RSD-TR-6-83

KINEMATICS AND FORCE CONTROL OF ROBOT GRIPPERS

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May, 1983

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Abstract

An examination of the kinematic, mechanical and control aspects of gripper design is presented. A new two-fingered gripper is introduced with control of both gripping force and finger position. A direct linear drive is chosen for this gripper because of a linear relationship between actuator input and finger position and because the gripping force is independent of gripper opening. An index, the gripper ratio, is introduced for indicating the payload-carrying capacity of grippers, with different designs. Hydraulically-actuated grippers generally have the highest gripper ratios (i.e. highest capacity). A novel control scheme for finger force is introduced. The scheme is based on stall characteristics of DC permanent magnet torque motors. During gripping, motor current is servoed to produce a particular stall torque that corresponds to a desired level of grippering force. Continuous operation of a torque motor in stall state is permitted as long as a safe level of current is not exceeded.

1. Introduction

Effective integration of manipulators in manufacturing tasks requiring small precise movements, such as assembly and machine loading and unloading depend largely on the kinematic structure and sensory capability of their hands. Early mechanical hands were designed as prosthetic devices to replace a missing anatomical limb. The human hand with its incredible dexterity and sensory capability served as a model for the design of artificial hands [1,2,3]. Not surprisingly these artificial hands emulated anatomical hands in both form and function. Reswick and Childress [3] provide excellent reviews of prosthetic hand and arm research. Later, anthropomorphic hands, generally mimicking simple forms of human grasping have been specifically developed for manipulators [4,5,6]. More complex forms of prehension [3] require articulated hands with few fingers. Several hands of this type have been designed to closely duplicate the dexterity of the human hand [7,8,9].

However, when the shapes and sizes of the objects manipulated are restricted to a certain range, simpler nonarticulating devices (.i.e. grippers) are used. These devices generally have one degree of freedom and are capable of controlling gripper opening only, but not gripping force. Sometimes grippers with two degrees of freedom are called for to permit rotation of the object while being grasped [6]. In such grippers, without force control, the gripping force can have many values depending on the elastic deformations induced in the gripper and object at the contact zone. Large contact forces can be generated when picking stiff objects without damaging them. But, if an object is too soft or fragile, large gripper forces can either crush the object or produce large undesirable deformations. Therefore, it is desirable to have force control in addition to position control in grippers.

The objectives of this report are

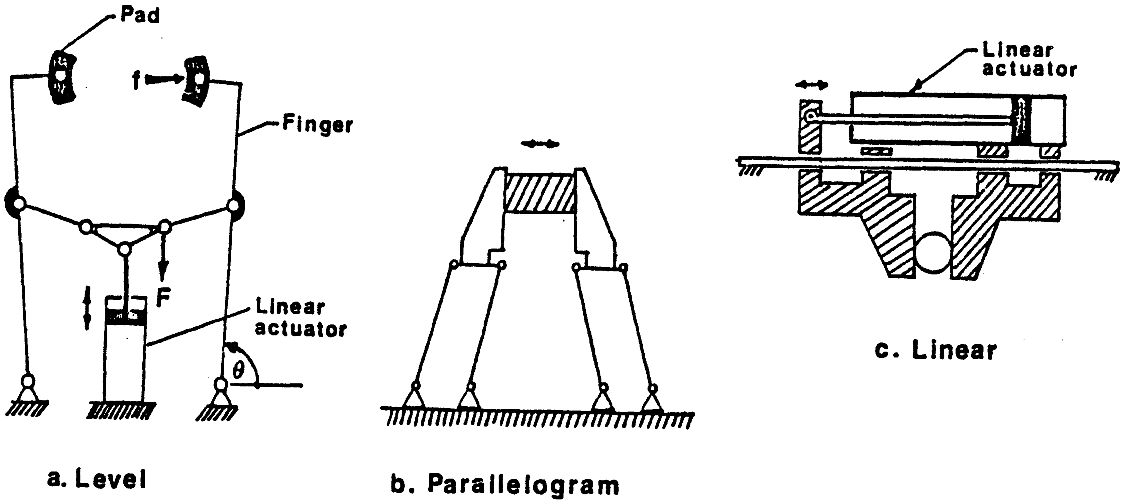
- to discuss the kinematic, mechanical and control aspects of gripper design in general,
- to introduce a new gripper that has linear finger motion and both gripping force and finger position control and
- to devise a control scheme including actuators and sensors for controlling force and position.

The design process was guided by the following criteria:

1. Rigid structure, sufficient strength and minimum backlash and tolerances between mating parts
2. Light weight
3. Controllable gripper opening and force
4. Effective sensing for feedback control

2. Finger Mechanism

A typical mechanical hand consists of fingers or jaws that move relative to the palm. The motion of the palm itself is controlled at the wrist. As shown in Figure 1, finger moving mechanisms can be classified into three types (1) **parallel plane** or **level** in which the finger tips move in parallel planes (Figure 1a), (2) **parallelogram** where the fingers undergo curvilinear translation (Figure 1b) and (3) **linear** where linear finger motion is generated directly via a linear actuator (Figure 1c). Such a classification is beneficial at the conceptual stage



a. Level b. Parallelogram c. Linear

Figure 1. **Finger moving mechanisms: (a) level, (b) cable and (c) linear actuator.**

for choosing a suitable kinematic arrangement (type synthesis). Kinematic structure strongly influences the coupling between input torque, gripper position and force. It is desirable to have a linear relationship between the generated gripping force and the input torque. Otherwise, a more complex control architecture is required to compensate for the nonlinear behavior present when the gripper force is a function of gripper opening. In addition, gripper opening control is greatly simplified if the opening is proportional to motion of the finger actuator.

3. Level Mechanisms

As shown schematically in Figure 1a, the fingers are of equal lengths and pivoted at their base such that each fingertip moves along a circular arc. A linear actuator is linked to all fingers to move them while the plane containing the fingertips remains parallel to its original orientation. Because of its simplicity, the level mechanism generally results in hands that are lighter than other mechanisms, but because of the large number of pivots it tends to have larger tolerance stacking and hence less accuracy.

In a level mechanism, the gripper force is not independent of finger position or gripper opening. In Figure 1a, the angle ϑ which defines the finger position changes when the force $\mathbf{F}$ is applied by the actuator. A simple geometric construction will quickly show that the fingertip force f is a function of ϑ. The gripping force itself depends on the tip force f, on the shape of the grasped object and on the geometry of the tip pads provided to increase contact forces. Thus, in level finger mechanisms, gripper force and opening are not proportional to actuator input which is undesirable from a control point of view.

4. Parallelogram Mechanisms

The mechanism is frequently used in manipulator hands to move two or three fingers along straight line paths (Figure 1b). If the weight of the grasped object is small compared to the gripping forces, the object can be treated as a two-force member which indicates that the gripping forces will always be normal to both the object and the finger at the points of contact (Figure 1b). This insures that the maximum gripping force is applied at all times. Another advantage is that the gripping force is independent of where the contact points are located along the fingers.

There are several ways with which a parallelogram linkage can be actuated (Figure 2). One of the links can be drive directly be a linear actuator (Figure 2c), by a cable drive (Figure 2b) or by a sector gear (Figure 2a). In all cases, the gripping force generated will not be independent of link positions. This nonlinearity is to be avoided if simple force control is desired.

Although all links in the parallelogram linkage undergo translation (i.e. they remain parallel to their previous positions), the paths of points on the links, including the fingertips, are not straight lines. Because of this, the task of picking up thin objects is difficult and requires coordination of fingers and arm motions. This problem is also present in level finger mechanism.

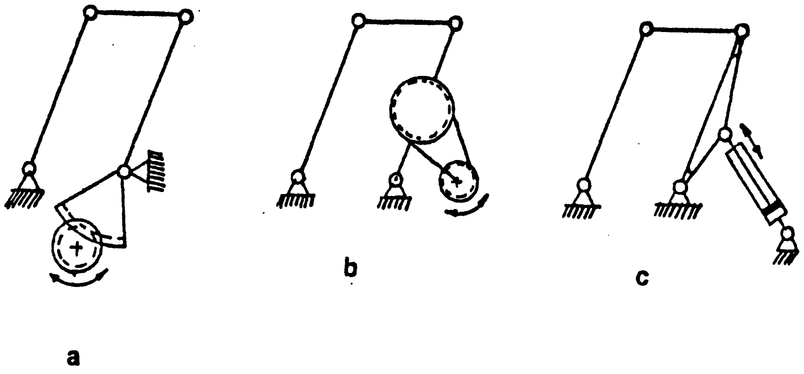


Figure 2. **Driving method of parallelogram finger mechanisms: (a) sector gear, (b) cable and (c) linear actuator.**

5. Linear Gripper Mechanism

In this mechanism, the fingers have linear motions under direct actions of a linear actuator, such as a cylinder or a power screw (Figure 1c). With this arrangement, the gripping force and finger position are both proportional to actuator force and displacement inputs respectively. This linear relationship between input and output promises simplicity of control system design and implementation. A gripper of this type was recently disclosed by IBM [10]. This gripper contains two fingers that are driven by a pneumatic cylinder. The cylinder operates one of the fingers of which motion is transmitted to the other finger via a rack and pinion arrangement. Because of support and motion transmission requirements, this type of gripper tends to be bulkier and more complicated mechanically than other types of grippers.

Table 1 summarizes the essential features of the three mechanisms discussed above so that they can be easily compared. It is clear that, among the three gripper mechanism listed, the linear mechanism, despite its mechanical complexity and bulk, promises simplicity of position and force control and, hence, it is the best candidate for the new gripper designed.

6. Gripper Ratio

The weight of the hand should be kept at a minimum so that the largest possible payload can be lifted for a given maximum total load. In addition, the gripper weight is typically a large fraction of the force measured by the wrist force sensors which makes measurement of small forces cumbersome. In order to make an objective comparison between different grippers with different weights and weight capacity, a simple index, the gripper ratio, is

Table 1 **Comparative Summary of Finger Mechanisms**

Category	**Mechanism**		
	Level	**Parallelogram**	**Linear**
Weight	Light	Heavier	Heavier
Complexity	Simple	More Complex	More Complex
Fingertip Path	Curved	Curved	Straight Line
Force/opening Dependence	Yes	Yes	No
Finger/actuator Relationship	Nonlinear	Nonlinear	Linear
Finger Speed			
Electromechanical	Variable	Variable	Constant
Pneumatic	Variable	Variable	Variable

$$\text{Gipper ratio} = \frac{\text{maximum payload}}{\text{gripper weight}}$$

The gripper ration is also influenced by the type of finger mechanism, the driving power source, gripper opening and grip actuator. With these factors being equal, larger gripper ratios imply better gripper designs. Table 2 summarizes gripper ratios, computed from manufacturers' produce literature for several gripper designs with different sources of power. Grippers driven by hydraulic gripper designs with different sources of power. Grippers driven by hydraulic power have the largest gripper ratios because of compactness and large forces delivered by hydraulic actuators. There is little difference between level and linear finger mechanisms when driven by hydraulic power. Linear mechanisms have slight weight capacity advantage over level mechanisms when electromechanical drives are used. For the same finger mechanism, very little difference in gripper ratio exists between pneumatically or electrically driven grippers (Table 2). Despite its load capacity disadvantage, electrical power is chosen to drive our gripper because of simplicity of implementing position and force control.

Table 2 Gripper for Different Grippers

Power	Finger Mechanism	Gripper Ratio
Hydraulic	Level	1.5 - 5.0
	Linear	1.2 - 4.0
Pneumatic	Level	0.4 - 2.0
	Linear	0.5 - 1.5
Electrical	Level	0.8 - 2.0
	Linear	0.5 - 1.0

7. Variable Gripping Force (VGF) Gripper

A gripper with adjustable gripper force and linear finger mechanism was designed at the University of Michigan (Figure 3). The gripper's two fingers are driven simultaneously by a torque motor via a mechanical drive consisting of bevel greats and power screws (Figure 3). Each of the two fingers is supported by two sliding bearings to resist gripping force moments. A nut attaches to the base of each finger to advance it when the power screw is rotated by a miter bevel gear. Both of the finger gears are driven by a third identical gear mounted directly on the output shaft of the motor. This bevel gear arrangement insures that the two fingers move at the same speed but in opposite directions.

The maximum opening of the gripper is 64 mm (2.5 inches) and its opening time is 0.9 s when driven by a torque motor having a peak torque (stall torque) or 0.353 N.m (50 oz-in) and a no-load speed of 140 rad/s (1,340 rpm). The gripper can lift parts that can weigh up to 1.4 kg and it itself weighs 1.6 kg. Thus, its gripper ratio is 0.86 which compares well to other electromechanical grippers that can have a ratio of as low as 0.5 (Table 2). The gripper force can be varied between 0 to 330 N (75 lbs.).

8. Gripper Sensors and Control

The action of the gripper is characterized by two states: movement of fingers without load or gripping without movement. If a permanent magnet DC motor is used to drive the fingers, these two states correspond to the free running point (point A) and the stall point (point B) on the performance curve of the motor as shown in Figure 4. Depending on the application, one or more of

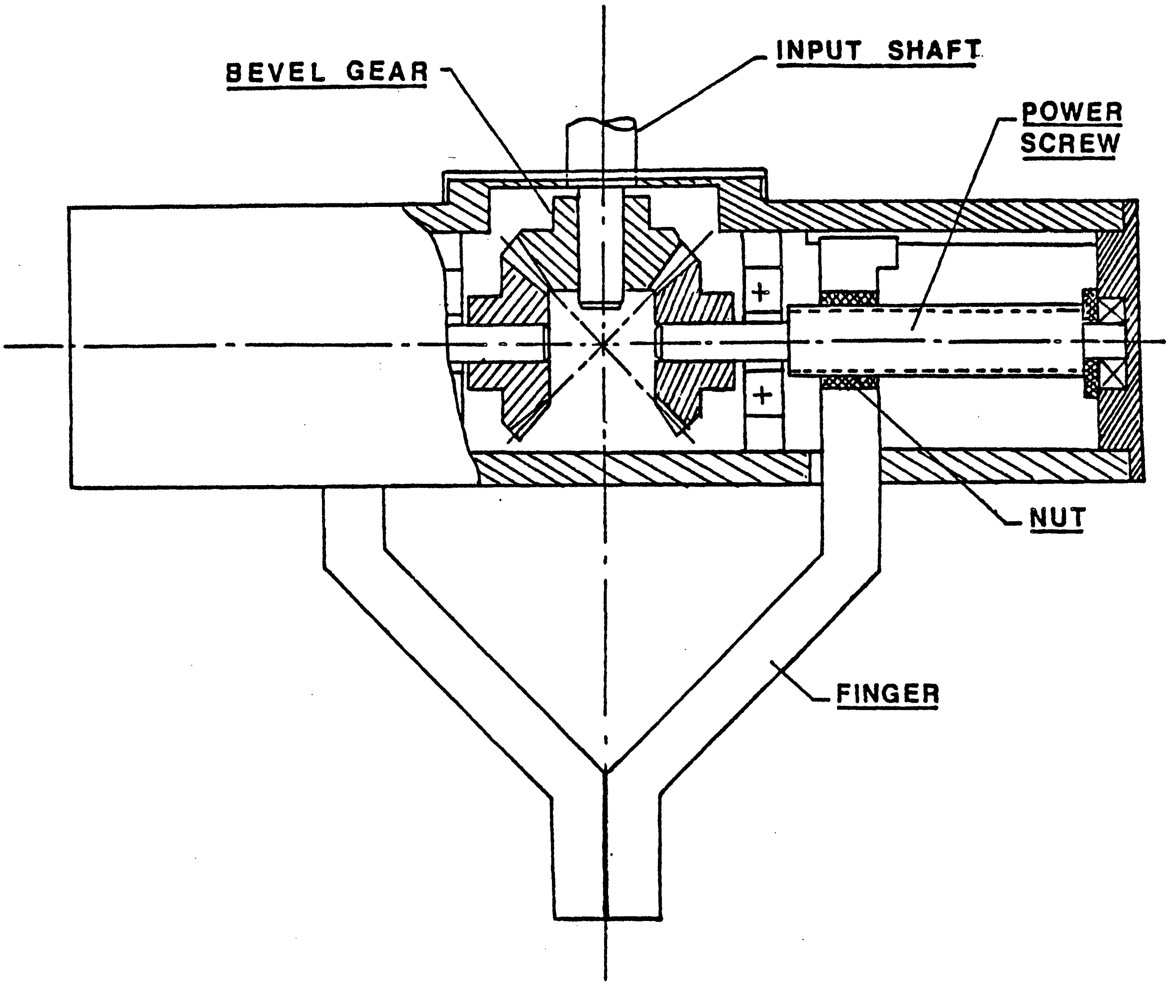


Figure 3. Cross sectional view of the gripper with some details omitted to expose gear and screw drive.

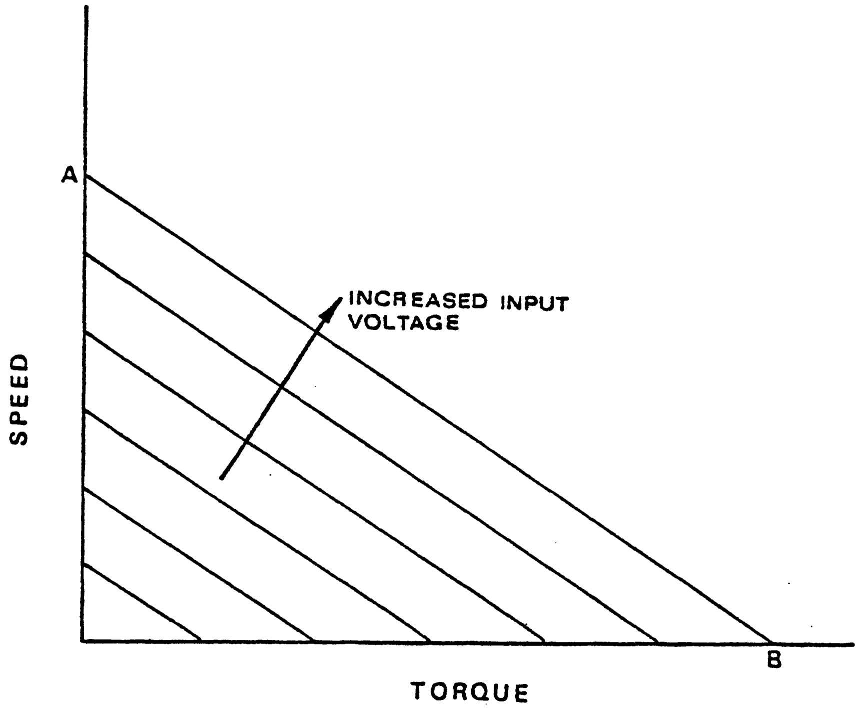


Figure 4. **Performance characteristics of a DC torque motor. Print A indicates the no-load speed. Point B indicates the stall torque.**

the gripper variables, force, position and speed could be controlled. control of gripping force is desirable so that an appropriate force is applied to hold an object without slipping or damaging of the object. The gripper speed can also be controlled, if the fingers are to be used to push a small object at a desired speed.

A hyprid scheme for active control of position and force in manipulator arms has been recently suggested [11]. In this scheme, a separate control loop is used for controlling force or position at a particular joint but not both.

Another method has been devised for controlling force or position in the individual fingers of an articulated hand [12]. The essence of this method is to manipulate fingertip stiffness and damping characteristics so that finger position response is approximately critically damped or that a finger is operated in a pure force servo mode [12].

Since the VGF gripper being introduced has only one degree of freedom, these two methods cannot be used. The control system architecture used is shown in Figure 5 for controlling position and force in the VGF gripper. There are two control loops in the system, one for force and one for position. Sensing of the gripper position can be accomplished by an incremental encoder or by a

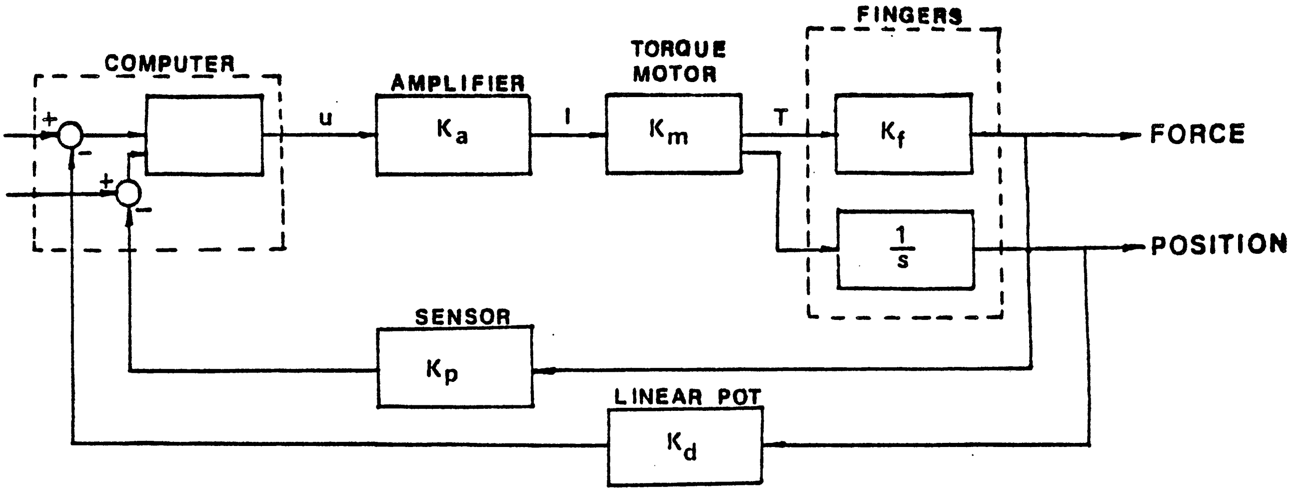


Figure 5. Force and position control system of the gripper, using a pressure sensor for force feedback.

linear or rotary potentiometer. The encoder produces output which is more compatible with computer control, but its operation is more complicated due to the need for zeroing the output to eliminate accumulated error. A linear potentiometer is used in the VGF gripper because displacement measurement is made directly unlike in the rotary potentiometer where a linear to rotary motion conversion is necessary. The external loop of Figure 5 controls the size of the gripper opening. The linear potentiometer measure the finger's position which is fed back to the servocontrol computer.

The inner loop of the control system (Figure 5) controls the gripping force. A pressure transducer can be used to sense the contact force, but compact pressure sensors are not currently available. Research continues to a develop compact semiconductor sensor for measuring pressure at a point [13] and the more advanced tactile sensors for skin-like sensing of pressure distribution [14]. A pressure transducer is generally adequate for force feedback in the force loop. However, until a suitable small and inexpensive pressure sensor becomes available, motor current feedback can be used instead of force feedback. In a torque motor, gripping force (or motor torque) is proportional to armature current except in the presence of Coulomb friction which results in a dead space nonlinearity in the force/current relationship.

Therefore, a current feedback loop is used in our VGF gripper (Figure 6). When the gripper holds an object, the torque motor is stalled. The current which is then supplied to the motor by the amplifier is proportion to stall torque which is in turn propositional to grippering force **F** (i.e. $\mathbf{F} \alpha I$). Across the amplifier, under stable conditions, the output I is proportional in the input u

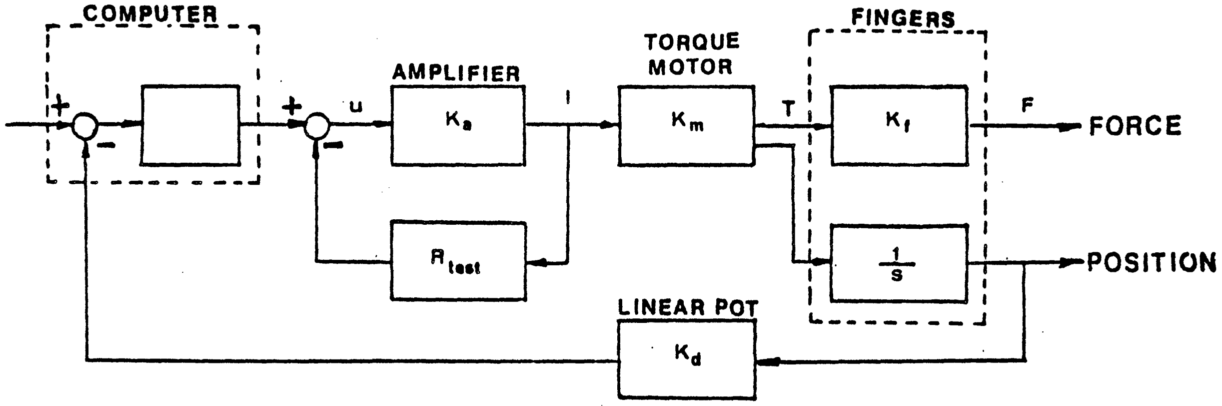


Figure 6. Force and position control system of the gripper using motor current feedback for force control during gripping.

(i.e. $I \alpha u$). Thus, when the motor is stalled, the gripping force **F** is proportional to the control command u. This is possible, since unlike other DC motors, the permanent magnet torque motor is designed to operate at stall state without heating damage, if a certain current level is not exceeded.

When a command u is issued to move the finger, only very small motor current is present which is fed back around the amplified causing the amplifier to saturate and effectively opening the current feedback loop. The fingers will move as fast as possible at a constant speed regardless of how large is the input u. This condition continues until the fingers touch the object and the contact force builds up rapidly. This increases the current fed back around the amplifier and closes the current loop. Thereafter, the current (which is α to the gripping force) is servoed bringing the force to the desired level set by u.

9. Conclusions

This report introduces a new two-fingered gripper in which both the gripping force and finger position are controlled. the variable grip force feature permits grasping and lifting of fragile objects without crushing them. The characteristics of several kinematic arrangements, including level mechanisms, parallelograms and direct linear drives are discussed to choose a satisfactory finger mechanism. The direct linear drive is chosen because it poses a linear relationship between actuator input and finger position and independence of gripping force from gripper opening.

A useful objective index, the gripper ratio, is introduced for comparing the payload carrying capacity of grippers with different kinematic structure and sources of power. The gripper ratio is simply the maximum weight of the object lifted divided by the gripper weight. Hydraulically-actuated grippers generally have the highest gripper rations (about 5). Pneumatic and electromechanical grippers have a gripper ratio of about 1. There appears to be little effect of finger mechanism type on gripper ratio.

The performance characteristics of DC permanent magnet torque motors are well suited for implementing gripper force control when only limited space is available. During gripping, the armature current can be servoed to produce a particular stall torque. This in turn generates a desired level of gripping force, if the finger mechanism insures a linear relationship between the input torque and the gripping force.

10. Acknowledgements

The authors extend their appreciation to Professors R. A. Volz and C.S. George Lee for their valuable suggestions and to the Center for Robotics and Integrated Manufacturing at the University of Michigan for technical and financial assistance.

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