network Controller

A neural network controller is ideal for this type of distributed control problem in which the transfer functions must adapt on multiple time scales. The most basic control law is the negative feedback between a sensor and its associated actuator. This can be represented by a sparsely connected two layer neural network, a few elements of which are

shown in Figure 3. The only requirement for the connectivity between sensor and actuator elements is that the influence is inverted. Thus when a sensor detects a bend in one direction, it orders the actuator to bend in the opposite direction.

The collection of polymer sensors constitutes a feature vector. This feature vector will be unique for any conformation of the braid.

A controller that could specify the desired feature vector should then be able to activate the collection of actuators until that desired feature vector is approached to within an acceptable error. One mechanism to accomplish this activation is shown in Figure 4. Only one additional vector of elements has been added to the two-layer network of Figure 3 to create the network of Figure 4, along with one new input from each element in that vector to its associated element in the output layer. The output element responds to the difference between its associated element in the feature vector and the actual sensor element potential. As the actuator bends in the direction that would shape the sensor to match the required potential from its element in the feature vector, the sensor takes that shape and reduces the activation of the actuator. The actual potential produced by the controller is a function of the bend sensed by the sensor, and not necessarily of the force produced by the actuator. This is important as other actuators are also contributing to the bend in the sensor.

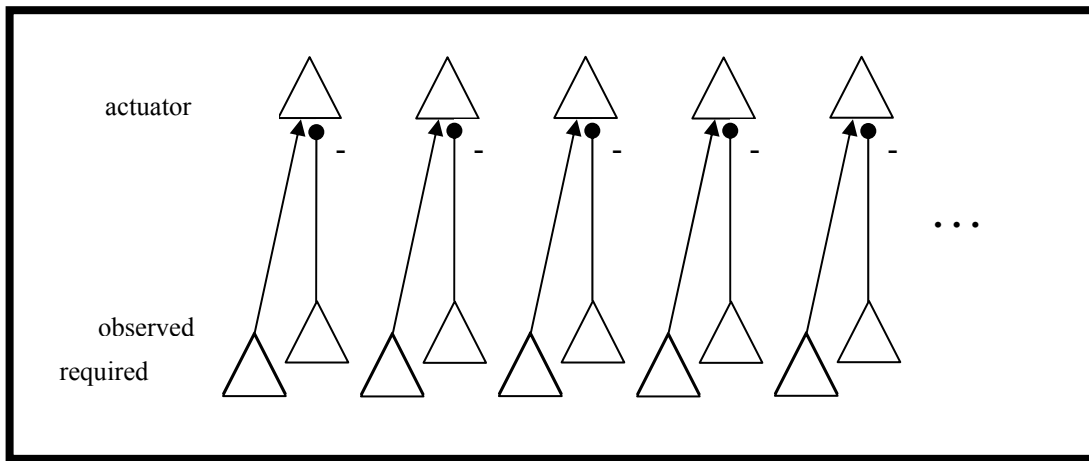


Figure 4: Comparison of required and observed feature vectors on the actuator elements.

The difficulty is in knowing what the sensor vector should be for any particular conformation of the braid. A solution to this difficulty can come from experience. We will be able to observe the feature vectors associated with different conformations of the braid by simply manipulating the braid and recording the sensor feature vector. The controller can do this as well by randomly activating the actuator elements and observing the net results for the braid and the associated sensor feature vector. When those results are needed again, the feature vector can be recalled, which will induce the appropriate activation pattern. We do not in this paper address the criteria by which a feature vector is required, but we have addressed this problem in other papers [4,19,20].

In our assembling of the braid, a bend will be imposed on each sensor. We should expect that the influence of the local reflex loop will be to attempt to reduce this bend by activation of the overlying actuator. So it will happen across the braid. The combined forces of all of the sensor-actuator loops will settle in a short time to minimal energy state, which we expect will look pretty much like a stretched version of the first image in Figure 1, as all bends will be minimized and balanced with other forces. If we wished to define a minimal energy state in some other configuration, such as that shown in Figure 2, we would have to reduce the drive presented by the many bent sensors. This could be easily accomplished by providing a negative (inhibitory) connection between the elements of the sensor vector, as shown in Figure 5. Surround inhibition is a ubiquitous property in natural neural networks and provides many useful functional enhancements to the network.

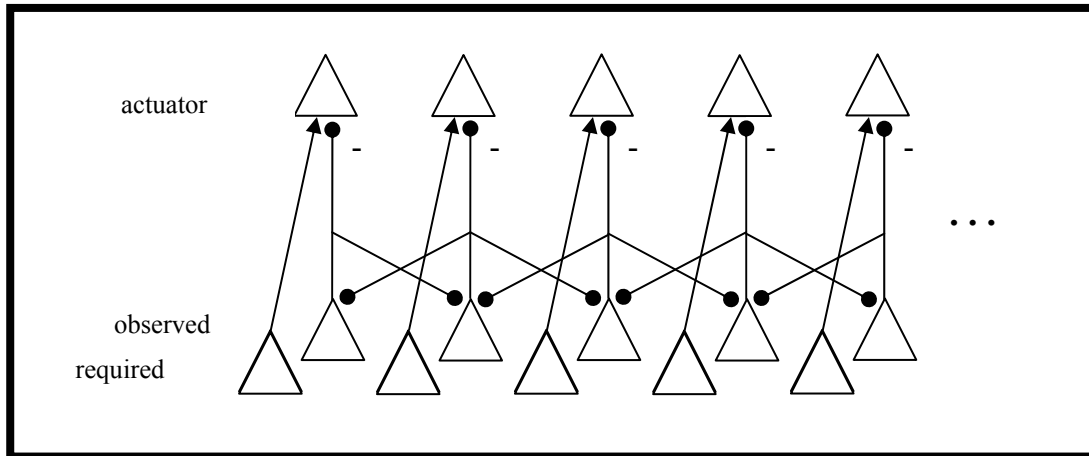


Figure 5: Lateral inhibition among sensor elements.

2.4.2 Artificial Immune System

Another control approach suitable for the control problem of our robot would be the artificial immune system based intelligent control. It has been known that the immune system promotes diversification. It evolves behaviors, which can deal with different situations [21]. The immune system is a distributed system, which means it has decentralized controller. It is a naturally occurring event–response system that makes it quickly adapt to changing situations. It also possesses a self-organizing memory, which is dynamically maintained. This makes it adaptive to its external environment. The immune system’s memory is content addressable, thus allowing situations to be identified by the same behavior. It is thus tolerant to noise [21]. Because of all these characteristics; therefore, the immune system would be expected to provide a new methodology suitable for dynamic problems dealing with unknown/hostile environments. Our general approach for implementing this controller on our robotic structure would be depicted as given in Figure 6.

The initial approach would be teaching and storing pre-defined configurations and motion types. Situations can be determined by gathering information through sensory feedback (vision, proximity, force, etc.) and consequently can be defined such that they determine types of configurations to be taken and/or types motions to be performed. Identified by the sensory feedback, situations such as the existence and type of obstacle, energy level, destination, type of terrain, visibility condition, etc, would trigger the behaviors such as explore, lateral motion, concertina motion, scale, climb, etc. Concentrations of behaviors and selected behavior would be determined by the dynamics of immune network.

2.4.3 Training

Both open loop and closed loop control of the artificial muscle will participate in the training process. In the open loop condition, artificial muscle will be first subjected to external forces and moments to take predetermined conformations. During these conformational changes, the changes in conductivity by each polymer sensor will be recorded. Then the process will be reversed and potentials calculated from conductivity/displacement functions will be applied to obtain the desired configuration of the artificial muscle. In the closed loop control phase, sensory input from sensors will be utilized as feedback and appropriate control functions developed by empirical estimation, or by an adaptive neural network, or by the artificial immune system controller will be applied to produce control signals for the desired configuration and motion of the braid capsul. Processing all the sensory information, making decisions, and taking appropriate actions will require the eventual design of multi-layered intelligent control algorithm. We expect that the adaptive neural network will serve the lower levels of control, based on embedded sensor feedback, while the artificial immune system controller will serve the higher levels of control, perhaps utilizing objectives and distance sensor information. These control algorithms will execute on a computer connected to the artificial muscle through the electronic interface.

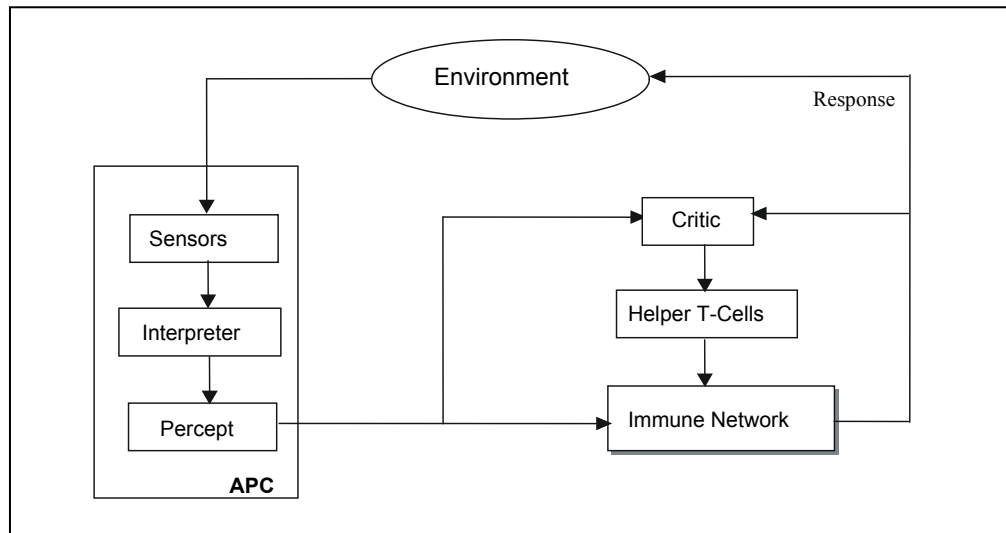


Figure 6: AIS based adaptive learning

3. FUTURE PLANS

Architecture questions to be addressed in future work include, but are not limited to the following for any particular application:

- Optimal geometry of polymer braid and reinforcements?
- Optimal relationships between sensor and actuator elements?
- Optimal patterns of polymer activation?
- Optimal trades between control of flexibility (rigidity⁻¹) and speed of change in conformation?
- Optimal design factors to minimize friction and to increase polymer lifetime?
- Optimal design factors to increase adaptation to damage?
- Optimal design factors to increase manufacturability, maintainability, and cost efficiency?

Because of the expected complexity of the polymer architectures, the development of control algorithms will continue to be a challenge. In addition, any physical implementation (prototype) must have available electronic circuitry to collect sensor input and distribute motor potentials independently to the multiple polymer segments. The physical implementation and testing of these designs is important to validate the modeling and simulation algorithms. Second the prototype will provide an easily appreciated demonstration of the capabilities of the artificial muscle. Third, the physical prototype will permit the testing of fabrication techniques and permit positive testing of durability during operation.

4. CONCLUDING COMMENTS

Our objectives with this work are to develop an electro-active polymer based motor component that will have the following characteristics:

- does not have an explicit frame, is highly flexible, and has a very low mass density,
- has a small electromagnetic signature,
- is free of conventional electric motors as well as mechanical structures/mechanisms,
- may be configured to a wide range of applications especially in robotics and prosthetics,
- has force/weight and motion degree of freedom characteristics that are similar to biological muscles.

We also are working control algorithms that

- permit coordination of many polymer segments simultaneously to execute
 - mobility patterns
 - manipulation patterns
- use force and position feedback generated by embedded polymer sensors
- adapt to time-varying loads, polymer fatigue, and segment loss.

Robotics has been an evolution of the field of automation where there has been a desire to emulate biologically inspired characteristics of manipulation and mobility. For advanced applications of autonomous robots, such as exploration, inspection, medical, reconnaissance, routing, mine clearing, hazardous waste cleanup, or rescue operations, robots have to move through complex terrain. This could mean climbing over large obstacles, getting into holes, or going through narrow passageways, where motion is restricted and very difficult. Wheeled and legged robots normally cannot climb higher than the radius of their wheels or length of their legs. Increased conformational flexibility may be achieved through increased numbers of motor elements, but, when using conventional mechanical systems, this adds undesirable weight, increases energy consumption, and significantly complicates the control problems. The design of an artificial muscle, in which the electro-active polymers serve sensor, structural, and actuator functions, departs from the dominant robotics paradigm. The use of braided electro-active polymers to serve as an effector organ is an innovative contribution. Robotic structures made out of electro-active polymers without explicit mechanical frames have not yet been reported. The concept of an all-polymer robot currently exceeds the state of the art, but its component emulation of biology is compellingly opportune. The proposed architectures are dynamically complex and thus require modeling and simulation to study. This approach is critical to transcend the feasibility threshold, and to understand the control issues.

The building blocks that the present project addresses should provide technologies appropriate for prosthetic applications and for some limited robotic actuators. This work will move the state of the art in mobile robotics toward the realization of artificial agents that resemble and emulate biological forms. While in the past, robots were always obvious as mechanical and predictable devices, the robots and robotic structures that will result from the present approach will embody the elements of plasticity, and exhibit a type of closed-loop control that is characteristic of biologically autonomous agents from round worms to man. The disciplines of robotics engineering and education should accommodate easily to this approach for the approach is none other than the science of biological structures and their control. With this approach the engineering of robotic and of prosthetic systems will be drawn closer to biology, shifting from rigid to flexible, malleable, and adaptive materials and processes.

Self-sufficient agents composed of electro-active polymer tissues are conceivable because such polymer components can be engineered in all of the necessary elements of a vital agency except reproduction. The successful demonstrations of all-polymer based robotic systems, incorporating actuators, sensors, pliant capsulation, energy transformers and storage devices, and adaptive controllers running on polymer logic elements could contribute to a major shift in society's perception of robots. That shift could permit the integration of artificial but biological-like self-sufficient agents into the human community.

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14. An example of peristaltic conduction is the mechanical process that moves food through the intestines.
15. Most multi-layer Perceptrons are fully interconnected between the layers.
16. On 25 February 2005, SSC San Diego submitted a patent application to the USPTO titled "Electroactive Polymer Structure" covering this concept.
17. Regeneration is a uniquely biological process that contributes to longevity, as well as to reproduction. We do not anticipate the emulation of this process through the use of polymer structures.
18. We ignore lateral friction for the moment as we intend for the polymer strands to glide past each other as the braid changes conformation. The strands are laterally separated by the interweaving of the braid, and lateral segments will generally be activated with similar potentials for cooperative action, though the activations may be slightly out of phase.
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