Stanford Human-Friendly Robot "S2RO"

Design and development of a safe, compact and high performance robot arm.

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Introduction

In recent years, there has been increased interest in the emerging field of *human-centered robotics*, involving close physical interaction between robots and humans. The applications include important areas such as medical robots, manufacturing, and entertainment. A major challenge in the development of human-centered robotics is safety: How can robots be sufficiently strong, precise and dexterous to do useful work while also being inherently safe for physical interaction?

Robots have traditionally relied on electromagnetic actuators, which offer excellent controllability but poor power/weight ratios compared to muscle. Even more limiting is their inability to exert large sustained forces without high transmission ratios between the motor and load. The high transmission ratios result in arms with high mechanical impedance, which are inherently less safe than their low-impedance biological counterparts whenever unexpected contacts occur.

During the past several years our group has investigated new actuation techniques to overcome the safety and performance limitations of existing technologies. We have developed the distributed macro–mini (DM2) actuation approach to address the problem of a large reflected inertia by partitioning torque generation into low- and high-frequency domains, which are controlled by distributed pairs of actuators. Two prototypes (Fig. 1) were developed to extend the DM2 approach to a combination of pneumatic and electromagnetic actuation. Pneumatic McKibben actuators provide high power and force density and inherently low mechanical impedance. However, the underlying nonlinear compressible gas dynamics involved make precise control difficult. By combining them with small electromagnetic actuators we were able to achieve a 10-fold reduction in effective inertia while maintaining high-frequency torque capability. The combination of two different actuation technologies comes at the expense of complexity in comparison to traditional robot design. To make this complexity manageable, we use miniaturized integrated pressure controllers and multi-material structures. As shown in the Fig. 1 (center), a controller using micro-valves and pressure sensors adapted from ink-jet printing technology is much lighter and more compact than a traditional pressure controller. By linking the pressure controllers with a single pressure line, we are further able to reduce the weight and part count.

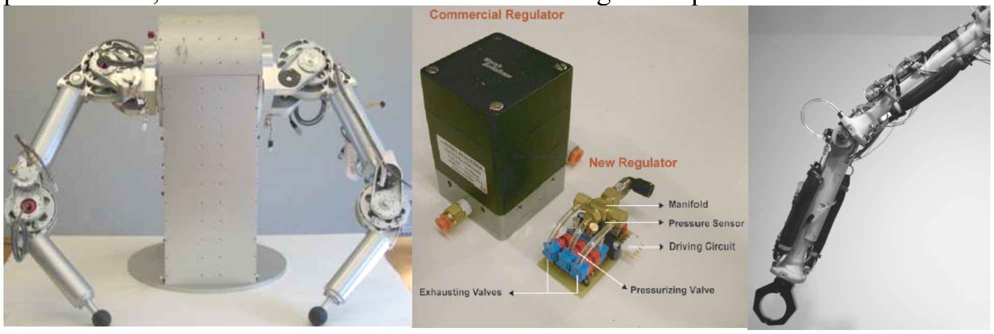
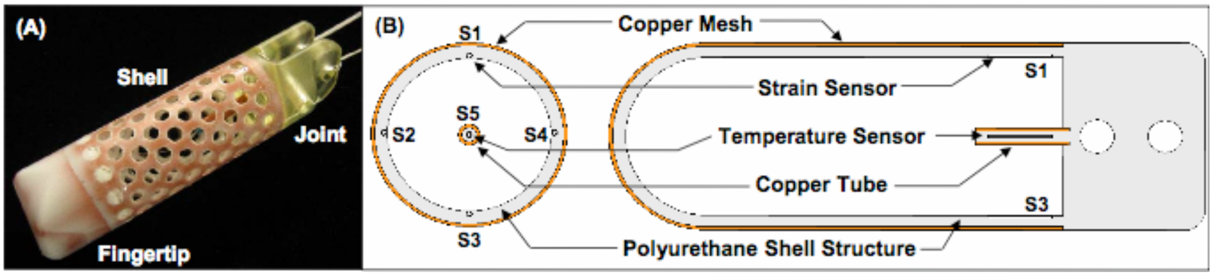


Fig. 1 –Prototype2 (left), new compact regulator (center), prototype 3 (right)

The next step is to integrate these components, along with additional sensors, into a single light-weight structure using the Shape Deposition Manufacturing (SDM) rapid prototyping process. SDM allows multiple materials, as well as sensors, actuators and other discrete parts, to be integrated in a single heterogeneous structure. The technology has been demonstrated for various bio-inspired robots in Cutkosky's lab. The ability of SDM to provide local variations in materials properties also permits structures with high specific strength and stiffness in selected areas while providing high impact energy absorption in other areas (Fig. 2). Built-in tactile sensing capabilities will improve the overall control and



safety of the system in conjunction with new control strategies that take advantage of the hybrid actuation approach.

Fig 2. Multimaterial exoskeletal finger with embedded fiber optic strain sensors (similar technology to be used for fabricating the arm in fig. 3)

Plan of activities

A first two-link prototype will demonstrate a 3D hollow-shell (Fig. 3, left) with integrated subsystems for electromagnetic and pneumatic actuation. A main electric and pneumatic "bus" will connect individual links to power the different actuation stages. Sensing will initially be limited to embedded strain sensors (optical or electronic) for intrinsic tactile sensing. These sensors will allow the arm to locate contacts that occur anywhere along the arm, but which may not produce loads in a load cell at the wrist. Thus, the arm will demonstrate an immediate improvement over existing arms, which are relatively insensitive with respect to unintended, contacts at random locations.

Subsequently, a compliant, sensorized skin will be added and its sensors will be integrated with the power and communications bus. The skin provides a higher resolution and more reliable location measurement for contact sensing, as well as immediate energy dissipation for accidental contacts. Active response to such events will be a component of the control development during the second and third year. The sensors fabricated into the skin may include simple binary sensors (as on a membrane keypad) or capacitive sensors, created using the silk-screen printing process previously used for compliant tactile sensors in Cutkosky's lab [Son96]. Both technologies result in robust, compliant arrays; the capacitive sensors have the advantage of producing accurate pressure distributions with low hysteresis but they require more processing. The decision about which technology to pursue will be based on the results of preliminary experiments during the first year and in consultation with GM research staff.

The prototype will be used in experiments to further develop the hybrid controller and demonstrate a combination of high load capability, low impedance and precise control of fine forces. Experiments will also be conducted to demonstrate the ability to tune arm impedance to accommodate different task requirements and to achieve an inherently safe transient response to unexpected collisions.

Results obtained in building and controlling the first prototype will guide the design of a second prototype, featuring 3-4 degrees of freedom and with an added force sensing wrist and underactuated end-effector. Distributed controllers will be mounted on each link to control local pressure valves and motors. A communication bus will connect the distributed controllers to the central processing unit located at the base of the robot. This second device will be the first computationally and mechanically "smart" human-safe robot arm (Fig. 3, right).
As an option, an active wrist, for a total of 7DOF, will be considered and investigated in collaboration with GM research staff.

[Son96] J.S. Son, M.R. Cutkosky and R.D. Howe, "Comparison of Contact Sensor Localization Abilities During Manipulation," *Robotics and Autonomous Systems*, Vol. 17, 1996, pp. 217-233.

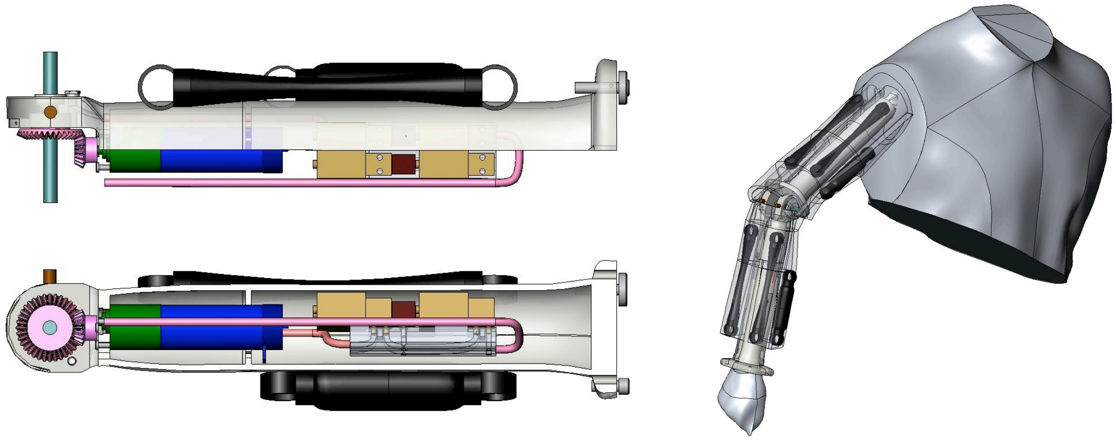


Fig. 3 - Overview of Stanford Human-Friendly Robot "S2RO"

Statement of Work

Year I

0-6 months

- Develop 2-link prototype featuring DM2 actuation and control, integrated bus for electronics and embedded sensors for force control and responsiveness to touch.
- Utilize Shape Deposition Manufacturing (Cutkosky's lab) to fabricate fiber-reinforced polymer prototype with embedded components for increased robustness and compactness.
- Develop refined version of actuation and gearing system, adapted from current prototype in Khatib's lab.
- Research solutions for wrist and under-actuated end-effector for incorporation into the final prototype.
- Initial visit by Stanford (Cutkosky and/or Khatib) to GM Research to discuss details of collaboration.

6-12 months

- Develop and demonstrate dynamic control with improved safety for unexpected contacts.
- Begin control experiments to assess improvements over conventional designs of comparable size and payload (e.g. WAM http://www.barrett.com/robot/products-arm-specifications.htm).
- Develop intrinsic tactile sensing for contact location and magnitude detection, including effects of nonlinearities arising from composite construction.
- Integrate 2-link arm with wrist and simple end-effector to evaluate task capabilities for next prototype.
- Fabricate 2nd copy of 2-link arm for delivery to GM for preliminary testing.

Milestones:

- Functional 2-link arm at Stanford and shipped to GM with provisions for integrated wrist and end effector. Travel by Stanford staff to GM research center to oversee tuning and installation of arm at GM. If possible, a (possibly not entirely finished) arm will be produced in time for a student to take it to GM while visiting for a summer internship.
- Working controller with provisions for incorporation of intrinsic tactile sensing and consideration of non-linearities (e.g. saturation).
- Initial comparison of performance with respect to conventional designs of comparable payload and size.
- Compilation of reports and publications based on Year I work.

Year II

0-6 months

- Begin design of shoulder for 4 DOF arm with integrated wrist and end-effector.
- Develop 2nd generation shell with energy absorbing skin and embedded sensing for responsiveness.
- Develop 2nd generation controller with explicit provisions for self-calibration and allowance for nonlinear effects.
- Visit by Stanford (Cutkosky and/or Khatib) to GM Research to discuss details of collaboration.

6-12 months

- Testing of shoulder design and of controller for 4 DOF prototype.
- Testing of shoulder + link in demonstration tasks with expected payloads, force levels and requirements for trajectory and force control.
- Testing of shell and sensory skin and integration with 2nd generation controller
- Preliminary analysis of energy efficiency and provisions to make the arm functional without external pneumatic supply (stand-alone capability).
- Visit to GM to oversee installation of modified controller and sensor suite.

Year II milestones:

- Results of experiments with a 4 DOF prototype consisting of modified 2 link design, new shoulder and integrated wrist.
- Demonstration of 2nd generation controller with self-calibration capabilities.
- Final design of 4 DOF fully integrated manipulator to be fabricated in Year III.
- Compilation of reports and publications based on Year II work.

Year III

0-6 months

- Fabricate 2 copies of integrated 4 DOF system including wrist and end-effector.
- Evaluate performance with respect to traditional solutions in realistic tasks, developed in consultation with GM staff.
- Begin tests to establish and quantify human-safe operation, including responsiveness to expected and unexpected human contact.
- Visit by Stanford (Cutkosky and/or Khatib) to GM Research to discuss details of collaboration.

6-12 months

- Integrate 2nd generation energy-absorbing sensory skin with 4 DOF system, including wrist and end-effector.
- Continue safety testing and characterization of self-calibration for applications tasks.

Year III milestones:

- Delivery of integrated 4 DOF system to GM
- Delivery of final version of controller.
- Delivery of complete test data including human-safe criteria and self-calibration criteria.
- Compilation of reports and publications based on Year III work.

Deliverables

Year I

Month 4 – Initial 2-link design specification document
Month 8 – 2-link arm delivered to GM
Month 12 – Performance comparison documentation and reports

Year II

Month 4 – Preliminary shoulder design for 4DOF system
Month 8 – 2nd generation shell with energy absorbing skin and embedded sensors delivered to GM
Month 12 – Final 4DOF design, including shoulder, 2-link arm, force wrist, and end-effector
Report on 4DOF design, new controller and sensing and comparison with state of the art technology (e.g. WAM).

Year III

Month 4 – Real world task performance evaluation and documentation,
Energy efficiency documentation
Month 8 – Human safe testing procedure and results documentation
Month 12 – Fully integrated 4DOF system delivered to GM with documentation.

Budget Justification

All salary, benefits, tuition and indirect costs are charged at standard university rates.

Travel is based on the assumption of three trips to conferences and/or sponsor per period.

Research materials and supplies include consumable materials for fabrication (adhesives, polymers, curing agents, mold release agents) as well as computer supplies.

Fabrication includes purchased items and permanent materials for each period as follows:

Fabrication Costs Breakdown

Item		Year I	Year II	Year III
Rapid Prototyping Lab fees	@2500/quarter	10000	10000	10000
consumable fixturing		8000	8000	8000
initial end effectors		1000	0	0
wrist for 4 DOF arm		6000	6000	0
end-effector for 4 DOF arm		0	6000	6000
Load cells		3000	0	4000
Sensors and instrumentation		2000	4000	5000
pneumatic components		4000	4000	4000
Electric motors		3000	3000	2000
Microprocessors, electronics		2000	3000	3000
Misc. hardware		1000	1000	3000
Total		**40000**	**45000**	**45000**

Note that although the 4 DOF arm will not commence fabrication until Period 2, some of the components for it will be purchased toward the end of Period 1.