# APPLICATION OF DEXTEROUS SPACE ROBOTICS TECHNOLOGY
## TO
## MYOELECTRIC PROSTHESES

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## ABSTRACT

Future space missions will require robots equipped with highly dexterous robotic hands to perform a variety of tasks. A major technical challenge in making this possible is an improvement in the way these dexterous robotic hands are remotely controlled or teleoperated. NASA is currently investigating the feasibility of using myoelectric signals to teleoperate a dexterous robotic hand. In theory, myoelectric control of robotic hands will require little or no mechanical parts and will greatly reduce the bulk and weight usually found in dexterous robotic hand control devices. An improvement in myoelectric control of multifinger hands will also benefit prosthetics users. Therefore, as an effort to transfer dexterous space robotics technology to prosthetics applications and to benefit from existing myoelectric technology, NASA is collaborating with the Limbs of Love Foundation, The Institute for Rehabilitation and Research, and Rice University in developing improved myoelectric control of multifinger hands and prostheses. In this paper, we will address the objectives and approaches of this collaborative effort and discuss the technical issues associated with myoelectric control of multifinger hands. We will also report our current progress and discuss plans for future work.

## INTRODUCTION

Robotics is one of the critical technologies necessary for future space explorations. Future space robots will require highly dexterous robotic hands to perform a variety of tasks. A major technical challenge in making this possible is an improvement in the way these dexterous robotic hands are remotely controlled or teleoperated. The required robotic hand teleoperation interface must be intuitive (requiring less operator training) and nonfatiguing (enabling longer shifts). A current method of teleoperation uses an exoskeleton glove controller to detect finger motions. These glove controllers are worn by an operator to control robotic hands located at a remote site. Glove controllers are usually bulky and heavy and sometimes interfere with hand movements. Consequently, NASA Johnson Space Center (NASA/JSC) is investigating the feasibility of using myoelectric signals to control dexterous robotic hands.

While NASA is advancing dexterous robotic hand technology, the Limbs of Love Foundation, a foundation dedicated to providing prostheses to handicapped children, is actively searching for ways to improve the state-of-the-art in prostheses. In an effort to transfer advanced space technology to practical ground-based applications, NASA has teamed up with Limbs of Love and a group of medical and prosthetics specialists, prosthetics users, insurance industry representatives, and university researchers to identify research objectives in prosthetic hands [32]. As part of this effort, the Automation and Robotics Division (A&RD) at NASA/JSC has been actively working with Rice University to improve dexterous hand design and to develop a method for myoelectric control of multifinger hands.

This paper describes the collaborative research between NASA/JSC and Rice University in developing improved prostheses. First, the paper reviews previous work in dexterous robotic hands, prosthetics, and myoelectric controls, then it outlines the goals and objectives as well as the approaches we are taking in this joint effort. This paper also reports progress we have made in the areas of dexterous robotic hand development and myoelectric control. Our efforts in these areas have forced us to consider several difficult design issues which will be discussed. Finally, the paper concludes by stating what our future work and expected accomplishments will be.

## PREVIOUS WORK

Over the past three decades, the myoelectric prostheses community reached a rough consensus that there are five types of grasp important in a person's daily activities: (1) three-jaw chuck or pincher grasp used to hold small objects; (2) lateral grasp, most often called a key grasp because it is used to hold a key while unlocking a door; (3) hook grasp, used to carry items such as books or a briefcase; (4) spherical grasp, where the thumb and fingers are wrapped around a spherical object; and (5) cylindrical grasp, where the thumb and fingers are wrapped around a cylindrical object [28] [40] [41]. Some consider the flattened hand (with thumb rotated completely out of opposition of the fingers) a sixth grasp, as it is essential in supporting flat objects such as trays.

Current commercial prostheses have a two-jaw pincher arrangement of fingers and thumb which gives some chuck and cylindrical grasping capability. More advanced prostheses, such as those described in references [12], [13], [27], and [34], have incorporated chuck and key grasps with spherical and cylindrical grasp options being provided by passive finger compliance. Weight, size, cost, and reliability of these advanced prostheses have been major reasons why they never became commercial products; however, recent advances in miniaturizing hardware and lowering power consumption and costs suggest that these problems may now be secondary to the control/user interface problem. In fact, the longest (over 15 years) multifunction prosthetic hand project, the Swedish hand, ended with this conclusion [2].

In parallel with the prosthetics research effort, the robotics community has been developing the theory of grasping and manipulation by multifingered hands over the past decades. (See, for example, the books by Mason and Salisbury [36] and Cutkosky [6]). Some multifingered robotic hands have been constructed. Hess and Li [16] provided an overview of several existing dexterous robotic hands for space applications, with the most dexterous of them being the Utah/MIT Dexterous Hand (UMDH) [23] and the Stanford/JPL Hand [36]. Based on their evaluations, Hess and Li have concluded that a six degree-of-freedom (DOF) robotic hand has sufficient articulation for grasping various shapes and providing some manipulation capability. Unfortunately, these early hands are too bulky and heavy to be feasible as a prosthetic device.

Although these complex robotic hands may not be feasible for prosthetics applications, they do serve as valuable tools to evaluate various grasping and manipulation strategies. These strategies usually involve complex algorithms and require sophisticated sensors now unavailable. One promising approach has been suggested by Speeter [39]. He uses a small set of basic grasping primitives, each of which is simple to program. This approach seems well-suited for application to teleoperation using probably a small set of myoelectric signals. Since each myoelectric input signal requires amplification, filtering, and processing, fewer inputs mean a less complex and less expensive user interface.

## RESEARCH OBJECTIVES

Our review of previous work in dexterous robotic hand and myoelectric control has shown that to develop an improved prosthetic hand, progress must be made in (1) increasing the articulation of prostheses beyond just a single DOF, and (2) improving myoelectric sensing capability to recognize different muscle patterns and map them into various grasp primitives. To achieve progress in these two areas, we must accomplish the following set of objectives:

- Design a robotic hand with human compatible functions, weight, and size.

- Develop electronics and algorithms for primitive-based hand control.

- Develop a myoelectric pattern recognition technique for multifinger hand control.

The first objective will make a dexterous robotic hand feasible for limb-deficient persons. This may mean increasing the number of active fingers and reducing weight and power consumption. The second objective is aimed at providing some local automation so that the user can interface with the hand using primitive-level commands (such as chuck grasp, key grasp, etc.). To differentiate one primitive command from another, we must be able to recognize the signature, or myoelectric pattern, associated with that particular primitive. Previous attempts to develop more capable myoelectric prosthetic hands have fallen victim to an inadequate myoelectric user interface. This is why the third objective is so essential.

By achieving these three objectives, both NASA and the prosthetics community will benefit from the results of this effort. In space, electrical power is a precious commodity and weight is a major concern; by making the robotic hands more compact and energy efficient, we are also making them more suitable for space applications. The electronics and algorithms for primitive-based control will fit in well with a layered architecture that also supports artificial intelligence technologies. If the third objective is also achieved, it will represent a breakthrough in teleoperation technology since cumbersome exoskeleton devices will not be required to operate dexterous robotic hands.

## APPROACHES

To achieve the three objectives, we are pursuing two parallel paths: JSC is focusing on developing advanced dexterous robotic hands, and Rice University is concentrating on developing improved myoelectric signal processing technology. In addition, we also solicit feedback from robotic hand experts, prosthetics users, and specialists to continually improve our design. These two technology development paths will eventually merge in a test bed environment where we can perform integrated evaluation of new prosthetics mechanisms and control.

## DEXTEROUS ROBOTIC HANDS

We began dexterous robotic hand development by procuring and evaluating commercially available, state-of-the-art dexterous robotic hands while developing in-house expertise. By understanding the features of existing hands, we would not have to reinvent the technologies already developed by others. The results of our evaluation helped us to understand the trade-off between function (dexterity, sensing) and form (size, weight).

To establish a reference point for our performance evaluation, we first examined conventional parallel jaw grippers. Conventional parallel grippers are typically designed to execute a pinch grip. This type of grip depends heavily on contact friction rather than contact geometry for stability. Most grippers today have only a single DOF; therefore, they cannot perform manipulation or securely grasp objects of various shapes. Prosthetic hands today function essentially like parallel jaw grippers, except that prosthetic hands generally have a more human-like external appearance.

### CTSD I Hand

For robotic applications, we took a minimalist approach in designing new hands. Instead of designing a highly complex robotic hand right away, we increased the complexity slowly, hoping to achieve the desired functions at a minimal cost. Our first attempt at robotic hand design resulted in the construction of the CTSD I Hand. (CTSD stands for Crew and Thermal Systems Division, the NASA/JSC organization responsible for developing the hand.)

The CTSD I Hand, shown in figure 1, has three fingers driven by a single DC motor. The three fingers are spaced 120 degrees apart, and they open and close simultaneously. Each finger contains three sections connected by joints. The sections are coupled by direct linkages; therefore, the push-pull motion created by the rod inside the proximal finger section will cause the other sections to move also. As the fingers begin to close, the distal finger section will bend around the object and trap the object within the grip of the hand for a secure grasp. The motions of the three fingers are also coupled by a cable-pulley system, so when any one finger is forced to stop, the other two will continue to close until all three fingers have stopped. Although this hand is a step beyond the simple parallel jaw gripper, it still has some drawbacks. The hand does not have enough independently controlled, articulated joints to allow alternate grasp arrangements, and it lacks the human look that is highly desired in a prosthetic hand.
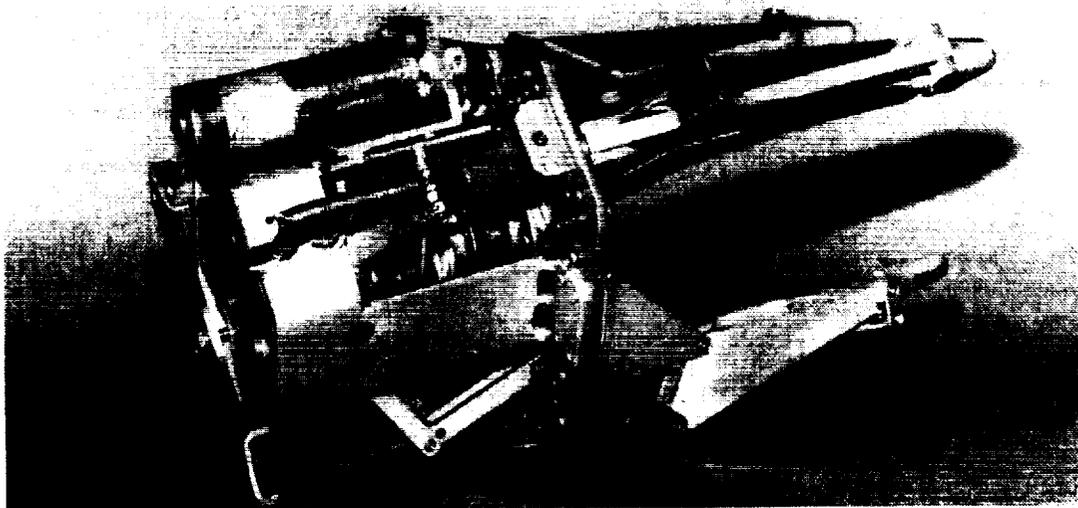
Figure 1. CTSD I Hand.

## CTSD II Hand

To improve the dexterity of the CTSD I Hand, we redesigned the fingers so they are modularized, each capable of moving independently from other fingers. The redesigned hand, named the CTSD II Hand, also has three fingers. However, there are several important differences. The fingers of the CTSD II Hand, shown in figure 2, are arranged in a two-opposing-one configuration to provide parallel grasping surfaces. This finger configuration is able to adapt to different shapes of objects better than the CTSD I Hand configuration. The modular finger design also allows additional fingers to be added if necessary. Each finger is driven by a single DC motor contained within the finger module. We also introduced tactile sensors and strain gauges on each finger to provide sensory feedback [16]. Silicon pads cover the tactile sensors for protection and provide a compliant, friction surface for a more secure grasp. The maximum amount of force each finger can exert is controlled by current-limiting circuitry in the control electronics. The CTSD II Hand contains many functional improvements over the CTSD I Hand. However, for prosthetics applications, the CTSD II Hand lacks adequate dexterity and a pleasing appearance.
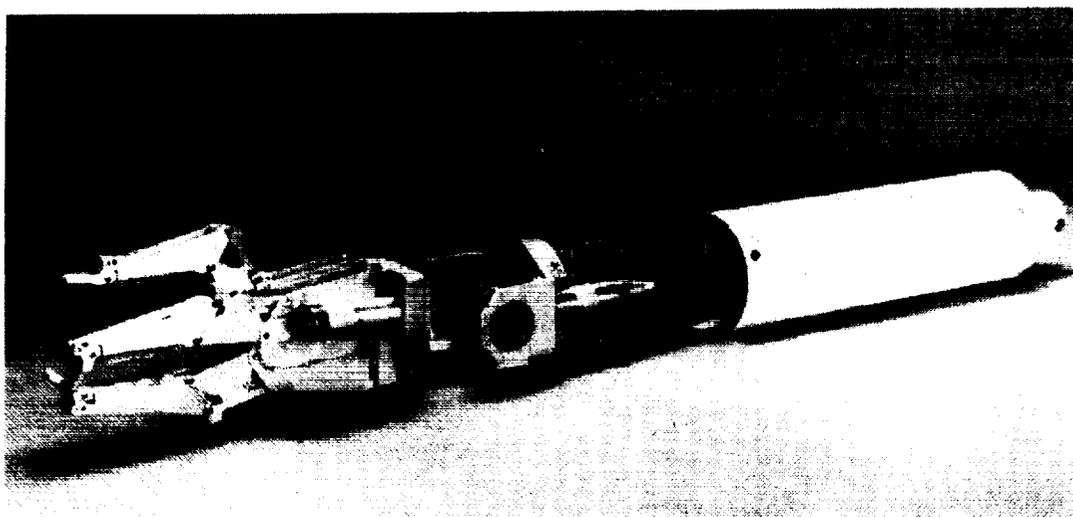


Figure 2. CTSD II Hand.

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## Utah/MIT Dexterous Hand

Our search for a robotic hand with human-like dexterity and appearance led us to evaluate the Utah/MIT Dexterous Hand (UMDH) [24]. The UMDH, shown in figure 3, is the most dexterous hand in the spectrum of hands available for our evaluation. It has 16 DOF arranged in an anthropomorphic configuration of three fingers and a thumb. The fingers and the thumb each have 4 DOF. Thirty-two pneumatic actuators operating at pressures up to 80 psi provide power to the hand. Tendons are used to transmit power from these pneumatic actuators to the joints through a system of pulleys and linkages called a "remotizer." Each joint is controlled by a pair of antagonistic tendons. Located inside each joint is a linear Hall Effect sensor that measures the joint angles. Hall Effect sensors are also located in the wrist to monitor the tendon tensions. A control box containing analog feedback control circuitry provides manual control of each joint with an interface for computer control that can be used in lieu of manual control [16].
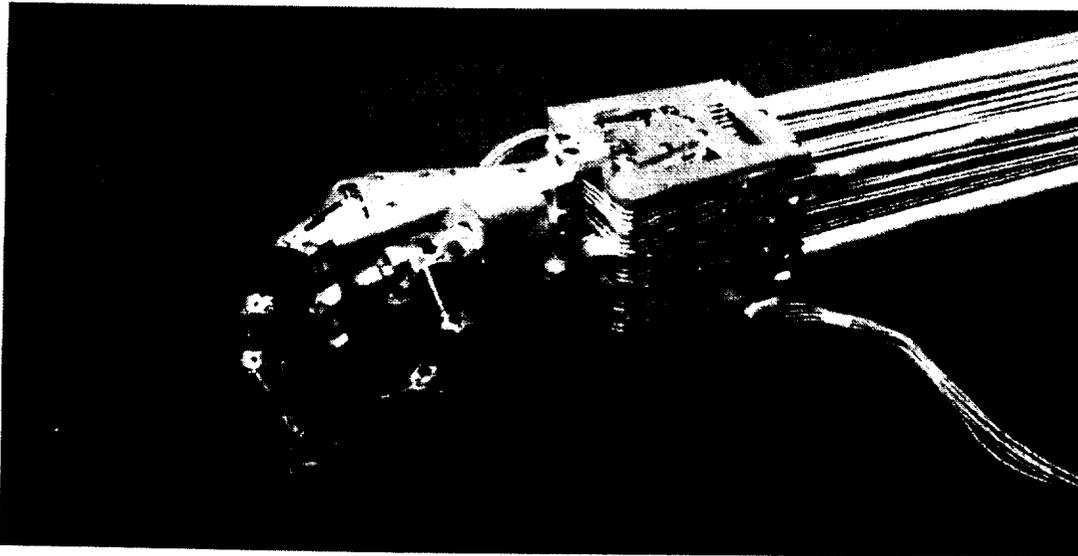


Figure 3. Utah/MIT Dexterous Hand.

It is obvious that the UMDH is not suitable for space robotics or for prosthetics applications. The pneumatic power system requires an air compressor too large to be portable, and the overall dimension of the hand system is too large to be mounted on a robot or a human user. However, the UMDH is a valuable test bed facility for us to evaluate and develop various control algorithms and grasp strategies for space and prosthetics applications. Later in this paper, we describe how the UMDH test bed is being used for prostheses development.

## Stanford/JPL Hand

We also evaluated the Stanford/JPL Hand designed by Dr. J. Kenneth Salisbury of Massachusetts Institute of Technology (MIT). The hand has 9 DOF in a nonanthropomorphic finger arrangement and a large envelope of excursion. The hand has three fingers, each with three joints. The joints are driven by a set of steel cables that transmit mechanical power from 12 remotely located DC motors equipped with position encoders. Located behind the proximal joint of each finger are four strain gauges that measure the cable tensions. The tension signals may be translated into joint torque signals which are used in servo control. The fingertips are made of a highly compliant elastomer that provides the friction contact necessary for a secure grasp. Figure 4 shows the Stanford/JPL Hand and its remote motor package.
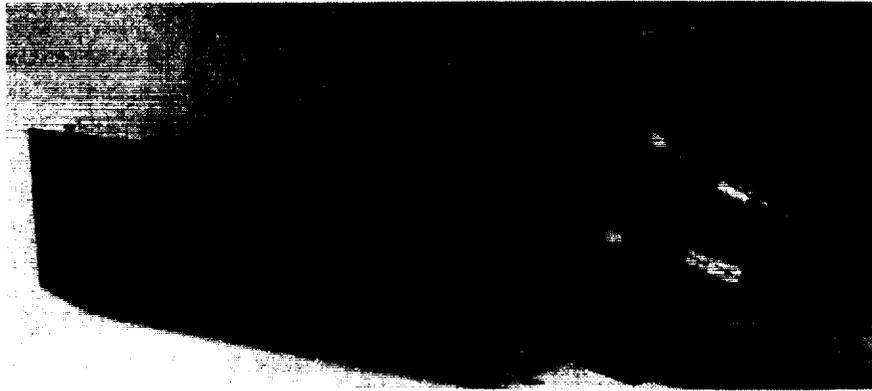
Figure 4. Stanford/JPL Hand.

Compared to the UMDH, the Stanford/JPL Hand is more compact, and its electrical power system is more compatible with space and prosthetics applications. While the size and weight of the Stanford/JPL Hand are acceptable for space robots, they are not acceptable for a prosthetic hand. Also, the Stanford/JPL Hand is not as anthropomorphic and visually pleasing as the UMDH.

Direct Link Prehensor

Our initial evaluation of the UMDH and the Stanford/JPL Hand showed us that a highly complex robotic hand will most likely require a large actuator package. This is unacceptable for both space and prosthetics applications; however, a smaller actuator package usually means less dexterity. Therefore, a compromise must be achieved between dexterity and packaging. Our search for an optimal solution that takes both packaging and dexterity into account brought us to the Direct Link Prehensor design.

The Direct Link Prehensor, as shown in figure 5, was originally developed by NASA Ames Research Center and Stanford University to function as a space suit end effector that fits over the hand like a glove. The prehensor has a total of 6 DOF in an anthropomorphic configuration. It has two fingers and a thumb, with the thumb opposing the two fingers at a fixed angle to provide grasping capability as well as some manipulation capability. The mechanical fingers are directly coupled to their human counterparts through a mechanical linkage system.



Figure 5. Direct Link Prehensor.

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The prehensor has been flown on the NASA KC-135 aircraft to evaluate grasping in a weightless environment using a mechanical hand [25]. This evaluation showed the prehensor's finger arrangement to be a good compromise between packaging and dexterity. A robotic implementation of the prehensor would require only six motors, which is substantially less than the UMDH and Stanford/JPL Hand. Even with only 6 DOF, the prehensor is capable of grasping objects of various sizes and shapes. It is capable of chuck grasps, pinch grasps, power grasps, hook grasps, and key grasps. Although the thumb does not have abduction/adduction movement, it is mounted at a 45-degree angle to provide a motion with a horizontal component. Despite lacking some important movements, we were able to twist open a bottle cap, manipulate small flat plates, grasp balls and cylinders, and pick up luggage with the prehensor.

## JH-3 Hand

After a fairly comprehensive evaluation of existing dexterous robotic hands, we selected the Direct Link Prehensor design as the baseline for an in-house developed robotic hand. After several design iterations (JH-1 through JH-2), we arrived at the JH-3 Hand. (JH stands for Jameson Hand, named after the designer Dr. John Jameson.) As shown in figure 6, the JH-3 Hand has an integrated hand-wrist-forearm package that approximates the combined size of a human hand, wrist, and forearm. Seven DC motors are packaged in the forearm: one motor per each DOF and one that controls the tendon tension. The wrist on the JH-3 Hand comes from a Remotec RM-10A robotic arm. Power is transmitted from the motors through a tendon-pulley system to each joint, much like the remotizer in the UMDH. This tendon-pulley system allows the hand to move freely with the wrist. The encoders on each motor and the strain gauges in the hand provide position and force feedback. Infrared proximity sensors were installed on the JH-3 Hand to provide autonomous adaptive grasping capability. The entire hand package contains current drivers for the motors as well as signal amplifiers for the sensors. Although the overall weight and package are still not quite acceptable (15 lbs), the JH-3 Hand does contain major improvements in packaging and sensing as compared to the UMDH and Stanford/JPL Hand.
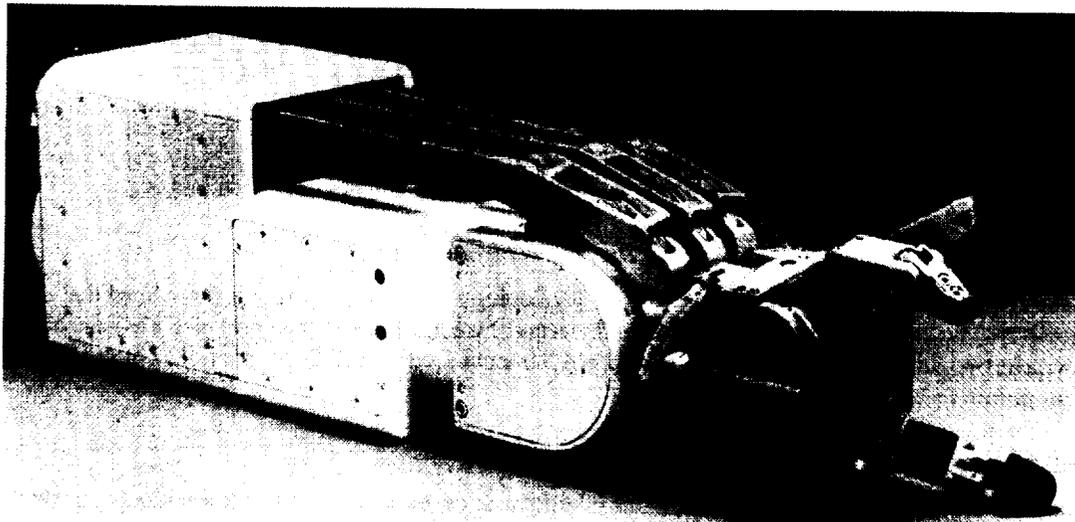


Figure 6. JH-3 Hand.

To evaluate the JH-3 Hand, we mounted the hand on the EVA Retriever, an in-house developed, highly autonomous, free-flying robot which operated on an air-bearing floor at NASA/JSC. From our evaluation, we arrived at two key conclusions related to prosthetics development. First, the mechanism for "remotizing" the actuators tends to add weight, bulk, and complexity to the overall system. Instead, local actuation requiring a minimum number of power transmission components is desired. There is a design trade-off between remote actuation and local actuation. Remote actuation adds to the overall weight of the system, but allows a more desirable mass distribution for moment reduction. On the other hand, local actuation tends to concentrate mass near the hand and amplifies moments about the elbow and

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shoulder. Second, the integrated hand-wrist-forearm design does not permit a simple integration of the JH-3 Hand with commercial robotic arms. Since most commercial robotic arms already come with a forearm fully integrated, installing a JH-3 Hand on these robotic arms requires redesign.

## JH-4 Hand

Incorporating the lessons learned from the JH-3 Hand evaluation, we developed the most recent hand design: the JH-4 Hand. This hand, shown in figure 7, contains two fingers and a thumb, each driven by two motors located right behind the proximal joint. Instead of remotizing the motors and transferring mechanical power through tendons and pulleys like the JH-3 Hand, motors in the JH-4 Hand drive the finger joints directly with a minimum number of gears. In making the fingers truly modular, we also packaged the drive electronics (e.g. current amplifiers, motion controllers) into each finger. An 80C196 microcontroller provides each finger with some local intelligence and serves as a high-level command interface.
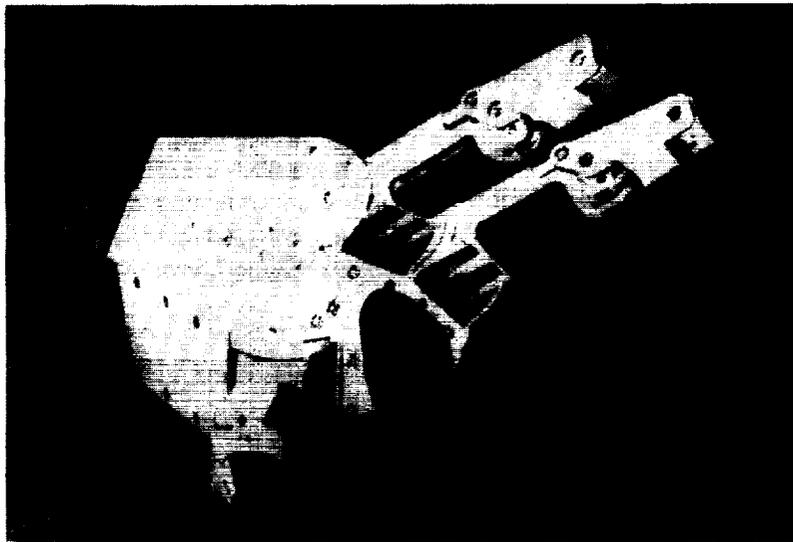


Figure 7. JH-4 Hand.

The JH-4 Hand represents our latest effort in developing a modular dexterous robotic hand that satisfies the stated objectives. The hand is near human-equivalent in terms of weight and size, and provides a reasonable degree of dexterity with its two fingers and a thumb. The microcontroller embedded in each finger provides a high-level command interface for primitive-based hand control.

## Rice Prosthetic Hand Prototypes

In parallel with these NASA/JSC dexterous robotic hand developments and with technical consultation from NASA A&RD experts, Rice University engineers have begun developing prototype anthropomorphic prosthetic hands. Two hands and one wrist unit have been built. Each hand has a thumb and four fingers with independent thumb and finger motion. One hand has a single-axis thumb which allows the thumb to swing through a full range of opposition to the finger tips and independent finger control on the index, middle, and ring fingers; the little finger is coupled to the ring finger. The other hand has a two-axis thumb which can abduct, oppose, and flex at its base; an independent index finger; and the remaining fingers coupled to complete grasps. Both hands can perform key, chuck, cylindrical, spherical, and hook grasps as well as completely flatten. The wrist unit is capable of flexing and roll. We are now beginning our second design iteration to simplify and strengthen the mechanisms to make them more reliable and easier to manufacture.

# MYOELECTRIC CONTROL

To achieve our third objective, we are investigating the feasibility of using myoelectric signals to control the robotic hands. Our first efforts are exploring the remote control or teleoperation scenario. Myoelectric teleoperation of dexterous robotic hands will require no mechanical parts, and may greatly reduce the bulk and weight now found in dexterous robotic hand control devices; however, this teleoperation scenario requires advances in the state of myoelectric control art. Improvement in myoelectric teleoperation of multifingered hands will also benefit the prosthetics users. For example, the level of myoelectric control of a dexterous hand achieved by an intact teleoperator will establish an upper performance bound for the amputee. Furthermore, some of the myoelectric signal processing techniques developed for teleoperation will transfer into prosthesis control.

Research in using myoelectric signals (also called electromyographic or EMG signals) to control prostheses dates from the late 1940's [35]. By the early 1970's, researchers were treating the myoelectric signals as an amplitude-modulated signal whose amplitude was roughly proportional to the force developed in the muscle generating the myoelectric signal. The consensus was that most of the information in a myoelectric signal was in the amplitude [18]. By the late 1970's, the model had matured to treating the myoelectric signal as amplitude-modulated Gaussian noise whose variance was proportional to the force developed by the muscle [31] [37].

Today's commercial myoprocessors used in prosthesis control are based on only one dimension of the myoelectric signal, the force level, and in a few cases, its rate of change. Researchers have successfully refined force estimation from the myoelectric signal [3] [5] [19] [24] [30] [31] [37]. Parker's work forms the basis of control multiple functions using different force levels on a signal channel [37]. Hogan's work was particularly significant in eliminating low frequency noise from the force estimates due to the spatio-temporal sampling artifact inevitable with skin surface electrodes [18] [19]. Jacobsen [24] refined use of the rate of change of force in elbow control of the Utah arm. A version of the Swedish Hand used rate of change of force to switch control functions [13]. Rice University researchers have investigated these force estimation results in operating a proportionally controlled grasp force with a three-fingered robotic hand.

These force-estimation techniques require a separable muscle contraction for each function commanded, making simultaneous control of two or more joints very difficult. A number of researchers, beginning with Wirta and Taylor [42], examined linear combinations of myoelectric force estimates from multiple channels to select different functions. The Swedish Hand developers applied these methods to selecting wrist and grasp [1] [2] [15]. The Japanese research team applied the technique to wrist control in the Waseda Hand 3 [27]. Jacobsen [22] and Jerard [26] formalized the mathematics for this approach and applied it to upper limb above-elbow prostheses. These force-estimating approaches require at least one electrode pair and signal processing channel for each muscle used, up to a dozen in some above-elbow experiments. Furthermore, force-estimating myoprocessors can be used only on superficial muscles [19], while most motions involve both superficial and deep muscles. In fact, any deep muscle activity reaching a force-estimating myoprocessor is mistakenly interpreted as superficial muscle activity. Therefore, it appears to us that to obtain multifunction sensitivity that is intuitively easy to use, all information in the myoelectric signal must be exploited, rather than just the force estimate. In addition to using superficial muscles (to which force-estimation techniques are limited), the deep muscles must also be used in myoelectric control systems.

Some researchers have considered shape and spectral characteristics of the myoelectric signal in addition to force estimation. Recent findings suggest that there is considerable information in the myoelectric spectra, if we can understand its coding. Examples include:

- Small muscles generally have fewer fibers per single motor unit (SMU) and therefore have power spectra containing more high-frequency activity than larger muscles with larger SMUs [33].

- Tissue (including other muscles) between the active muscle and the measuring electrode acts as a low pass filter to myoelectric signals, thus excessive low-frequency power densities may indicate cross talk from adjacent muscles [33].

- Action potential conduction velocity decreases with fatigue, causing gradual shifts in power from higher to lower frequencies during sustained forceful contractions [33].

- SMU recruitment order is stable for a given task [7]. Short-time spectra of myoelectric signals associated with a given rapid movement does not vary as much as previously thought [14].

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The full spectrum of the myoelectric signal has been examined using techniques involving statistical pattern and spectral analyses [8] [9] [10] [11] [29] [38]. Evidence of movements having distinct spectral signatures has been reported by Lindstrom and Magnusson [33], DeLuca [7], and Hannaford and Lehman [14]. The spectral signature of the initial muscular recruiting phase of arm motions to select up to six functions of an upper limb prosthesis from a single myoelectric signal has also been exploited recently by Hudgins [20].

Hudgins' [20] use of spectra-related parameters, such as zero-crossing and slope changes, and the use of Short Time Fourier Transforms by Hannaford led us to focus on the time-varying spectrum of the myoelectric signal in our research. We have been studying the correlation between the myoelectric spectrum in the initial recruiting phase of a motion with the type of motion. We are following the lead of Saridis [38], Doerschuk [8], Kelley [29], and Hudgins [20] in using the traditional single-muscle signals. However, our work differs from previous work of other researchers in that we are using the actual frequency spectrum to discriminate different grasping motions. Also, previous work has focused on arm, not hand, motions and on parameters derived from the spectrum rather than the actual spectrum.

## Myoelectric Experimental Setup

To evaluate various myoelectric control techniques, we developed a unique myoelectric data collection system which enables us to capture up to eight myoelectric data streams while simultaneously recording the motion of the subject's hand. Previous myoelectric researchers have had only limited, if any, capability to measure motion while measuring myoelectric signals.

Figure 8 is a block diagram of the data capture system. We use the Dexterous Hand Master (DHM), an exoskeleton glove manufactured by EXOS, Inc., of Cambridge, Massachusetts, to measure the subject's joint angles. The DHM glove, also used by NASA/JSC as a master to teleoperate dexterous robotic hands, measures parameters related to joint angles for four joints on the thumb and each of three fingers (index, middle, and ring) [43].

We use the Grass Instruments (Quincy, MA) Model 12 amplifier to measure myoelectric signals. It consists of a differential amplifier, a high-pass filter (with roll-off frequency adjustable from 0.01 to 300 Hz) to block DC and motion artifact, a low-pass filter (adjustable from 30 to 20,000 Hz) to limit aliasing, an adjustable gain amplifier stage, and an isolation to protect the subject from the electric shock hazards of power supply and computer equipment. This sequence amplifies the differential myoelectric signal from skin-surface electrodes (around 1 millivolt in amplitude) to several volts. Differential input reduces the 60 Hz interference (typically much larger than the myoelectric signal) from lights and equipment.
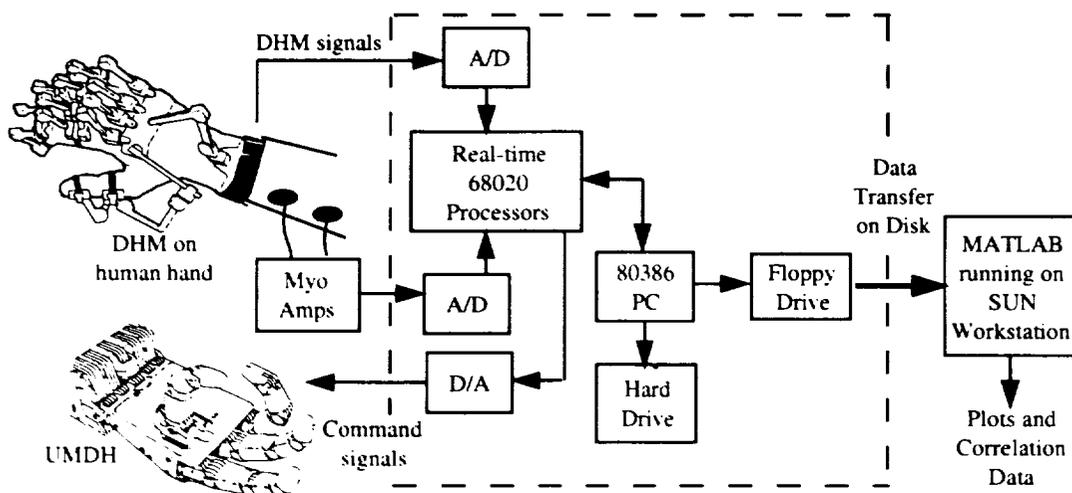


Figure 8. Myoelectric data capture system.

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Both DHM and myoelectric amplifiers are connected through Burr-Brown MPV950S analog-to-digital converter (ADC) boards to 68020-based Ironics IV3204 and IV3201 microcomputers. These capture up to 32 channels of data at 1000 samples per second per channel. An 80386 Radix PC transfers data to MATLAB format disk files. The ADC and Ironics and Radix computers are on a VME bus and do double duty as the control computer for the UMDH, with which we plan to demonstrate myoelectric teleoperation. We used Math Work's (Natick, MA) MATLAB software, Version 4.1, for off-line data analysis and plotting.

Based on our early findings in the myoelectric spectra, Rice University also developed a real-time myoelectric control implementation test bed consisting of miniaturized myoelectric amplifiers with fixed 20 to 500 Hz bandwidth and a personal computer incorporating an Elf-31(TM) board and signal processing development software by Atlanta Signal Processors. The Elf-31 includes high-speed analog-to-digital conversion and digital signal processor (TMS320C31). With this system, we can capture multiple myoelectric signals, compute their spectra on the Elf-31, and process the spectra into a grasp selection using the personal computer, all in real time. NWorks (TM) software by Neural Ware, Inc. (Pittsburgh, PA) facilitates development of neural networks for the classification of the spectra, if the user chooses a neural network approach.

## Preliminary Myoelectric Results

Our first use of these systems investigated direct use of the myoelectric spectrum to differentiate the key and chuck grasps. The key and chuck grasps differ in thumb position relative to the fingers. The thumb opposes the side of the index finger in the key grasp, while it opposes the tips of the index and ring fingers in the chuck grasp. Anatomy suggests that differentiating between these grasps requires measuring intrinsic thumb muscle activity in the hand and extrinsic finger and thumb activity in the forearm. We restricted measurements to the forearm, however, to keep the teleoperator's hand free of movement-encumbering hardware and increase our work's applicability to the prosthetics community.

We used the NASA/JSC data collection system (mentioned earlier) to capture myoelectric data during these two grasps. The human subject did a series of key and chuck grasps with the lateral side of the forearm resting on a horizontal surface or hanging vertically. We made no attempt to control the starting position (a relaxed posture) or grasp precisely. The subject was the judge of consistency in these positions. We later used DHM finger trajectory data to check for consistency and correctness of the grasp and to locate the initiation phase of the corresponding myoelectric signals.

We are now testing various myoelectric signal processing schemes on these data streams. One was an adaptation of the approach by Hudgins et al., [20] at the University of New Brunswick, where they computed mean absolute value, mean absolute value slope, zero crossings, and waveform length on biceps and triceps in 40 ms windows in the first 240 ms of arm motions, such as elbow flexing and humeral rotation. A multilayer Perceptron neural network used these features to classify the arm motions with 70 to 98% accuracy, depending on the human subject. Our initial implementation of this scheme yielded a maximum of 80% correct accuracy for our grasping test set. We believe that the decreased accuracy may be due to (1) increased difficulties in detecting the grasp start (since the myoelectric signal amplitude is smaller) and (2) differences in the way muscles used in fine motion control (such as grasping) and coarse motion (such as arm motion) are recruited. Inaccuracies due to the latter may be reduced by reoptimizing window size and characteristics. More algorithm experimentation and trials on more human subjects are needed to confirm this, however.

We have also tested several schemes which use the myoelectric signal's magnitude spectra directly. The most successful of these have used the upper portion of the myoelectric spectrum, the 75 to 250 Hz range. Muscle fiber length, diameter, and action potential conduction velocity as well as distance to the electrode dominate this portion of the myoelectric spectrum. A multilayer Perceptron receiving inputs of the 75 to 250 Hz spectrum in six 40 ms windows (as in the UNB scheme) from the distal channel in figure 9 classified the test set signatures 93% correctly.

We have also experimented with multiple channel configurations. Figure 9 shows our dual channel electrode configuration; the distal electrode pair (D1 and D2) measure extrinsic thumb muscle activity while the proximal pair (P1 and P2) measure finger flexion and extension activity. Computing 6 values of the 75 to 250 Hz spectrum in larger (240 ms) windows on both channels during the motion's initiation phase yields a set of 12 features that a multilayer Perceptron can classify 86 to 91% correctly, depending on the human subject. We implemented this approach in real time on our Real-Time Myoelectric Control Implementation Testbed and used it to teleoperate the Rice-developed prosthetic hands described previously.

C-4.
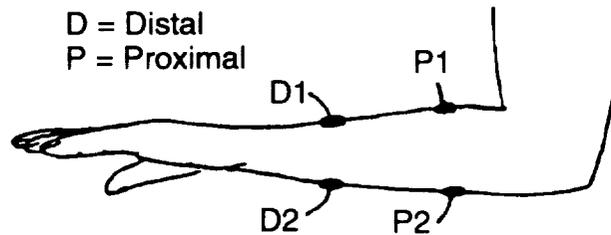
Figure 9. Dual channel electrode configuration.

While still below our grasp discrimination goal of 100%, these early results refute the long-held assumption that myoelectric signals from the forearm are inadequate for differentiating thumb motions.

We have begun experimenting with the 3 to 75 Hz portion of the myoelectric spectrum, which is dominated by muscle recruitment dynamics. Theoretically, task-specific SMU recruitment should show up in this portion of the spectrum, and this may be the key to increasing grasp selection accuracy above 93%. To date, we have not been successful with direct use of the magnitude spectrum in this region, in spite of the implied usefulness in references [7], [14], and [20] and the results of the adaptation of the UNB scheme, which implicitly used the entire spectrum. The UNB scheme has phase information embedded however. Since we expect the recruitment portion of the spectrum to be much more time-varying, it will be especially sensitive to window characteristics. We are continuing experiments with varying window size, overlap, and type.

## CONCLUSIONS AND FUTURE WORK

This ongoing joint research effort between NASA/JSC and Rice University is entering its third year. In the past two years, we have made significant progress in accomplishing the three stated objectives. We have evaluated several commercially available dexterous hand designs and gone through several iterations of our own in-house designs. We made progress in reducing weight and packaging of dexterous robotic hands while maintaining an acceptable level of dexterity, and realized the current design in the JH-4 Hand. We have begun development of prosthetic hands that incorporate lessons learned from robotic hand design and control.

Meanwhile, we also made significant progress in understanding myoelectric control theory. We have developed a unique myoelectric data collection system featuring recording of joint motion, and developed a test bed for evaluating various signal processing techniques. Initial results of over 90% correct grasp discrimination suggest that myoelectric commanding of grasp primitives is feasible. Eventually, we plan to evaluate the feasibility of myoelectrically controlling individual fingertips to augment grasp primitives.

If myoelectric control of dexterous robotic hands can be made both intuitive to operate and repeatable, a myriad of opportunities in both space robotics and prostheses development will open up.

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