IC
Postdoctoral
Research Fellowship
Program

Example for Submitting a Research Proposal

Smart robot appendages with integrated actuators, sensors and preflexes

Topic 8.9. Enabling Technologies for Robotics

A. Proposed Research

Robots have traditionally been designed with mechanical structures, actuation and sensing treated as separate concerns and accomplished with separate subsystems. In contrast, Nature tightly integrates the passive mechanical properties of limbs with their sensing and actuation. A muscle, for example, is an energy storage and dissipation element, a tunable spring and a system containing many sensors, as well an actuator.

The work proposed herein combines recent advances in creating robotic appendages with integrated actuation and sensing and in the modeling and control of such integrated limbs. We propose to share a post-doctoral fellowship between two leading institutions in the areas of biomimetic robot design, fabrication, modeling and control.

Smart appendage design and fabrication

The work will draw upon previous developments in creating multi-material, compliant appendages with built-in energy storage and damping to simplify control and increase physical robustness. Examples include the feet of Spinybot, a robot that climbs vertical surfaces using arrays of compliant microspines [2] and the legs of Sprawlita [1] a hexapedal robot inspired by the cockroach.

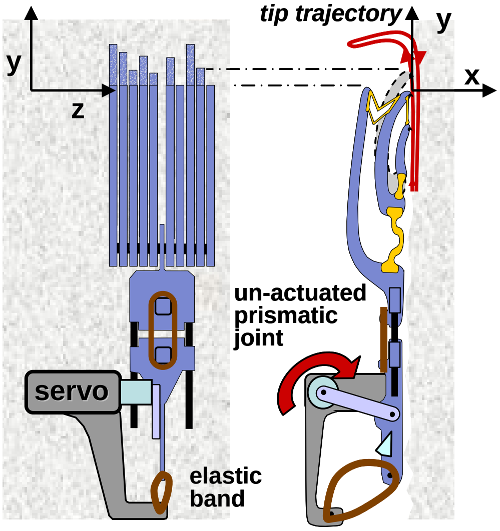

Fig 1. Spinybot under-actuated leg promotes spine engagement with a single actuator and passive compliances.

A feature of the Spinybot and Sprawlita legs is that they are under-actuated i.e., they have fewer motors than degrees of freedom. A consequence of this approach is that actuation and structural design must be considered together – the structure absorbs and stores energy imparted by the actuator at certain parts of the locomotion cycle and releases it at others. The behavior is a function of the compliances in the structure, of the actuator force/torque trajectories and of external loading. In the case of Spinybot, for example, the result is a “J” shaped trajectory (Fig. 1) achieved with a single actuator. In addition, the foot is highly compliant in the direction perpendicular to the wall on first contact, but stiffer once the spines have engaged and body loads are applied. In biology, the analogous behavior of compliant, damped structures gives rise to “preflexes” that help to stabilize and simplify the control of limbs in various animals [3,5]. It is a particular challenge to synthesize mechanisms with the right combination of properties and this is a component of the proposed work, as described in the next section.

The second fabrication challenge is to integrate sensing with actuation and structural design. We believe that the creation of sensor-rich feet, claws, pincers and antennae will ultimately involve the fabrication of sensor arrays *in-situ* on multi-material structures and we are developing the technology to make this possible. The proposed approach is to combine lithographic patterning with the Shape Deposition prototyping process [4] to create arrays of sensors such as strain gages on curved polymer surfaces. The metal patterns will be thickened, where necessary, using electroplating. Discrete devices for multiplexing, etc., will be surface-mounted to the patterned circuit. Preliminary tests on sample structures suggest that this approach will produce strain gages of acceptable quality for use in controlling a limb.

Smart appendage modeling and control

Part of the reason for a reluctance to utilize integrated sensor/actuator/structure systems in robots in the past is that they are more challenging to model and control. At the lowest level, the load/deflection and impedance characteristics of the structure must be analyzed. These characteristics contribute directly to the preflexes embodied in the limb as it responds to unexpected loads.

At the next level are opportunities for more efficient motor control. (We anticipate that the actuator will be electromagnetic, unless rapid advances occur in the field of artificial muscles.) A potential advantage of integrating a motor with an under-actuated compliant limb is that the motor can be used more efficiently. The structure can absorb and release energy when it is most needed at parts of the locomotion cycle. The structure also isolates the motor somewhat from unexpected collisions between the appendage and environment. Consequently, the limb is more robust.

At a higher level we are concerned with sensor/actuator loops. For example, if an unexpected contact force is sensed mid-way along a limb, how should the limb respond? The response at this level should take advantage of the preflexes that arise from the limb structure and configuration.

The current state of the art is that while tools exist for analyzing compliant, integrated sensor/actuator structures, the models are imprecise. Moreover, designing such integrated structures is a trial-and-error process. A challenge that the post-doctoral fellow will be encouraged to address is to develop methods for *synthesizing* integrated, under-actuated limbs and their controllers to achieve desired behaviors.

Management Plan

The laboratories involved have a record of successful collaboration and have exchanged visits and worked closely together on an ongoing project. The management plan takes advantage of this interaction and aims to strengthen it with a shared post-doctoral fellow. A likely candidate has been identified and his CV is included in this proposal.

It is expected that the fellow will spend substantial periods of time at both institutions. An initial period will allow him to become familiar with the modeling and behavior specification tools. During this time, the he will communicate regularly by participation in weekly conference calls that already take place between the laboratories and learn about the fabrication capabilities and process planning methods so that he can develop a model of a prototypical integrated limb.

The next period will be spent fabricating and testing a series of structures, starting with simple specimens and culminating in a compliant, actuated, sensate limb that could be used for the next generation of climbing robot. The test specimens will allow the post-doctoral fellow to refine a method for fabricating arrays of sensors and to correlate the results of loading the specimens with the models.

A final period will be spent controlling the newly fabricated smart appendages and integrating their instrumentation with that of the overall robot platform. The candidate will bring his acquired expertise in fabricating sensor arrays on multi-material compliant parts.

B. Expected Outcomes and Relevance to the Intelligence Community

Novel discoveries by the post-doctoral fellow will lead to development of compact, multi-material, multifunctional structures with integrated sensing and actuation. Such structures are the building blocks of all animals, but practically unknown in man-made devices. The technology used to design, analyze and fabricate these structures is applicable whenever the following characteristics are at a premium: small package size, complex geometry, integrated actuation and sensing, robustness and strain tolerance, locally tuned stiffness and damping.

The immediate application is stealthy, climbing robots that employ dry adhesives and microspines for climbing hard vertical surfaces. The work to be undertaken by the post-doctoral fellow will complement these efforts and permit greater attention to the underlying science and technology for designing, fabricating and analyzing smart appendages. Other applications of the same science and technology include advanced prosthetic devices for wounded veterans, implantable medical devices, and other robotic and unmanned vehicle applications.

Period	Activities	Milestone Deliverables
0-6 month	Develop dynamic behavior models of compliant, integrated actuator and structure.	Model of prototype limb that can be fabricated
6-12 month	Develop and test compliant structures with *in-situ* fabricated sensors.	Fabrication method for patterning sensors on 3D compliant structures.
12-18 month	Develop prototype multi-material limb with integrated actuation and sensing.	Limbs for next-generation bio-inspired climbing robots.
18-24 month	Refine local sensing and control of actuation for limb. Integrate limb with robot platform.	Smart robot appendages with integrated actuators, sensors and preflexes.
24-36 month	If it is determined to continue the fellowship into a third year the focus will be on expanding the approach to additional applications.	

References

[1] J.G. Cham, S.E. Bailey, J.C. Clark, R.J. Full and M.R. Cutkosky, "Fast and Robust: Hexapedal Robots via Shape Deposition Manufacturing," *Intl J Robot Res*, (21)10, 2002 pp. 869-883.

[2] Kim, S., Asbeck, A., Provancher, W., and Cutkosky, M.R., “SpinybotII: Climbing Hard Walls with Compliant Microspines,” to be presented at ICAR, Seattle, WA, July, 2005.

[3] Kubow, T.M. and Full, R.J., The role of the mechanical system in control: a hypothesis of self-stabilization in hexapedal runners. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences*, 354(1385):849–861, 1999.

[4] Weiss, L.E., Merz, R, Prinz, F.B., Neplotnik, G, Padmanabhan, P, Schultz, L, and Ramaswami, K., “Shape deposition manufacturing of heterogeneous structures,” *Journal Of Manufacturing Systems*, 1997, v.16, no.4, p.239-248.

[5] X. Xu, W. Cheng, D. Dudek, M.R. Cutkosky, R.J. Full, and M. Hatanaka, "Material Modeling for Shape Deposition Manufacturing of Biomimetic Components," DETC2000/DFM-14022, Proc. ASME DETC/DFM Conf., Baltimore, MD, Sept, 2000.

PRINCIPAL INVESTIGATOR

BIOGRAPHICAL SKETCH

NAME	POSITION TITLE

EDUCATION/TRAINING *(Begin with baccalaureate or other initial professional education such as nursing, and include postdoctoral training.)*

INSTITUTION AND LOCATION	DEGREE (if applicable)	YEAR(s)	FIELD OF STUDY

A. Positions and Honors.

Positions and Employment

Other Experiences and Professional Memberships

B. Selected publications (most recent, in chronological order). Do not include publications submitted or in preparation

POSTDOCTORAL FELLOW

BIOGRAPHICAL SKETCH

NAME	POSITION TITLE Postdoctoral Fellow

INSTITUTION AND LOCATION	DEGREE *(if applicable)*	YEAR(s)	FIELD OF STUDY

A. Positions and Honors.

Positions and Employment

Other Experiences and Professional Memberships

B. Selected publications (most recent, in chronological order). Do not include publications submitted or in preparation

Budget and Justification:

Category	**Year 1**	**fringe**	**Year 2**	**fringe**
PERSONNEL				
	$3,602	$1,045	$3,782	$1,097
	$42,000	$7,140	$44,100	$7,497
Total	**$45,602**	**$8,185**	**$47,882**	**$8,594**
	$53,787		**$56,476**	
TRAVEL				
domestic	$0		$0	
foreign	$3,000		$2,000	
Total	**$3,000**		**$2,000**	
OTHER EXPENSES				
publication costs	$1,000		$1,500	
equipment maintenance	$0			
Additional personnel	$1,600		$800	
imaging time	$40,000		$20,000	
Total	**$42,918**		**$22,300**	
DIRECT COSTS	**$99,705**		**$80,776**	
INDIRECT COST	$9,970		$8,078	
TOTAL COST	**$109,675**		**$88,853**	