

Voice Coil Actuators for Human-Robot Interaction

An Exploration of the use of Electromagnetic Voice Coils as Compliant, Force-Controlled Actuators in Direct-Drive Robots for Visual and Tactile Interaction with Humans

John McBean, Cynthia Breazeal

MIT Media Laboratory

Robotic Life Group

Cambridge, MA

jmcbean@mit.edu, cynthiab@media.mit.edu

Abstract—The growing field of human-robot interaction (HRI) demands robots that move fluidly, gracefully, compliantly and safely. This paper describes our recent work in the design and evaluation of long-travel voice coil actuators (VCAs) for use in robots intended for interacting with people. The basic advantages and shortcomings of electromagnetic actuators are discussed and evaluated in the context of human-robot interaction, and are compared to alternative actuation technologies. Voice coil actuators have been chosen for their controllability, ease of implementation, geometry, compliance, biomimetic actuation characteristics, safety, quietness, and high power density.

Keywords- *Voice coil, actuator, human-robot interaction, HRI, tactile, compliance.*

I. INTRODUCTION

Comparisons of robot actuator technologies typically reveal the appealing high power densities of electromagnetic actuators, and the high pressures of hydraulic, electro-active polymer (EAP), piezoelectric and shape memory alloy (SMA) actuators. The conventional metrics of comparison for these actuators tend not to clearly identify which technologies are most suitable for high degree of freedom robots intended for tactile interaction with people. Such comparisons also tend to be misleading in that they may overlook some of the bulky infrastructure required for the implementation of the actuators. Hydraulic actuators, for example, are particularly attractive for their high pressures, low power holding forces, and relatively high speeds. It should not be overlooked, however, that hydraulic actuators are conventionally messy, high maintenance, very stiff, and require large amounts of material overhead for pumps, fluid lines, valves, accumulators and the like. In the selection and development of an appropriate actuation technology for interactive robots, we have considered conventional metrics of comparison (pressure, power density, and controllability), but the relatively young field of human-robot interaction (HRI) demands that substantial

consideration be given to the metrics of noise, quality of motion, low inherent mechanical impedance (high backdriveability), geometric configuration, robustness to overloading, and safety.

We are designing and building a 6 degree of freedom (DOF) direct-drive robotic arm, using voice coil actuators (VCAs), that will serve as an evaluation platform for the actuators themselves, for viable control systems for such robots, and for testing of interactive modes and experiences through HRI studies.

This paper will begin with brief descriptions of many available actuation technologies. This will serve as motivation for the work being done on voice coil actuators. The paper will then describe the attributes of voice coil actuators, their advantages and shortcomings (specifically in the context of tactile human-robot interaction), and design parameters that affect their performance. In section IV, we will discuss the design and construction of the actuators that we are using in our robotic arm, as well as a brief description of the arm itself. We will show some preliminary results in section V.A: actuator performance curves and qualitative analyses of the actuators and the arm as HRI demonstration and testing tools. Finally, section V.B will summarize results this far, and propose potential future work in the area of novel actuator design for the emerging field of HRI.

II. BACKGROUND AND MOTIVATION – ACTUATOR COMPARISON SYNOPSIS

A. Introduction

A comprehensive comparison of conventional actuator technologies was published by Hollerbach, Hunter, and Ballantyne in 1992 [1] and is still very much relevant today. The vast majority of actuators used in robotic systems to date employ one or more of the technologies described in that paper. Many of these technologies have been proven to be robust, cheap, and readily available. Under a paradigm where robots are expected to be bulky,

dangerous, rigid, precise, and serve strictly industrial applications, many of these conventional technologies excel. A recent push for biologically-inspired robots that interact directly with humans has spurred much research in artificial muscles. Many of these younger, biomimetic materials-based actuation technologies are beginning to provide competition for conventional technologies as robotic actuators [2], [3], [7].

First, we will define some terms that will be used in the discussion of the different actuation technologies. *Power density* is the amount of mechanical power output an actuator can produce, normalized by its mass or volume. *Mass power density* is measured in Watts per kilogram; *Volume power density* is measured in Watts per cubic meter. *Peak pressure* is the maximum force an actuator can produce, divided by the cross-sectional area of the actuator. *Pressure density* is the peak pressure attainable by the actuator, normalized by its mass. *Maximum strain* is the maximum percentage by which the actuator can change its length while producing a force. *Efficiency* refers to the overall energy conversion efficiency – the mechanical output power of the actuator divided by the power input to the actuator (electrical, chemical, thermal). Finally, *work density* is the amount of work generated over one full cycle of an actuator, divided by the actuator volume.

B. Actuator Technologies

The following table comprises a combination of our own work and research, as well as that of Madden, Hollerbach, Hunter, and Ballantyne [1], [2]. Attempts to make fair comparisons of actuator technologies can be misleading, as universal metrics for evaluating performance are difficult to find, and often do not take into full account all of the components of the actuators. For example, note that no units have been chosen for the comparison of the speeds of the different types of actuators. This is because a rigorous experiment has not been conducted where each of the actuators is subjected to a comparable speed or frequency response test; hence the speeds of the actuators are loosely characterized and described in the table. Other examples are the apparent high pressure and power densities of hydraulic and pneumatic actuators. Traditionally, this evaluation neglects the mass of the material overhead (pumps, valves, fluid lines, etc). This is acceptable only for very high DOF robots, where the mass and volume of the material overhead is in fact small compared to the overall mass of the system). An effort has been made to highlight, where possible, such ambiguities in actuator comparison. Further, we have made attempts to describe the actuator characteristics that are especially relevant to HRI robot design.

TABLE I. ACTUATOR TECHNOLOGY SYNOPSIS

Technology	Description
Mammalian Muscle	Moderate peak stress (0.35 MPa) Moderate strain (20%) Moderate power density (50W/Kg) High (and variable) compliance Flexible form factor Produces smooth, fluid motion Low material overhead Low-moderate pressure density Moderate speeds Unilateral (Pull-only) actuation Inefficient at zero-velocity (holding) forces.
Electromagnetic (VCAs)	Low peak stress (0.05-0.1 MPa) Large strain (50%) High power density (200 W/Kg) Efficiency varies from high (~90%) at high speeds and short strokes to low (~5%) at low speeds and high stroke lengths Fast High compliance Form factor compatible with human-form design Produce smooth, backlash-free, quiet motion Low material overhead. Few moving parts; robust to overloading Bi-directional (push-pull) actuation High force applications require mechanical transformers
Hydraulic	High peak stress (20 MPa) Large strain (50%) High power density (600 W/Kg) (difficult to account for material overhead mass, and extremely high instantaneous power delivery) High stiffness Very high material overhead (valves, lines, pump, accumulator, filters, etc) High maintenance Bilateral actuation Moderate-high speeds (although inefficient at high speeds)
Pneumatic	Moderate peak stress (0.7 MPa) Large strain (50%) High power density (200 W/Kg) (difficult to account for material overhead mass, and extremely high instantaneous power delivery) High efficiency (~90%) Fast, but with moderate settling times due to compressible gas and control difficulty. Moderate compliance High material overhead Bilateral actuation

Pneumatic (continued)	Often loud	Liquid Crystal Polymers (continued)	field induced strain) Moderate-high efficiency Difficult to control (creep) New material High driving voltages Slow
Piezoelectric	High peak stress (35 MPa) Low strain (1%) Very low power density (0.1 W/Kg) Very high speeds (high frequency, very short stroke actuators – less practical for robotic applications) Moderate material (and control) overhead Must be driven with high voltages Quiet Bilateral actuation “Inchworm” and “Waverotor”- type actuators have been developed with larger strains and lower stresses	Conducting Polymers	High stress (5-34 MPa) Low strain (2%) High stiffness Low driving voltage (~2V) High work density (100kJ/m ³) Slow Bilateral actuation Low efficiency
Magnetostrictive	High peak stress (10 MPa) Low strain (2%) Very high power density (5 W/Kg) High efficiency (~80%) High speeds are possible Usually unilateral actuation High material overhead (bulky magnets or coils are required for activation)	Molecular Actuators	Moderate-high stress (>1 MPa) Moderate-large strain (20%) High work density (100kJ/m ³) Low driving voltage (~2V) Slow Unilateral actuation New technology
NiTi Shape- Memory Alloy (Thermal)	Very high peak stress (200 MPa) Low strain (1-8%) Very high power density (100kW/kg) Very low efficiency (<5%) Very difficult to control Slow Low voltage activation Low cycle life Unilateral actuation Can have good form factor for mammal-form robots	Carbon Nanotubes	High stress (>10MPa) Very small strain (0.2%) Low driving voltage (~2V) Inefficient Unilateral actuation Expensive
Dielectric Elastomers	Moderate-high stress (1-10 MPa peak) Moderate-large strains (20%-380%) Moderate efficiency (15%-90%) Fast Require high voltages Unilateral actuation High material overhead (Pre-stretching mechanisms required)	Ionic Polymer Metal Composites (IPMC)	Large strain Low driving voltage (<10V) Unilateral actuation Low efficiency
Relaxor or Ferroelectric Polymers	High stress (45 MPa) Low strain (<7%) High work density (<1MJ/m ³) High stiffness Exhibits hysteresis High driving voltages (>1kV) Unilateral actuation Large material overhead (power supply, control electronics)	Ferromagnetic Shape Memory Alloys	High stress (<9 MPa) Small strain (<10%) Fast High efficiency Unilateral actuation High material overhead (field magnets)
Liquid Crystal Polymers	Low-moderate stress (0.01-0.45 MPa) Moderate-high strains (2%-45%, depending on whether thermal or		

III. WHY VOICE COIL ACTUATORS?

A. VCA Technology

Voice coil actuators have been around for decades. They have been used primarily as the sources of force in audio loudspeakers, and as drive mechanisms for disk drive read heads. As described in Section II, they are characterized by high power densities, high bandwidths, and relatively low pressures. A voice coil is an electromagnetic actuator that generally consists of one or more coils of wire placed in a magnetic field, such that there is a force produced when current flows in the coil. The voice coils discussed in this paper use permanent magnets as the magnetic field source. The force produced by the actuator (the voice coils described in this paper are linear, rather than rotary actuators) is given by

$$F = n\pi d i B \sin\theta, \quad (1)$$

where n is the total number of coils of wire, d is the average diameter of the coil, i is the current in the wire, B is the magnetic field strength, and θ is the angle between the magnetic flux lines and the direction of the current. Focus areas for improving the force outputs of VCAs are evident from (1). Square wire has been used to increase coil winding density (increasing n for a given volume). Attempts to increase the currents thermally permissible in the coils include development of low resistance coil materials, use of active cooling techniques (Hunter, Hollerbach, Lang, Umans, Garabrieta, and Vaaler [1]), and the use of ferromagnetic fluid suspended in the air gap between the coil and the magnet. Since heat adversely affects that magnetic field strength of permanent magnets (especially NdFeB), the benefits of increased heat dissipation are twofold. Much work has been done to increase the magnetic field strength across the air gap. Permanent magnet materials, such as NdFeB, with higher magnetic remanences and higher temperature tolerances have been developed. Actuator geometries have been refined so as to “focus” the flux in the air gap and minimize leakage (BEI Kimco Magnetics [5]). The use of ferromagnetic fluid also increases the field strength and uniformity, but its effects are limited due to its low magnetic saturation. The preceding techniques have been shown to greatly improve VCA performance. In the construction of these prototype actuators, however, we have opted for a simple design, leaving room for the implementation of such techniques in future revisions.

Voice coils are typically uncommutated, meaning the entire coil becomes energized when a voltage is applied. This represents a source of inefficiency for voice coils, as waste heat is produced even in the coils that are not contributing significantly to the force produced by the actuator. For this reason, VCAs with arbitrarily long strains are typically not found.

B. Voice Coil Actuators for Human-Robot Interaction

For their application to HRI and force-controlled robots, VCAs have many advantages over other forms of actuation [6], [10], [11]. The major advantages of electromagnetic actuators are their speed, smooth, silent operation, high efficiencies, ease of implementation, and robustness to overloading. If, for example, a directly-driven VCA is pushed against the direction of its force, it will simply continue to apply a force proportional to its current, and allow itself to be backdriven if the force exceeds that value. Power input to the actuator in the form of current is then dissipated as heat. This fundamental property of VCAs (and all backdriveable actuators) is a key safety advantage for robots intended to touch, and be touched by, people. VCAs tend to have only one moving part, with only two points of contact (bearings at either end). This makes for an actuator with low wear, long life, quiet operation, and excellent shock loading tolerance.

Another major advantage that VCAs have over mammalian muscle, and other forms of actuation that

imitate it closely, is that VCAs are bilateral actuators, meaning they can push or pull with comparable force. This eliminates the cumbersome, bulky, and often difficult to control need for bilaterally opposed pairs of actuators at every joint. Effectively, the *power density* of VCAs ought to be compared to *half* that of unilateral actuators, when they are being considered as sources of force for robotic joints which will undergo flexion and extension. If we consider the metric of *Pressure density*, bilateral actuators (such as VCAs) have a twofold advantage over their unilateral counterparts (such as muscle).

For high force applications, mechanical transformers (gear reductions, for example) are needed to transform the power delivered by electromagnetic actuators (such as VCAs) from high speed/low force to high force/low speed. Mechanical transformers usually introduce backlash, noise, unwanted stiffness, and control problems. They also decrease robustness and increase maintenance requirements. This, of course, is the fundamental problem with VCAs, and necessitates that direct-drive robots using VCAs use larger actuators than might be necessary if a different actuation technology were chosen, or if mechanical transmissions were used. Due to their high power densities, electromagnetic actuators sized to achieve a certain force for an application will be found to have higher power outputs than required for the application. This mismatching of peak power and peak pressure (where mechanical transformers, or geartrains are not used), is discussed further in section VI. Our VCAs have demonstrated sufficient pressures to be free of the need for mechanical transformers of any kind, for use in non-mobile, low-payload HRI robots comparable in size, shape and strength to humans.

While rotary electromagnetic actuators (brushed or brushless DC motors, for example) have similar performance characteristics to VCAs, they have a distinct geometric disadvantage when compared to VCAs, for use in human-form robots. VCAs have a similar form factor to human muscle – they can have large length/diameter ratios (meshing symbiotically with limbs of mammalian-form robots), they can have comparatively high strains, they are linear actuators, and can therefore be implemented in ways that look and behave like mammalian muscles without the use of bulky, heavy, or complex drivetrains. Rotary actuators, on the other hand, would have to be oriented parallel (preferably concentric) with the axis of the joint, and in order to occupy the same volume as a corresponding VCA, would have to have a diameter or length that would extend far beyond the envelope of the form factor of a human limb. Further, if the rotary actuator should be oriented in a more geometrically favorable way, a drivetrain may be necessary to transmit the mechanical power from the actuator to the joint axis. Such drivetrains introduce backlash, noise, jitter, stiffness, and control problems, while increasing system mass, volume, and susceptibility to breakage.

The low peak pressures produced by VCAs (approx. a factor of 4 lower than that of human muscle, for short durations) require that the actuators are oversized in comparison to muscle, and are weaker than a muscle of similar size would be. Consequently, the test arm we are

building is approximately the size of that of a child, and has strength performance that ranges from significantly weaker than a child (for short durations) to comparable strength to a child (for longer durations) [8]. Since many HRI robots may find their applications in areas that do not require high payloads, high contact forces, or high inertial forces, the compromise between decreased strength and smooth, quiet, backlash-free, fast, easily-controlled motion seems acceptable.

IV. DESIGN

A. Actuator Design

We have chosen a moving-magnet design, as opposed to moving coil design for the VCAs to be used in the arm. While a moving-magnet design can result in a slightly greater moving mass [5] (this, of course, is not always the case and depends on the coil mass and whether the VCA is being designed for high force or high speed operation), it affords a simpler construction geometry enabling smaller, more streamlined actuators. A sectional view of one wrist actuator can be seen in Fig. 1. The stator consists of two independently wound coils inside of a thin iron shell. The rotor is a cylindrical, axially magnetized NdFeB permanent magnet, with shafts extending from each pole, supported at the ends in linear bearings. The lengths of the rotor and the coils are designed such that throughout the range of motion of the actuator, one coil remains in the magnetic field of the south pole of the rotor; the other coil, the north. The current in each of the two coils is in opposite directions, matching the opposing polarities of the magnetic fields at either end of the rotor. The strokes of the bicep and wrist actuators are 4.7 cm and 2.5 cm, respectively. Fig. 2 shows the finished bicep and forearm actuators.

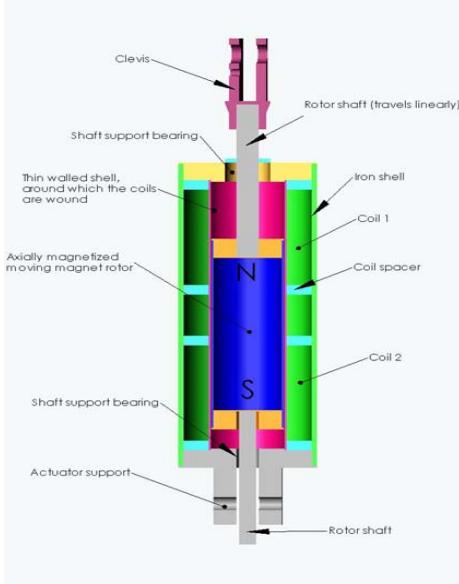


Figure 1. Section view of forearm VCA



Figure 2. Bicep and Forearm VCAs

We have built and tested a variation on this traditional voice coil design (see Fig. 3). By effectively stacking smaller VCAs within one, and connecting their outputs to a common rotor such that their forces sum in a parallel fashion, the limit on peak actuator pressure effectively vanishes. Practical design considerations would of course limit the pressures achievable, but the force produced in the actuator will grow linearly with length, while the diameter stays constant. This of course would make VCAs look more attractive with respect to the metric of peak pressure, once again making it difficult to characterize the actuators in a normalized way such that they can be compared fairly with other technologies. The technique of increasing length for higher force is relevant because it is sometimes the case in designing human-form robots (with limbs having high length/diameter ratios) that adding width, or thickness to the actuators (limbs) is very costly, but longer actuators, as means to higher forces, can be accommodated. A 3-stage prototype of a VCA using this design has been built and has verified the possibility of increasing peak pressure in this manner, but will not be used in the construction of the direct-drive arm presented in this paper.

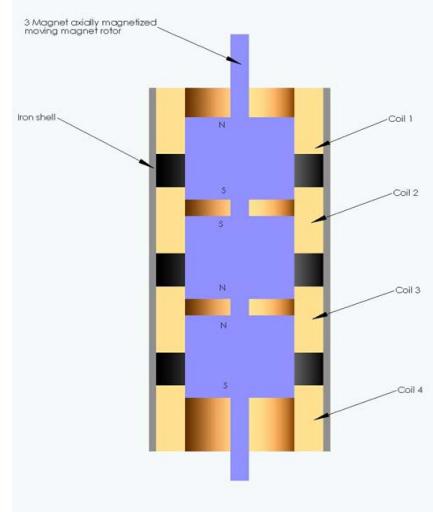


Figure 3. Section view of series-stacked VCA

B. Implementation – Direct-Drive VCA Arm

Fig. 4 shows a solid model of the lower 4 degrees of freedom of the 6 DOF direct-drive robotic arm being built. VCAs are being used to drive the bicep and forearm degrees of freedom, as well as 2 shoulder degrees of freedom (not pictured). All bearing points are preloaded, to ensure that the structure of the arm does not compromise the smooth, muscle-like performance of the actuators. There is a 6 axis force/torque sensor in series with the upper arm, used primarily to measure inertial forces (for trajectory control). Local force sensors (closer to the end-effector) will be used to form force-control loops around contact and payload forces. Position feedback is obtained via rotary Hall Effect sensors at each of the joints. In future revisions of the VCAs, we hope to include integrated position and force sensors. At present, we have manufactured all parts, and are currently assembling the arm. The immediate next step will be in-place testing of the actuators.

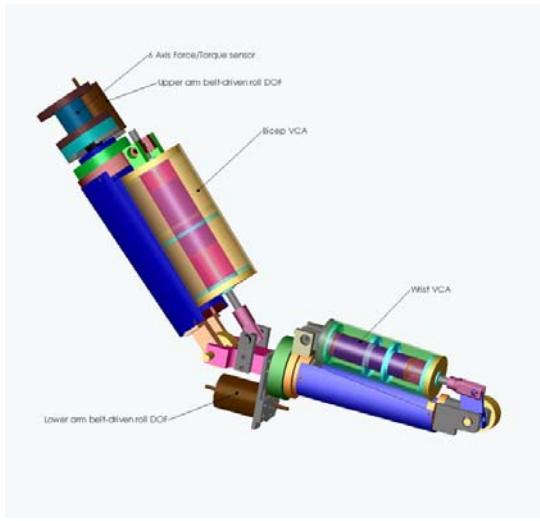


Figure 4. Solid model of Direct-drive VCA and DC motor-driven robotic arm

V. PRELIMINARY RESULTS AND FUTURE WORK

A. Results

Preliminary results using the VCAs described in this paper are promising. The actuators to be used in the arm have been tested; their performance curves are shown in Fig. 5. Ten-second peak pressures are approximately 1/7th that of human muscle, with substantially higher pressures attainable for shorter durations. As expected, the actuators run smoothly, quickly and silently, and their form factor will fit compactly in the human-form arm. Actuator constants for the two VCAs that were tested are 6.2 N/A and 11.3 N/A for the forearm and bicep actuators, respectively. With peak forces approximately 11 times greater than the actuator weights, the actuators are very capable of performing well in a lightweight robotic arm.

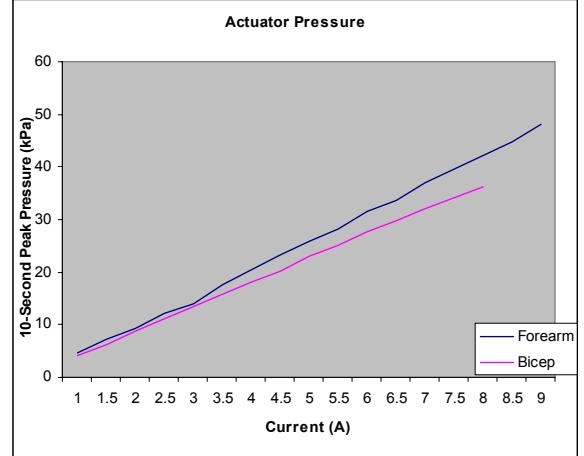


Figure 5. VCA pressure performance curves

B. Future Work

The compromise in using VCAs as actuators for HRI robots is evident. They have been chosen for their high quality of motion, fast response, controllability, and form factor. The tradeoff is that they are less efficient at low speeds than other actuation technologies, and must be oversized due to their low pressures. This preliminary study has shown that, for applications to medium DOF, non-mobile robots for tactile interaction with people, this tradeoff is acceptable.

In an attempt to tackle the main shortcoming of VCAs, we have conducted preliminary research on compact electro-hydraulic systems that would marry the high power densities of electromagnetic actuators with the high pressures of hydraulic actuators. We believe that a strong potential exists in using a voice coil-driven miniature hydraulic pump, packaged within a hydraulic actuator (cylinder) to leverage some of the benefits of the two forms of actuation. Such an actuator could eliminate the need for hydraulic lines and valves, while taking advantage of the strong, fluid motion of hydraulic systems, the form factor of the two forms of actuation, their quiet and controllable operation, and their high power densities. Fig. 6 shows our prototype of a self-contained electro-hydraulic actuator comprising a brushless DC motor, a miniature gear pump, and bellows-style pistons at either end. The system is fully sealed, and the motor operates submerged in the working fluid. Initial results have revealed that VCA-piston pump designs may afford higher pressures and efficiencies.

Dynamic and kinematic models for VCAs are fairly well understood and straightforward, enabling high control system gains, and the potential for implementation of complex adaptive control techniques. We have developed Kinematic and dynamic models for the arm, as well as control systems that will drive it. The project is still focused on the design of the actuators themselves, however, so control systems will not be discussed in this paper. Direct-drive VCAs lend themselves to force and impedance control techniques, due to their low mechanical impedance and high bandwidths. Explorations of such

control systems are the subjects of the next vein of work on this project.



Figure 6. Self-contained electro-hydraulic actuator

Many of the artificial muscle technologies currently under development have shown encouraging results as emulators of human muscle. In many respects (cost, availability and safety of materials, ease of implementation, controllability, maximum strain, efficiency, and speed) VCAs rival these up-and-coming technologies as candidates for use in HRI robots. In other respects (pressure density, efficiency at low speeds, form factor, and flexibility), VCAs may one day be overshadowed by one or more of these alternatives. In the meantime, and with room for improvement, VCAs show great promise as primary movers for force-sensitive robots for human interaction.

ACKNOWLEDGMENT

This research is the work of the Robotic Life Group at the MIT Media Laboratory. The work is funded by the Digital Life and Things That Think consortia. Many thanks to Jessica Vechakul and Jeremy Scholz for their ongoing work on the arm project, and to Guy Hoffman for his editorial insight.

REFERENCES

- [1] J. Hollerbach, I. Hunter & J. Ballantyne "A comparative analysis of actuator technologies for robotics", O. Khatib, J. Craig & Lozano-Perez Eds, *The Robotics Review 2*, MIT Press, Cambridge MA 1992, pp 299-342.
- [2] J. Madden, N. Vandesteeg, P. Anquetil, P. Madden, A. Takshi, R. Pytel, S. Lafontaine, P. Wieringa, and I. Hunter, "Artificial Muscle Technology: Physical Principles and Naval Prospects", under review, submitted to *The Journal of Oceanic Engineering*, 2004.
- [3] Y. Bar-Cohen, Ed, "Electroactive Polymer (EAP) Actuators as Artificial Muscles, Reality, Potential, and Challenges", SPIE Press, 2001.
- [4] S.E. Salcudean and L. Stocco, "Isotropy and Actuator Optimization in Haptic Interface Design", IEEE International Conference on Robotics & Automation (San Francisco, CA) April, 2000.
- [5] Anthony C. Morcos, "Voice Coil Actuators for use in Motion Control Systems", online content available at: <http://www.motion.org/9804morc.htm>, 1998.
- [6] H. Asada and J.-J. Slotine, "Robot Analysis and Control", Wiley Interscience, 1986.
- [7] Y. Bar-Cohen, Online content available at: <http://ndeaa.jpl.nasa.gov/nasa-nde/lommasescap/EAP-web.htm>, 2004.
- [8] E.J. McCormick, "Human Factors in Engineering and Design", McGraw-Hill, 1976.
- [9] Online content available at: <http://ndeaa.jpl.nasa.gov/nasa-nde/lommasescap/actuators-comp.pdf>, 2004.
- [10] K. Youcef-Toumi, "Design and Control of Direct-Drive Robots – a Survey", O. Khatib, J. Craig & Lozano Perez Eds, *The Robotics Review 1*, The MIT Press, 1989, pp.283-302.
- [11] N. Hogan and E. Colgate, "Stability Problems in Contact Tasks", O. Khatib, J. Craig & Lozano Perez Eds, *The Robotics Review 1*, The MIT Press, 1989, pp.339-348.
- [12] J.Paine, "Piezoelectric Step and Repeat Hydraulic Motor Phase I STTR", online content available at: http://www.darpa.mil/dso/thrust/matdev/chap/briefings/timchap2000day1/Paine_PiezoStep.pdf, 1999.
- [13] Online content available at: <http://www.consult-g2.com/papers/paper15/paper.html>.
- [14] Honda Motor Company, Online content available at: <http://world.honda.com/ASIMO/P3/spec/>, 2004.
- [15] Gill Pratt, "Biologically Inspired Components of Robots – Sensors, Actuators and Power Supplies", unpublished, 2002.