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).