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DESIGN AND CONTROL OF A MULTI-FINGERED ROBOT HAND PROVIDED WITH TACTILE FEEDBACK

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Abstract

The design, construction, control and application of a three finger, nine degrees of freedom robot hand, with built-in multi-component force sensors are described. The adopted gripper kinematics are justified and optimized with respect to grasping and manipulation flexibility. The construction features miniature DC-motor drive systems imbedded into the fingers. The control is hierarchically structured and is implemented on a simple PC-AT computer. The hand's dexterity and "intelligence" are demonstrated with some experiments.

1. Introduction

The fascinating dexterity and versatility of the human hand caused many people to dream about the development of a mechanical equivalent of their own hands. For about fifteen years, researchers in the whole world [1],[2],[3],[4],[5],[6] are challenging this problem and yet their results seem to be rather poor in comparison with the natural example. On the other side, when looking at the present day two jaw industrial grippers, the developed multifingered grippers really are a big step forward, without being copies of human hands.

Generally spoken a robot end effector or gripper has two functions. In the first place it should be able of grasping a wide variety of objects in order to augment the versatility of the robot on which it is used. On the other hand, it should be able to perform short-range manipulations without the necessity to move the whole robot arm, thereby providing local redundancy. Especially in assembly tasks these fine manipulations can be very useful.

Our aim at K.U.Leuven was not to build an equivalent of the human hand, but rather to construct a dextrous end effector providing both grasping and manipulating functions [7]. Unlike most other designs, the main effort was given to the manipulating function. The mechanical design is not optimized with respect to weight requirements, as our first intention was to demonstrate that a multifingered gripper provided with force sensor feedback, even when using a rather small controlling computer, really can perform the desired manipulative dexterity.

2. Kinematic consideratons

2.1. Basic presumptions

When designing a multifingered gripper the number of fingers to be used is the first problem to cope with. For every finger also a suited layout has to be chosen. By the formulation of a minimization function one can find a solution for this problem. As described by Salisbury and Craig [8], the contact between an object and a finger can be classified by the number of degrees of freedom (d.o.f.) of relative motion it permits. It is evident that the number of d.o.f. is inversely related to the number of constraints on object motion (c.o.m). For every type of contact, the numbers of constraints and degrees of freedom are listed in table 1. The term *soft finger* is used to denote a contact area with enough friction to resist moments about the contact normal.

Table 1 : Contacts between object and finger

Type of contact	Symbol	c.o.m.	d.o.f.
Planar contact with friction	x_6	6	0
Line contact with friction	x_5	5	1
Soft finger	x_4	4	2
Point contact with friction or planar contact without friction	x_3	3	3
Line contact without fritition	x_2	2	4
Point contact without friction	x_1	1	5

Further, one could define *active joints* and *passive joints* [7]. An active joint is a joint where the relative positions of the two links can be set by external means. An example of an active joint is a servoed joint. A passive joint is a joint where the relative positions of the two links is depending on constraints imposed by the kinematic linkage.

In our design, we assume a *fingertip-type prehension* of the object. This kind of prehension, where every finger has only one contact with the object, is only one of the six possible types of hand prehension [9]. It was chosen because of its excellent moving capabilities, which was, as stated before, considered more important than the lack of performance when speaking in terms of grasping. Furthermore it is simplifying considerably the control of the gripper.

2.2. Kinematic criteria

Starting with these presumptions one can formulate some kinematic criteria that have to be met by every hand design based on a fingertip prehension:

- To be able to move the object in n degrees of freedom, a minimum of n degrees of freedom is needed at each finger-object linkage. So when the contact has 1 d.o.f. the connecting linkage needs n-1 d.o.f.

- Each finger has to be able to reach the required contact point, so the minimum number of active joints will be equal to the dimensionality of the object.
- To be able to completely restrain a three-dimensional object from motion, the minimum number of restrictions of all contact points is six.
- The contact between object and finger is not a permanent contact. Therefore at least one additional connectivity restriction has to be added.

2.3. Minimization of the number of active joints

To facilitate the control of the gripper, one could minimize the number z of active joints in the system :

$$\text{Min } z = 3x_1 + 3x_2 + 3x_3 + 4x_4 + 5x_5 + 6x_6, \tag{1}$$

where x_i (i=1,...6) are defined in table 1. The problem is subjected to following conditions:

$$x_1 + 2x_2 + 3x_3 + 4x_4 + 5x_5 + 6x_6 \geq 7 \tag{2}$$

$$x_1 + x_2 + x_3 + x_4 + x_5 + x_6 \geq 2 \tag{3}$$

$$x_1 + x_2 + x_3 + x_4 + x_5 + x_6 \leq 5 \tag{4}$$

$$x_1, x_2, x_3, x_4, x_5, x_6 \geq 0 \text{ and integer} \tag{5}$$

Condition (2) means that we need at least seven (six for mobility and one for connectivity) constraints. When only using point contacts without friction, this condition becomes:

$$x_1 \geq 7$$

This is the same condition as stated by Lakshminarayama [10]. Conditions (3) and (4) are expressing that a hand should have at least two and at most five fingers. They are based on the fact that every finger has only one contact with the object.

The problem (1) as described above is a linear integer programming problem that can be solved by the simplex method using Gomory's algorithm. This yields as optimal solution :

$$z = 7 \quad x_1 = 0 \quad x_2 = 0 \quad x_3 = 1$$
$$x_4 = 1 \quad x_5 = 0 \quad x_6 = 0$$

So a two-fingered hand with at one finger a point contact with friction and at the second finger a soft finger contact is using the smallest possible number of active joints namely seven. The drawback of this gripper is its limited ability to resist moment about the line connecting the contact points and also its limited mobility.
To improve mobility one could replace the point contact by a plane contact with friction which requires two extra active joints. Because the surface geometry of the object has to match the surface geometry of the plane, this solution lacks universality.

The next choice is to build a robot hand with three fingers. Thus changing the right hand side of equation (3) yields following results:

$$z = 9 \quad x_1 = 1 \quad x_3 = 2 \quad x_2, x_4, x_5, x_6 = 0$$

Because a point contact without friction is a rather academic concept, the finally constructed hand has three fingers, each finger having three active joints and a point contact with friction at the fingertip.

3. Mechanical design

3.1. Configuration

When designing a finger with three active joints, several combinations of rotational and translational joints are possible. Translational joints would imply a very complicated construction, so we preferred to use only rotational joints. Even when using only rotational joints, still a wide variety of possible finger designs exists, and there seems to be no evident criterion to make a selection. Therefore only the three configurations, described in figure 1 and mainly inspired on the human finger, are further considered.

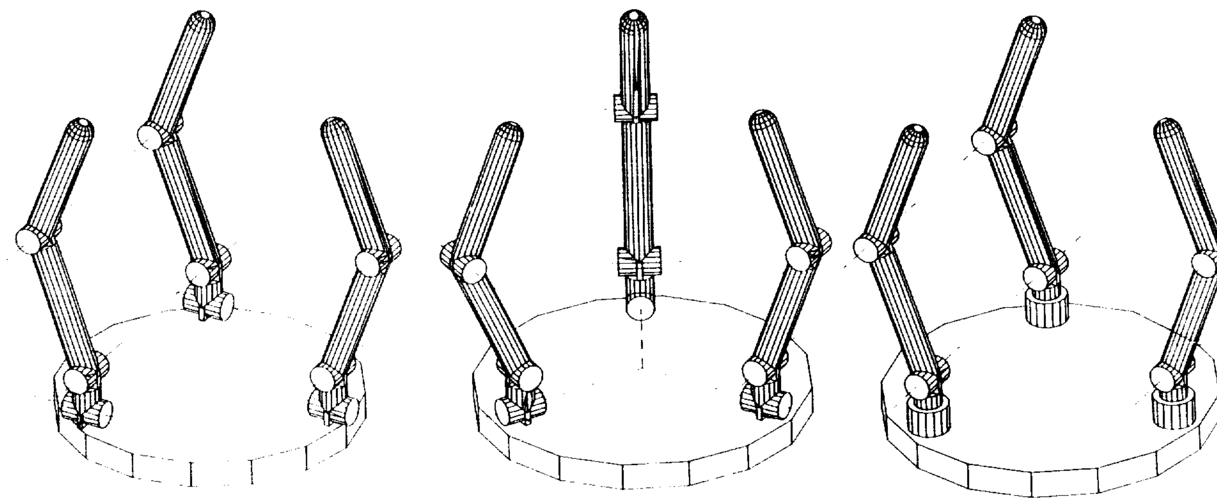


Fig. 1. Possible hand configurations

To make the final choice, we studied these designs for their grasping ablility of some simple geometric forms :
- A square object is grasped with the fingers working as a two-jaw parallel gripper. When the finger shape is cylindrical all three configurations can perform this task.
- For a vertical cylindrical object, the first configuration cannot make a line contact for all fingers. The other two configurations are equivalent.
- When grasping a small horizontal cylinder the fingers of the second design may touch each other so that only the third design remains.

This configuration has a drawback for manipulating the object, because of a singularity in the working space at the rotating axis of the first joint. Therefore the working space had to be limited.

3.2. Construction

To simplify the construction of the first prototype, we designed fingers with built-in electrical actuation, rather than using a remote tendon type actuation. Electrical actuation was also very attractive because of the ease of control. So the fingers are constructed from rotational joints driven by dc motors, using planetary reduction gears to generate an acceptable torque. Some motor parameters (gearbox included) are:

dimensions	24 x 60 mm
weight	1.2 N
max. speed	6.8 rps
max. torque	2.3 Nm
gear ratio	1 : 1164

A miniature incremental position encoder (125 pulses/rev.) is attached to the axis of every motor. Due to the high transmission ratio, this results in a very high resolution of the position measurement (145500 pulses/ finger rev.). Every finger is also equipped with a three dimensional force sensor using strain gauges. These force sensors were built as a combination of one ring dynamometer and two cantilever boxes [7]. The characteristics of the sensors are :

maximum force	50 N
resolution	0.2 N
nonlinearity	< 1 % full scale
average cross sensitivity	< 10 %
acquisition speed	20 kHz
bandwidth	25 Hz (determined by the filters)
drift	10 % full scale in 4 h

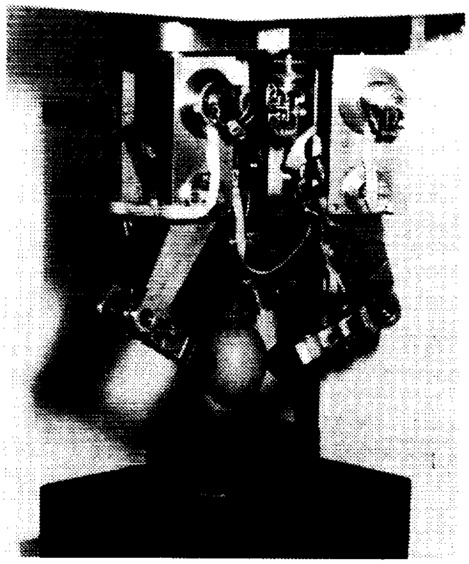
The final design of the three-fingered gripper can be seen in figure 2. On the photograph the gripper is mounted on a fixed structure, grasping a chicken egg. The mechanical size of the fingers is determined by the size of the components. Every fingertip is equipped with a rubber ball to introduce friction at the contact points. The force sensors built-in in the first phalanx are clearly distinguishable. The amplifiers for the strain gauge signals are placed on the bottomplate of the gripper together with all other connectors for the motors and the encoders.

4. Controller design

4.1. Mathematical gripping model

For real applications the radii of the contact surfaces may not be too small in order to limit the contact pressure. This means that a point contact becomes a ball contact which makes the kinematic relations between finger and object much more complicated. The use of a soft layer at the contact point will create a second problem. When using a soft layer, a force tangential to the contact area will shift the center of a ball contact. As a consequence the contact point will shift when there is a rotation around the normal line. One can conclude that the calculation of the exact kinematic relations becomes very difficult in practical applications so that there has to be some possibility to compensate for calculation errors.

One of the solutions is to have compliances at the finger tips in order to compensate for position errors. This method is also very useful to compensate for small fingertip deviations caused by the controller itself. Otherwise the coordinated movement of the three fingers would require a very complicated servo system. The proposed gripping method simulates a three dimensional spring behaviour at finger tip. As a consequence the position accuracy of the object relative to the gripper base becomes rather low. However, from extensive experience with active force feedback at K.U.Leuven [11], a robot with a compliance at the end effector is still able to do accurate operations when the external forces working on the object are measured and fed back to the controller.



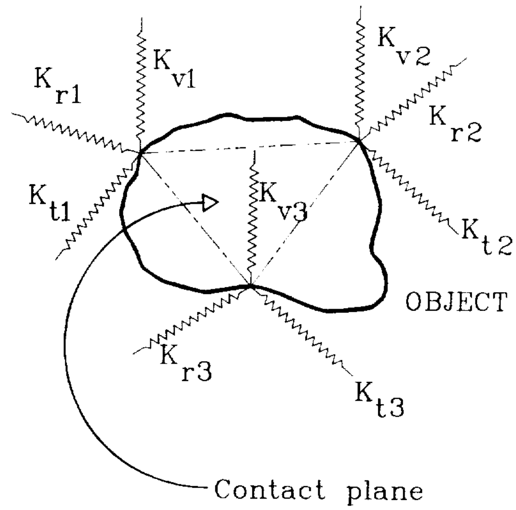


Fig. 3. Contact plane definition

Fig. 2. General layout of the dextrous gripper

When the object is held by three sets of three linear springs working through the contact points, the contact plane is defined as the plane passing through these three points (Figure 3). The object can be moved relative to the gripper base by moving the contact plane. The positions of the contact points and springs relative to the contact plane remain the same.

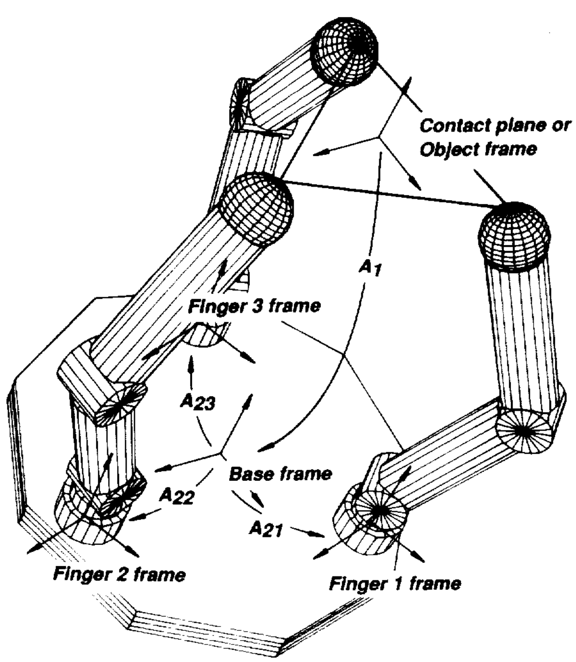


Fig. 4. Coordinate frame definitions for transformations from object frame to finger joints

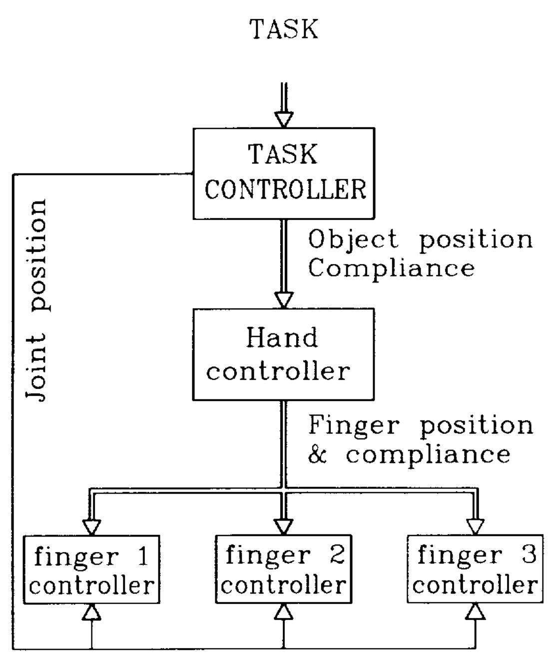


Fig. 5. Control hierarchy for dextrous gripper

To calculate the joint positions of each finger, the coordinates of each finger tip in the contact plane relative to the object frame, are transformed to the hand base frame by means of transformation matrix A_1 (Figure 4) and to the finger base frames through transformations A_{2i} (i=1,2,3). To move the object, transformation matrix A_1 is calculated for the successive positions.

4.2. General controller structure

The controller is hierarchically divided into three main levels: the finger controller, the hand controller and the task controller.
Normally the hand level has the control over the finger level. As can be seen on figure 5, there is some special case where the joint positions are almost directly routed from task level to finger level. This happens when the fingers have no contact with the object and are following a preprogrammed approach path in order to grasp the object. The precise working of this case is discussed further.

4.3. The finger controller

Basically each finger of the robot hand is controlled as an active stiffness system, where the finger tips are programmed as two linear springs (vertical and radial) and one rotational spring. The fingers are thus controlled in cylindrical coordinates as shown in figure 6. In fact this is a simplification of the finger model described above (three cartesian springs attached to the object). These simplifications were made to reduce the required computing power. The inputs to the finger controller, coming from the hand controller, are :

- spring rates for radial,vertical and rotational springs;
- vertical, radial and rotational position of the finger tip relative to the finger frame.

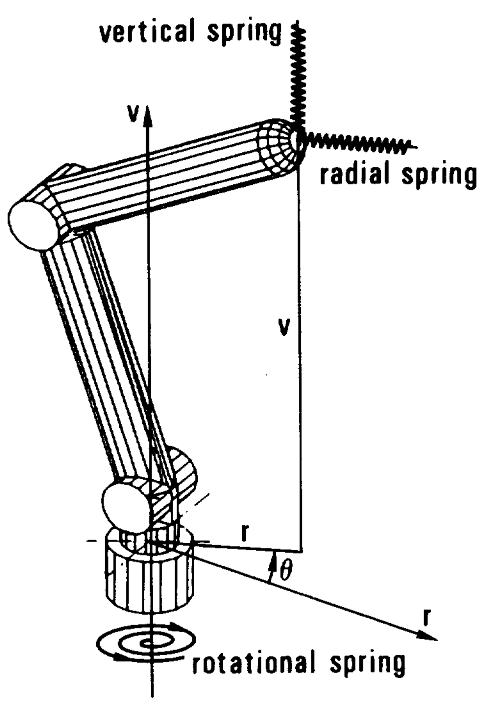


Fig. 6. Cylindrical coordinates used for spring definition

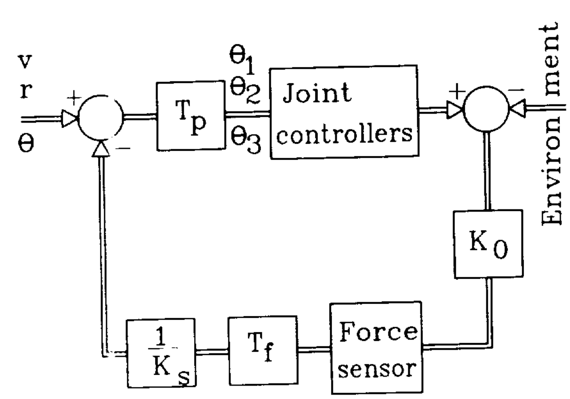


Fig. 7. Finger controller layout

The software controlled spring is realized by using a multidimensional stiffness controller with internal position loop. The internal position loop scheme was chosen mainly because of the higher bandwidth of the position measurement in comparison with the force measurement. The additional passive compliance which is usually needed for an internal position loop was unnecessary because of the high resolution of the position measurement [11].

Figure 7 shows that the cylindrical finger coordinates (v,r,θ) are tranformed to joint coordinates $(\theta_1\theta_2\theta_3)$ for the joint position controllers. The new position results in an external force (determined by the contact stiffness K_o), measured by the strain gauges. This signal is passed trough an analog low pass filter before it is converted into a digital signal. The force measurements are transformed by T_f into the cylindrical coordinate system of each finger. They give the measured forces in radial and vertical direction and a moment around the rotational axis. Both moment and force are multiplied by the desired spring compliance $1/K_s$. The result is subtracted from the desired position.
Digital PD-controllers are used to control the finger joints. Velocity feedback is calculated from the position by differentiation of the encoder signal, as there was no place to use a tachometer.

4.4. The hand controller

The task of the hand controller is the coordination of the position of all fingers. One has to make a distinction between the grasping and the manipulation of an object.
During the grasping (before there is contact between the fingers and the object), the object does not move and the position of the contact plane relative to the robot hand base remains unchanged, while, however, the positions of the finger tips relative to the contact plane or object frame are changing. This seems somewhat contradictory because of the fact that the contact plane was defined as a plane formed by the fingertips. But this definition was only valid when there is a contact between finger and object. In this case the con-tact plane is formed by three arbitrarily predefined points on the object where the gripper is going to grasp it. So one can have the impression that the fingers are direcly controlled by the task level as was indicated in figure 5.
A second phase is the manipulation of the object relative to the hand base. As explained above, this is done by moving the contact plane, formed by the contact points. The position of the finger tips relative to the contact plane remains unchanged. The movement of the contact plane consists of a rotation and a translation relative to the hand base. The rotation transformation is using the RPY angles formalism.

4.5. The task controller

The task controller is controlling the performed operations. This controller is written in a high level language unlike the two previous controllers that are written in assembly language. It is providing a set of subroutines which make it very easy for the programmer to develop a specific application program.
We take as an example a task that requires the robot hand to grip an object, move it in vertical direction and then move it back until it is touching the base. Figure 8 gives the Fortran program performing this task.

```
c gripping the object
      do 100 contactforce=0
      touch1
      touch2
      touch3
100     continue
c move in vertical direction
      moveinz (disp)
c move down until vertical force equals
c "touchforce"
200     moveinz (-1)
      getforce (fz)
      if ( fz < touchforce) then
      go to 200
      return
      end
```

Fig. 8. Sample program of grasping task definitions

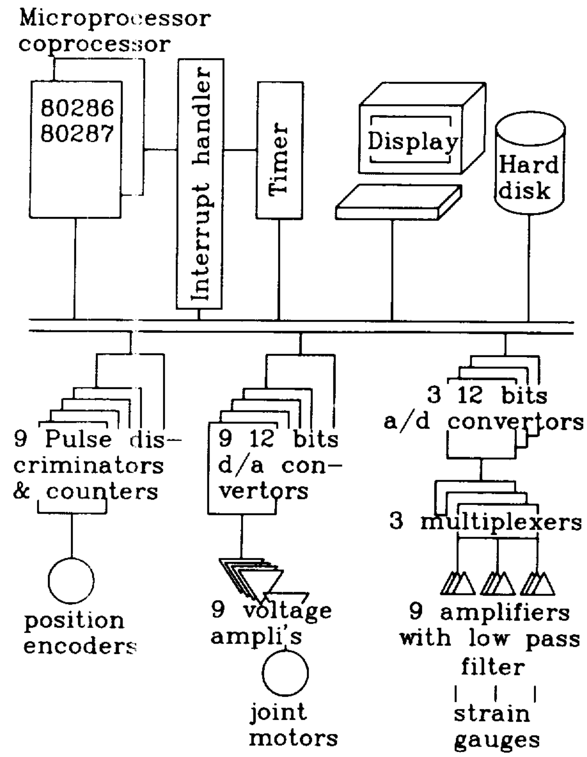


Fig. 9. Hardware configurations of the hand controller

4.6. Hardware construction

Figure 9 gives a description of the hardware implementation of this controller as it was developed in 1986. The controller is based on the Intel 80286 microprocessor with 80287 numerical coprocessor, both running at 9 Mhz. This system has 512 kbyte ram memory,20 mbtye mass-storage, a timer and an interrupt handler. The interfaces built to connect the robot hand to the controller are :

- decoder inputs for the incremental optical position encoders.
- digital to analog converters (12 bits) with power amplifiers to drive the servomotors
- analog to digital convertors for measuring the outputs from the force sensors

As the floating point operation speed of the controller was insufficient to perform all coordinate transformations, some calculations had to be made by using integer arithmetic, resulting of course in a decreasied accuracy of all mathematical operations.

5. Experiments

5.1. Manipulation of an object

This experiment was set up to prove the ability of the gripper to absorb the error between calculated and real position of the contact points. It also demonstrates that it is possible to manipulate objects having a complicated and only approximately known geometry. The setup of this experiment is shown in figure 2. The fingertip was assumed being a point and no correction was

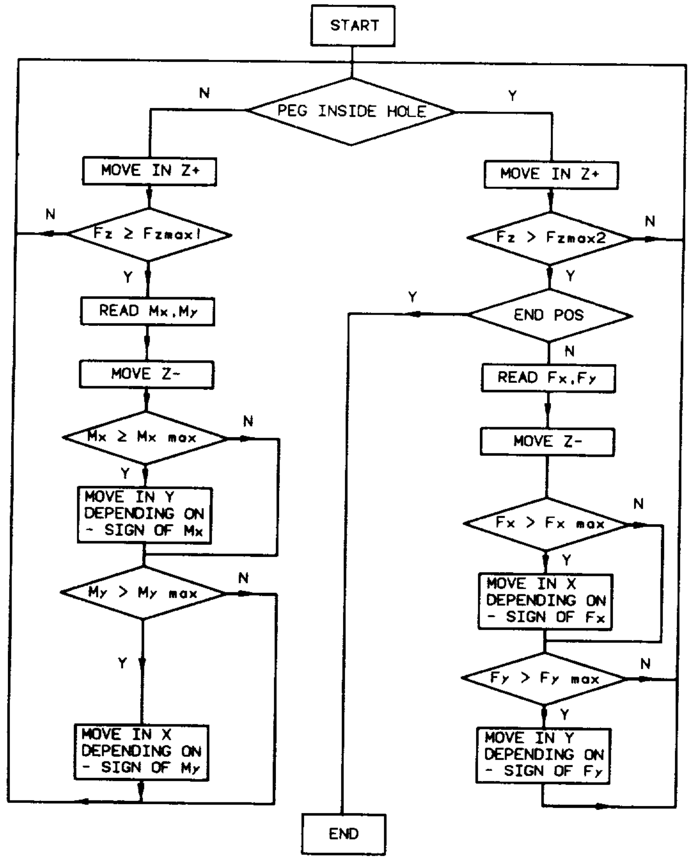


Fig. 10. Flow chart of insertions task

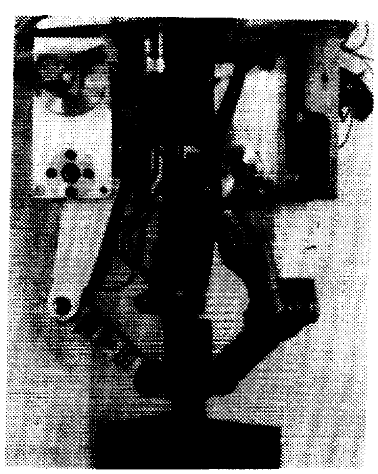


Fig. 11. Peg-into-hole insertions setup

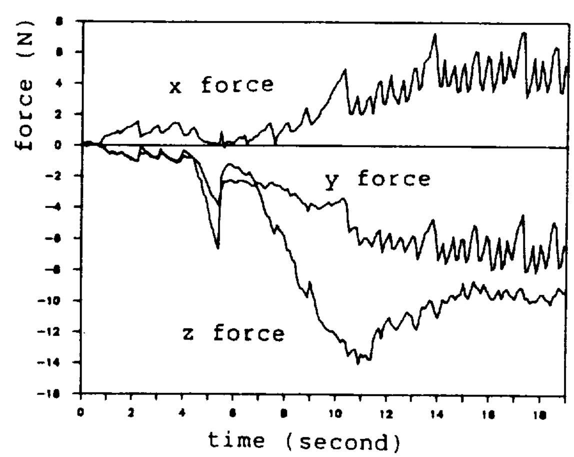


Fig. 12. Force history during insertion

made for the shifting between fingertip and egg. In a first step the gripper will grasp the egg by approaching the fingers until there is a contact force detected. Once there is contact, the egg can be translated or rotated in any direction in space. Of course every movement is subject to the limited workspace of the gripper.

5.2. Peg into hole insertion

By using a chamfered peg and an adapted compliance one can eliminate centering errors during an insertion [12]. This method works well if the initial displacement error is smaller than the dimension of the chamfer.
Our experiment (Figure 11) uses an unchamfered peg to be inserted in an unchamfered hole with a clearance of 0.1 mm. The use of a searching algorithm makes insertion possible even with an initial displacement error of one fourth of the diameter of the hole. The flow chart for the algoritm is shown in figure 10. If the peg is not precisely centered when starting the insertion, the force in the vertical direction increases until it reaches a maximum preset level. The program then calculates the forces in both horizontal directions to find out the magnitude and direction of the moment acting on the peg because of the eccentric insertion. The object will be retracted until the vertical force equals zero and then will be moved to another position following the direction of the calculated moment. This procedure will be repeated until the vertical movement surpasses a preset distance after which the peg is to be considered as rightly centered inside the hole. During the last part of the insertion,some adjustments of the peg position will be carried out in order to keep the horizontal forces as low as possible.

The forces working on the object during the inserton can be seen in figure 13. Both horizontal directions correspond to x and y; z is the vertical insertion direction.

6. Further developments

The first aim of this project was to build a dextrous multifingered gripper with extensive grasping and manipulative capabilities, with a limited computer budget, as is common for space applications. Therefore no attempt was made at this stage to optimize the mechanical design.

The next step is to improve the design to arrive at a more technically sound concept. Therefore the volume and weight need to be reduced and the actuator capabilities increased. The next design will not only allow a three fingered grasp, but also other types, like e.g. a planar grasp [9]. This implies another type of force sensing.

The first problem was to find a suitable actuator. A theoretical study [13] comparing electric, hydraulic, pneumatic and shape memory actuation, proved electric actuation to be the most appropriate solution, especially when taking into account the development time and costs. Parallel developments in other labs showed also the need for a remote tendon type actuation. So we decided to develop a cable pulley actuation driven by a linear electric actuator. As there was not a suitable commercial device available for our application, a new actuator was designed. Figure 13 shows a cross-section of this device. It is built up around an Inland frameless high torque rare earth DC motor and uses a miniature high precision ball screw

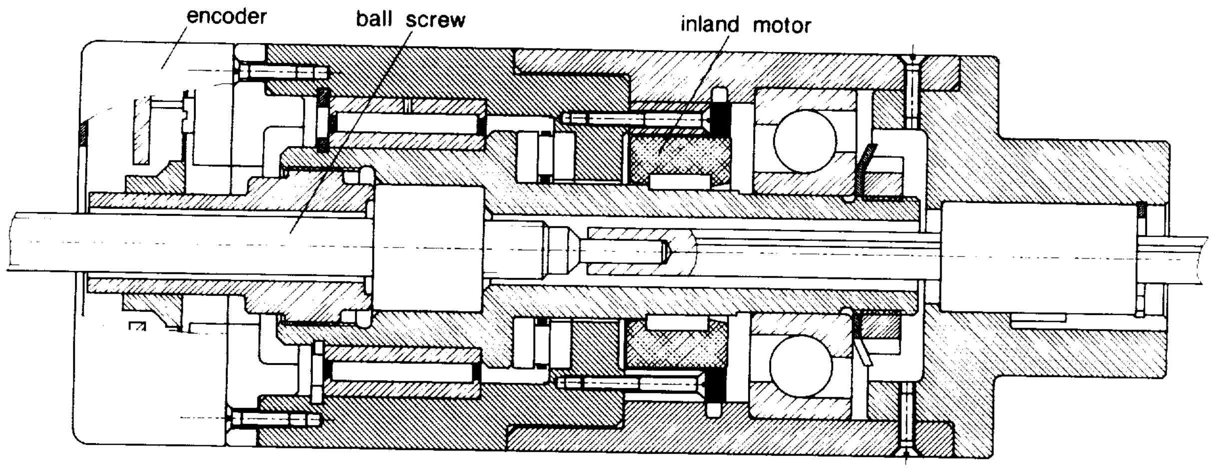


Fig. 13. Linear actuator for controlling tendon-controlled finger

to obain a linear movement. The actuator is designed to reach a peak force of 300 N with a linear stroke of 30 mm. A first prototype is presently being tested.
Also a first model of a finger with cable-pulley actuation is built. We designed a three joint finger driven by four cables, three for flexion and one for extension. It is intended to equip this device with an already developed tactile sensor based on conductive rubber [14].

7. Conclusion

A universal gripper should have two functions : grasping and manipulating an arbitrary object. The main effort in this study was given to the manipulating function. By minimization of the number of active joints, is was found that a three fingered hand with in total nine active joints is the most optimal design in the case of a three fingertip grasp.
Active compliance has proven to be an effective solution for certain problems, occuring during the manipulation of an object by a multifingered gripper. The practical applicability of this method was demonstrated with a simple multifingered gripper, controlled by an ordinary personal computer. Actually this gripper is redesigned to optimize its mechanical construction and to extend of its gripping capabilities. The final aim is not to build an equivalent of the human hand, but rather to construct an industrial end effector providing both dextrous grasping and moving functions.

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