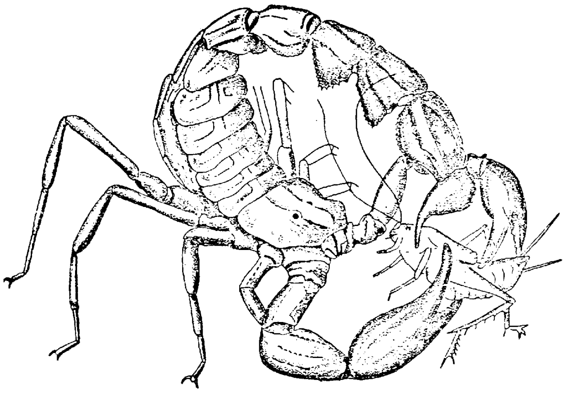
2. Abstract

The proposed research is aimed at developing a new class of biologically inspired robots that exhibit much greater robustness than today's robots for performing in unstructured environments. This new class of robots will be substantially more compliant and stable than current robots, and will take advantage of new developments in materials, fabrication technologies, sensors and actuators. Applications will include autonomous or semi-autonomous tasks such as reconnaissance and de-mining for small, insect-like robots and human interaction tasks at a larger scale. The research involves a close collaboration among robotics and physiology researchers at Stanford, U.C. Berkeley, Harvard and Johns Hopkins Universities.



The work has five main components:

(1) We will investigate the mechanisms by which lower animals, particularly insects, achieve exceptional physical robustness and an ability to accomplish basic tasks such as locomotion despite large perturbations in the environment. Studies of insect kinematics, dynamics, structural elasticity, muscle activitation and sensing will provide insights for the design and control of small robots, sensors and actuators. Insects are ideal for these studies because of their comparatively simple motor control systems.

(2) The passive mechanical properties and 'preflexes' that are evident in insects must be augmented with adaptive strategies if robots are to cope with a range of unstructured environments and with multiple tasks. We will therefore investigate the motor control and adaptation strategies that higher animals, particularly humans, use to cope with unexpected variations in tasks and the environment. We will determine how impedance is specified and varied in response to changing task requirements.

(3) The insights obtained from the investigations of passive and 'preflex' behavior in insects and active adaptation in humans will be tested in the control of small and large robots. Tasks will include locomotion and manipulation of awkward and delicate loads, with applications to retrieving wreckage from the ocean floor, de-mining and handling human bodies. The investigations will begin using robots that employ mostly off-the-shelf technology and will progress to robots that take advantage of new materials, fabrication, sensing, and actuation technologies as they become available during the project.

(4) We will take advantage of new developments in shape deposition manufacturing (SDM) to develop biomimetic robot structures with complex three-dimensional geometry, tailored compliance and damping properties, and embedded sensors and actuators. The structures will overcome many of the limitations present in today's robots assembled from metal parts and off-the-shelf components. We will begin with individual modules, such as leg or finger joints with built-in actuation and sensing, and progress to entire limbs, and robots composed of a mix of SDM and conventionally manufactured parts.

(5) The development of biomimetic robot structures is critically dependent on better actuation and sensing technology. We will therefore conduct research on embeddable actuators and sensors especially suited for biomimetic robots at small and large scales.

"Behold Behemoth ... His bones are tubes of bronze, his limbs like bars of iron." [Job 40.18]

3-A Technical Description

Consider a crab scuttling through the surf zone and grabbing some prey. Although the crab has a primitive brain and motor control system it accomplishes these tasks robustly, and in an extremely challenging environment that would quickly damage most robots, or at least leave them stymied. The point here is that if we are to develop robots that can survive in unconstrained environments such as the surf zone for de-mining beaches, or the ocean floor for retrieving wreckage, we must adopt some of the same strategies that crabs and other animals employ for survivability and robust task execution.

In contrast to the crab, today's robots are built like miniature Behemoths, with metal links, ball bearing joints and steel cables powered by DC motors. The mechanisms are stiff and very under damped. Much of the control effort is expended on achieving precise endpoint position or force control, using a small number of high-accuracy sensors. As a result, robots can surpass human performance for highly constrained tasks but cannot function in unconstrained environments as well as the simplest of animals.

We propose to examine how invertebrates and other "lower animals" exploit structural compliance and damping, as well as muscle activation patterns, and to apply these findings in the design and control of a new breed of robots. The resulting designs will utilize recently developed layered manufacturing methods in which combinations of hard and soft materials can be deposited and integrated with sensors, actuators and other elements to create novel devices. From the standpoint of control we will study how muscular activation patterns are learned, and adapted to meet changing task and environmental conditions, and we will apply computational models of those adaptation mechanisms to robotic locomotion and manipulation. The results of this joint research will be demonstrated in the development of small, robust robots for reconnaissance, de-mining and similar applications and of larger devices that must be compliant for safe interaction with people.

In the following subsections we describe the main areas of research that we are bringing together for this proposal. In each subsection, we characterize the work done in these areas as well as their relevance to the proposed objectives. In the next section we briefly describe our experimental and technology transition plans.

Area 1: Physiology of Insects, Arthropods and other Animals

Biological Inspiration

Nature uses soft materials frequently and stiff materials sparingly (Vogel, 1995). Stiff materials such as teeth, mandibles and bones often have special applications where rigidity is essential to function. Human engineers have thus far preferred stiffer materials such as metals, wood, and ceramics. Part of the reason for the difference between human and natural technologies may result from a difference in apparent design philosophy. Nature’s prime rule often appears to be sufficient strength - not a resistance to deformation, but to breakage. Adding extra material to reduce bending and buckling appears costly and in some cases risky because of brittleness, whereas providing sufficient strength may be cheap. Understanding the advantages and disadvantages of compliant versus stiff biomaterial placement is an endeavor that will lead to the enormous advances necessary to reveal the secrets of nature’s design rules. When discovered, these rules will undoubtedly allow humans to capitalize on the biomaterial properties and their arrangement that nature has been using so successfully for millions of years.

In nature, the range of “softness” or stiffness is exceptional - from the soft tissues of a sea anemone to the stiffest shells of bivalve clams. In many instances this range can be found within a single individual. Animals most often have cuticles, shells or bones connected by softer or more compliant tissue. The apparent “softness” of an appendage or body depends on at least two features, the stiffness of cuticle, cartilage, shell or bone and the number of joints. Insect cuticle is surprisingly compliant and must contribute to their ability to change shape and slip through the smallest of cracks. Blickhan, Full and Ting (1993) showed that even the calcified shell of crabs possessed stiff struts, but had large areas that bend, buckle and bulge during locomotion. The effect of the number of compliant joints is equally impressive. This feature appears to allow the rigid, but multi-segmented brittle star arm to have dexterity comparable to that of the compliant arm of a muscular hydrostat such as an octopus.

The role of the mechanical system in the control of “soft” manipulators

Self-stabilization by limb morphology. Full (1989) has shown that the most successful animals on earth - the arthropods - are actually “soft”. Both the number and arrangement of segments as well as segment stiffness appear to play a role. Rigid segment, statically stable models simply can’t explain agile running, turning, climbing, and recovery from perturbations.

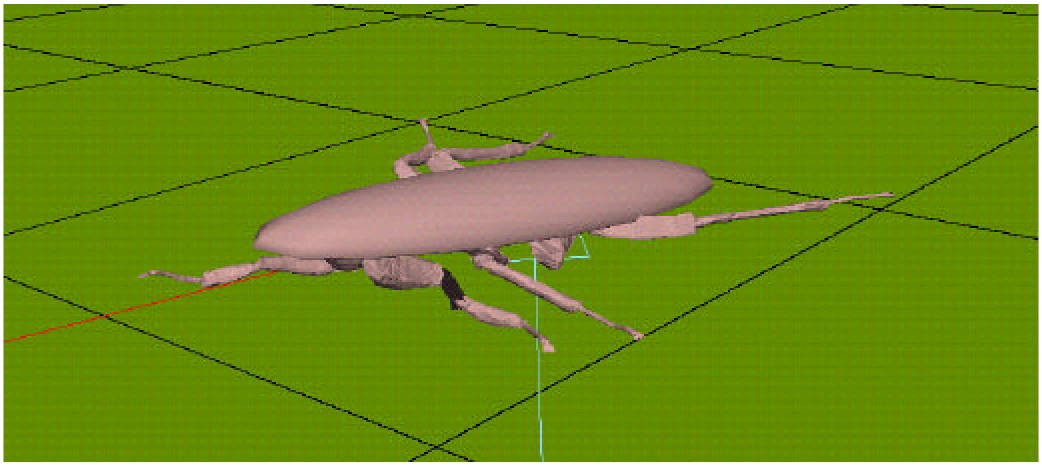


Figure 1. A dynamic cockroach model, created in collaboration with the MIT Leg Lab, is stable when stiffness and damping feedback are added to the feed-forward joint torques.

It is a fact that many-legged, sprawled postured animals are highly statically stable (Ting et al., 1994). Most possess a wide base of support and a low center of mass. They often have at least three legs on the ground. Yet, the locomotion of polypedal, sprawled postured animals must be considered a rapid, repetitive, gross behavior. Full (1993) has shown that locomotion in polypedal animals is dynamic, from a walk to a trot to a gallop.

The location of the actual compliant elements remains unknown. In insects, the arthropodial membranes of the joints or the leg segments themselves are the most likely candidates. Katz and Gosline (1994) showed that the exoskeleton of a locust leg could bend like a pole, store elastic strain energy and release it during a jump.

Full et al, (1991) has shown that during compliant running in many-legged animals, each leg functions differently. In most trotting quadrupeds and bipeds all the legs work the same. Each one first slows down and then speeds up the center of mass. During a step, the first leg of an insect only generates decelerating forces. The force pattern for the second leg looks much like that produced by a human leg, first decelerating and then accelerating the body. The major accelerating force can be attributed to the third leg, which pushes the body from behind. When summed the whole body force pattern of a spring-mass system emerges. Large lateral forces, often ignored or considered undesirable, balance over a stride.

The advantage of “soft” or compliant appendages radiating out from a central body becomes obvious when the animal or three-dimensional dynamic model locomotes over rough terrain or experiences an environmental perturbation. The combination of material properties and morphology produces a remarkable *self-stabilizing* system. A force from one direction produces correcting forces in the opposite direction. The large lateral and opposing leg forces of sprawled postured animals allow them to recover more rapidly from perturbations than more upright postures.

Full’s PolyPEDAL Lab has shown that a substantial portion of locomotor control can simply reside in the mechanical design of the system. Control results from the properties of the parts and their morphological arrangement. In other words, there is no explicit feedback control of global variables such as hopping height, posture, or speed. The only control is local, at the joints. Feedforward, simple, predictive planning can be effective for rapid, repetitive, gross behavior if it works hand-in-hand with the mechanical system.

Full’s recent data on the unparalleled maneuverability of insects suggest the possibility that simple feedforward control sets the general, dynamic bouncing locomotor rhythm. During climbing, turning, and maneuvering over irregular terrain, animals use virtually the same gait as in horizontal locomotion - an alternating tripod. On top of this they layer a change to execute a maneuver. There is no precise foot placement, no follow the leader gait, and a leg does not to have time to react to tactile sensory feedback within a step. Position control using reflexes is improbable if not impossible.

Given the importance of dynamic, complaint mechanical systems in nature, Full will provide biological inspiration toward the design of “soft” legs for agile locomotion and manipulation. From an extraordinary array of nature’s design ideas, Full will characterize and convey the advantages and disadvantages of variation in the number of appendages, their workspace, the number of joints, their degrees of freedom, the number of segments, the morphology of segments, segmental stiffness (all in collaboration with Cutkosky), sensor placement (in collaboration with Kenny) and the contribution of joint synergies to control (in collaboration with Howe and Shadmehr).

Self-stabilization by preflexes at a joint. Full’s recent research on the simulation of polypedal locomotion suggest that self-stabilizing behavior can result from the interplay of two components - a motor program and preflexes. Utilizing only feedforward torques from a *motor program* to the joints of a three dimensional dynamic model of an insect results in unstable locomotion. However, when the appropriate “softness” - springs and dampers - are added to the joints, locomotion becomes stable (Fig. 1). Since control by springs and dampers or rapid acting servos is a near zero order response, it is faster than any actual biological reflex. Hence the term *preflex* was first coined by Brown and Loeb (1997). A preflex is a response of the mechanical system due to the intrinsic, non-linear properties of the musculo-skeletal system (e.g. short-range stiffness, force-velocity relationship or impedance) functioning at a joint. Muscles can be active, but are not reactive to neural reflexes.

Preflexes could greatly simplify control. Full and his laboratory will attempt to characterize the “softness” of insect/crab appendages and their joints. They will accomplish this by conducting simulations in concert with direct experiments. The PolyPEDAL lab has the capacity to measure individual and whole body leg forces of running animals. They propose to develop leg and whole body perturbation methods that impose known displacements or forces to legs or the body of running insects as well as insect legs in isolation possibly attempting manipulation tasks. These experiments will be conducted in collaboration with Howe and Shadmehr who can provide quantitative, novel approaches to analyze these data. At the same time, they can suggest which findings might be insightful because of known control problems, which can be easily solved by learning and which can be scaleable to systems of different size.

Full’s laboratory also has the capability to measure the muscles involved in preflex self-stabilization. Full has argued that it is becoming increasingly evident that to understand muscle function in a multiple muscle system, at least two data sets are desirable for each muscle. First, the capacity of the muscle should be determined in vitro and in simulation under a wide range of stimulation pattern, strain and activation phase. These data can produce a functional space of the potential performance of the muscle. Second, measurements of realized muscle function are essential in as many behaviors as possible, either in vivo or under in vitro conditions mimicking the muscle’s function in vivo. Full can characterize both potential and realized function. First, he can measure a muscle’s potential to generate mechanical power by using the work loop method (Josephson, 1985). He imposes cyclic length changes on a semi-isolated muscle while measuring force and then searches for the optimal muscle length, strain, stimulation phase and pattern. He also has produced computer simulated work loops to estimate the potential for muscle work over a broader parameter space. Second, he can approximate the muscle’s realized function during locomotion. He uses videographic analysis, dissection and simulation to determine the actual strain experienced by the muscle. Electromyographic recordings provide the pattern with which the muscle are activated by neural input during locomotion. Using the work loop technique with realized strain and stimulation pattern he tests the frequently proposed hypothesis that muscles in vivo, during locomotion, operate near the conditions that result in the generation of maximum mechanical power output in vitro.

Figure 2. Three-dimensional musculo-skeletal model of the leg of B. discoidalis constructed by Full's lab. Simulations such as these are used to help characterize the role of individual muscles in locomotion.

It turns out that the exoskeleton of arthropods makes the determination of musculoskeletal strain and the recording of electromyograms (EMGs) relatively simple. The origins of individual muscles can be precisely located on the exoskeleton and used for accurate EMG electrode insertion. The exoskeleton also provides a rigid surface for the placement of markers that are visible during high-speed videography. The joint we selected (coxa-trochanteral-femoral joint) is a simple joint with one degree-of-freedom (Fig. 2). Joint angles can be related unambiguously to musculo-apodeme length. Most importantly, they chose particular insect leg muscles because they are innervated by a *single motor axon*, which allows precise definition of the neural input, both its duration and pattern. Full and Ahn (1995) have developed a three-dimensional musculo-skeletal model of the leg of *B. discoidalis* itself. Full's laboratory has the ability to stimulate all 21 leg muscles in an insect leg, impose forced oscillations with a muscle lever and at the same time measure force. The results provide interesting, and surprising, insights for robot design and actuation. For example, in examining two muscles that are used at the same time for running, one functions as a motor and the other as a damper.

Full's laboratory will work closely with Kazerooni, also at Berkeley, on compliant actuator development which emulates the non-linear Hill properties of muscle. Full will provide biological inspiration of any parameter values which can assist in moving robot actuators toward the behavior of muscle. In addition, Full will abstract the features of multiple muscle function in nature. For example, it is well known in biological systems that muscles have different properties and morphological arrangements which lead to essentially a spectrum of gear ratios, yet multiple actuators or their equivalent have seldom been incorporated in robots. Finally, Full's recent data has shown the inadequacies of the Hill model, particularly as it relates to stretch activation and shortening deactivation. Collaboration with Full will allow Kazerooni's actuators to incorporate these findings and surpass the performance of the classical Hill model.

Active stabilization in arthropods

Active stabilization of dynamic locomotion does have a role even in arthropods. Classical, reactive, reflexive feedback may serve to signal the state change from running to the appropriate maneuver. Here adaptive control may prove to be invaluable. Use of adaptive control could produce new central laws for the motor programs and significantly improve the feedforward signal. Multivariable, continuous feedback is also essential for large disturbances and perturbations that require several cycles or many steps for complete recovery. Important to note is that preliminary data from Full's dynamic simulations reveal that even classical feedback can be highly effective when it is local, decentralized, and distributed.

To date, the control of dynamic locomotion by the nervous system of arthropods has received less attention than in mammals. Nearly all of the studies on control of legged locomotion focus on slow, novel precise behavior. Still, studies of slow, statically-stable hexapods such as stick insects and crustaceans have yielded remarkably robust, decentralized control models for many-legged organisms (Cruse, 1990). Biologically-based controllers show these control models primarily solve the problem of how to produce the rhythmicity characteristic of locomotion, but also correctly model responses to perturbations (Bassler, 1988).

These models have several important common features. Most importantly, the control model proposes that locomotory control is distributed among the legs. Separate controllers determine the movements of each leg, and coordination among legs emerges from interactions between separate leg controllers. Oscillations in leg movements result from peripheral feedback in the form of position sensors at the joints detecting whether the leg has reached the anterior extreme position (AEP) or the posterior extreme position (PEP). These sensors modulate the state (power or return phase) of the leg (Bässler, 1983). Inter-leg coordination emerges from the interactions between leg controllers. Interactions are modeled as "influences", which act to alter the AEP and PEP positions of the leg controllers.

As discussed in the following sections, in order to take advantage of the robustness of biologically-inspired controllers derived from arthropods, it will be necessary to reconcile the kinematic output of the inter-leg controller with the dynamic (impedance) control hypothesized to be important for leg and whole-body stability and control.

Area 2: Motor Learning and Control

The passive properties of biological appendages are complemented by equally important muscle activation strategies that, at least in the case of higher animals, can adapt to changing environmental conditions. In this portion of the research we will extend ongoing research on motor learning and adaptation and apply the resulting models to robotic mechanisms at both small and large scales.

Why muscle-like actuators are not enough

In insects, the passive properties of muscles serve as a powerful stabilizing mechanism during locomotion. However, as the size of the animal increases, the biological design begins to increase its reliance on sensory feedback to augment the mechanics of the muscles in order to robustly control the limbs. For example, in a recent experiment where biologically accurate muscles were constructed and coupled to a human size forearm (Chou and Hannaford 1997) it was found that with position and velocity sensory feedback from the muscles a simple local controller resembling the neuronal system of the spinal cord could effectively stabilize the limb and modulate its compliance and damping. However, when neural feedback from the muscles was removed, the system had great difficulty compensating for the inertial properties of the limb and was unable to interact with novel forces. This effect has been demonstrated in numerous experiments on deafferented animals, but perhaps best shown in humans who have lost sensory feedback from their muscles (Sanes and Shadmehr, 1995): these individuals are highly unstable and can only make slow, jerky movements. In short, passive mechanical properties of the muscles maybe a desirable design rule for our actuators, but biological examples suggest that this alone is unlikely to be a sufficient condition for robustly controlling the limb.

Reflexes are the mechanism through which the nervous system controls compliance and damping of the limb. For example, when humans try to catch a ball, there are complex temporal modulations of the compliance and viscosity of the arm: about 100 msec before impact, the direction of viscous resistance vectors rotate close to the expected direction of impact generated acceleration (Lacquaniti, 1993). Because the end-point mass matrix representation of our arm is not isotropic, direction of force at impact and that of resulting acceleration will not be colinear, requiring the brain to use a model of the arm's dynamics to estimate an optimal orientation for the viscous resistance at the wrist, allowing the ball to softly land in the hand. Briefly stated, reflexes are feedback driven systems whose set points are changed as a function of expected dynamics of the task.

Arrival of sensory information at the reflexes not only allows for rapid response of the muscles to perturbations, but also provides the nervous system with another crucial bit of information: errors in modeled dynamics. Assume that a muscle actuated limb is interacting with an unknown mechanical environment. When activations are assigned to the muscle actuators, the motions and forces that result are a function of the coupled system. In order to learn dynamics of the novel environment, the adaptive controller needs to be able to de-couple self-generated sensory feedback from that of the environment. The biological system appears to do this through an estimation of the sort of sensory feedback it should have received at the level of reflexes if the limb was uncoupled. The difference is the action of the environment, and it can serve as an error signal for the adaptive controller to learn the environment's dynamics. Indeed, humans who lack sensory feedback from their arm muscles do not learn how to control their arms in novel mechanical environments (Gordon et al 1995) suggesting that adoption of limb compliance and viscosity may be crucial for design of robotic systems which aim to perform multiple tasks in unstructured environments.

The aim of this part of the proposal is to determine principles of how humans learn to adapt their compliance in a range of tasks, and develop guidelines that help us build better, more compliant and more robust robots that exploit passive properties and preflexes of the muscle-like actuators.

An experimental approach to discover principles of human adaptive control

Work in Shadmehr's lab has described an experimental framework for understanding how humans go about modulating arm impedance in order to stabilize their hand while interacting with an unstable system (Shadmehr and Mussa-Ivaldi 1994b, Shadmehr et al 1995). In this work, humans learn to make reaching movements while holding an unstable mechanical system as described by a force field (Fig. 3) (Shadmehr and Mussa-Ivaldi 1994a, Shadmehr et al 1993). The force field is produced by a robot, and subjects move the end-effector of the robot in the task. In the null field, subjects are able to make accurate, smooth movements (Fig. 4a). When the robot produces a novel force field (Fig. 4b), it becomes unstable. In trying to move the arm while holding this system, movements deviate from the straight trajectories (Fig. 4c).

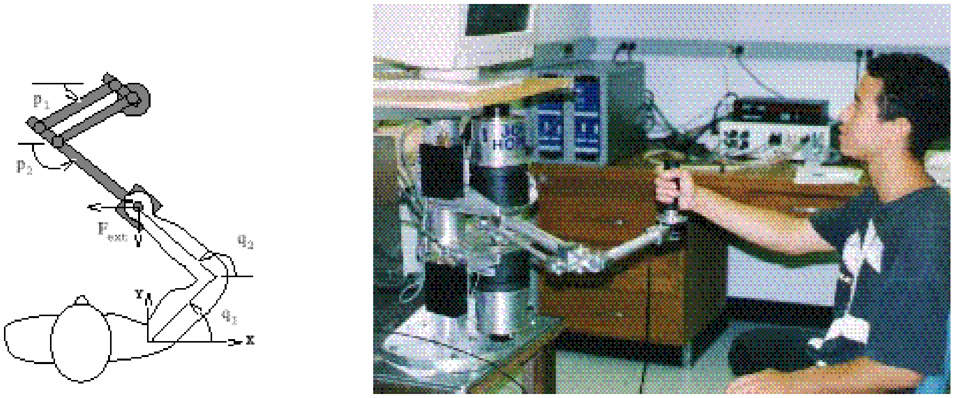


Figure 3. The robotic manipulandum and the experimental setup. The manipulandum is a very low friction, planar mechanism powered by two high performance torque motors. Subject grips the handle of the robot. The handle houses a force transducer. The video monitor facing the subject displays a cursor corresponding to the position of the handle. A target position is displayed and the subject makes a reaching movement. With practice, subject learns to compensate for the forces produced by the robot.

The resulting stability of the movement is well accounted for by a biomechanical model of the arm (Shadmehr and Mussa-Ivaldi, 1994b). Using a biologically realistic model of the musculature it was found that the spring-like behavior of the muscles acted in concert with the reflex system to stabilize the arm even though the dynamics of the task had been radically altered. This is further indication of the importance of having well designed actuators. Nevertheless, while the system is stable, performance is far from ideal. With practice, the trajectory in the field (Fig. 4d) converges to that observed in the null field (Fig. 4a), as subjects learn to produce forces which essentially cancel the imposed force field (Fig. 4e). In principle, two biomechanical mechanisms may be responsible for this adaptation. By increasing stiffness of the arm (co-contraction) the subject can cancel most perturbing forces regardless of their direction. Alternatively, the subject may learn to activate muscles in a way that moves the equilibrium point of the system so that the resulting impedance locally cancels the effect of the force field. This has two consequences. 1. In the case that the change in impedance locally matches the field, movements converge to the smooth trajectories observed in the null field. 2. If the field suddenly returned to null, what results are after-effects, as in Figure 4f, but the system remains stable. The evidence suggests that the subjects are learning to command a novel pattern of muscle forces, modulating impedance of the arm to locally match that of the task.

A computational framework to describe how the humans go about learning modulation of arm impedance for interaction with a novel force field is shown in Figure 5. The essential components of the adaptive system are internal models (IMs) which predict the temporal pattern of sensory feedback that should be received for the pattern of muscle activations that have been commanded. The error or mismatch is computed at the level of reflexes and serves to not only modulate the impedance at the individual muscle level, but perhaps more importantly, to provide crucial information for adaptation of the IM.

This adaptation is the key element which allows the human limb to work smoothly in a wide variety of mechanical environments. A number of conclusions regarding the organization of the IM have been arrived at through the work of Shadmehr and colleagues. The pattern of generalization of the IM after training on a small data space suggests that the basis functions used by the brain to represent the IM are state and not time dependent and that the domain of these basis functions has a coordinate system close to that of the muscle sensors as opposed to visual sensors (Shadmehr, 1994). Furthermore, the ability to learn control in multiple environments is made possible by a gradual, time-dependent process during which the parameters of the recently learned IM become stable and resist change

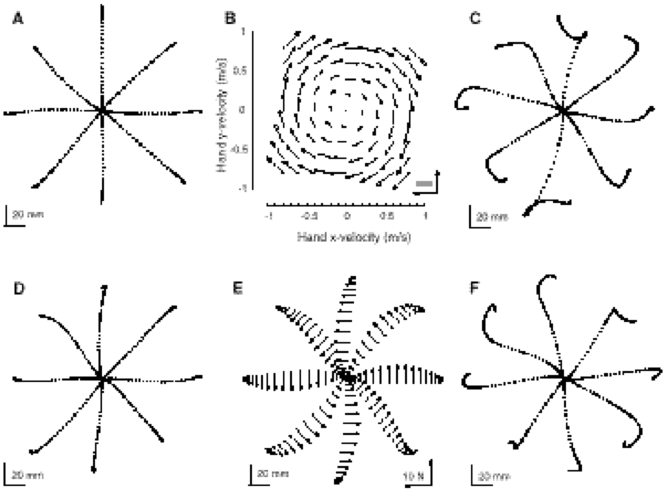


Figure 4 (a) Hand path of a typical subject in the null field (points are 10 msec apart). (b) Force field produced by the robot. (c) Hand path during early stage of training in the field. (d) Hand path after 300movements. (e) Forces produced by a trained subject to counter the effect of the force field. (f) While training in the field, random targets are presented with the force field turned off, resulting in after-effects.

(Brashers-Krug, 1996 and Shadmehr, 1997). This appears to be an organizing mechanism for the adaptive controller, allowing it to separate dynamics of the environment into distinct classes and presumably facilitate future identification after only a few movements in the field.

Proposed Research

While work in the Shadmehr Lab has concentrated on some of the principles that govern learning of IMs for the human adaptive controller, little work has been done on examining changes that result in the arm's impedance as the IMs adapt. Discovery of the rules that govern these changes and applying them to muscle-like actuated robots are the

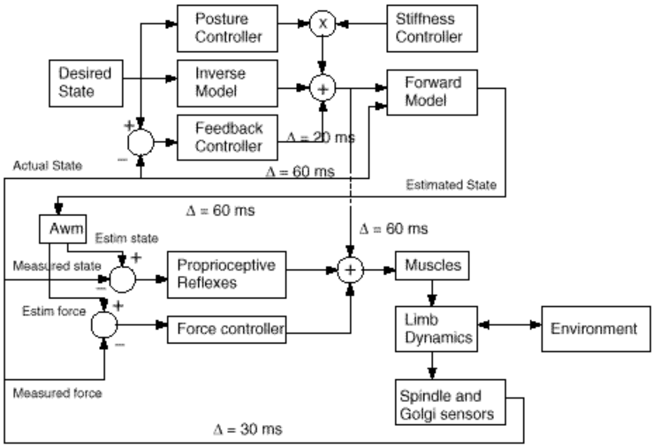


Figure. 5. A block diagram of the adaptive control system for the human arm. Muscle-like actuators are coupled with a reflex system which modulates compliance and damping as a function of a setpoint. The setpoint is provided by the internal model, predicting the expected feedback from the sensors. Activations add at the motor neurons (MN). Δ refers to the delays in information transmission

aims of this part of the proposal. In particular, the main questions are: 1) how to maintain stability of the limb once the object is in grasp, and 2) how to grasp the object. Shadmehr's lab, in collaboration with Howe's lab, will tackle the problem of limb control, discovering the relation between impedance modulation in the arm and manipulation task requirements. The context is unstructured environments, especially unstable payloads, e.g., carrying a human, unconscious or struggling, in a dynamic environment, e.g., wave action at the surf zone. The human experiments will initially focus on adaptive control of arm impedance in unstable environments using Shadmehr's 2-D planar robot (Fig. 3). In Years 1 and 2, Shadmehr's lab will quantify how the human arm's compliance and viscosity adapt to a variety of passive environmental changes, i.e., when the environment presents a novel force field but the field is not implicitly time dependent. The essential questions are how the setpoints for the reflexes are modulated when the arm is initially faced with the unknown environment, and how these setpoints vary as the adaptive controller gains experience in the field. The answer to the first question will provide us with strategies on how to design the controller's reactions when our muscle-like actuated robotic limb is initially faced with the unknown environment. The answer to the second question will provide guidelines on how to adapt to the environment. In Year 3, Shadmehr's lab will begin investigating learning control of active environments. An active environment of particular interest is that of waves, where a time-dependent process initiates generation of a force field. This is a crucial problem for limbs which wish to stably hold a prey or another object in a changing dynamic environment. In Year 4-5, the work will be expanded to include unstable payloads using instrumented objects. Howe's lab will assist in design of these types of payloads where, for example, center of gravity and moment of inertia shift. We will examine how the human adaptive controller modulates the arm's compliance to respond to these active environments.

Working in parallel, Howe's lab will implement impedance modulation strategies gained from Shadmehr's work on a 4 DOF Whole Arm Manipulator(WAM) robot. In Year 1, muscle-like properties will be programmed into the actuators of the WAM robot and these preflexes will be endowed with a reflex like system which integrate sensory feedback from the joints with setpoints from the adaptive controller. In Years 2 and 3, Howe's lab will develop controller/learning structures to implement design rules gained from Shadmehr's experiments in modulating compliance in unstructured environments. In Years 4-5, Kazerooni's motors that have independent controllable impedance and torque will be applied to insect as well as macro-scale manipulation.

Area 3: Robot Control and Impedance Modulation

Humans modulate their limb impedance to deal with uncertainty in the environment in two different contexts. The first is the use of a specific limb impedance to deal with the demands of a task; an elegant example is an expert skier who can glide smoothly down a slope covered with bumps, which may be randomly distributed but whose characteristics are known. Here the leg impedance is set to act as a tuned suspension, so the skis track the uneven terrain while the trunk moves almost unperturbed. The second context is impedance modulation to cope with unknown situations; this is seen in the skiing example when beginners over-tense their leg muscles in an effort to tightly control ski position. The transition between these two contexts frequently requires the learning of an internal model (IM) of the task. Then the limb impedance may be set to match the task requirements, and model-based feedforward control can play out the appropriate neural commands in anticipation of the task requirements. This minimizes effort and attention requirements, and often results in graceful and efficient task execution.

The robotics community has recognized the importance of manipulator impedance control in contact tasks for several years. Unfortunately, while this technique tells us how to control a robot so that it exhibits a specified impedance, it provides little guidance about which impedance to choose for specific tasks. Analysis has provided insight in a few simple tasks, such as deburring and symmetric peg-in-hole insertion, where use of the correct impedance greatly improves performance. But in less structured tasks, the role of impedance and guidelines for selecting appropriate values is not clear. The proposed human experiments thus promise to provide immediate insight into the impedance selection problem.

There is considerable literature on robot control with compliant joints (Cannon et al 1984), structures and actuator/transmission (Pratt 1996). However, emphasis in this work has been on accurately modeling dynamics and achieving precise endpoint control with combination feedfoward and extra state feedback. Our argument is that this approach is inappropriate. Robots should perform tasks robustly despite unexpected variations in loading, force field, terrain and other environmental variables.

Robot controller structure for uncertain environments

The results of these human experiments have immediate application to robot control and a controller structured after the human model is proposed (Figure 6). The controller impedance is initialized by considering task requirements, such as predicting the necessity for high or low impedance in the appropriate directions for the task. Based on human experimental results, a learning impedance modulation is added. The task is then executed and results are evaluated (a performance criteria or objective function is needed). An internal model is subsequently built.

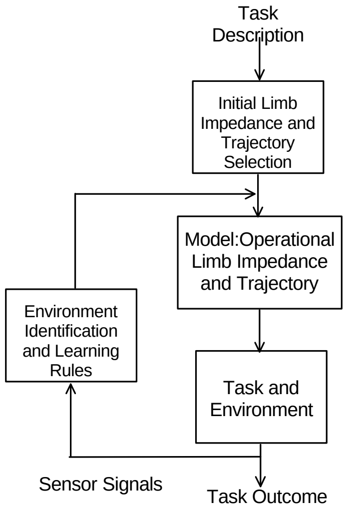


Figure 6. Robotic task and impedance learning process.

The general mechanical model building process is a largely unexplored research area. Work on simple single degree-of-freedom systems is difficult to generalize. Generic identification techniques are largely aimed at finding values for the parameters in an assumed model structure. Real tasks in uncertain environments may not be easily described by analytical models. It is not, for example, generally possible to associate force-motion relationships with particular directions; these can change during many tasks (e.g. carrying a flailing human). This may often be like the pre-learning case, where there is no internal model, and the impedance selected by the human will lend insight into appropriate strategies for these cases.

We will also gain insight into this process by looking at what environments humans are able to build models for. For example, vector fields with curl are difficult to learn (Shadmehr and Mussa-Ivaldi 1992). In general, robot controllers should use models when they are available, and heuristics derived from human observation when none are appropriate. Models can greatly improve performance, but it is essential to develop more general empirically derived methods available when models fail.

When to model, and model identification techniques

Determining the appropriate role of models in this control process is essential. In many situations in unstructured environments, it will not be possible to use models to improve performance. This may be because the environment and task are new to the controller, or because the task itself requires continuous sensory feedback to accomplish the goal. In these situations, the controller must nonetheless select an impedance and trajectory to use in attempting the task. Again, from the human and insect/arthropod experiments, we will determine and emulate the human strategy in such situations. From previous work on biomechanical motor control, we conjecture that a useful approach will involve use of a model of the arm’s kinematic and dynamic properties, together with a conservative estimate of the environment’s properties. Since the worst case for interaction (most potentially destabilizing or damaging) is often a rigid environment , a low manipulator impedance will often result in the best initial impedance: the arm can “give” in response to unexpected disturbances.

This scheme makes use of the fact that although the environment may be poorly known, the arm itself can be quite accurately characterized. Calculation of the kinematics and dynamics of the manipulator are one the notable successes of robotics research over the past few decades, and experiments show that they work well in practice -

unlike the interactions with poorly characterized environments that we will address. Our system will thus make use of the arm's characteristics, and following the human model described above, will use the differences between the resulting behavior of the arm and the actual forces and motions to identify the environment and task.

For situations where learning of task-related impedance modulation is possible, we will develop techniques for identifying environmental characteristics and creating appropriate models. In previous work we looked at algorithms for automatically identifying parameters of unknown objects in the environment (including mass, size, and friction) based on robot sensor signals during manipulation (Shulteis et al. 1996). In addition, we have derived methods for determining the kinematic constraints on grasped objects (Dupont et al. 1997).

Based on this work, we propose a structure for identifying task and environmental properties. First, the controller will use knowledge of the task domain and environment if available. For example, it may be clear that the payload to be grasped is a single rigid body (like a tool), or that the surface to be moved along is compliant, which indicates which model to use. Then sensor data can be used to find the parameters in the model, following conventional identification techniques. In the example of the single rigid object moving in free space, the model framework is the equation of motion, and force-acceleration-gravity information from manipulation is used to find the payload mass, moments of inertial, etc.

More interesting situations arise, however, when a single model is not available. In this case use sensor data to differentiate between various model possibilities. For example, position-dependent force implies stiffness, velocity dependence implies viscosity, etc. In general it will not be possible to uniquely define the environment (especially for multi-object interactions and time-varying environments), but any model information that becomes available can help improve performance, and improve efficiency and reliability. One key outcome of the proposed work will methods for determining how to vary impedance in response to *partial* knowledge of the environment.

In the proposed work, Howe and Shadmehr will begin in year 1 by formulating an initial muscle-like controller for joints of the Whole-Arm Manipulator (WAM) robot. This robot, manufactured by Barrett Technologies, is an intrinsically low-impedance manipulator very well suited . The weight of moving elements of the arm links is only 7 lbs, while tip forces are 6 lbs, and the arm's cable transmissions have very low friction, making this an ideal test bed for the proposed work. The WAM robot arm is also robust, since the last link is an aluminum rod, so unexpected crashes won't damage the arm. This manipulator will also be used with a simple gripper in the grasping experiments described below.

In years 2-3, we will develop controller/learning structures to implement human compliance strategies in unstructured environments. Years 4-5 will examine the range of attainable impedance, time response, etc., and task performance, to determine where specialized actuators are best (in collaboration between Howe, Kazerooni, and Shadmehr).

Grasping

Grasping is a particularly interesting and appropriate task for investigating the role of impedance modulation in motor control. It is a fundamental part of manipulation, since an object must often be grasped before anything else may be done with it. Grasping also entails interaction with an extremely broad range of impedances: before contact, impedance of the environment is zero (free space), while after grasping, the arm is coupled to the payload, which may have a very high impedance (massive and/or stiff).

Studies on biological grasping are relatively few. They have been mostly concerned human manipulation, but the complexity of multifingered hands with complex innervation is daunting. Studies such as Johansson's have outlined force control strategies and the role of contact sensing in only the simplest cases (grasp-and-lift of parallel sided objects, with little uncertainty). A number of multifingered robot hands have been produced in research laboratories, but they are not able to perform even simple grasping in the presence of uncertainty. What is lacking from all of these studies is an understanding of how to use impedance modulation, not how to coordinate many fingers.

We believe that the correct biological model for advancing our understanding of the control of robotic grasping is not human manipulation, but simple animals like crustaceans and arachnids. These creatures use a few simple, compliant, and tough links (claws and legs) as effectors, with minimal sensors (often hairs) distributed on exoskeletons. They use simple visual feedback, not complex "scene understanding." We note that these biological components are similar to technological components that have been developed in recent years.

An example will illustrate the importance of impedance modulation in grasping. The strategy begins with the use of low gripper impedance at first contact so that uncertainty in object position will not generate large forces. Once contact is established, simple contact sensors can detect where object is located, then bring more points on the manipulator into contact with the object. The final step is to increase forces and stiffness of the gripper appendages, to obtain good control of the position of the object and resist disturbances.

Note that this strategy is intrinsic in biological systems, because muscles stiffen with increased force. In previous work we have measured the stiffness of human fingers as instrumented objects are manipulated (Figure 2) (Hajian and Howe 1997). Thus in free space before contact, the fingers are compliant, and as grasp force increases stiffness automatically increases as well. The key point is that this approach requires a low impedance manipulator, not a dexterous hand. This makes grasping (arthropod-style, rather than human-style) an ideal application focus for investigating the role of impedance modulation in manipulation.

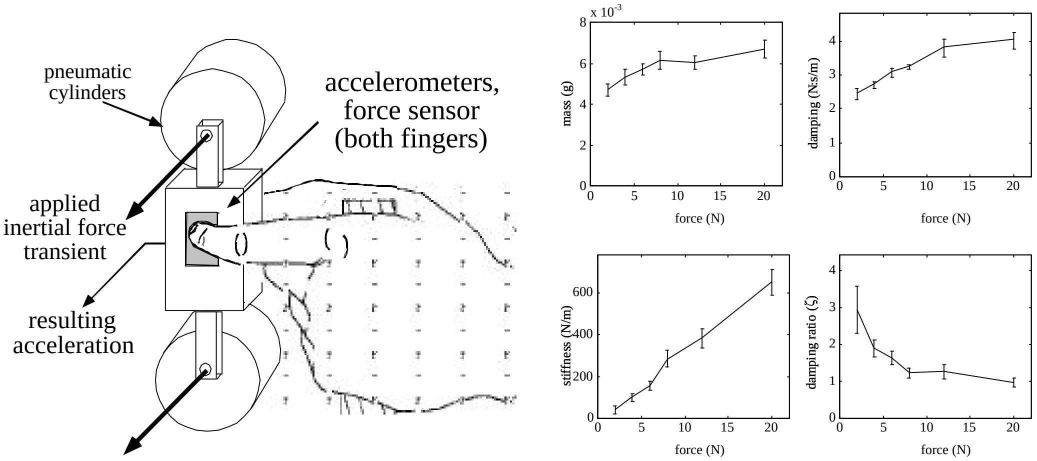


Figure 7. (a) Apparatus for measuring finger impedance in pinch grasp: pneumatic cylinders impart inertial transient while sensors measure resulting force-motion relationship. (b) Measured finger impedance: stiffness rises proportionately with increasing finger tip force (from Hajian and Howe 1997).

In the proposed project, Full will study arthropod manipulation, and work with Howe to characterize these manipulation strategies in engineering terms. Howe will use the Whole-Arm Manipulator (WAM) as a variable-impedance testbed for the implementation of these algorithms. In years 1-2, Howe will work with Shadmehr as described above to implement the muscle-like compliant controller described above. In parallel, a simple visual tracking system will be constructed, based on the successful system developed by Prof. Greg Hager at Yale University and previously used with Howe in collaborative experiments (Son, Howe, Wang, and Hager 1996). The BarrettHand, a low-DOF gripper designed for use with the WAM, will be integrated with the arm controller.

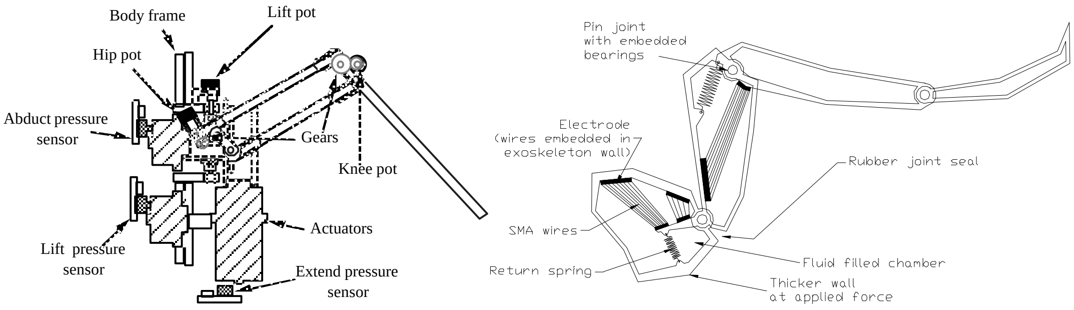
A contact sensing system will also be developed, based on technology developed in previous ONR-funded research (Howe et al. 1995). This system will provide relatively coarse contact location and magnitude information (1 cm/1 N), but the WAM arm’s intrinsic low impedance, combined with the compliant controller, will enable grasping of a wide range of objects in unstructured environments. By the end of year 3, the contact sensing systems and simple visual servoing system will be integrated with the complaint controller. We note that this integration process is in itself an area of considerable current interest in robotics research, and anticipate significant progress from this phase of the project in itself.

Years 4 and 5 will focus on the development of arthropod-inspired grasping algorithms, in a collaboration between Howe and Full. Initial work will use descrete objects in uncluttered settings to test the compliance controller and contact sensing algorithms. Later tests will involve probing to disambiguate objects in more complex settings such as piles and structures. The goal will be to determine the situations where and to what extent the modulation of gripper impedance will increase the robustness and effectiveness of grasping in unstructured environments.

Area 4: Robot Design and Fabrication

A number of researchers in the robotics community have drawn inspiration from biological models over the years. As our understanding of biological mechanisms improves, the desire to apply similar mechanisms to robots has increased. Until recently, it has been impractical to build devices with complex three-dimensional structures that combine engineered compliance and damping properties, sensors and actuators.

Even the most sophisticated of today's insect robots reveal compromises that must be made when constructing robots from common engineering materials such as aluminum tubing and off-the-shelf motors, bearings, sensors etc. To illustrate this point, Figures 8a and 8b are two different designs for the leg of an "insect robot." Figure 8a is a leg of a robot developed by Stanford Ph.D. candidate M. Binnard while he was a student in the MIT AI lab. For comparison, Figure 8b shows a prototype design employing three-dimensional plastic "exoskeleton" surrounding cooled shape-memory actuators and embedded elastomeric spring elements.



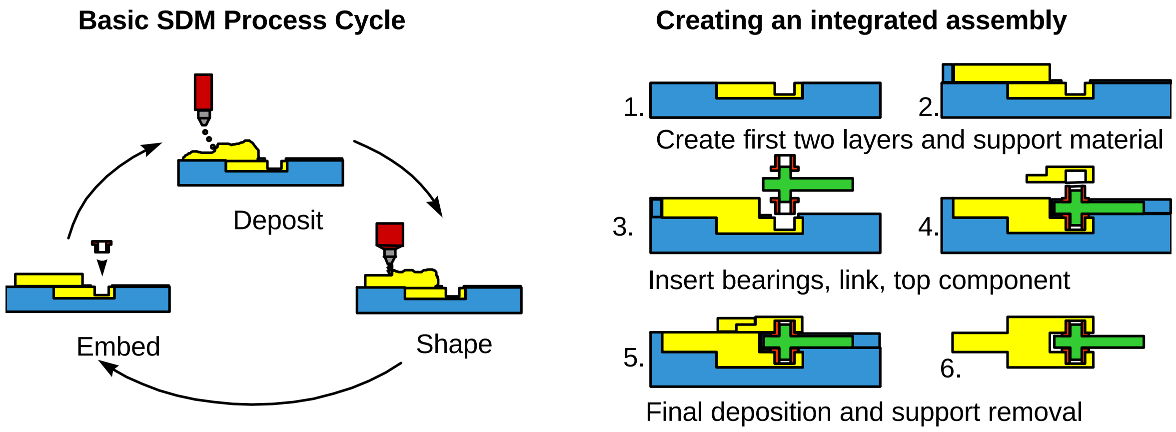
(a) (b)

Figure 8. Design of an "Insect Leg". (a) Leg designed by conventional motors, bearings and sensors. (b) a prototype design of the same leg employing three-dimensional plastic "exoskeleton" surrounding

Designs like that in Figure 8b are made possible by a new class of manufacturing processes. In these processes, called shape deposition manufacturing (SDM), materials are alternately added and removed in incremental steps. The working material is encased in a sacrificial support structure so that conventional fixturing difficulties are avoided. SDM processes allow plastics, metals and ceramics to be deposited and shaped, layer by layer, into almost arbitrary three dimensional geometries with continuous variations in density, alloy concentration and other materials properties. Convoluted three dimensional cooling channels and internal cavities are also much easier to fabricate that with any traditional manufacturing methods.

Shape Deposition Manufacturing

The Stanford Rapid Prototyping Lab and the Center for Design Research have recently been awarded grants to establish a Design and Manufacturing Interface for SDM processing. The technology is still evolving, but acceptable surface finish and structural integrity are today obtainable with a range of materials that includes low shrinkage plastics (typically using machinable wax as the support material) and metals such as stainless steel and Invar (using copper as a support material). For Soft Robots, it is expected that plastics such as high density polyurethane, with mechanical properties similar to Nylon, will be especially useful.



Basic SDM Process Cycle

Creating an integrated assembly

Figure 9. Shape Deposition Manufacturing (SDM) involves a repeated cycle of depositing materials and then shaping them to obtain desired tolerances and finish. Discrete components can be added at any point during the

The essential difference between SDM processing and conventional manufacturing is illustrated in Figure 9. In conventional manufacturing, parts are shaped (e.g., milled on a CNC milling machine) and then assembled with fasteners. In SDM manufacturing "integrated assemblies" are composed in a repetitive process in which layers of material are first deposited and then shaped. A problem with conventional manufacturing methods is that, for small devices, the amount of "real estate" consumed by fasteners can become excessive. Figure 10 illustrates what happens when we try to connect a small electric motor to a leg linkage. Many extra parts are required to connect the motor to the link. When this motor is attached to a robot frame, there is further inefficiency. For example, the casing of the motor could be eliminated and integrated into the chassis of the robot.

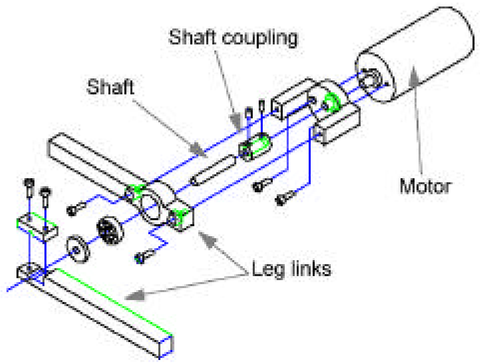


Figure 10. Creating small motor/linkage assemblies becomes difficult when conventional parts and manufacturing methods are employed

If an electromagnetic actuator is desired, then a much more efficient solution is to embed the actuator directly into the chassis or "body" of a small robot and to connect it directly the limb that it is supposed to move. This approach becomes possible with SDM manufacturing. A similar argument can be made for sensors. Instead of purchasing a conventional angle encoder and attaching it to a motor we can embed sensors directly into the robot structure.

Proposed experiments

The development plan emphasizes refinement of critical components before tackling the major integration and complexity challenges of constructing a complete robot. Our work will begin with the construction and analysis of individual joints using a combination of SDM and embedded components. We will evaluate several different actuator technologies (see Table 1 below), using these primary criteria: robustness, force and power density, muscle-like properties, ease of embedding and integration in small or large devices.

As our experience grows, we will begin integrating embedded sensors and actuators with these joints to develop complete legs and fingers. We anticipate multiple design-fabrication. Qualities and parameters to characterize include: robustness (resistance to damage), force-velocity curves, power input, power output, and workspace. During development of these leg/finger designs we will produce a design library of single-axis joints and other “primitives” to facilitate their re-use in future revisions and in robots of different scales (e.g., human-sized).

Actuator type	Advantages	Disadvantages
Electromagnetic	Mechanically simple Well understood Easy interface with electronics	Low power density Low force density Battery limitations High speed, low force
Hydraulic	High force Power density Scales well for small machines	Leaks Weight of fluid Requires recirculation High pressure (>1000 psi)
Pneumatic	High force Power density Scales well for small machines Flexibility Moderate pressure (~100 psi)	Controllability Seal vs. Friction tradeoff
Shape Memory Alloy	High force Flexible packaging Looks like muscle	Elaborate cooling required Very low efficiency (~2%)
Piezo-electric	Mechanically simple	Low power output Poor speed control Requires high voltage

Table 1. Comparative merits of different actuation mechanisms for biomimetic robots

After developing satisfactory leg/finger designs, we will begin integration of a complete insect-like robot that will attempt to capitalize on Full’s discoveries, particularly the insects’ use of pre-programmed force patterns that are stable with a variety of external disturbances. Full has shown how the force pattern produced by cockroaches produces stable, straight line, constant velocity motion, and that small, open-loop modifications to this pattern, allow turning and climbing. Our goal is to build a machine that can operate with a similarly simple high-level control system. We believe this approach will lead to robust robots that can operate in unstructured environments without elaborate sensory systems (like vision) and internal models of the environment.

The first robots we construct will be relatively simple, possessing only 4 or 6 independent Degrees-of-Freedom. In effect, these robots will be “mechanically programmed” to use a tripod gait like the cockroaches Full studies. The front and rear legs will move together; perhaps with mechanical linkage, but more likely with separate actuators with a shared valve or amplifier. This approach will permit us to quickly get a robot working, and allow preliminary experiments before undertaking the large assembly, debugging, and maintenance tasks involved with building a robot with 20 degrees of freedom and dozens of sensors.

In the second phase of our work (years 4, 5) we will explore adaptation and impedance modulation strategies, as developed in work of Shadmehr and Howe, to extend the range of tasks that our robots can perform.

The experimentation and fabrication plan that we describe is critically dependent on advances in sensor and actuation technology. Therefore, Cutkosky’s group will collaborate closely with Kenny and Kazerooni in these areas.

Sensors and Actuators for Biomimetic Robots

Compared to even the simplest of organisms, today's robots are extremely impoverished with regard to actuation and sensing. Animals are equipped with many redundant sensing and actuation elements. For example, the scorpion on the title page of this proposal typically has multiple muscles (long and short, fast and slow-acting) for each joint and numerous fine, short hairs over its body, including the gripping surfaces of its claws, that help it to locate and robustly manipulate its prey. In comparison, the "insect" robot Hannibal at the MIT AI lab, arguably one of the most sophisticated and sensor-intensive robots in existence, has approximately 150 sensors and uses perhaps 50 of them at any given time (Ferrel, 93).

Admittedly, many of the redundant actuators and sensors found in biological organisms may not be needed for robust task performance in unstructured environments. Some may represent hereditary baggage and others may be compensation for relatively slow neural transmission and processing rates. Nonetheless, we argue that biomimetic robots should have substantially more sensing and actuation than the typical robot today with one motor and one fragile encoder per degree of freedom. Therefore, research on embeddable sensors and actuators is an important component of this project.

To meet the need for better sensing, we will follow two approaches. One relies on silicon microfabrication technologies to produce silicon microsensors, such as encapsulated pressure sensors, thermometers and accelerometers which can be embedded into a structural element made by shape deposition fabrication. The other will rely on the insertion of polymer-based sensing materials suitable for strain detection into these same structural materials. The silicon microsensors will have to be small enough to avoid altering the mechanical characteristics of the supporting structure, whereas the polymer microsensors can be distributed throughout the structure.

Silicon microfabricated sensors

For more than 20 years, researchers have been developing micromechanical sensors based on silicon fabrication techniques and a variety of electromechanical sensing techniques. The simplest of these sensing techniques relies on the piezoresistive properties of doped silicon, which enables detection of strain at the ppm level with simple electrical measuring circuits. Pressure sensors, accelerometers, flow sensors, and many other physical sensors have been developed based on silicon piezoresistors, and it is possible for these sensors to be thin enough to be inserted into a shape-deposition fabricated structure during fabrication. There are two problems. First, the mechanical characteristics of the silicon, such as the bulk modulus, are generally very different from the host materials that would be chosen for a biomimetic robot. To overcome this problem, it is necessary to be sure that the sensor structures are too thin to affect the properties of the structure. For example, it is possible to fabricate piezoresistive strain gauges to measure lateral tension with thickness of less than 1 micron. "Wires" which allow electrical connection to external circuitry can be made from the same 1 micron thick structural elements, and can be arranged in thin layers with only slight impact on the mechanical performance of the structural element.

The second problem with embedded sensors is the need to bring electrical connections to the outside of the supporting structure in a way which does not alter the properties of the structure. We may either utilize conductive polymers for this purpose, or we may fabricate ultrathin doped silicon interconnects which are too thin to alter the mechanical properties of the structure. Generally speaking, interconnections from embedded sensors are a serious problem. Our work will address this problem, seeking appropriate solutions based on use of compatible materials, such as polymers or silicon wires. The sensor and systems depend on these interconnects, so a robust solution is called for.

Polymer-based sensing

Eventually, it is important for the embedded sensors to be made from materials that are mechanically compatible with the rest of the structure to be instrumented. True biological systems rely on sensory response from embedded cells in the skin or other tissues to gather sensory information. Generally, the "performance" of these mechanical biosensors is very poor by industrial standards. Nevertheless, the combinations of signals available from arrays of different types of sensors enables biological systems to recognize signals and execute tasks. Following in this direction, we will experiment with some recently-developed mechanical sensing materials which are based on carbon-impregnated polymers. These materials offer resistance values which are dependent on applied mechanical pressure or tension, and segments can be inserted into biomimetic structures during fabrication.

Raychem Corporation has developed a family of such materials and is beginning to explore their use in various industrial applications. For our applications, materials of this class offer the advantage of mechanical compatibility, and the capability for detection of appropriate mechanical signals. These materials will not offer the best possible performance (sensitivity, linearity, dynamic range, etc.) for measurements of mechanical force, but mechanical sensors for biomimetic structures do not need to be optimized, because the signals of interest are not small and do not need to be precisely measured.

Together, these approaches will provide data on available signal levels, and on use of mechanically-compatible sensing materials for biomimetic structures. When integrated within a complete system, these sensors will enable experiments to test control strategies and the operation of a complete system.

Design and Control of New Actuators for Interactive Tasks

Existing electromagnetic actuators are designed to serve in a wide variety of industrial tasks such as robotics, factory automation, and aerospace industries. These industrial actuators, however, often fail to achieve a level of performance comparable to human muscles in even the simplest of tasks. For example, humans excel at avoiding obstacles, assembling complex parts, and picking up fragile objects. Moreover, the nonlinear dynamic properties of human muscles are characteristically absent in the dynamic properties of the actuators that are used in existing robotic systems. Our hypothesis is that to develop robust operation in unstructured environment, the electromagnetic actuators of the biomimetic robots should exhibit behavior similar to that of muscles. We hypothesize that it is misguided to power robotic systems that must perform interactive tasks with electromagnetic actuators that lack performance characteristics similar to those of human muscles. Since the human arm is always stable in interaction with the environment, the integration of robot and environment via the above method will also be stable if the actuators exhibit the same dynamics as those of the human arms. Therefore, the objective of this study at UC Berkeley is to design and construct actuators which behave as Hill's model of human muscles predicts. Hill's model of the human muscles is one of the most effective models in representing the dynamic characteristics of the human muscles.

There are two approaches to human muscle modeling. One is based on the molecular or fiber range of the muscle (Crago 82, Crago 90, Stein 82, Zahalak 80, Marsden 80), and the second is based on the relationship between the input and output properties of the muscle (Cooke 79, Cooke 80, Houk 79, Ramos 90, Wieneke 84, Winters 85, Winters 90). We have chosen the second approach and reported our preliminary work (Kazerooni 93 and Kazerooni 94) as applied to the control of orthotic devices. With this second approach, there is less concern about the internal structure of the components in the model; the detailed dynamics of nerve conduction, muscle contraction, and central nervous system processing are implicitly accounted for in constructing the dynamic model of the human arm muscle. The second approach is based on the human muscle model developed by Hill (Hill 70) which consists of three elements: two positioned in series, with the third in parallel with them. The two in series consist of a force-generating element simulating the active muscle contraction and a non-linear impedance simulating the tendon stiffness. The parallel element consists of a non-linear impedance which simulates the passive nature of the muscle. The force-generating element, not modeled specifically in Hill's model, has two basic characteristics: length-tension and force-velocity relationships (Berthoz 70, Burke 76, Wilkie 50). These characteristics which are functions of human posture parameterize every human muscle.

In our previous research, we developed rules for the design of a supervisor controller for interaction with environment. The structure of this controller depends not only on the environment dynamics, but also on the robot dynamics. We found that in order to guarantee robot-environment interaction stability and achieve high performance within a wide bandwidth, the robot dynamics must be chosen from a class of dynamic systems that meets the stability conditions derived in (Deseor 75). We derived these conditions in several inequality forms. For example, in the simplest case (i.e., linear system domain), the frequency spectrum of the machine dynamics must be smaller than a function that is strongly influenced by the environment impedance (Kazerooni 94). This frequency domain inequality manifests itself as a norm inequality in the non-linear domain. Through our analysis, we noticed that Hill's model-based behavior for the robot well satisfies the stability conditions.

Therefore our first objective is to evaluate the increased performance in robot-environment interaction if the robot actuators behave as Hill's model predicts. We will emulate the non-linear Hill model characteristics in the actuators of a previously developed robotic system at the University of California-Berkeley. Once the model is emulated in the robotic device, the parameters can be adjusted to result in a desired bound on the interaction force. The "adjustment" here refers to a systematic approach to scaling the parameters for the robotic device to achieve optimal performance in compliance control (Kazerooni 86) while instability is prevented. In this way, the robotic device can be used to interact with the environment. Since the human arm is always stable in interaction with the environment, the integration of robot and environment via the above method will also be stable. This is true since the actuators exhibit the same dynamics as those of the human arms. The above logic can also be stated with formal mathematics; since the dynamics of the human arm and the device (after emulation of Hill's model), both are strictly passive, it can be shown, via the Passivity Theory, that the overall dynamics (i.e., of the device and machine taken as a whole) result in a strictly passive and consequently stable system (Kazerooni 89).

Our second objective is to derive the design principles of a very small electromagnetic actuator that, without the use of emulation software, inherently behaves as Hill's model predicts. This second task will address the development of high performance, yet simple, reliable, robust, and low-cost, actuation systems for robotic devices. A prototype actuator that behaves dynamically as Hill's model predicts will be designed and built, and its performance will be evaluated. The main component is the moving core of the actuator, made of neodymium bonded with structural adhesive to a low-carbon steel yoke. A typical existing actuator has torque-velocity characteristics which are independent of the position of the core (rotor) and can be represented by a straight line as shown in Figure 11. In our proposed research, we will study how to generate, within the hardware, an inherent variation of the torque with position and velocity. This property will produce emulation of the desired human muscle characteristics in the actuator. Preliminary investigations reveal that we can design the actuator to yield a specific variation of internal parameters in open loop. This is equivalent to a non-linear feedback implemented internally in the actuator, instead of externally via software. Variations in the following parameters will generate position-dependent torque: asymmetric stator winding, intentional variation in wire thickness (gauge), stator diameter and thickness, rotor diameter, and eccentricity of the rotor relative to the stator and the resulting variable gap. Note that variations in the above parameters do not superimpose linearly because the characteristics of magnetic flux as a function of several variables cannot be expressed with linear equations (For the sake of brevity, we skip the equations that describe the flux characteristics.) Based on our study, we believe that the air gap variation between the rotor and the stator will be an important factor. The second important factor in generating this torque (force in linear actuator) will be the asymmetric winding procedure. According to our previous study, these variations will lead to position-dependent current, back emf voltage, and motor constants. We are in the process of developing software to design this kind of motor (both linear and rotary). For a given set of human random maneuvers (shown by squares), such software yields a set of parameters for the motor. In Figure 11, the curve (marked by 37 Amp) shows the resulting torque-velocity characteristics which are different from the characteristics of the standard DC motors (i.e., a straight line). This figure shows how the new actuator optimally covers all human maneuvers. In the proposed study we will arrive at different families of very small actuators, each corresponding to a distinct shape of the rotor (eccentricity) and stator winding (variable gauge). Values for both characteristics will be selected, and a strategy for commutation will be chosen to obtain the required torque profile. We will design and build the resulting motors and experimentally verify their performance.

Industrial Applications

The results of this research work will lead to a different kind of actuation for industrial applications. The existing state of technology in electromagnetic actuation uses a rather conventional method. Although the existing electromagnetic motors have been quite useful in various industrial tasks, their dynamic principles are inherently different from human muscle dynamics. This research work will lead to the design of new actuation systems for various industrial tasks that require interaction with environment and with humans. Extenders are robotic systems that are worn by humans to maneuver heavy loads or impose large forces. Several research efforts were conducted on

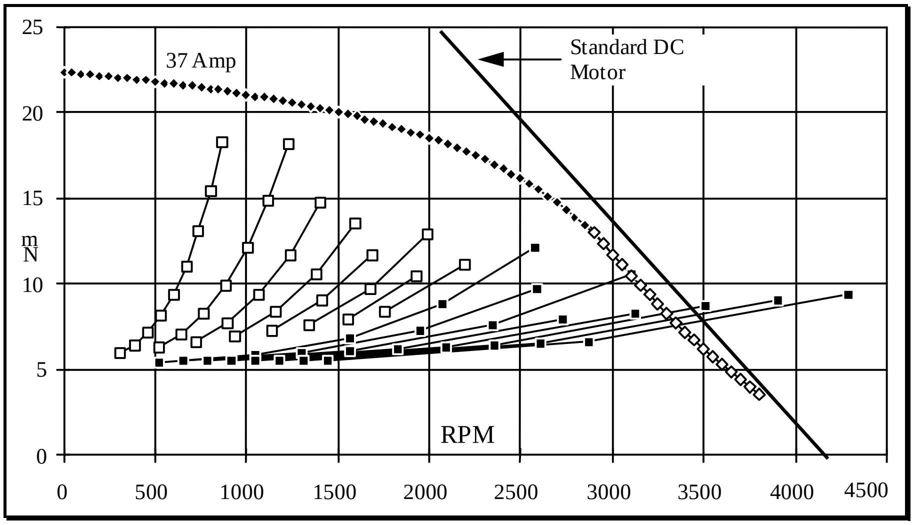


Figure 11. The required power is shown by the scattered points (squares) measured from human random maneuvers. The curve marked by 37 Amp represents a motor winding that behaves like Hill's model and satisfies the required power optimally. The straight line shows the standard DC motor satisfying the required power -- the standard DC motor is over-designed at low speed.

the control of the human extender and on the basic principles of human machine interaction via the transfer of power and information signals in the Human Engineering Laboratory at UC Berkeley. The actuators proposed in this research effort will be evaluated for interactive tasks shown in Figure 12.

Figure 12. Examples of interactive tasks between humans and electro-mechanical machines.

Biomedical Applications

We believe that it is rather inefficient to compensate human motor abilities with the help of actuators that fall short in performance characteristics comparable to those of human muscles. We believe the technology that will be developed can be used to design high performance, yet simple, reliable, and low-cost, actuation systems for orthotic devices. It is our hope that, with the knowledge acquired through these research efforts, more affordable technology will be available to motor-impaired patients within a few years. This investigation will direct the attention of research scientists to a totally different way of thinking about orthotic actuation: an actuation system similar to human muscles. The existing architecture of electromagnetic actuation has evolved from the current nature of use in industrial tasks (rotating shaft), not from its need in orthotic devices. It seems impractical to continue using industrial drive systems to actuate orthotic devices.

Expected Outcomes

Scientific results

The main expected scientific results are as follows:

- A better understanding of compliance and damping in locomotion and manipulation by animals, leading to the development of models that can be used to predict performance and guide robot design efforts.
- A better understanding of *preflexes* as well as learned muscle activation patterns in achieving fast, stable behavior in uncertain environments. This will lead to motor learning or adaptation patterns that can be applied to robots.
- Design and control strategies for robotic devices that capitalize on structural elements and actuation mechanisms for robust task execution.
- Adaptive approaches that help robots come to terms with significant passive admittance and exploit it in the face of changing environmental conditions.
- Biomimetic structures that can be tested to confirm hypotheses about the roles of specific compliance and actuation mechanisms in biological organisms as well as robots.
- Design rules for biomimetic structures with built-in sensors actuators and local control.

Applications - DoD And Commercial

This research will result in the creation of functioning prototypes of soft crab robots capable of surviving and functioning in hostile environments. Such robots would be useful for such tasks as reconnaissance, de-mining, retrieval or clearing underwater or in hazardous environments.

Prototypes of soft robots capable of working safely and efficiently with and around people will also be created. Such robots would enhance the capability of human/robot interaction, allowing each to utilize their strengths and compensate for inadequacies.

Both applications will include integrated sensing, actuation, control and tuned passive properties. The design process of robots will be enhanced by utilization of new manufacturing and biological research.

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3-B Management Plan

We contend that human engineers are now capable of designing "soft" manipulators that begin to approach the effective performance of those in nature. However, after extensive discussion among the participants of the present proposal, we are certain that the production of "soft" manipulators requires a truly unprecedented integration among investigators with appropriate expertise. Each component interacts and is dynamically coupled with all other components. For example, the self-stabilizing properties of the mechanical system affect the actuator and sensor design, the choice of controller and the adaptation scheme used to improve performance. Unless these interactions are considered and investigated, we are unlikely to produce machines that attain performance in any way comparable to that which has evolved over millions of years in nature. System components simply can't be studied in isolation. Therefore, we argue strongly that the following essential areas must be developed in concert with one another:

I Biological inspiration on the role of the mechanical system in the control of locomotion and manipulation (Full).
    1. Self-stabilization by limb morphology.
    2. Self-stabilization by preflexes at a joint.
II Motor control and learning (Howe, Shadmehr)
III Compliant Actuators (Kazerooni)
IV Sensors (Kenny)
V Rapid prototyping of biomimetic structures and integrated assemblies (Cutkosky)

Team cohesion

The project will include a number of mechanisms to ensure the required level of interaction between the team members. These include: annual meetings, joint experiments and analytical efforts among specific team members, and a sequence of demonstration tasks.

The annual Biomimetic MURI team meeting will take place in the San Francisco Bay Area, permitting access to design labs and fabrication facilities at Stanford and biological and mechanical engineering labs at Berkeley. The first meeting, which will focus on planning, will take place within three months from the start of funding. At subsequent meetings researchers will exchange results from the previous year and make detailed plans for collaborations and the demonstration experiments. We will also maintain a Biomimetic MURI web site containing papers and reports generated by the project.[1] This site will also function as a clearinghouse for planning joint work, and keeping all team members up to date on project progress.

As described throughout the proposal, this project relies on collaboration between the diverse team members. Specific joint work includes:

- Cutkosky, Kenny, and Kazerooni will work together to build small robot hardware throughout the project.
- Shadmehr and Howe will build instrumentation and conduct human motor control experiments together.
- Full and Shadmehr will advise Kazerooni on muscle-like actuator properties and performance characteristics.
- Shadmehr will advise Howe on human control strategies for robotic implementation.
- Full will advise Howe on crustacean manipulation strategies.
- Howe will take a sabbatical in California in 1998 to work with Berkeley and Stanford team members at the beginning of the project.
- Stanford Ph.D. student M. Binnard will continue to be a liaison between Full’s group and Cutkosky’s group, providing advice on mechanism design.

Work statement

The table on the following pages describes the parallel tasks that will be conducted during each year of the project.

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[1] A prototype of the web site was constructed for collaborating on this proposal. The URL is http://cdr.stanford.edu/touch/biomimetics, login= “onr_guest”, password = “chitin”).

	Stanford (Cutkosky and Kenny)	**Berkeley** (Full)	**Berkeley** (Kazerooni)	**Harvard** (Howe)	**Johns Hopkins** (Shadmehr)
Year One	- Construct individual joints using combined SDM and embedded parts. - Explore actuation alternatives (SMA, ultrasonic piezo, etc.) - Quantify compliance, damping, efficiency, robustness to external loading. - Apply stiffness matrix and impedance modeling to cockroach model (Full).	- Characterize and convey advantages/ disadvantages of biological systems for actuators (Kazerooni), structures (Cutkosky), joints and control (Howe and Shadmehr). - Begin literature survey on manipulation tasks of arthropods	- Evaluate potential increased performance in robot-environment interaction if the robot actuators behave as Hill's model predicts. Quantify preferred parameter ranges. - Incorporate data from biological systems provided by bio. team members (Full, Shadmehr).	- Formulate initial muscle-like controller for joints of WAM robot: preflexes and reflex-like system integrating sensory and adaptive processes (Shadmehr, Full). - Implement and test controller on WAM hardware. - Implement simple visual tracking system	- Measure arm impedance and adaptation strategies in passive environments. - Advise on human impedance modulation strategies for robot control (Howe).
Year Two	- Develop individual legs/fingers using SDM and conventional processing with actuation and sensing (Kazerooni). - Preliminary work on embedded silicon sensors and interconnects. - Investigate feasibility of 3D CAD and muscle placement data for ‘insect' limb (Full) - Begin examination of advantages of multiple, redundant actuators and sensors.	- Compliant actuators: design evaluation (Kazerooni), measure muscle impedance. - Compliant joints/ multiple muscles: design evaluation (Howe); measure insect joint impedance - Characterize biological advantages of: number of appendages & joints, segment morphology, segmental stiffness (Cutkosky), sensor placement (Kenny); joint synergies (Howe and Shadmehr). - Videotape arthropod manipulation.	- Begin development of high performance, yet simple, reliable, robust, and low-cost, actuation systems for robotic devices. Initial focus is parametric study of elecromagnetic interaction design options. - Collaborate with Cutkosky to explore actuator design suitable for miniaturization.	- Develop controller/learning structures to implement human compliance strategies in unstructured environments (Shadmehr). - Begin development of contact sensor system for WAM arm. - Implement code to coordinate arm and visual system. - Integrate simple gripper with arm control. - Perform initial grasping/probing experiments.	- Measure arm impedance and adaptation strategies in passive unstable environments; construct control and adaptation model. - Advise on human impedance modulation strategies for robot control (Howe).

Year Three	- Apply control and adaptation principles from Howe, Shadmehr to coordinate control of joints and limbs. - Conduct experiments in coordinated legs/fingers for locomotion/ manipulation taking advantage of Full's new results on manipulation. Refine actuators and embedded sensors. Design and Production of experimental robot with parts produced with SDM	- Compliant actuators: design evaluation (Kazerooni); measure muscle impedance (preflexes). - Compliant joints: design evaluation (Howe and Shadmehr); measure insect joint impedances Design force measurement during arthropod manipulation Research on sensor and manipulation of fingers/claws	- Continue development of compliant actuators. Incorporate task and characterization data (Full, Shadmehr). - Produce actuators for ‘insect’ limb testbed (Cutkosky).	- Develop controller/learning structures to implement human compliance strategies in passive unstructured environments (Shadmehr). - Quantify performance of adaptive controller in same tasks as human experiments. - Integrate contact sensing system with arm/hand control code. - Design instrumented active objects to measure arm impedance in unconstrained tasks (Shadmehr).	- Measure arm impedance and adaptation strategies in *dynamic* unstable environments; construct control and adaptation model. - Design instrumented active objects to measure arm impedance in unconstrained tasks (Howe).
Year Four	- Explore sensors and interconnects for biomimetic structures. - Construct 'insect' robots from mix of SDM and conventional parts. - Explore running on rough (fractal surface) terrain for comparison with Full's experiments involving cockroaches running on identical surfaces. - Explore manipulation of unknown objects, exploiting sensor and actuator redundancy and passive impedance for robustness.	- Compare joint design with human data (Howe and Shadmehr) - Compare actuator design with muscle data (Kazerooni) - Evaluate manipulator designs and control systems (Cutkosky, Kenny) - Measure kinetics of arthropod manipulation	- Continue development of compliant actuators. Incorporate task and characterization data (Full, Shadmehr). - Incorporate results of first insect limb experiments to produce second generation small actuators	- Develop controller/learning structures to implement human compliance strategies in *active* unstructured environments (Shadmehr), and characterize performance. - Develop arthropod-inspired grasping algorithms (Full); initial testing.	- Use instrumented active objects to measure arm impedance in unconstrained tasks (Howe). - Advise on biological strategies for robot control (Howe, Curkosky) and actuator properties (Kazerooni).

Year Five	- Continue refinement of biomimetic 'modules' (joints, legs, fingers, with built-in actuation and sensing) to improve reliability and performance. Incorporate improved sensing (Kenny) and actuation (Kazerooni) technologies. - construct second generation 'insect' robots from mix of SDM and other components to test locomotion and manipulation in unstructured environments. Quantify performance. - Conduct experiments on adaptation, using results from Howe and Shadmehr, and quantify improvements in performance, using first-generation devices.	- Test small "soft" manipulator in the apparatus used to study animals for direct comparison. - Provide biological inspiration for redesign of small "soft" manipulator.	- Continue development of compliant actuators. Incorporate task and characterization data (Full, Shadmehr). - Develop actuation designs tailored for SDM processing and incorporate built-in sensing	- Construct manipulator using muscle-like actuators (Kazerooni, Cutkosky). - Examine range of attainable impedance, time response, etc., and task performance, to determine where specialized actuators are best (Kazerooni, Shadmehr). -Complete implementation of arthropod-inspired grasping algorithms, and test on geometrically similar tasks to compare robot and arthropod performance (Full).	- Use instrumented active objects to measure arm impedance in unconstrained tasks (Howe). - Construct model of impedance modulation and adaptation strategies. - Advise on biological strategies for small robot control (Howe, Curkosky) and actuator properties (Kazerooni).

3-C Facilities

Stanford University SDM Facilities

The use of Shape Deposition Manufacturing for the proposed work is heavily subsidized by other funding from the National Science Foundation (MIP-9618050: Prinz, Cutkosky, et al), DARPA and industrial sponsors. The fabrication will take place in the Stanford Rapid Prototyping Laboratory (see Figure 11), which consists of seven processing stations including 5-axis CNC milling, plasma-based microcasting, laser deposition (2400W Nd:Yag), low temperature deposition of UV-curable and two-component resins, shot peening, grit blasting, and cleaning. Currently the system is capable of producing metal and plastic parts from sub-millimeter sizes to a maximum of a 240 x 240 mm footprint up to a height of 250 mm. Future plans include adding add a 3-axis CNC EDM machine to increase material removal capabilities, a second CNC milling machine with gelcasting deposition heads for ceramic processing and an induction deposition station to facilitate metal droplet deposition through induction heating. We will also add thinfilm processing technologies, such as sputtering and photolithographic masking into the Stanford facility to allow the fabrication and embedding of electronic components and the fabrication of micro-mechanical structures.

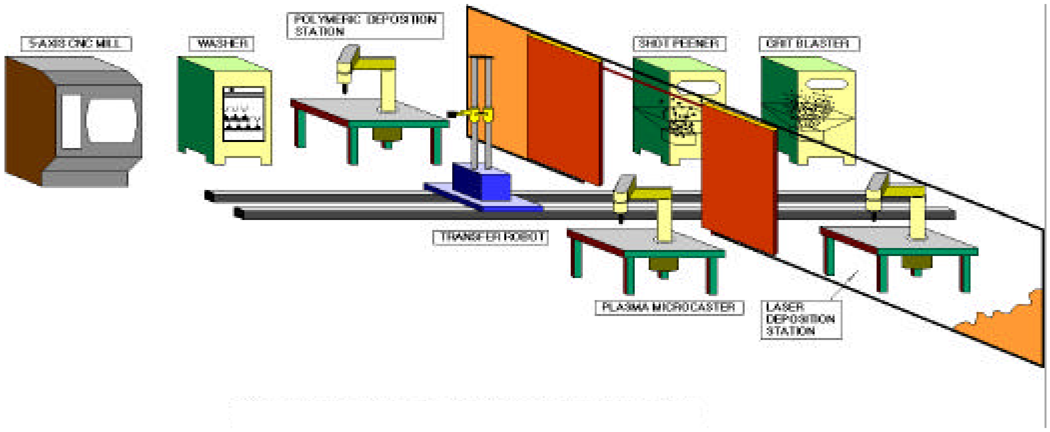

Figure 11. *Stanford Rapid Prototyping Lab*

Stanford Dexterous Manipulation Lab

Additional work will take place at Professor Cutkosky’s Dexterous Manipulation Laboratory, which adjoins the Rapid Prototyping Lab. The laboratory is equipped with three industrial robots, two dexterous robot hands, and a number of real-time computers and associated instrumentation for research in manipulation with tactile or haptic sensing. The Dexterous Manipulation Lab is also part of the Stanford Center for Design Research, with extensive CAD facilities.

Stanford Micro-Structures and Sensors Lab

Professor Tom Kenny’s Stanford Micro-Structures and Sensors Lab is focused towards further refinement of tunneling sensors, the development of fabrication techniques for novel micromechanical structures, and the study non-classical phenomena within this context. Lab facilities include precision laser interferometry for measurements of micromechanical motion, and test instrumentation for accelerometers, pressure sensors, cantilever beams, infrared sensors, and other physical sensors. In addition, the group makes use of the Stanford Center for Integrated Systems and the Ginzton Microfabrication Lab for silicon micromachining and other materials

U.C. Berkeley Human Engineering Laboratory

Professor Kazerooni’s 3,600 square-foot Human Engineering Laboratory (HEL) is available for the design and construction of the human power amplifier and actuator described in this proposal. This laboratory has the essential infrastructure and the professional staff to design all kinds of electromechanical, pneumatic, and hydraulic systems. This laboratory houses a dozen micro-computers and workstations for real-time control and design. The lab is also equipped with a complete set of measurement, diagnostic, and electronic system analyzers. The infrastructure and experience available in this laboratory, which have evolved throughout a decade of research work in the design of assist systems, will nurture this project to maturity. A CNC five-axis Machining Center (made by Sharp), a CNC Turning Center (made by Mori Seiki with live tooling), and an EDM machine (made by Fanuc) are some of the major computerized machine tools that are available for precision machining of the robot components. All machines are hard-wired to two workstations.

U.C. Berkeley PolyPEDAL Laboratory

The PolyPEDAL Laboratory studies the locomotion of small, many--legged animals. Our 1800 ft^2 laboratory contains four types of work-stations. The Energetics work-stations consist of miniature treadmills, O2 and CO2 analyzers for the estimation of the metabolic cost of locomotion. The Mechanics work-stations include high-speed video cameras for three dimensional kinematic analyses and several force sensitive platforms for three dimensional kinetics. The Muscle work-stations consist of computer controlled muscle levers and EMG data acquisition. The Modeling work-stations consist of SGI computers with muscle and whole-body dynamic modeling programs. We also have access to a biological visualization center and an ecological scanning electronic microscope which allows pictures of living tissues.

Harvard University Facilities

Howe's laboratory has extensive facilities for the experimental investigation of sensing and control in biological and robotic systems. These facilities have been developed in the course of many previous studies of tactile sensitivity and motor control in humans. The laboratory also has extensive instrumentation for the measurement of mechanical parameters such as displacement, velocity, and force. There are complete facilities for testing and calibration of tactile sensors, and for measurement of their mechanical properties. The laboratory has a number of personal computers, including real-world interfaces (A/D and D/A boards, multi-axis motion controllers, etc.). The Division of Engineering and Applied Science's computer support group includes full-time professional staff members. This group maintains dozens of networked UNIX workstations and many personal computers. The Division's Scientific Instrument Shop has complete facilities for precision fabrication, including the construction of biomedical and flight-certified experimental apparatus.

John Hopkins University Facilities

The Johns Hopkins Laboratory for Human Motor Learning is headed by Dr. Shadmehr. The lab has the facilities to design and build small, portable robots for the purpose of interaction with the human arm. The lab currently houses a two-link, portable robotic manipulandum that has traveled widely and has been used to produce novel force fields for the purpose of experiments on human adaptive control. Various neurophysiological measuring devices such as EMG are also housed. Seven workstations provide for the computing requirements. The infrastructure and experience available in this laboratory will nurture this project to maturity.

3-D Education and training

Each principal investigator will support two graduate students or one graduate student and one post-doctoral researcher for the proposed research. Associated students in each laboratory will be positively affected, particularly those working on the NSF project mentioned above.

Each university offers seminars that feature the current research being performed. Information and discoveries from the proposed research will be included in this curriculum. Through the NSF/DARPA rapid prototyping center at Stanford, a large national design community will be affected.

3-E Collaborations and transitions

The proposed research by Full's polyPEDAL Lab is an obvious extension of their present ONR funded (N00014-92-J-1250) research on legged maneuverability. The current proposal attempts to discover the mechanisms of self stabilization. The research proposed in the present white paper would take the next logical step and attempt to discover its mechanism.

The research by Cutkosky and Howe is an extension of their completed ONR project (N00014-92-1887), which improved dexterous manipulation and developed multiple robot sensors. In addition, the proposed research will enhance work being done under a grant from NSF and DARPA to design a manufacturing interface for the SDM process (MIP-9618050), and STTRs with Immersion Inc., Virtual Technologies and Schilling.

The SDM testbeds have significant industrial exposure. The USAMP (U.S. Automotive Materials Partnership) consisting of GM, Ford, and Chrysler has chosen SDM as a candidate technology for fabrication of production quality tooling. General Motors has placed an engineer from its Rapid Prototyping Laboratory in Warren, Michigan at Stanford's Rapid Prototyping Laboratory to perform a Ph.D. exploring the use of SDM for of a class of automotive dies. Other companies, including Alcoa in Pittsburgh and UT Technologies in Los Angeles, are helping to refine the SDM process for factory use. SDM is an emerging node on the ARPA-sponsored ACORN project that provides network based design and manufacturing services for applications such as fabrication of wearable computers. Two commercially available SFF processes are part of ACORN. Stereolithography is offered by ALCOA and Soligen is offering 'Metal Parts Now' using the MIT 3D printing process for producing ceramic shell molds for casting. We will make these services available through SAMUEL if they are needed.