Artificial Arms Evolve from Robots, or Vice Versa?

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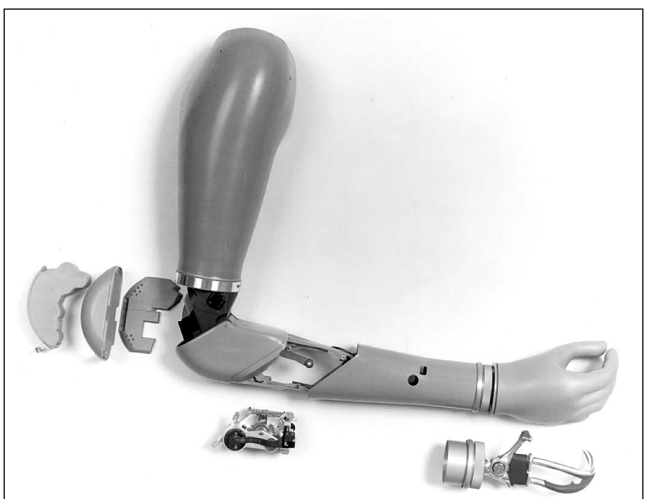
There is a close relationship between robotics and prosthetic devices (artificial limbs) since both provide human-like motion and prehension. In general, prosthetic devices have benefited from the development of robotic technologies. Interestingly, researchers at the Center for Engineering Design at the University of Utah developed the Utah Arm, a three-degree-of-freedom elbow prosthesis, prior to developing the Utah/MIT Dextrous Hand, a robotics end-effector. These research projects spawned two new companies—Motion Control, Inc., the manufacturer of the Utah Arm, and Sarcos, Inc., a robotics company under the leadership of Stephen C. Jacobsen.

The Utah Artificial Arm

Since its inception in the late 1970s, the Utah Arm has employed ambitious and innovative control technology [1]. High-speed, responsive control of a prosthetic elbow was a primary goal of the Utah Arm, requiring several technical innovations in adaptive filtering, freeswing, state switching control, and hand control.

The Utah Arm utilizes transducers for velocity and electromyographic (EMG) signals, which represent the muscle activity of the wearer. These signals must be filtered to enable precise elbow positioning. The adaptive filtering developed for the Utah Arm improves accuracy by reducing noise at slow speeds and then broadens bandwidth to allow more responsive control at higher speeds. These innovations required a level of technical sophistication unheard of in a prosthetic device at the time of its introduction in 1982.



The original Utah Artificial Arm was developed in 1980. The internal control circuits are housed in smooth molded plastic covers that are light, strong, and cosmetic.

Freeswing, a unique feature of the Utah Arm, mimics the ability of the natural arm to fall freely with low impedance when the muscles are relaxed. This feature requires elbow control to transition from an open-loop rate control to a closed-loop zero-load state when the wearer relaxes the muscles. Freeswing provides the wearer of the arm with a more cosmetic, relaxed look and feel as the wearer swings the prosthesis. Functionally, this feature is also important for many of the most challenged patients, allowing them to lower their forearms (extend the elbow) with minimal effort.

State switching refers to the hybrid nature of the control. For example, the arm wearer must be able to lock the elbow to hold heavy loads, requiring the elbow to transition from a high-speed/low-torque state to the locked state in which loads as high as 50 lbs can be supported by the forearm. Also, the wearer's EMG signals are transferred to the command of the hand when the elbow is locked. Specifically, the elbow lock engages automatically whenever the wearer holds the elbow stationary for a preset length of time, an easy action for the wearer since the elbow would naturally be held still when the wearer wishes to use the hand. When the wearer wishes to reposition the elbow, a rapid contraction of both control muscles is performed, causing the lock to disengage and control to transfer back to the elbow. In an interesting feature, the elbow lock is inhibited electronically whenever the freeswing feature is in effect, that is, when the muscles are relaxed and the zero-load condition is achieved. This feature contributes to the feel of a free elbow when the wearer relaxes the control muscles. Needless to say, an important part of the fitting process is the muscle retraining necessary to master all the skills required to operate the prosthesis smoothly.

Control of the artificial hand opening and closing (enabled when the elbow is locked, as described above) is optimized by a proportional, finely adjustable controller operating in an agonist/antagonist fashion by the two control muscles, usually the biceps and triceps. The command signal is the result of the difference between the two muscles' EMG signals, thus providing proportional control of the prosthetic limb. The gain, threshold, and differential gain can be adjusted and optimized by the prosthetist, who works interactively with the patient to finetune the accuracy and speed of the hand. Although future versions may incorporate force feedback, allowing more precise servo

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control, open-loop rate control has been surprisingly accurate and manageable. With good muscle training, most patients can demonstrate excellent hand control. The controller allows hand speeds higher than 250 mm/s from muscle EMG inputs of only 5 μV, which is approximately the effort required to lift a pinky finger in a normal forearm.

Robotics Developments

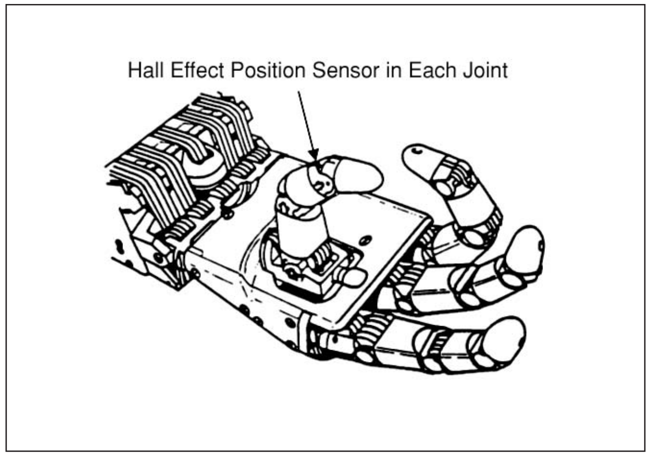
During the 1980s, the Center for Engineering Design at the University of Utah and the Artificial Intelligence Laboratory at MIT cooperated in the development of robotic end-effectors to study machine dexterity [2]. The central objective was to replace and augment human skills with robots that could execute tasks with greater economy, higher performance, and reduced possibility of human injury—the usual goals for robot manipulators.

However, the designers also sought to apply the lessons of the Utah Arm to the end-effector; that is, they sought to achieve some of the gracefulness of the natural hand and arm through high-speed, low-impedance actuators with variable compliance. In addition, the anthropomorphic configuration of distal, low-impedance machine joints (shaped much like the human hand) with proximal, high-bandwidth actuators was attempted. The human analogy was also extended to the actuator design, where light, strong “tendons” were used in agonist/antagonist pairs for each powered degree of freedom, pulled proximally by responsive pneumatic actuators.

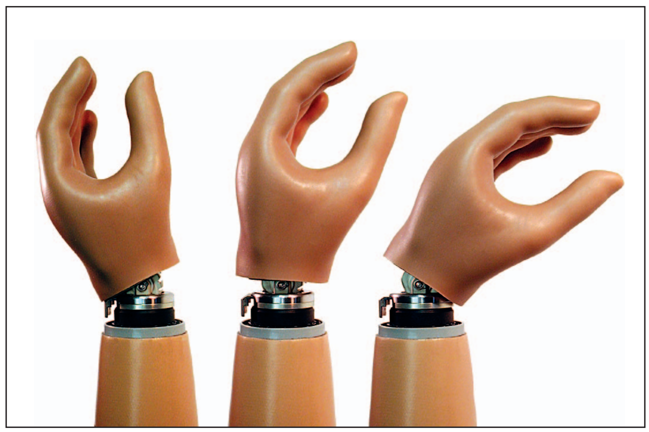
Another important feature of the Utah Arm development was the modularity inherent in the design. Field service was made practical for the Utah Arm through the modularity of the electronics and elbow drive. Similarly, the Dextrous Hand was designed so that maintenance would be practical. This design also enabled the development of alternative configurations with subsets of the full set of actuators, if desired.

The designers addressed issues in materials and structures, internal and external sensors for position and torque, signal amplification and conditioning, type and location of actuation, communication, and analog/digital computation. Early versions of the digital control system consisted of five Motorola 68000 microprocessors, 40 channels of digital-to-analog conversion, and 320 channels of analog-to-digital conversion. A higher level controller managed all system gains, deployed data, interpreted primitive commands, and monitored the system for errors. The Dextrous Hand was generally considered to be among the most successful attempts at approximating the performance of a human hand, in terms of dexterity and gracefulness. Characterizations of individual finger actuators demonstrated a bandwidth up to 60 Hz (even faster that the human finger) and achieved coordinated manipulations, such as turning a nut onto a bolt. Gripping modes included terminal opposition of each of the three fingers against the thumb, palmar prehension, spherical grip, lateral opposition (key grip), finger-to-finger opposition, and digito-palmar opposition (finger hook-and-pull). Videos of these features are available at www.sarcos.com.

Comparing the functions of prosthetic devices with those of advanced robots such as the Dextrous Hand reminds us that the design constraints for robotic and prosthetic devices are significantly different. For example, power consumption in most robotic applications is not constraining. In fact, the Utah/MIT Dextrous Hand was driven by a pneumatic power supply, which was about the size of a washing machine and operated from an ac electrical



The Utah/MIT Dextrous Hand. This anthropomorphic robotic hand was built by Sarcos Corp. in the 1980s. The devices were used in research applications throughout North America for control experiments in teleoperation and control systems. For more information, see www.Sarcos.com.



The Motion Control Hand. This single-degree-of-freedom hand can open and close, while the wrist has a “wrist flexion” degree-of-freedom. Wrist flexion is a prosthestics term indicating flexion and extension, which are actually two directions of the same degree-of-freedom. In the picture, the hand is shown both flexed and extended. For further detail, see www. UtahArm.com.

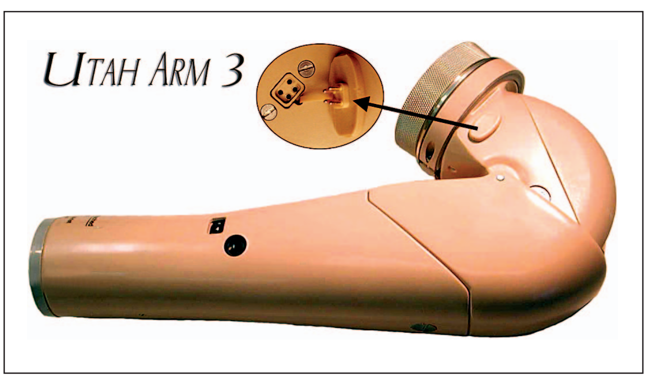
outlet. The Dextrous Hand had 16 degrees-of-freedom and 32 electro-pneumatic actuators. The original version of the Utah Arm, which weighed a none-too-light 3 lb, operated from a 12-V rechargeable battery pack with only 450 mA-hour capacity. A natural arm, from mid-humerus down, weighs considerably more at 6–8 lb in an adult male but is held on better than prosthetic arms.

The Motion Control Prosthetic Hand

A recent development is the Motion Control Hand prosthesis, developed over the past six years by some of the same engineers who helped develop the Utah/MIT Dextrous Hand. This project is supported by NIH funding (NICHD grant # R44HD36119-03). Powered by a lightweight lithium ion battery and driven by a rare earth dc permanent magnet motor, this single degree-of-freedom hand opens and closes in a three-point grasp mode. The flexion wrist, which allows flexion and extension of the hand to 30° in each direction, has been designed into the same volume as other prosthetic hands and so does not represent a compromise in greater length. Passive (meaning the wearer can reposition it with their other hand) pronation/supination is possible through the quick-disconnect wrist system. The quick disconnect makes the Motion Control Hand compatible and interchangeable with other electric hand systems. Optionally, it is compatible with an electric pronation/supination motor.

Control Processor Development

Since the mid-1990s, Motion Control, Inc. has offered a microprocessor-based controller for a prosthetic hand and wrist. The microcontroller facilitates automatic adjustment of control parameters. A PC-based user interface enables training, troubleshooting, and adjustment, and the controller features digital input signal processing. The limitations of the current microcontroller include large package size, high current consumption, low bandwidth, a small amount of RAM and ROM, and limited development tools.



The Utah Arm 3. This prosthetic device incorporates numerous improvements, including a microprocessor for filtering, communication, and control. For more details, see www.UtahArm.com.

Recent advancements in commercially available microprocessors, however, have reduced current consumption, increased bandwidth, and decreased size. Furthermore, the implementation of new features has been eased by several technological advances, such as increased RAM and ROM, high-cycle-life-onboard EEPROMs, internal high-bandwidth PWMS, integrated communication protocols, and improved development tools [3], [4].

Current development work has focused on the creation of a microprocessor-based controller for the third-generation arm, the Utah Arm 3. Experiments using a microprocessor to control a prosthetic arm have been conducted for over 20 years, beginning with the earliest controller development at the University of Utah and continuing at Motion Control in collaboration with Parvus Corp. High current consumption, the low bandwidth of early controllers, and the physical size of the microprocessor hampered early trials (about 1980). Recently, Motion Control has completed development of a controller that incorporates several new features, including force loops closed in software (these loops had previously been closed by analog electronics to achieve sufficient bandwidth), auto-adjustment of control parameters, increased communication speed to the user interface running on a PC, lower power consumption, smaller package size, and, finally, more sophisticated control algorithms.

The innovations in the Utah Arm 3 rely on a range of technologies. For example, clock speeds for closed-loop control typically need to be more than ten times the frequency of significant disturbances affecting the feedback loop. Since the positionally controlled prosthetic arm and terminal devices have disturbances of 10–20 Hz, control update cycles of 100–200 Hz have been implemented. With clock speeds of 4 MHz and a relatively simple control algorithm, adequate closed-loop position control has readily been achieved. On the other hand, force-loop disturbances typically range from 50 to 100 Hz. With these disturbances, external analog force loops were previously used to achieve smooth control of force and torque despite stiff drives with backlash and friction. With clock speeds now approaching 50 MHz, force loops, which heretofore were achievable only with analog circuits, are possible within the digital controller.

Sampling and processing of EMG, which is essential for user control, is realized by an auto-adjust algorithm facilitated by the use of on-board RAM. Increases in available RAM, ROM, and clock speed have also sped up the wearer/prosthetic communication interface by an order of magnitude. The added ROM and RAM will allow for more control options and more sophisticated control. Additional improvements to the controller have reduced the power consumption by a factor of two, thus increasing battery life for the prosthesis wearer. Finally, the present microcontroller, which is a 64-pin fine-pitch surface-mount device, is sufficiently small to allow an optional configuration of the controller placed *inside* the hand. This packaging saves valuable space within the prosthesis, so that longer amputation lengths can be considered for fitting without making the prosthesis longer than the natural arm.

Although the development of microprocessor control for externally powered upper-limb prostheses has been an engineering challenge, the effort has had a significant payoff. The current system has features that would not be feasible without a microcontroller. Furthermore, iterative improvements to control, the introduction of new features, and enhancement of the user interface can be easily implemented, enabling the rapid development of future versions.

References

[1] S.C. Jacobsen, E. Iversen, D. Knutti, R. Johnson, and K. Biggers, "Design of the Utah/M.I.T. Dextrous Hand," in *Proc. IEEE Int. Conf. Robotics and Automation*, 1986, vol. 3, pp. 1520–1532.

[2] S.C. Jacobsen, D.F. Knutti, R.T. Johnson, and H.H. Sears, "Development of the Utah Artificial Arm," *IEEE Trans. Biomed. Eng.*, vol. BME-29, no. 4, pp. 249–269, April 1982.

[3] S.G. Meek, R.B. Jerard, H.H. Sears, D.F. Knutti, and S.C. Jacobsen, "Control of elbow/hand state in the Utah Arm," in *Proc. 38th Annu. Conf. Engineering in Medicine and Biology*, Chicago, IL, Oct. 1985, p. 49.

[4] H.H. Sears, J.T. Andrew, and S.C. Jacobsen, "Experience with the Utah Arm hand and terminal device," in *Comprehensive Management of the Upper-Limb Amputee*, D.J. Atkins and R.H. Meier III, Eds. New York: Springer-Verlag, 1989.

Correction

In the December 2004 issue of *IEEE Control Systems Magazine*, there were two errors that appeared in the obituary for Prof. Alexander Yakovlevich Lerner. The first name of Prof. Sakharov should be Andrei. Prof. Alexander Yakovlevich Lerner was erroneously referred to several times as Prof. Alexander Yakovlevich. *IEEE Control Systems Magazine* assumes responsibility for these errors.

President's Message

(continued from page 8)

(CACSD)—are to be congratulated for a job well done. Experience has shown that holding these meetings jointly results in considerable synergy as well as improved organizational efficiency and less financial risk to the Society. In the future, we may see the joint CCA/ISIC/CACSD become a regular event.

Update on OFAC

I know that many of you have been following with great interest the developments regarding OFAC constraints on the IEEE and on IEEE members from countries that are under U.S. trade embargo. I am pleased to report that, as of 9 October 2004, the IEEE reestablished electronic communication for members in these countries. This means that members in embargoed countries will receive their IEEE renewal packages, will be able to access their IEEE publications subscriptions through IEEE *Xplore*, and will no longer be excluded from consideration for various grades of membership including Senior Member and Fellow. Organizers of local events in these countries will also have access to all information and guidelines that IEEE makes available on the Web for such purposes. A letter from 2004 IEEE President Arthur Winston went out to all IEEE members in Iran, Cuba, and Sudan informing them of the change. This is, of course, a very positive development and we hope that CSS members in these countries will choose to reconnect with our Society and its activities. I will pass along additional information as it becomes available.

Looking Ahead

In 2005, the CDC will be held jointly with the European Control Conference (ECC) in Seville, Spain. This is the first time that the CDC and ECC have been combined. Eduardo Camacho as general chair, Roberto Tempo as program chair, and the entire conference team are working hard to ensure both a superior technical program and excellent local arrangements. Having been in Barcelona for the 2002 IFAC and, just recently, in Madrid for the 2004 CLAWAR (Climbing and Walking Robots Conference), where I thoroughly enjoyed myself, I am excited to return to Spain in December and hope to see record attendance in Seville.

In addition, we can look forward to visiting Portland, Oregon, for the 2005 ACC, Cyprus for the 2005 ISIC, and Toronto, Canada for the 2005 CCA, in addition to an impressive list of other CSS cosponsored events. Be sure to visit the Society Web site (http://www.ieeecss.org) from time to time to review the latest information on our conferences as well as member activities.

We all understand the importance of feedback and the fact that the longer it is delayed, the more difficult it is to make enhancements. Therefore, in closing, I would like to encourage every member of the Society to provide me with timely comments, suggestions, criticisms, and anything you feel will help us provide better service to our members. I can always be reached at mspong@uiuc.edu. I wish you the best of health and happiness for 2005.

Mark W. Spong
President
IEEE Control Systems Society