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A Set of Grasp Requirements for a Dexterous Robot Hand Based on Existing Crew Aids, Tools and Interfaces

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Abstract

This paper describes the development of a database of grasping requirements for existing crew aids, tools (CATs) and interfaces used during extravehicular activity (EVA). This database identifies the basic grasping requirements of 242 CATs and interfaces found in the EVA Tools and Equipment Reference Book. The results of this study show that over 50% of these grasps are cylindrical, and that it may be possible for a three-fingered hand to achieve over 90% of these grasps. This has led to the development of a multi-fingered dexterous robot hand that can achieve cylindrical grasps, while producing the holding strength necessary for grasping several CATs and interfaces included in the database.

1 Introduction

For decades, researchers have been developing new methods of improving productivity in space. Both human and robot operations are constantly being studied to address this issue. With the construction of the International Space Station (ISS) underway, the need for productive operations is becoming increasingly important. ISS operations will require over 960 man-hours of EVA [11]. A mission of this magnitude raises important time and safety issues. In order to help with these operations, robots need to be designed to be compatible with existing (CATs) and interfaces, making the transition from human operations to robot operations (and vice-versa) as simple as possible.

Many end effectors exist that strive to achieve human hand functionality by using an anthropomorphic design [4-7]. The human hand is very complex, and robot hands that are developed to imitate them tend to be complex as well. Other end effectors are less complex, such as the simple gripper, or utilize interchangeable end effectors. Although these can be simple in design, they lack the versatility of more complex, anthropomorphic hands. These simple hands will require new tools for EVA operations, which increases operation costs.

In robot hand design, there has always been a trade-off between simplicity and dexterity. Most of the robot hands in existence are either highly dexterous and complex, or simple in design with low dexterity. Two examples that show this range of simplicity and dexterity are the Robonaut hand [7] and the Ranger interchangeable end effector mechanism (IEEM) [1]. The Robonaut hand is a highly anthropomorphic, highly dexterous hand that can achieve a large amount of the human hand functionality. With this ability comes a high level of complexity in terms of structure and control. Conversely, the Ranger IEEM is simpler in design, yet requires more than one end effector to achieve its goals.

The purpose of this study is to find the requirements for a hand that lies in the middle of these two extremes. To accomplish this, 242 CATs and interfaces were studied. A database was then created where basic and specific

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grasp(s) are assigned to each CAT and interface, based on its size and intended use. The grasps that occur most often drive the initial design requirements for the Space Systems Laboratory (SSL) Hand; a simple, dexterous hand for space operations.

2 Grasping Database

The CATs and interfaces considered are located in the EVA Tools and Equipment Reference Book [9]. The study was limited to 242 CATs and interfaces that are currently used and only used outside the Space Shuttle, as EVA robotics is the primary area of interest. Future prototypes and ISS tools were ignored since many are still in development.

The CATs and interfaces in [9] are categorized according to their function. These categories include: body and equipment restraints, cutters, drive tools, electrical equipment, fluid transfer tools, levers, photographic and lighting equipment, power equipment, sockets, stowage, wrenches, and other miscellaneous equipment such as the manned maneuvering unit (MMU), extravehicular mobility unit (EMU) and their docking adapters.

The grasps that were assigned to these CATs and interfaces were taken from a grasp taxonomy developed by Cutkosky and Wright [2]. This taxonomy represents the most common types of grasps that occur in a common machine shop, and was developed specifically to aid in designing advanced, cost-effective hands. It is well established and has been used widely in robot hand design. The taxonomy is divided into two basic grasps, power and precision, which are further divided into several specific grasps. The grasping database contains several pieces of information on each CAT and interface. These include dimensions, force and torque requirements, location in [9], basic and specific grasp assignments, and flight availability (standard or flight specific). The database also indicates which tools are used during the Hubble Space Telescope servicing missions. Figure 1 shows an example entry from the wrench tool section of the database.

In some cases, many grasps may apply to one CAT or interface. The simplest grasp that enables a hand to utilize the tool was chosen. When necessary, more than one grasp was assigned, such as when a tool requires grasping and the use of a pip pin simulaneously. The assignment of grasps was done subjectively, where each CAT and interface in [9] was examined as thoroughly as possible without having access to the actual item. Furthermore, some entries did not specify force and torque requirements, which are task-specific.

The total occurrences of each type of grasp were summarized to clearly show which grasps are the most common. This summary is shown in Figure 2. When looking at the taxonomy, one can see that several of the grasps are cylindrical. The grasps that were categorized as cylindrical for the purposes of this study are large diameter, small diameter and medium wrap. As Figure 2 shows, these grasps represent the majority (52.5 percent) of the total number of CATs and interfaces. Upon additional inspection of this summary, it was determined that a three-fingered hand may be able to achieve several of these grasps, perhaps over 90 percent. Again, this is based on the inspection of the CAT or interface and its grasp(s) taken from the taxonomy.

Equipment Title	**Dimensions (inches)**	**Force/Torque (lbf/ft-lb)**	**Reference Page**	**Basic Grasp**	**Specific Grasp**	**Grasp Number**	**Availability**	**HST**
	(height x width x length) (diameter x length)	Force/Torque or tool representing a force/torque	EVA Tool and Equipment Reference Book				Flight specific or standard	
WRENCH TOOLS								
Forceps	5.6 x 9.9 overall 1.44" finger rings		F-7	Precision	2-finger	8	Standard	
Needle nose pliers	1.5 x 8.9 overall 1.75" finger rings		P-33	Precision	2-finger	8	Standard	
Vise-grip pliers	2.5 x 10.06		P-35	Precision/Power	2-finger, medium wrap	8, 3	Standard	
1/2" ratcheting box end wrench	1.25 x 0.75 x 4.0 handle		W-5	Power	Medium wrap	3	Standard	
5/16" ratcheting box end wrench	1.0 x 0.25 x 9.5 handle		W-7	Power	Medium wrap	3	Standard	
7/16" and 1/2" box end wrench	1.38 x 0.75 x 4.0 handle		W-9	Power	Medium wrap	3	Standard	
7/16" ratcheting open end wrench	1.35 x 0.78 x 6.5 handle		W-11	Power	Medium wrap	3	Flight specific	
Adjustable wrench	1.25 x 0.75 x 4.0 handle		W-13	Precision/Power	1-finger, medium wrap	9, 3	Standard	
Contingency strut wrench	1.25 x 0.75 x 16.0		W-15	Power	Medium wrap	3	Flight specific	
RMS MPM wrench	1.3 x 0.5 x 6.26 handle		W-27	Power	Medium wrap	3	Standard	
Shuttle umbilical retraction system wrench	0.63 x 1.38 x 4.7 handle		W-29	Power	Medium wrap	3	Standard	

Figure 1: An example category entry in the grasping database

Category	Occurences	% of Tools
Basic Grasp		
Power	71	29.34%
Precision	92	38.02%
Precision/Power	79	32.64%
Specific Grasp		
1-finger	61	25.21%
2-finger	92	38.02%
3-finger	2	0.83%
4-finger	1	0.41%
Adducted thumb	17	7.02%
Disk (Power)	17	7.02%
Disk (Precision)	13	5.37%
Large diameter	14	5.79%
Lateral pinch	24	9.92%
Light tool	25	10.33%
Medium wrap	49	20.25%
Small diameter	64	26.45%
Sphere (Power)	1	0.41%
Sphere (Precision)	1	0.41%

Figure 2: Summary of total grasp occurrences

3 Robot Hand Design

Based on the results of the grasping database, the initial hand design was a three-fingered hand optimized for cylindrical grasping. This optimization was accomplished through a non-anthropomorphic, opposable configuration, which some studies show offers a strong cylindrical grasp [8].

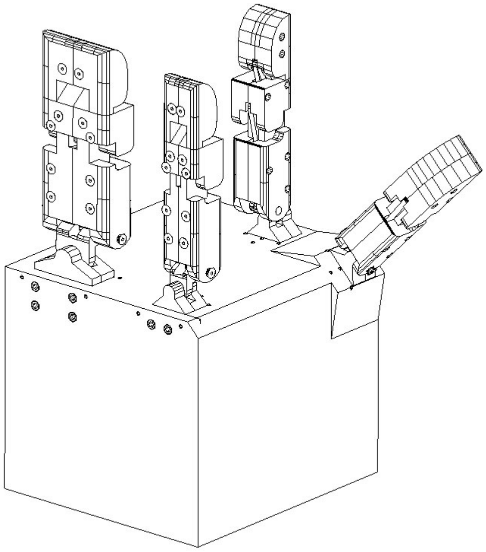


Figure 3: The SSL Hand

The SSL Hand (Figure 3) has a total of 12 independent degrees of freedom (DOF). It consists of three types of fingers; the standard finger (index), a wide grasping finger (middle and ring) and a thumb. Because the CATs and interfaces are intended for human use, these fingers are similar to those of a human in size and functionality [3]. However, their configuration is unlike that of a human hand in order to study the possible benefits of a non-anthropomorphic design. The thumb was added for tool actuation, such as squeezing a trigger, and offers the benefit of simultneous grasping and three-fingered manipulatoin. The thumb was not included in the primary grasping study since a three-fingered cylindrical grasp is the main design criterion.

The standard fingers oppose each other on the hand, offering two-fingered manipulation. The grasping finger is designed to allow this manipulation while simultaneously grasping the tool. All fingers are mounted into the base, which houses the tendon routing system that drives the fingers. An official "palm" was unnecessary for the testing purposes of this study, which are described in section 3.3.

3.1 Finger Design

All fingers have the same basic design with similar ranges of motion and actuation schemes. The standard and grasping fingers each consist of a yoke, proximal, middle and distal segments, three aluminum drive linkages, a series of stainless steel pins for linkage and tendon termination, and three sets of springs for passive finger extension (Figure 4).

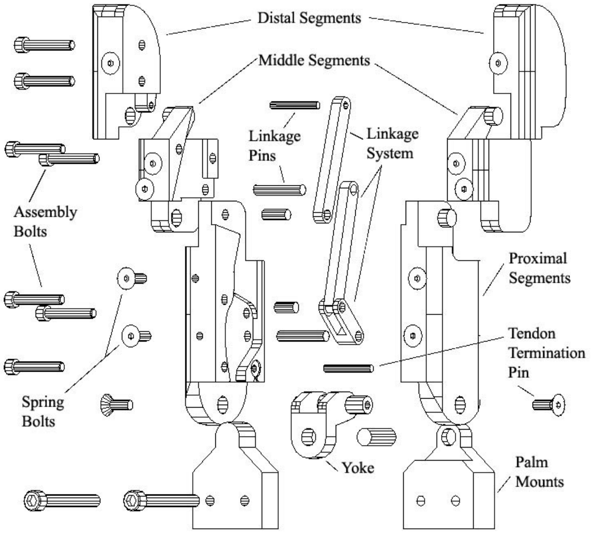


Figure 4: The standard dexterous finger

The palm mounts, yoke and the shell of the finger were fabricated using rapid prototyping technology, which allows a quick and low-cost verification of the design.

The load bearing parts were machined from aluminum for increased strength.

3.2 Finger Drive System

The tests in this study consisted of demonstrating the SSL Hand's static grasping capabilities. For this reason, no motors have been incorporated at this point. Instead, each finger is driven by four tendons, which are actuated by hand through a turnbuckle leadscrew assembly. The head joint has a yaw motion of ± 40° (joint 1) and 120° of pitch (joint 2). Joint 1 yaw motion is driven by two tendons in opposition, while the joint 2 pitch is driven by a third tendon (Figure 5).

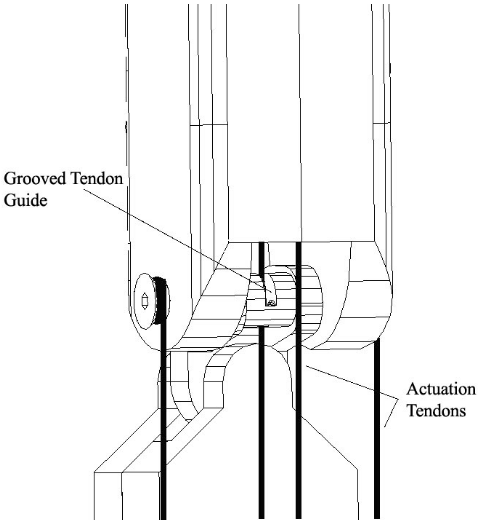


Figure 5: Tendon drive system

A fourth tendon drives joints 3 and 4 through a parallel linkage system (Figure 6), which presents a complex problem in finger kinematics. To ensure that these joints move in a way that resembles human finger motion [3], a mathematical analysis was done for the four-bar linkage that connects them [8]. As a result, joint 4 moves through 60° of pitch as joint 3 pitches through 90°.

Because the standard serial velocity-force propagation technique does not apply, the kinematic analysis was accomplished through a static force-moment balance. This method sets all forces and moments of each link in the 6-link parallel system equal to zero. The result is a set of 18 equations and 18 unknowns, which can be solved to give the joint 2 and 3 tendon tensions for a given fingertip force. This offers a kinematic model that uses the Jacobian matrix to relate fingertip forces to tendon tensions. This analysis works only for the planar case (ignoring joint 1), and changes with finger position. These constraints were possible due to the method of testing, which ignores all forces and moments outside the plane containing joints 2 through 4, including wrenches on the fingertip.

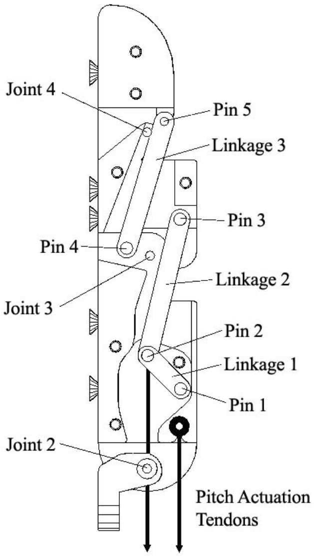


Figure 6: Parallel linkage system

3.3 Testing and Results

The basic task set consisted of demonstrating several cylindrical grasps, ranging from 0.75 to 1.50 inches. Most of the CATs and interfaces in the database have dimensions within this range. The hand was mounted upside down on a test stand, while a load was applied to the grasped objects (Figure 7). The results of these tests show that the SSL Hand is fully capable of holding a 20-lb. cylinder with two fingers. This is the maximum tool force allowable by the NASA-STD-3000 [10]. Furthermore, the grasping finger alone was able to hold 13 lb.

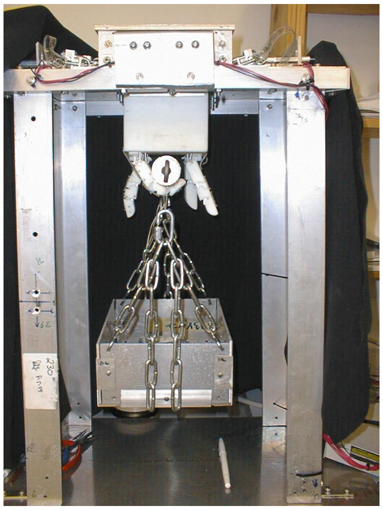
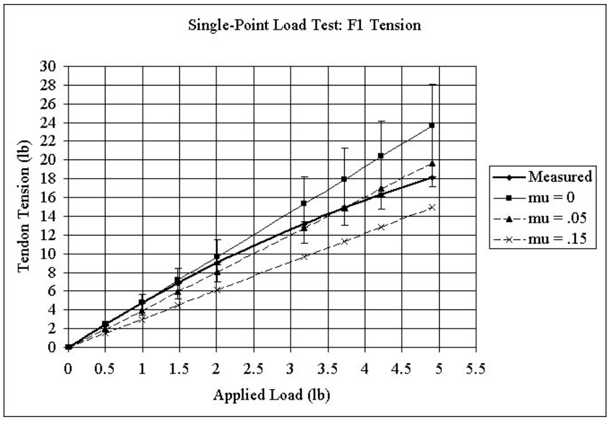


Figure 7: Test setup

A second test was done where a load was applied to a single point on the fingertip. By doing this, the measured tendon tensions can be directly compared with the tensions predicted by the kinematic model, and the estimation of friction in the system can be verified. Figure 8 shows how the actual tendon tensions compare with the model, and that the static coefficient of friction of the system is approximately 0.05.



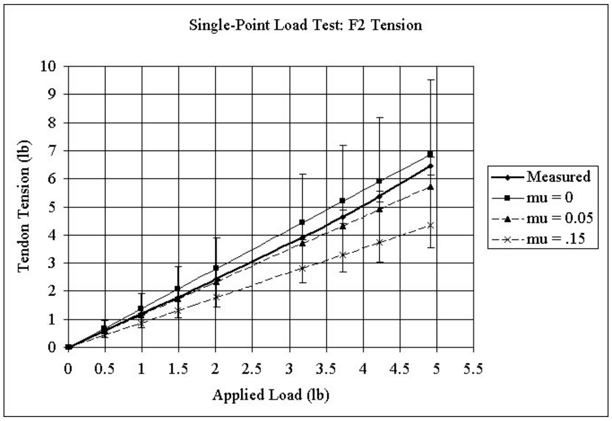


Figure 8: Measured and predicted tendon tensions

In Figure 8, F1 and F2 represent the joint-2 and joint-3 actuation tendons, respectively. The slight nonlinear nature of the curves is a result of a small amount of slipping at the tendon termination points, as well as stretching of the tendons themselves. The error bars on the predicted zero-friction curve are model errors due to finger position measurement inaccuracies.

A secondary task is the demonstration of how the hand can grasps a variety of common tools, including a power drill (Figure 9), needle-nose pliers, a 3-inch cylinder and a common EVA ratchetless wrench. The SSL Hand showed its ability to grasp all theses objects with a fair amount of stability.

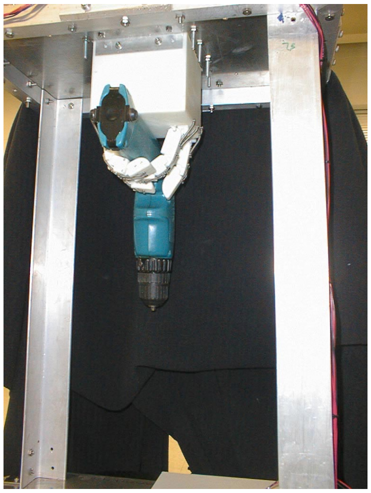


Figure 9: The SSL Hand grasping a common drill

4 Conclusions and Future Work

This paper presents the development of a database of grasping requirement based on existing CATs and interfaces. This database shows that a cylindrical grasp is required for more than 50% of these tools, while over 90% may be manipulated with a three-fingered hand. These results have in turn led to the development of a simple yet dexterous robot hand that is optimized for cylindrical grasping. This represents the first step in developing a hand that lies in the middle of the simplicity/dexterity spectrum by being dexterous enough to utilize the majority of CATs and interfaces, but as simple as possible in design.

Future efforts will focus on further testing of finger structure, various cylindrical grasps and alternate tendon routing schemes. This will lead to the incorporation of motors and sensors for finger control and object manipulation, and further palm development to study finger configuration, compliance and grasping stability. With these systems in place, it is hoped that the SSL Hand will be able to demonstrate its utility in space operations.

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