HEURISTIC CONTROL

OF THE UTAH/M.I.T. DEXTROUS ROBOT HAND

Final Report

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ABSTRACT

The main thrust of this work has been to analyze basic hand grips and sensor interactions that a dextrous robot hand will need as part of the operation of an EVA-Retriever.

The work focused on understanding what is to be done with a dextrous robot hand and how such a complex machine might be controlled. It was assumed throughout that an anthropomorphic robot hand should perform tasks just as a human would; that is to say, at least initially, the most efficient approach to developing control strategies for the hand would be to model actual human hand actions and do the same tasks in the same ways[1]. Therefore, a Heuristic approach to control was developed.

The tasks performed by human hands are extremely complex involving the movement of many fingers and joints and contact between numerous surfaces, that is, contact at an infinity of points. In addition, multiple sensors including force/touch, vibration, shear and sometimes heat must be taken into account. Each movement and task involves a multitude of these force/touch interactions and a number of sub-sequences and events, the aggregate of which, can only be termed a skill. In addition, I have tried to understand just what is to be done with a dextrous hand. Therefore, basic hand grips that human hands perform, as well as hand grip actions were analyzed.

It was also important to examine what is termed *sensor fusion*. This is the integration of various disparate sensor feedback paths. These feedback paths can be spatially and temporally separated, as well as, of different sensor types. Neural Networks[2] are seen as a means of integrating these varied sensor inputs and types. Basic Heuristics of hand actions and grips were developed. These Heuristics offer promise of control of dextrous robot hands in a more natural and efficient way. Emphasis was also placed on possible methods of implementing these techniques. Future work will be to continue development of routines and Heuristics and use them to control the Utah/M.I.T. dextrous robot hand. A smart robot hand, one that can adapt to new situations and develop new skills is a goal of researchers working with dextrous robot hands. It is an ultimate goal that a smart hand will be able to develop its own Heuristics which will make its operation and use even more efficient and its control more simple.

Introduction

The EVA-Retriever

The EVA-R will evolve into a completely autonomous mobile robot. The robot will be used for retrieving objects which have floated free from Shuttle or Station and will secure or stabilize objects as need be. EVA-R can be used to assemble structures and as a general Astronaut's assistant. The robot will have a vision system and possibly some form of laser ranging device. It is expected that the EVA-R will be able to recognize tools and other objects and upon voice command locate, identify, track and retrieve them. EVA-R will ultimately use tools to perform work assignments.
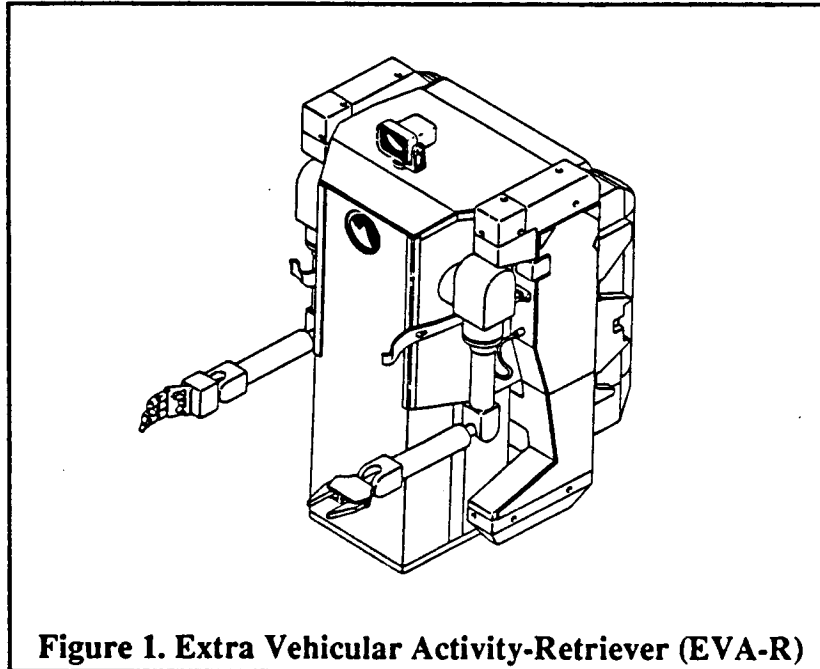

Figure 1. Extra Vehicular Activity-Retriever (EVA-R)

As can be seen in figure 1., the EVA-R will reside in an MMU and will have two arms. At least One arm will have a smart dextrous hand like the Utah/M.I.T. hand.

An autonomous mobile robot will require several new and emerging technologies. These include :

1. Neural Networks which have been trained to identify and interpret sensory input.

2. AI languages such as CLIPS that can interface with the neural networks and be programmed to deliver higher level commands to the robot and aid in task planning and execution.

3. Dynamic adaptive task planners[3,4] which can make decisions based on sensory information, task safety, present and evolving conditions, changing goals, and previous experience.

4. The robot must have the ability to learn from its experiences and discard useless information. This type of learning by the robot may possibly be implemented through neural networks.

5. Dextrous hands for using tools and performing skilled tasks.

6. Touch sensors and vibration/feeling sensors incorporated into the hand at appropriate places.

7. Vision sensors and ranging sensors for navigation and identification of objects.

8. Voice Recognition and understanding so that it can carry out command given by an Astronaut.

Development of Neural Network technology is key to the the implementation of a fully functioning autonomous mobile robot. Whether the neural networks are hard-wired or simulated they will require faster chip computational speeds and large amounts of nonvolatile memory. The various components of the robot must have separate and parallel networks. The hand will have neural networks for sensing which will be distinct from the vision networks and voice recognition networks. A guidance navigation and balance network would be used to integrate and interpret the various outputs of the other nets. Layered between the networks would be an AI language such as CLIPS. A top or overseeing AI layer would manage the robots activities.
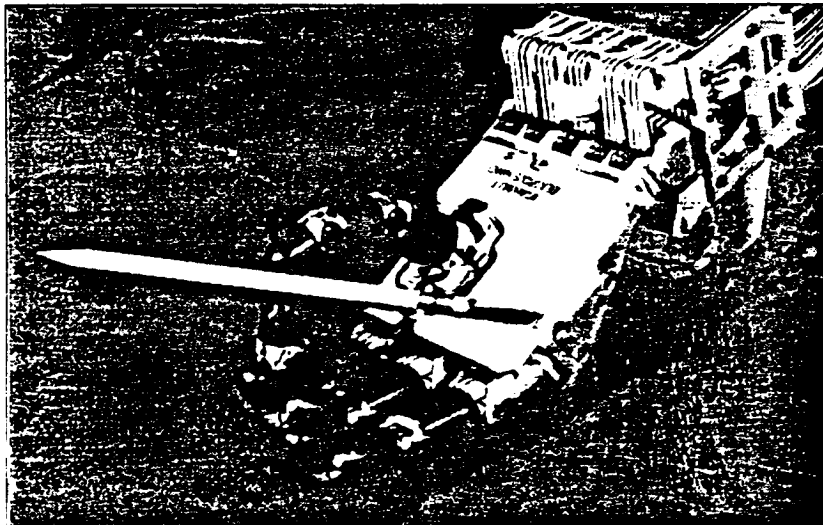
The Utah M.I.T. Dextrous Robot Hand

Figure 2. The Utah/M.I.T. Dextrous Robot Hand

The Utah/M.I.T. dextrous robot hand is a four fingered hand with each finger having multiple joints. This includes one thumb which opposes the three fingers. There are three joints in each finger which serve to curl the finger, and one base joint which rotates the entire finger back and forth in the plane of the palm. The hand is capable of graceful and delicate movement just as a human hand is and, therefore, can perform many human hand actions.

Findings

Kinematics

To study control strategies and simulate hand actions a kinematic solution of the hand was sought. A typical finger is considered and can be referred to a single point or coordinate system in the palm. Using the Denavit-Hartenberg notation, the position and orientation fingertip is expressed as a series of matrix transformations.
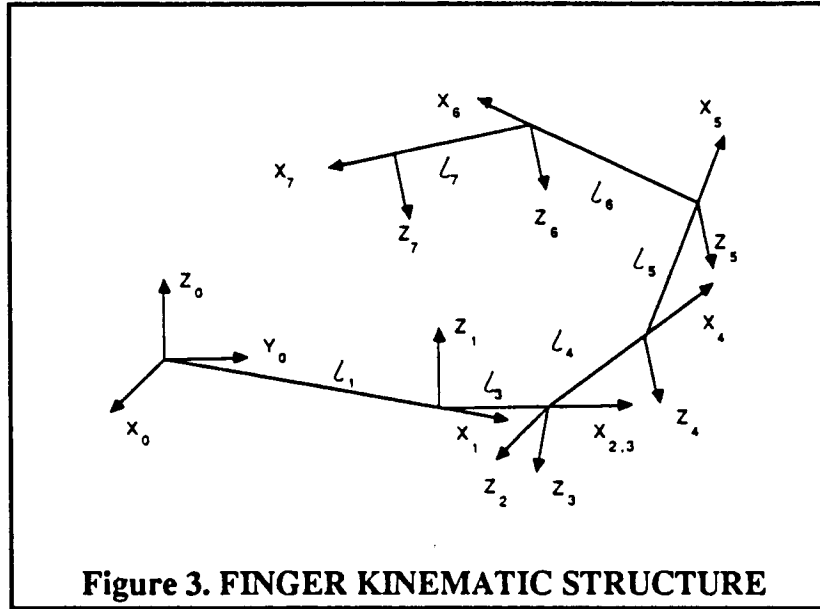

Figure 3. FINGER KINEMATIC STRUCTURE

The transformation from the reference coordinate system (X_0, Y_0, Z_0) to a typical fingertip (X_7, Y_7, Z_7) is given by

The fingertips position and orientation are given by :

(1.) $\quad T = A_1^0 A_2^1 A_3^2 A_4^3 A_5^4 A_6^5 A_7^6$

A_i^{i-1} are matrix transformations that give the coordinate system at point i along link l_i from i-1th joint i-1 to ith joint [5,6]. Since A_1^0 and A_2^1 are constant matrices let

(2.) $\quad T^* = (A_1^0 A_2^1)^{-1} T$

(3.) $\quad T^* = \begin{pmatrix} n_x & t_x & b_x & P_x \\ n_y & t_y & b_y & P_y \\ n_z & t_z & b_z & P_z \\ 0 & 0 & 0 & 1 \end{pmatrix}$

The upper left hand 3x3 contains the direction cosines that give the orientation of the fingertip and the first three elements of the fourth column give the position of the fingertip from the (X_2, Y_2, Z_2) coordinate system.

Using the Denavit-Hartenberg Notation a homogeneous transformation from the i-1th joint to the ith joint along link l_i is :

$$A_i^{i-1} = \begin{pmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & a_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i & a_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

where θ_i is a rotation of the revolute joint i, d_i is for a prismatic joint (here = 0), a_i is the link length, and α_i is the link twist. For a typical finger

$$A_1^0 = \begin{pmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & l_1\cos\theta_1 \\ \sin\theta_1 & \cos\theta_1 & 0 & l_1\sin\theta_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

θ_1, θ_2 are constant. $\alpha_1 = 0, \alpha_2 = \pi/2$ and $l_2 = 0$. For convenience $\theta_3 = 0$. Then $\alpha_3 = \theta_3$. Also, $\theta_4 \approx 30°$ and $\alpha_4 = 0$. Therefore, A_4^3 is a constant matrix.

$$A_2^1 = \begin{pmatrix} \cos\theta_2 & 0 & \sin\theta_2 & 0 \\ \sin\theta_2 & 0 & -\cos\theta_2 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad A_3^2 = \begin{pmatrix} 1 & 0 & 0 & l_3 \\ 0 & \cos\theta_3 & -\sin\theta_3 & 0 \\ 0 & \sin\theta_3 & \cos\theta_3 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

and for i = 4,5,6,7 the transformations and their inverses are [7]

$$A_i^{i-1} = \begin{pmatrix} \cos\theta_i & -\sin\theta_i & 0 & l_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i & 0 & l_i\sin\theta_i \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad (A_i^{i-1})^{-1} = \begin{pmatrix} \cos\theta_i & \sin\theta_i & 0 & -l_i \\ -\sin\theta_i & \cos\theta_i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

from (2.)

$$T^* = A_3^2 A_4^3 A_5^4 A_6^5 A_7^6$$

Postmultiplying both sides by $(A_7^6)^{-1}$ yields.

$$T^*(A_7^6)^{-1} = A_3^2 A_4^3 A_5^4 A_6^5$$

Premultiplying both sides of the equation by $(A_3^2)^{-1}$ equating both sides and solving for θ_3.

$$(A_3^2)^{-1} T^*(A_7^6)^{-1} = A_4^3 A_5^4 A_6^5$$

$$\cos\theta_3 (P_x - l_7 n_x) - \sin\theta_3 (P_y - l_7 n_y) = 0$$

$$\theta_3 = \tan^{-1}\left(\frac{P_x - l_7 n_x}{P_y - l_7 n_y}\right)$$

Solving for θ_5. Let

$$W = (A_3^2 A_4^3)^{-1} T^* = A_5^4 A_6^5 A_7^6$$

$$(A_5^4)^{-1} W = A_6^5 A_7^6$$

Equating sides evaluating and solving yields :

$$\theta_5 = \tan^{-1}\left(\frac{W_{23}}{W_{13}}\right)$$

Solving for θ_6, θ_7 in a similar fashion.

$$(A_6^5)^{-1}(A_5^4)^{-1} W = A_7^6$$

$$\theta_6 = \tan^{-1}\left(\frac{W_{13}\cos\theta_5 + W_{23}\sin\theta_5}{W_{13}\sin\theta_5 + W_{23}\cos\theta_5}\right)$$

Taking the ratio of the 2,4 term to the 1,4 term and solving yields :

$$\theta_7 = \tan^{-1}\left(\frac{P_y(\cos\theta_5 \cos\theta_6 - \sin\theta_5 \sin\theta_6) - P_x(\cos\theta_5 \sin\theta_6 + \sin\theta_5 \cos\theta_6) + l_5 \sin\theta_6}{P_x(\cos\theta_5 \cos\theta_6 - \sin\theta_5 \sin\theta_6) + P_y(\cos\theta_5 \sin\theta_6 + \sin\theta_5 \cos\theta_6) - l_5 \cos\theta_6 - l_6}\right)$$

In the above relations :

$$W_{13} = b_x \cos\theta_4 + b_y \cos\theta_3 \sin\theta_4 + b_z \sin\theta_3 \sin\theta_4$$

$$W_{23} = -b_x \sin\theta_4 + b_y \cos\theta_3 \cos\theta_4 + b_z \sin\theta_3 \cos\theta_4$$

Transforming back to the base coordinate system (X_0, Y_0, Z_0) from the (X_2, Y_2, Z_2) coordinate system.

$$B_x = \cos\theta_1(B_{x0} \cos\theta_2 + B_{y0} \sin\theta_2) + \sin\theta_1(B_{y0} \cos\theta_2 - B_{x0} \sin\theta_2)$$

$$B_z = \cos\theta_1(B_{x0} \sin\theta_2 - B_{y0} \cos\theta_2) + \sin\theta_1(B_{x0} \cos\theta_2 + B_{y0} \sin\theta_2)$$

$$P_x = \cos\theta_1(P_{x0} \cos\theta_2 + P_{y0} \sin\theta_2) + \sin\theta_1(P_{y0} \cos\theta_2 - P_{x0} \sin\theta_2) - l_1 \cos\theta_2$$

$$P_z = \cos\theta_1(P_{x0} \sin\theta_2 - P_{y0} \cos\theta_2) + \sin\theta_1(P_{x0} \cos\theta_2 + P_{y0} \sin\theta_2) - l_1 \sin\theta_2$$

$$N_x = \cos\theta_1(N_{x0} \cos\theta_2 + N_{y0} \sin\theta_2) + \sin\theta_1(N_{y0} \cos\theta_2 - N_{x0} \sin\theta_2)$$

$$N_z = \cos\theta_1(N_{x0} \sin\theta_2 - N_{y0} \cos\theta_2) + \sin\theta_1(N_{x0} \cos\theta_2 + N_{y0} \sin\theta_2)$$

$$B_y = B_{z0} \quad , \quad N_y = N_{z0} \quad , \quad P_y = P_{z0}$$

The Thumb is opposite the fingers operates in an opposing direction.
In this case :

$$\theta_2 = \xi_2 + \pi, \quad \theta_4 = \pi/2.$$

Traditional Kinematics Versus the Heuristic Approach

Traditional mathematical approaches involve dynamic modeling with the equations of motion. These models solve for end effector orientation, position, motions, and forces; also joint angles and torques. This is feasible for robots and machines with few degrees of freedom and simple geometries. However, Even for relatively simple robot mechanisms, the mathematics can be intractable. The complexity of a dextrous robot hand and the need to include smart and adaptive control suggests the use of heuristic methods. Asada and

Slotine[5] page 185 state, " ... very few manipulators are capable of such seemingly simple tasks as driving a screw or turning a crank." They were discussing a class of problem called Compliant Motion control which they define as " ... concerned with the control of a robot in contact with its "environment" - an object to manipulate or assemble ...".

The difficulties of compliant motion control when there are only a few points of contact between the manipulator and the work piece further point out the futility of using traditional mathematical approaches. This is especially true when a dextrous hand is concerned and there are an infinite number of points, indeed surfaces, which are in contact with an object being manipulated. A purely mathematical approach would require major breakthroughs and brand new insights.

As further evidence, Jacobsen, co-inventor of the Utah/MIT hand [1,2], in his speech to the Space Operations Automation and Robotics SOAR Conference at NASA/JSC August 6, 1987 stated of the dextrous hand he had created, "we really don't know how to control these things". He went on to state that you must understand what it is you really want to do with them. For example, what is a grip and how do you do various grasps.

Insight into the efficient performance of manipulator tasks is easily obtained by close observation of ones own manual skills and abilities. The proper placement and number of contact sensors is important. It is also of primary importance to examine the issues of what is termed *sensor fusion*. This is the integration of various disparate sensor feedback paths, spatially, temporally and sensor type (touch and vision for example).

The Heuristic Approach

Webster defines heuristic as follows : Serving to guide, discover, reveal. Valuable for stimulating or conducting empirical research but unproved or incapable of proof.

Used here, it is the development of AI techniques to control ROBOT devices. Heuristic approaches offer advantages in that they allow controlling the robot hand in human-like, complex operations and motions which are difficult if not impossible to describe in a mathematical fashion at the present time. They involve developing rules of thumb and implementing them in an AI sense. This does not rule out the melding of traditional control and mathematical structure with AI-control, learning and expert system supervision[9]. There could be control on a machine or low level by kinematic and dynamic analysis with Robustness and flexibility supplied by expert systems. An implementation might involve the use of neural networks for low (machine) level control. Neural nets would develop skills in performing tasks in a fashion similar to the development of dextrous skills in a human. The ultimate test of a particular implementation will be the ability of the robot to perform tasks in new and unfamiliar situations and the ability to make judgement type decisions when needed.

Classification of Hand Actions

An understanding of how a hand performs a particular task is gained by understanding what those tasks are. Hand Actions are developed as a means of classifying the various tasks to be performed by the dextrous robot hand.

After an object has been gripped, there are many actions that are possible. A few basic actions that the hand will have to perform are listed below.

- Holding : Maintenance of a grip
- Pulling : Grip + Holding + Force in the direction of the wrist
- Pushing : Contact with an object + a Force away from the wrist
- Feeling : Contact with an object to discover its characteristics.
- Rotating : Grip + Wrist rotation accompanied by a possible sinusoidal movement of the fingers.
- Turning (wrench) : Grip + Force in the direction of the palm and perpendicular to the wrist axis.

Common among hand actions are grips. To understand how to perform the various hand actions listed above it is necessary to first study grips and grip primitives. These are basic contact configurations that a dextrous hand must be capable of performing.

Classifications of GRIPS

- Gripping : is the act of securing an object with the hand.

- Grip Primitive : A grip which is used to hold an elementary object or object type and is distinguishable from other grips by a unique geometric pattern of the fingers.

- Elementary Object : From a gripping point of view , all objects are composed of elementary objects such as cylinders, spheres,large planar surfaces, etc.

Grips can be divided into states that are generally distinguishable from each other by their geometry, function or some combination thereof. A grip for an object type can be scaled within limits as a function of object size. A heuristic can handle the break down of scaling.

Spherical and Cylindrical Grips

ELEMENTARY GRIP PATTERN CHART					
OBJECT	FINGER/JOINT in °	0	1	2	3
CYLINDER	THUMB	0	φ	φ	φ
ROD	FINGER 1	φ	"	"	"
	FINGER 2	"	"	"	"
	FINGER 3	"	"	"	"
CYLINDER	THUMB	45°	0	0	0
LEVER	FINGER 1	φ	φ	φ	φ
	FINGER 2	"	"	"	"
	FINGER 3	"	"	"	"
SPHERE	THUMB	0	φ	φ	φ
	FINGER 1	-μ	"	"	"
	FINGER 2	0	"	"	"
	FINGER 3	μ	"	"	"

$$\mu = \max \angle \quad , \quad \phi = 2\tan^{-1}(l/2r)$$

The angles ϕ are calculated with equal length finger links. Actual angles can be determined using the kinematics calculations or by measurement with the robot hand. The chart above serves to illustrate the general relationship between the angles. *In a Spherical or Cylindrical Grip it is the thumb and the 0 joint that give a grip its unique configuration.*

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*For a cylindrical lever grip, the thumb is rotated along the axis of the shaft. Presently, the Utah/M.I.T. hand cannot rotate the full 90 degrees to accomplish this. The hand can only rotate ≈ ±45° from the normal to the plane of the palm. A future version of the hand will be capable of rotating ±90°: (personal conversation with Jacobsen).

Flat Surface Grips

A flat object, from a one handed gripping perspective, is one in which the only grip opportunity arises on a side of the object and the fingers and thumb are in contact with opposite parallel faces of the object. There are generally three sub categories of grippable flat objects.

FLAT SURFACE GRIP PATTERN CHART					
OBJECT	FINGER/JOINT in °	0	1	2	3
SMALL EDGE	THUMB	0	0	0	0
non-massive	FINGER 1	0	φ	φ	φ
(FINGERTIP)	FINGER 2	0	"	"	"
	FINGER 3	0	"	"	"
SMALL EDGE	THUMB	90	0	0	0
non-massive	FINGER 1	0	φ	φ	φ
(PINCH)	FINGER 2	0	"	"	"
	FINGER 3	0	"	"	"
massive	THUMB	90	0	0	0
(PALM GRIP)	FINGER 1	0	90	0	0
depends on	FINGER 2	0	90	0	0
edge width	FINGER 3	0	90	0	0
LARGE EDGE	THUMB	0	0	0	90
(Largest	FINGER 1	0	0	0	90
Grasp)	FINGER 2	0	0	0	90
	FINGER 3	0	0	0	90

1. Small Edge Non-Massive object: The edge width is less than the distance from thumb base to finger base. In this case a fingertip grip is used. Another grip can be used in this case, with the thumb and first finger. The sheet rests against the outer side of the first finger and presses or pinches the sheet against this finger. The remaining fingers are closed against the palm to give support to the first finger.

2. Small Edge Massive object: The edge width is less than the distance from thumb base to finger base. The object is massive relative to hand strength so that a firm grip is needed. The palm of the hand is used as a support platform and the fingers secure the object. To do this the thumb is rotated 90° so that it aids in the platform that the palm makes. This platform is placed on one side of the flat object. The fingers then wrap around the edge of the object. One corner of the edge (the corner farthest away from the palm) rests in a 90° bend formed by the finger joints. This bend is formed as close to the palm as possible (for strength of grip) at the same joint level in all fingers.

3. Large Edge: The edge width is greater than the distance from thumb base to finger base but less than the distance between the outer most finger joints and thumb joints when all joints are at 0 angle. In this case, a minimum distance between the object edge and the palm of the hand and maximum finger and thumb surface area contact with the object is sought.

Altered Grips

These are grips that are used with any object ,even an elementary object for which there is a grip primitive. They are used to grip the object in a different fashion to serve a different purpose. For example, a screw driver is basically a cylinder but when this tool is to be used, a cylindrical grip primitive is altered so that a force along the axis of the screw driver can be applied and a wrist turning motion along the arms axis is performed. An altered grip can be thought of as a task grip.

Task or Tool Grips

A tool from a gripping perspective is composed of elementary objects (see Classification of Hand Actions). However, when a tool is used the grips that are used are not elementary grips but are grips that take into account the forces and motions that are needed to perform a task.

Most EVA tools have cylindrical handles or handles that can be gripped with a cylindrical grip [10,11].

The tool generally lays across the palm of the hand. For example a flashlight, hammer or screwdriver. An automatic screwdriver or drill which has a gun configuration is used with a cylindrical type grip. The trigger is actuated by the first finger which uses a variable cylinder configuration.

TASK/TOOL GRIP PATTERN CHART					
OBJECT	FINGER/JOINT in °	0	1	2	3
SCREW DRIVER	THUMB	90	0	0	0
FLASH LIGHT	FINGER 1	0	.5 φ	φ	φ
HAMMER	FINGER 2	φ	.75 φ	"	"
	FINGER 3	φ	φ	"	"
ELECTRIC	THUMB	0	0	0	0
DRILL	FINGER 1		0	X	X
	FINGER 2	0\	φ	φ	φ
	FINGER 3	0	"	"	"

In the Electric Drill grip X is a variable angle representing the pulling of the trigger. $0 \leq X \leq \phi$.

Interpolated Grips

This type of grip is a combination of other grips (Elementary/Task) and is used to create or compose a new grip of an object whose grip is not known. An example of an interpolated grip would be a manual gear shift lever in an automobile that is a long cylindrical shaft with a spherical knob on top.

INTERPOLATED GRIP PATTERN CHART					
OBJECT	FINGER/JOINT in °	0	1	2	3
GEAR SHIFT	THUMB	90	0	0	0
(Spherical	FINGER 1	-μ	φ	φ	φ
top)	FINGER 2	0	φ	"	"
	FINGER 3	0	φ	"	"
VALVE-	THUMB	-μ	φ	φ	φ
HANDLE or	FINGER 1	-μ	φ	φ	φ
DOOR KNOB	FINGER 2	0	2φ	2φ	2φ
(Spherical)	FINGER 3	90	90	90	90

These are a two examples of interpolated grips. It is necessary to develop an Interpolated Grip Strategy in order to create a truly smart hand.

Location of Sensors

LOCATION of CONTACT SENSORS CHART					
GRIP	FINGER/LINK	PALM	1	2	3
FLAT SUR-FACE	THUMB	0	1	1	1
SMALL EDGE	FINGER 1	0	0	0	1
(FINGERTIP)	FINGER 2	0	0	0	1
	FINGER 3	0	0	0	1
(PINCH)	THUMB	0	1	1	1
	FINGER 1	0	side	side	side
	FINGER 2	0	0	0	0
	FINGER 3	0	0	0	0
SPHERE or	THUMB	1	1	1	1
CYLINDER	FINGER 1	1	1	1	1
	FINGER 2	1	1	1	1
	FINGER 3	1	1	1	1
VALVE	THUMB	1	1	1	1
DOOR KNOB	FINGER 1	1	1	1	1
	FINGER 2	1	side	side	side
	FINGER 3	0	0	0	0

A necessary condition to perform various human like grips and tasks is the use of contact sensors. Particular grips require the placement of touch sensors in specific locations. The chart above was created using grips from several other charts. A zero indicates no sensor needed and one indicates the need for a sensor at that location. Although only one chart is given the chart indicates that a contact sensor is needed at each link and also in the palm at the base of each finger. In addition, sensors are needed along two of the fingers. Finger one requires sensors along the outside (right side looking toward the palm) at every link and finger two will require sensors on the same side as finger one on the two end links.

Grip Alteration Action

A *Grip Alteration Action* is used to change from one grip to another. The reasons for doing this are to position the object differently in the hand for a particular purpose. Those purposes could range from attaining a more secure grip to a specific grip that is used with a tool. Some tools require a changing grip for their use such as an automatic drill/screw driver. Using a hammer on earth requires grip alteration during usage. A hammer grip slides on the hammer shaft allowing gravitational effect plus the lever effect to increase its kinetic energy. In the case of a tool, there may be several grip alteration actions that are used.

Clips and C

CLIPS is a forward chaining language developed at NASA/JSC[12,13,14] by the AI section of the Mission Planning and Analysis division. It is written in the C language and is closely associated with C. C programs can be called from CLIPS and C programs can call CLIPS routines. It also has interfaces to ADA and Fortran although these are not as easy as with C. The language is easy to learn and affords easy implementation of pattern matching.

Heuristic Control Using CLIPS

As an example of a control structure using CLIPS

```
(defrule grab-handrail
       ?f1  <-  (close-hand standard-handle1 ?speed)
           ;If the pattern above matches a fact that had been
           ;previously asserted, this rule will be put on the
           ;agenda and will be ready to fire. Also, the variable
           ;?speed is instantiated with the value located at that
           ;position in the pattern.
  =>
     (retract ?f1)
     (assert (status good-grab = (grab standard-handle1 ?speed))))
           ;grab is a c routine that does the actual hand closing.
           ;status good-grab is asserted as a new fact.
```

Neural Networks and C

A Neural Network Simulator written in C is being developed at NASA/JSC[15] by the AI section of the Mission Planning and Analysis Division. C routines and therefore, CLIPS routines should be callable from this environment and visa versa. At present the networks are back propagation.

A spatial-temporal neural network* could be used to fuse and integrate sensory feedback in the hand. Given point contact sensors, as opposed to an array of sensors, one at each link and one or more in the palm of the hand a simple spatial-temporal network could be developed and trained to recognize space-time patterns of contact. If the space-time pattern of contact *approximates* a pattern that had been previously learned then that pattern would be recognized and further action could or could not be taken based on that outcome. For example, there are typical space-time contact patterns that arise in the

gripping of a cylinder. Assuming that the object had been previously identified as a cylinder a particular space-time contact pattern would confirm that the proper grip on the cylinder had been made. That pattern, might first include palm contact, followed by base finger link contacts and so on, out to the fingertips. If a neural network implementation operated in real time a deviation from that pattern during grip execution could possibly signal that corrective action is necessary to complete and secure the grip. In addition, given a real time network, palm contact could signal to the controlling software to begin the cylindrical grip. Alternatively, the actual grip could be implemented by a neural network that had been trained to respond to patterns of contact input.

* J. Freeman, Ford Aerospace, Johnson Space Center, personal conversation.

Heuristic Grip Summary

1. A Cylindrical grip primitive can be used for most objects.

2. Grip as close to the center of mass as possible[16].

3. If the object's characteristic length (in the grip region) is $L_{object} < 3/4 L_{hand}$ the distance from the wrist to the fingertips, a one-handed grip will probably work.

4. For objects with characteristic lengths (in the grip region) $L_{object} < l_{tip} + l_{tip-1}$ the two outer finger link lengths and $F_{hand}/M_{object} \ll 1$ a fingertip grip can be used.

3. Use hand sensors touch and vibration to determine if grip is slipping.

4. Touch sensors are used to signal the beginning of a grip action.

5. Use vision sensors for sufficient condition confirmation that a grip has been successfully made.

6. Plan Grip Action Script and continuously monitor safety during execution.

7. In general it is the thumb and 0 joint that give a grip its unique configuration and therefore function.

Conclusions

Future Work and Recommendations

The work reported in this paper is by no means exhaustive. It serves to illuminate a path that can be followed with what I feel will be real tangible results and successes in the development of an autonomous robot with a dextrous hand. The fabric which ties all of the components together will be the development and application of Neural Networks to sensors and learning, further development of an AI language such as CLIPS that can easily interface the Neural Networks, and the development of a dynamic adaptive task planning strategy. Also, it is necessary to develop an Interpolated Grip Strategy in order to create a truly smart hand. This would be part of the dynamic adaptive task planner.

Recommendations

Sensors : Contact sensor are needed at each link and also in the palm at the base of each finger. Sensors are needed along the side of two of the fingers.

Neural Network research should be applied the sensor fusion problem.

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