11-1-2004

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Design And Testing Of A Prototype Gripper For A Wheelchair Mounted Robot

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Mechanical Engineering
Department of Mechanical Engineering
College of Engineering
University of South Florida

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Date of Approval:
November 1, 2004

Keywords: rehabilitation, grasp, contact forces, labview, force sensors

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Koushik R. Barhale

ABSTRACT

The application of technology makes a lot of things easier, but for individuals with disability, it makes things possible. Rehabilitation robotics aims at providing robotic devices, which can act as functional extensions of the user, while performing basic activities. Providing a well-designed gripper as its end - effector can greatly enhance the performance of a rehabilitation robot. The gripper performs simple tasks like picking up objects, manipulating objects, which help in performing activities of daily living.

This thesis describes the development of a prototype gripper for a wheelchair mounted robot. The pre-development surveys conducted before the development of commercialized robotic assistive devices were analyzed and user task priorities were understood. The role of the gripper as an object-grasping device was focused upon.

The size and weight parameters, which the gripper should effectively grasp, were decided. Based on these parameters, a prototype was developed. Force sensors were used to monitor the gripping forces. The data was acquired using a Data Acquisition System. The gripping forces were measured using a Labview program that utilized the force-voltage relationship for the sensor. This relationship was obtained by performing calibration experiments. The performance of the prototype was tested using objects that are used in everyday environment was analyzed by conducting a set of experiments. A relay circuit was designed that would stop the motors once the gripping forces exceeded a threshold value for a given object. This avoided any damage to object during the gripping process. The gripping forces measured were found to be in close agreement to the theoretically calculated force values.

Chapter One

Introduction

1.1 Motivation

Rehabilitation robotics has shown promise in improving the quality of life of individuals with disabilities. The conceptual similarity between a robot arm and a human arm has resulted in robots manifesting as assistive devices in different configurations. The configurations of rehabilitation robots that are commercially successful can be categorized as manipulators mounted on vocational workstations, mobile robots and robots mounted on mobile platforms e.g. wheelchair-mounted robots.

Extensive studies in dynamics and workspace analysis have enabled the robots to work successfully in structured environment. Research in sensor technology and teleoperation makes functioning of a robot possible in unstructured and hazardous environments. Robots are becoming more and more versatile with a growing number of accomplishable tasks. Most of the robots used in rehabilitation applications are essentially modified industrial robots that have adapted to work in an unstructured environment. These robots have four or five degrees of freedom with a workspace planned out carefully to suit the needs of individuals with disability. However, most of the rehabilitation robots use primitive end - effectors with a two fingered "pinch" to grasp objects. Very few of the grippers have sensory feedback. This seriously hampers the performance of the entire robot as far as grasping and manipulation capabilities are concerned.

Assistive devices like prosthetic arm act as a direct extension of human hand. Such devices use human nerve control for operation and cannot be effectively used as rehabilitation devices. Highly complex, artificial hands with incredible performance nearly as capable as the human hand have been developed. However, the complexity and cost of such devices make them an impractical option as a gripping device on a rehabilitation robot.

This thesis is an attempt towards a practical solution of providing a low cost, high performance gripper for a rehabilitation robot. The study of design parameters, explained in the subsequent chapters, has resulted in a three articulated finger gripper with force feedback as a proposed solution to the above-mentioned problem.

1.2 Thesis Objectives

- Understand the task priorities for individuals with disabilities. Identify the tasks and role of the gripper in accomplishing these tasks.
- Design, develop and test a prototype that would perform the tasks outlined in the user task priorities.
- Identify the areas for improvement and recommend suitable modifications in the prototype for performance enhancement.

1.3 Thesis Outline

Information about the disability scenario in North America, pre-development surveys, and user task priorities is provided in Chapter Two. The mechanism used for the gripper is described in Chapter Three. The specifications of the hardware used are presented here. Chapter Four explains the sensors, data acquisition system, force feedback system and the force measurement circuits. The experiments performed to analyze the performance of the gripper are listed in Chapter Five. Results are analyzed and discussed in this section. Chapter Six provides the conclusions and future recommendations.

Chapter Two

Background

2.1 Disability Scenario in North America

The "Americans with Disability" Act 1990 defines disability as a physical or mental impairment that substantially limits one or more major life activities. [1] According to the U.S. Census Bureau Report in 1997, there were 52.6 million Americans with Disabilities and 33.0 million with severe disabilities. 10.1 million individuals needed personal attention with one or more Activities of Daily Living (ADLs) and Instrumental Activities of Daily Living. (IADLs). Approximately 25 million individuals had ambulatory disabilities and 14.7 million individuals had severe ambulatory disabilities. Approximately 2.2 million individuals used wheelchairs. [2]

The survey also reflects the socio-economic impact of disabilities on the life of individuals. Persons with disabilities had higher rates of unemployment and substantially lower median income as compared to persons without disabilities. The percentage of individuals below the poverty line was higher for individuals with disabilities than those without disabilities. The high school dropout rate for individuals with disabilities was much greater than that of persons without disabilities. Table 2.1 gives an overview of the disability scenario with special attention given to the ambulatory disabilities. It also reflects that a vast number of people were unable to perform Activities of Daily Living and Instrumental Activities of Daily Living, independently. This results in higher rates of unemployment and hence higher rates of poverty as is shown by the figures in the table.

Table 2.1 Statistics of 1996 Survey of Income and Program Participation: August – November 1997

Categories	Number with Specified Characteristic (in thousands)		Percent with Specified characteristic	
	Number	90 percent confidence interval (±)	Percent	90 percent confidence interval (±)
All Ages	267,665	(X)	100.0	(X)
With a disability	52,596	814	19.7	0.3
Severe disability	32,970	673	12.3	0.3
Need personal assistance with an ADL or IADL	10,076	390	3.8	0.1
Ages 15 and over	208,059	(X)	100.0	(X)
Used a wheelchair	2,155	183	1.0	0.1
Used a cane, crutches or a walker (not a wheelchair)	6,372	313	3.1	0.2
Had difficulty seeing	7,673	342	3.7	0.2
Unable to see	1,768	166	0.8	0.1
Had difficulty hearing	7,966	348	3.8	0.2
Unable to hear	832	114	0.4	0.1
Age 25 to 64 years				
With any disability	26,493	612	100.0	(X)
In poverty	5,669	295	21.4	1.0
With a non-severe disability	9,794	385	100.0	(X)
In poverty	1,018	126	10.4	1.2
With a severe disability	16,700	496	100.0	(X)
In poverty	4,651	268	27.9	1.4
No Disability	112,604	1,007	100.0	(X)
In poverty	9,376	377	8.3	0.3

Source: U.S. Census Bureau

2.2 Role of Rehabilitation Robots as Assistive Devices

Rehabilitation is an activity, which aims to enable a person with disabilities to reach an optimum mental, physical and/or social functional level. [3] The term ``assistive technology" means technology designed to be utilized in an assistive technology device or assistive technology service. The term ``assistive technology device" means any item, piece of equipment, or product system, whether acquired commercially, modified, or customized, that is used to increase, maintain, or improve functional capabilities of individuals with disabilities. The primary goals of Rehabilitation Engineering and

Assistive Technology are to understand the needs of an individual with a variety of functional impairments, to explore a wide range of applications for available technology and to expose the users to this technology and assess their response to it. [4]

Robotics in rehabilitation provides considerable opportunities to improve the quality of life for a person with physical disability. The primary benefit of a rehabilitation robot is that it reduces a need for a human attendant. The operator can use the device independently and may develop a level of self-esteem and functional independence. Personality issues, loss of privacy and higher costs associated with a human attendant can also be eliminated with use of a rehabilitation robot. [5]

Many of the manipulator configurations that were developed for industrial robots are used as rehabilitation robots. However, there are some fundamental functional differences in the two types of robots. Industrial robots normally operate in a structured environment with predefined tasks, separate from the user. Furthermore, trained personnel operate industrial robots. Rehabilitation robots integrate humans and robots in the same tasks, requiring certain safety aspects and special attention to the Man–Machine Interaction. They operate in a highly unstructured environment performing tasks that cannot be programmed easily but can be controlled. Hence rehabilitation robots require the user in direct control of the device. [3]

A rehabilitation robot is distinct from other assistive devices like prosthesis and orthosis, in that it may be located remotely from the body while performing its mission of augmenting manipulation function. [5]

A rehabilitation robot has many forms, which may be generally described in terms of two operating approaches, the robot as an assistant and the robot as an extension. Based on these two approaches, many rehabilitation robots were developed in North America and Europe. The three categories of rehabilitation robots, which enjoyed a fair degree of commercial success, are:

- Vocational Robots.
- Robots on Mobile Platforms. (Wheelchair mounted robots).
- Mobile robots.

2.3 User Task Priorities

In order to have a better understanding of the expectations of the user from the assistive device, extensive pre-development surveys were conducted between 1986 and 1991. Four separate research groups at Bath Institute of Medical Engineering, U.K., Middlesex University, U.K., University of British Columbia and Queen Alexandra Institute, Canada conducted surveys before the development of rehabilitation robots like Wessex trolley mounted robot, Atlas Robot, Inventaid Arm, RAA and Middlesex arm. In all 139 individuals with Spinal Cord Injury (SCI), Multiple Sclerosis and a variety of physiological and neurological impairments participated in the surveys. Questions about the comfort levels of users in performing activities of daily living and tasks at workplace were asked. The prospective users were asked about the tasks they expected the robots to perform for them. Based on their responses, the user task priorities were identified as shown in table. [9], [10].

Table 2.2 User Task Priorities

	BIME	Middlesex	Queen Alexandra	University of British Columbia
Total number of subjects	42	50	36	11
Reaching, Stretching, Gripping, pick up objects	--	22	18	9
Reach or pick up from the floor	4	12	4	--
Cooking, Frying Food, Drinks	16	10	8	2
Eating, Drinking	4	9	--	6
Personal Hygiene, Dressing	2	3 8	11 3	7 4
Gardening,/Hobbies and Crafts/Leisure	1	13	8	7

2.4 End Effectors on Rehabilitation Robots

The end- effectors of any robotic system are of critical importance because it physically interacts with the environment. A well-designed end-effector with sensory feedback can greatly increase the system performance and make the robotic system more reliable while working in unstructured environment.

A gripper on an assistive robot acts like a functional replacement of human hand. It should have enough versatility and reliability in its grip, so that it can effectively perform the functions of the human hand.

The study of the user-prioritized tasks suggests that the role of the gripper in accomplishing these tasks is:

- Grasping: In tasks like reaching, stretching, gripping, picking up objects and other tasks, the gripper needs to grasp the object of different shapes and sizes.

  The typical shapes handled by the gripper are:

a) Cylindrical Objects: A cylindrical object has curved faces which make gripping with two jaw gripper difficult. To grasp such an object, the fingers must curl around the axis of the object so that the contact surface area is much larger. Spherical Objects: A spherical object with its curved surfaces demands the fingers to wrap around the object and cage it. This reduces the possibility of the object slipping away between the fingers.

b) Objects with Planar Faces: A pinch gripper can handle such objects with the jaws pressing against the object faces. However, in order to optimize the grasp, the fingers need to align along the edges of the object.

c) Oblique Objects: An object with irregular faces can best be handled if it is caged within the fingers of the gripper.

- Manipulate Objects: The task of manipulating objects in tasks like cooking, feeding and personal hygiene can be simplified as handling the objects (Grasping) and moving the objects relative to the robot arm. This function is possible only if the robot hand has an active wrist (a wrist capable of performing roll/pitch or yaw motions) or articulated fingers or both of them. Manipulation functions add dexterity to the gripper and make them capable of performing operations beyond pick and place operations.

- Sensory Function: Sensors on the robot gripper make it more independent to perform in an unstructured environment and reduces the cognitive load on the user. The sensors provide the user with data, which can be used as feedback and make robot operation more safe and reliable. Position sensors give the user the idea of exact location of the joints of the robot arm and hence it can move in the workspace without colliding with obstacles. Force sensors give the user an idea about the amount of force the gripper is exerting on the object. The monitoring of the forces results in grasping objects without dropping or crushing them.

Based upon the ability of the gripper to successfully perform the above-mentioned functions, the minimum configuration needed can be summarized as shown in the table

Table 2.3 Requisite Configurations for Various Gripper Functions [11]

Type of Finger	Functions		
	Grasping	Shape Accommodation	Manipulation
2 Rigid Fingers	Yes	Yes	No
2 Articulated Fingers	Yes	Yes	No
3 Rigid Fingers	Yes	Yes	No
3 Articulated Fingers	Yes	Yes	Yes
>3 Rigid Fingers	Yes	Yes	No
>3 Articulated Fingers	Yes	Yes	Yes

2.5 Literature Review

Karel Capek's 1921 play Rossum's Universal Robots originated the term "robot" to the world. However the deeply rooted concept of as a "tin man" has come a long way to the present day concept of robots and particularly rehabilitation robots. The promise shown by rehabilitation robots and the boom in capital investment during the 1980s saw vast developments in the intelligence and performance levels of today's assistive robots.

Initial developments with robots as assistive devices started in 1969 with the Rancho's Golden Arm. However these robots, more specifically powered orthoses, depended heavily on the residual sensory perception and hence could be used only by a limited section of users.

The idea of using an end -effector of rehabilitation robot as functional replacement of human hand has resulted in different designs of grippers/end -effectors. The next section studies the specifications and features of grippers on commercially available robotic assistive devices.

The focus of this thesis is to present a gripper design that can be used as an end -effector on a wheelchair mounted robot. The specifications and features of end -effectors on commercially available wheelchair mounted robots are discussed in this section. End - effectors on workstation-mounted robots, which can be used on wheelchair mounted robotic arms, are also discussed here.

a) Manus [12]

The gripper forms the most versatile part of the Manus. It has a gripping force of 2 kg (4 lb, 20 N). The three hinge fingertips of the Manus gripper are covered with an anti-slip material, which prevents the slipping of the object being grasped. The gripping force is variable and can be controlled by the user. The maximum spread between the fingertips is 9 cm (3.5"). The safety feature for the gripper is its ability to be opened, manually, without damaging it.

Figure. 2.1 Manus Gripper

b) Raptor [13]

Richard Mahoney and his team, at Rehabilitation Technologies Division, Applied Resources Corporation developed a wheelchair-mounted robot called "Raptor". The manipulator has a capacity to lift and manipulate 5 lbs of mass in a workspace radius of 48 inches. The user using various input techniques like joystick, keypads and sip-puff method can control the device. Low operating speeds (<2 RPM) and safety devices like slip clutches make this device a very reliable device for rehabilitation applications in Activities of Daily Living.

Figure.2.2 Raptor

c) KARES [6]

KAIST, in South Korea, developed KAIST Rehabilitation Engineering System (KARES). It consists of a 6 DOF arm attached to a powered wheelchair. The major focus of research at KAIST was to study the performance of a haptic device while performing Activities of Daily Living. The role of the end -effector in this device is that of a gripper holding a camera, used in visual serving. The important criteria for the end -effector were to minimize the mass of the end -effector and eliminate the backlash in the movement of the cameras. This prompted for the use of a tendon pulley mechanism instead of a gear mechanism. The steel tendons transmit driving force from the motor, using a pair of wires.

d) Weston Wheelchair Mounted Robot [7]

The initial experiments to monitor the performance of the Weston Wheelchair Mounted Assistive Robot were performed using a prosthetic device as the end -effector. The poor results resulted in the development of a two-jawed mechanism that served as the gripper. The two jaws moved in a parallel plane because of a four bar linkage mechanism. A D.C. motor driving non-backdriveble gear train actuates the mechanism. The compliant elements in the drive train allowed for variable gripping force. The finger profile is slim enabling the user to have a better view of the object being gripped.

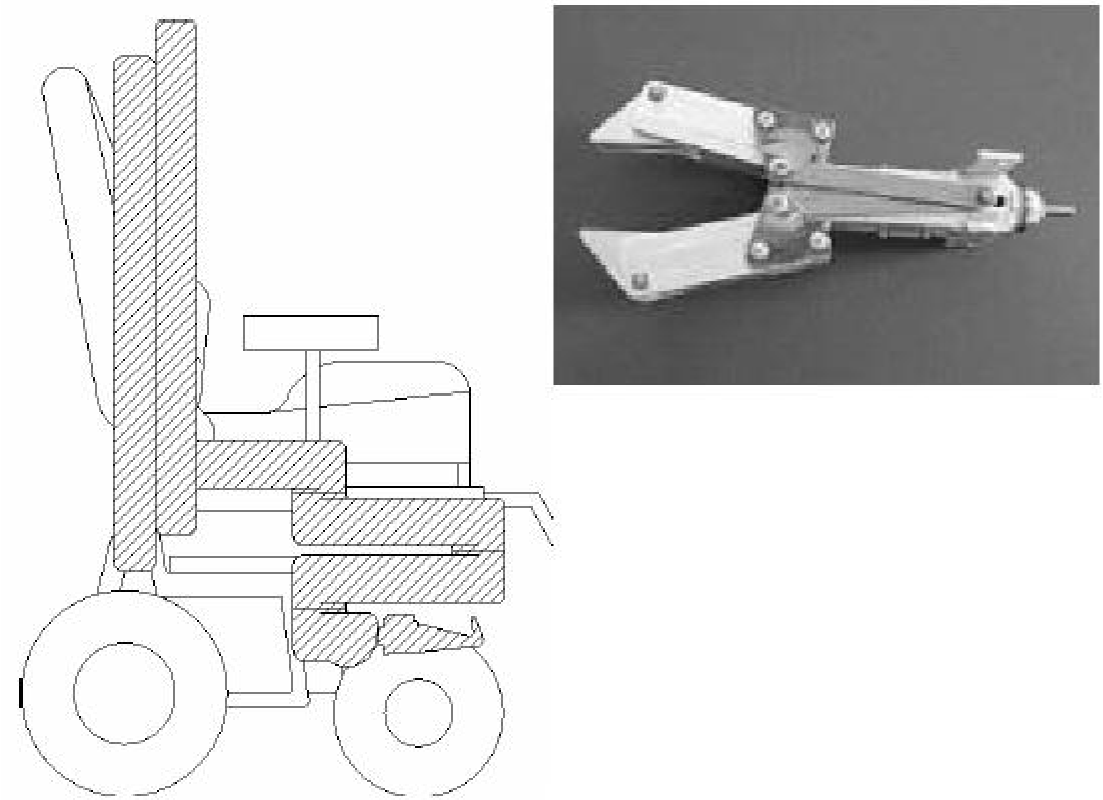


Figure 2.3 Weston Wheelchair Mounted Robot and its Gripper

The end -effectors used on Workstation based robots, like DeVAR and RAID, showed promise as devices, which can be used on wheelchair mounted robots. The specifications of these devices are discussed in detail.

e) DeVAR[8],[14]

Figure 2.4 Otto Bock Griefer on DeVar Robot

Desktop Vocational Assistant Robotic Workstation (DeVAR) is a PUMA 260 manipulator developed by Stanford University and Palo Alto VA rehabilitation center. The end- effector is an Otto-Bock Greifer prosthetic hand, which measures the hand opening with an accuracy of 0.6 mm. The greifer is a useful aid when powerful and precise grip is desired. It is extremely precise due to Dynamic Mode Control (DMC), which significantly improves its functional capabilities. The opening width of the gripper is 95 mm with a variable gripping force in the range 0-160N. The gripper weight is 540 gm.

Chapter Three

Design Procedure

3.1 Design Approach

Two approaches have been identified in design of rehabilitation devices. First approach can be called as “customized approach”, wherein the target population is identified. The needs of the users are identified and a device to cater these needs is designed. Smaller the target population more is the number of specific needs that need to be addresses. The other approach is to define the tasks that the device should perform and design accordingly. More the number of identified, more is the versatility of the device and also the complexity of the robot.

The task-based robot can be more effective by modifying the environment in which it operates. By implanting sensors, it can be adapted to function in a semi-structured environment.

Before designing the robot, it is necessary to identify the tasks, which the users were and were not able to do, and the hypothetical suggestions as to how an assistive device would aid the user in accomplishing them.

Based on this understanding and the amount of versatility desired, the tasks to be performed by the new design can be defined.

3.2 Mechanism Description

The gripper is a three articulated finger unit. Each finger has two links, which are actuated by a 12 VDC, 8 R.P.M. Gear Motor. The motion is transmitted from one joint to another using a gear drive. The gripper is capable of handling complex shapes and can handle objects weighing a maximum of 2 Kg and within the size range of 1.0” to 3.5”.

The three fingers of the gripper are mounted on a circular disc and are 120 apart. The fingers can be moved relative to each other (closer and away) using a lead screw mechanism actuated by a DC Gear Motor. A power-nut meshes with the lead screw in order to convert the rotary motion of the lead screw into a linear motion. The linear motion of the lead screw is transferred to the curvilinear motion of the gripper fingers using a linkage mechanism. The linkage mechanism is analogous to a crankshaft-connecting rod mechanism.

The fingers are attached to the end of a short link (crank). This link is fixed at the other end to the base plate using a pin joint. The connecting rod is attached to the crank between the pin joint and the fingers. Initially the fingers are aligned vertically and are 3.5” away from the centerline of the lead screw. As the crank rotates, they follow a curvilinear path and at the when the lead screw stops rotating, the fingers are about 1.5” away from the centerline of the lead screw. All objects with sizes in the range 1.5”-3.5” are grasped in this motion of the gripper. The finger motors are then activated for additional support.

For handling objects smaller than 1.5”, the finger motors are used. The gear mechanism is designed such that, the lower link moves at twice angle of that of the upper link. The lengths of the links are such that with approximately 25° rotation of the upper link with respect to vertical, the links are in contact thereby grasping any object within that size range. Meanwhile, the lower links rotate at about 50° resulting in the object getting caged between the fingers. As a result, the chance of objects slipping between the fingers is very little and hence the reliability of the gripper is very high.

3.3 Mechanism Kinematics

Nomenclature

μ:	Coefficient of friction
F_g:	Gripping Force (lb)
L_1:	Length of link 1 (in.)
L_2:	Length of link 2 (in.)
α:	Angle between link L1 and vertical (°)
r:	Length of the crank (in.)
l:	Length of Connecting rod (in.)
x_p:	Distance between power-nut and base plate (in.).
θ:	Angle between crank and vertical (°).
φ:	Angle between connecting rod and vertical (°)
n_f:	Number of fingers
W:	Mass of the object to be held (lb)
g:	Acceleration due to Gravity (inch/s^2)

Design Calculations:

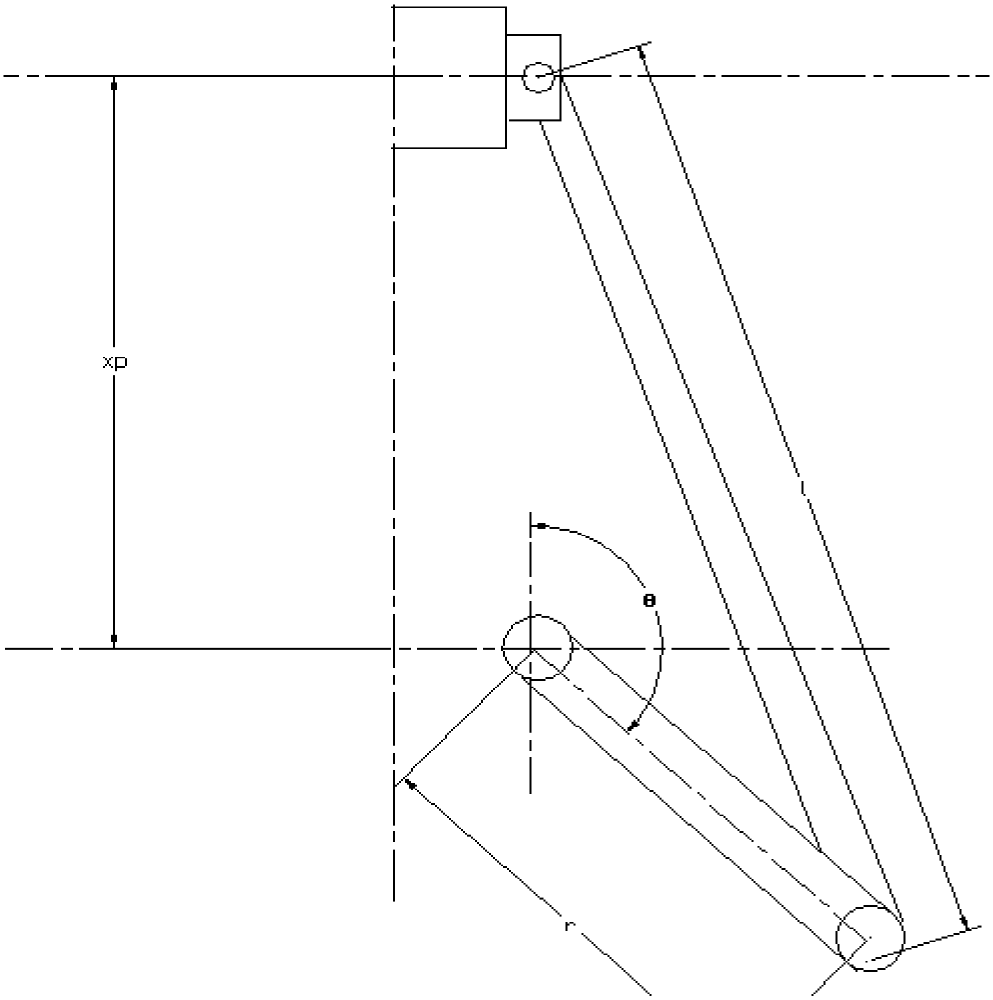


Figure 3.1 Determination of Minimum Length of Lead Screw

The angle θ is ideally restricted from θ=0°-180°. However, due to link interferences, the angle is restricted approximately between 60°-120°.

The length of the crank r=2.25”.

The length of connecting rod l=3.5”.

When θ=90°,

$$x_p = r\cos\theta + \sqrt{(l^2 - r^2\sin^2\theta)}$$

=2.6809”

When θ=180°

$x_p = r\cos\theta + \sqrt{(l^2 - r^2\sin^2\theta)}$

$= 1.25''$

Therefore, the vertical travel of the power-nut when the crank moves from horizontal position to the vertical position

$= x_p - x_p'$

$= 1.4309''$

Result of the motion of the crank on the finger motion:

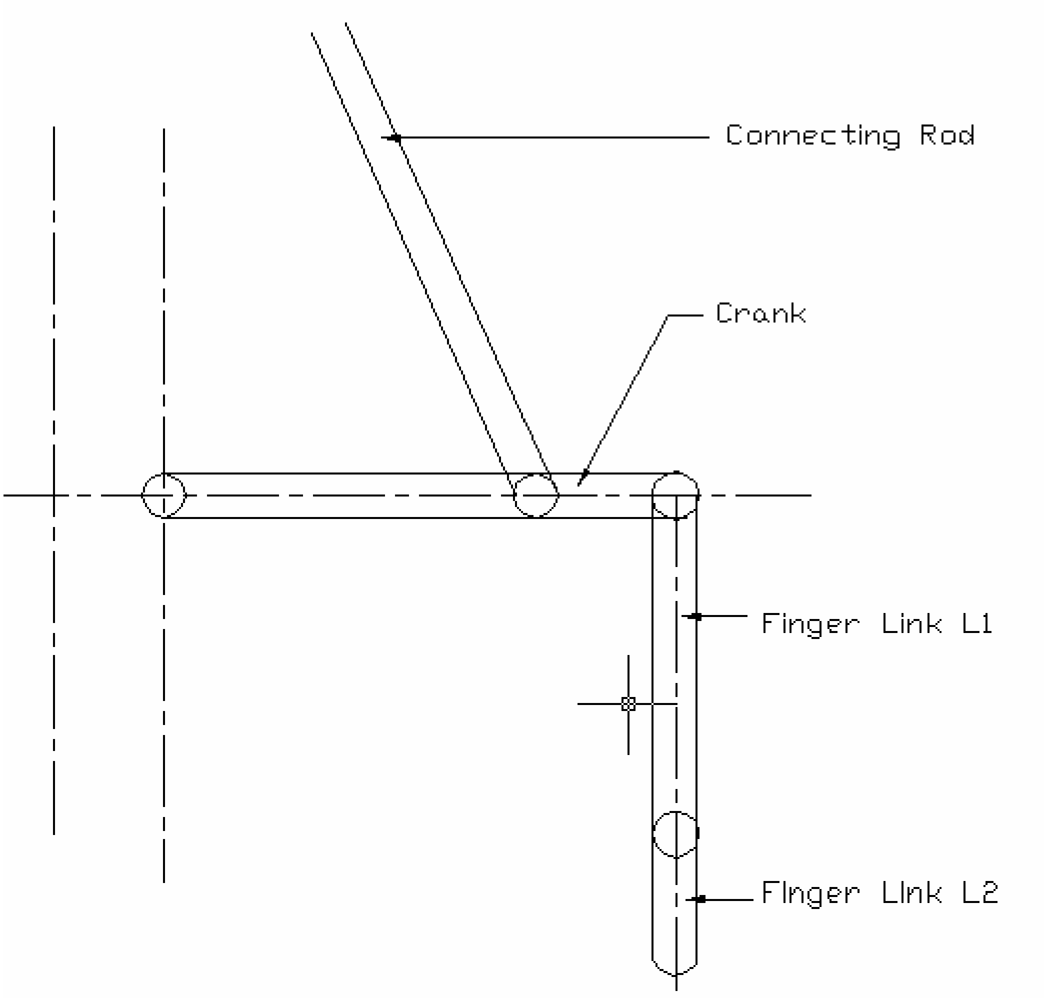


Figure 3.2 Initial Position of Gripper

As a result of the motion of the lead screw through 1.43”, the crank rotates through 90°. The subsequent position of the gripper is as shown in Fig. 3.3.

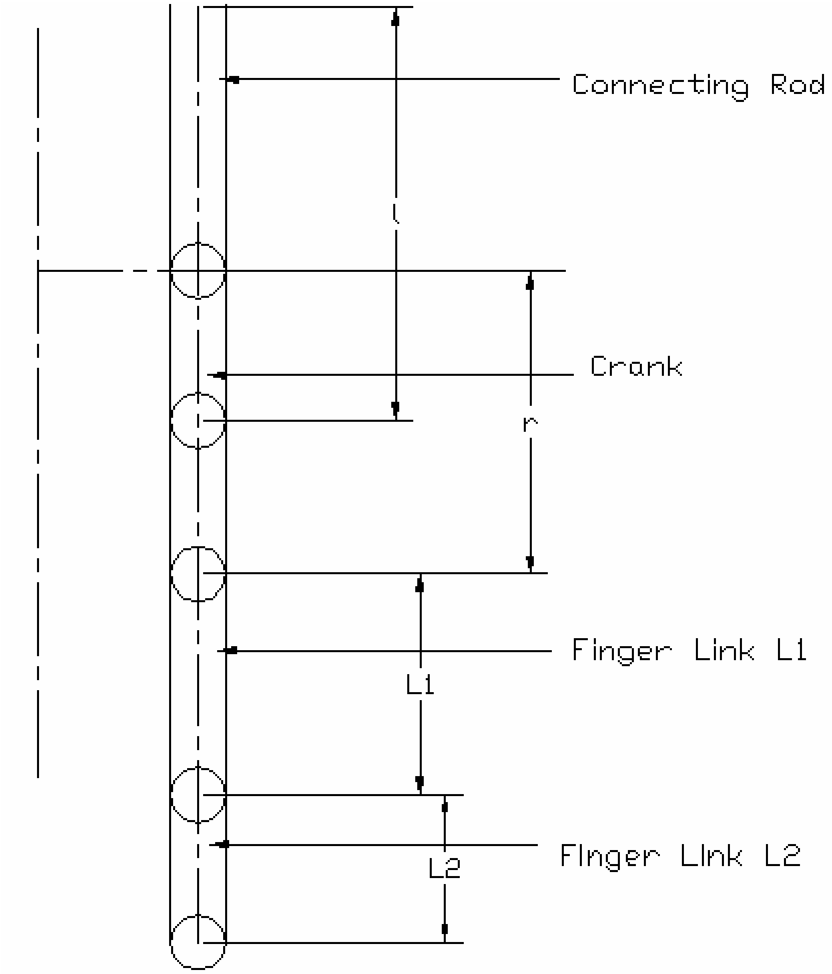


Figure 3.3 Ideal Position of the Gripper Fingers after the Lead Screw Motion

Finger Motor Actuation

Objects between the size range 1.5-3.5” can be grasped during the motion of the lead screw. For grasping objects smaller than 1.5” the finger link motor needs to be actuated. The fingers have a range of motion ‘α’ between 0-45°. However, due to the lengths of the links, the fingers touch each other as ‘α’ approaches 25°. For α=25° and θ=180°, the position of the gripper is approximately as shown in fig. 3.4

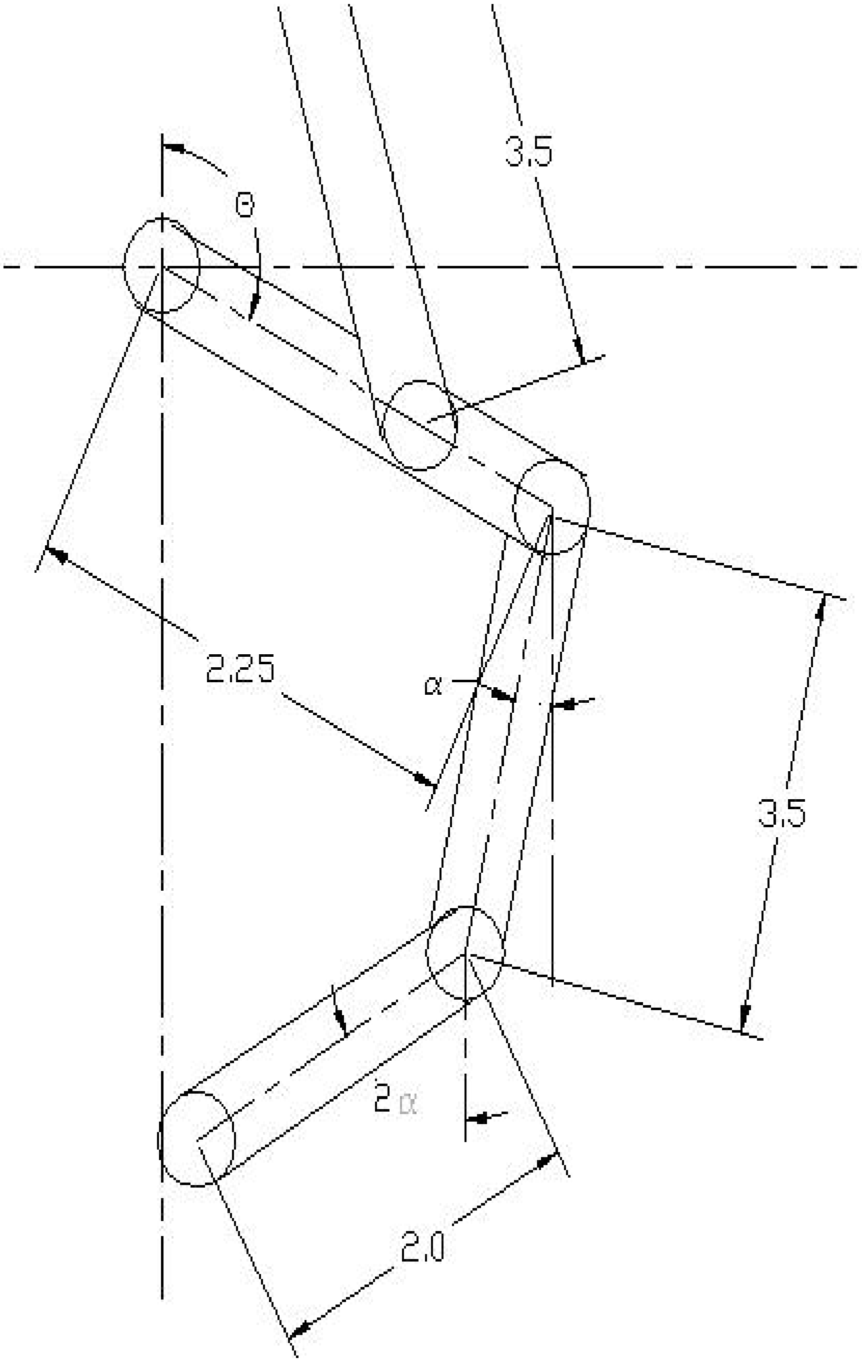


Figure 3.4 Finger Motor Actuation

Gripper Length:

The gripper length can be estimated by summing up the link lengths in initial and final position. The length calculated in the second fig.3.5, is an ideal situation. Owing to interference between links, the actual length is slightly less than the value shown.

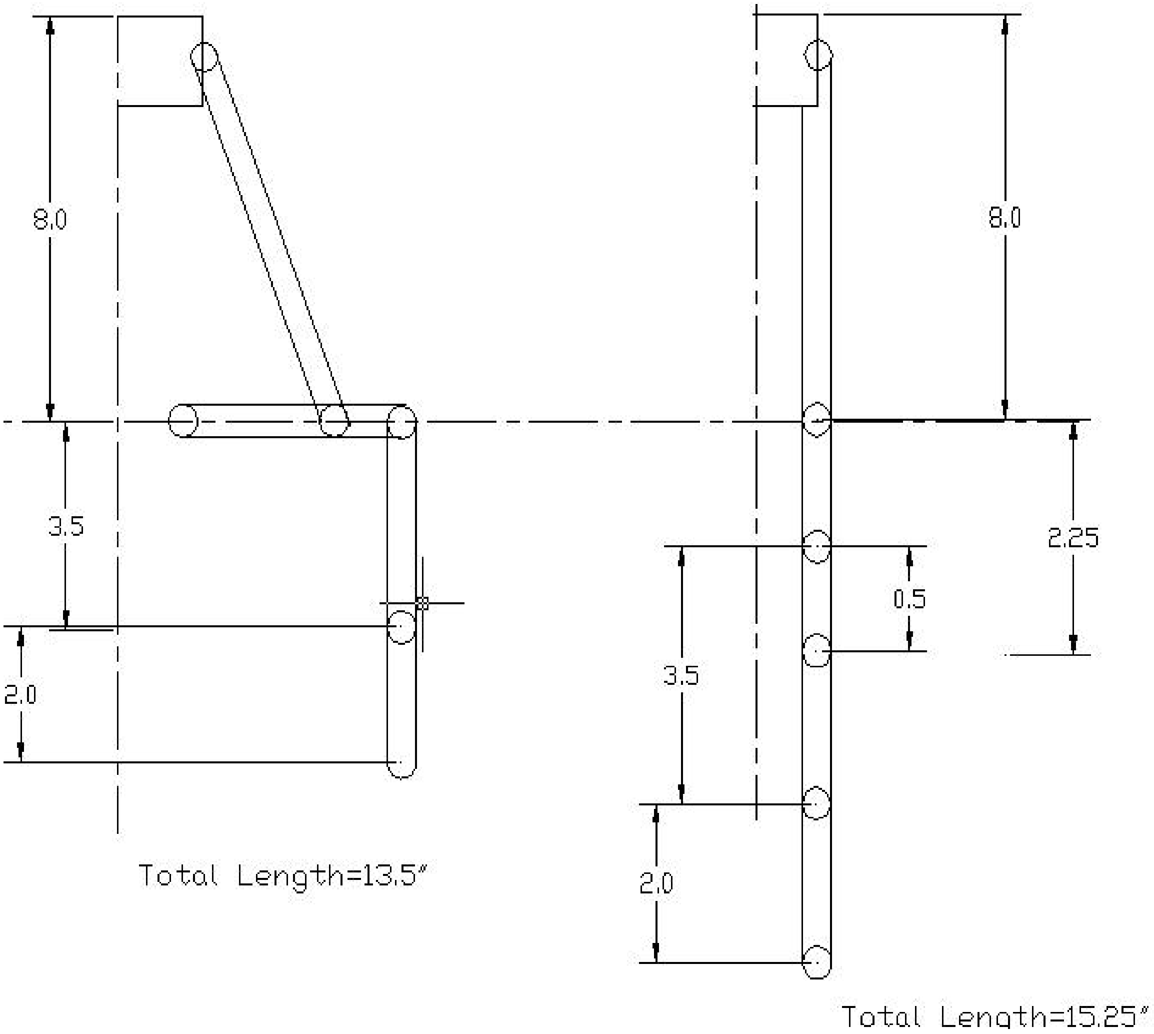


Figure 3.5 Estimation of Gripper Length

The important parameters of the gripper are summarized in Fig. 3.6.Table 3.1 gives the ideal and actual parameters for the gripper.

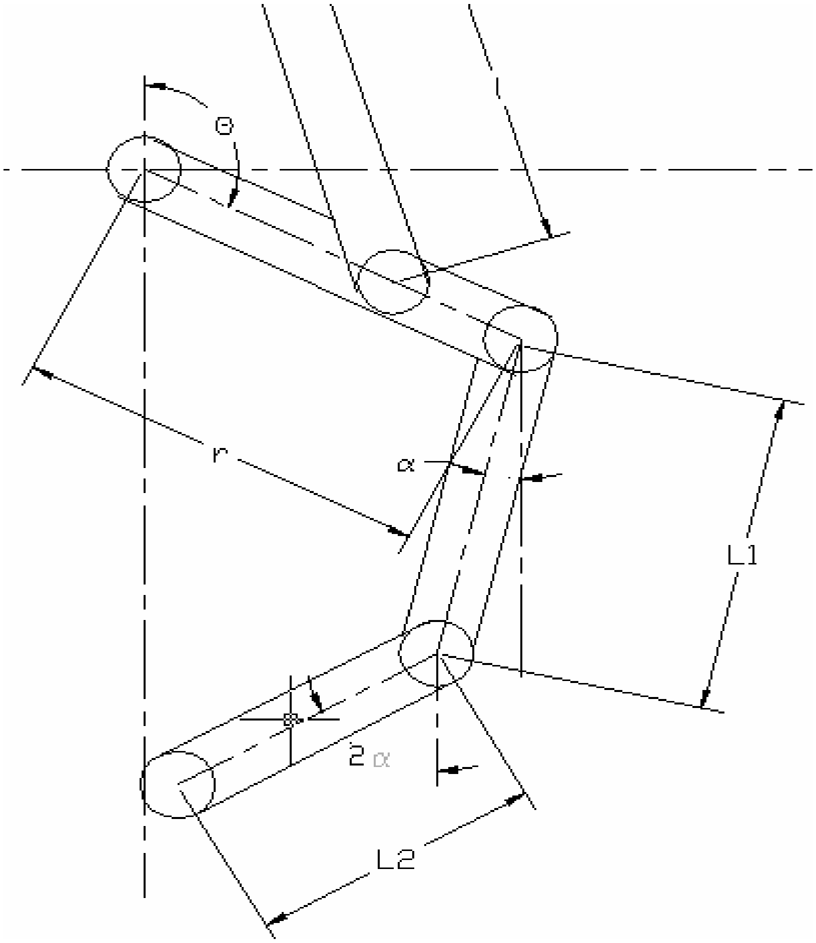


Figure 3.6 Gripper Parameters

Table 3.1 Gripper Parameters

Parameter	Ideal Value	Actual Value
A	0-45°	0-25°
Θ	0-180°	60°-120°
L1	3.5”	3.5”
L2	2.0”	2.0”
R	2.25”	2.25”
L	3.5”	3.5”

3.4 Estimation of Gripping Forces and Torques

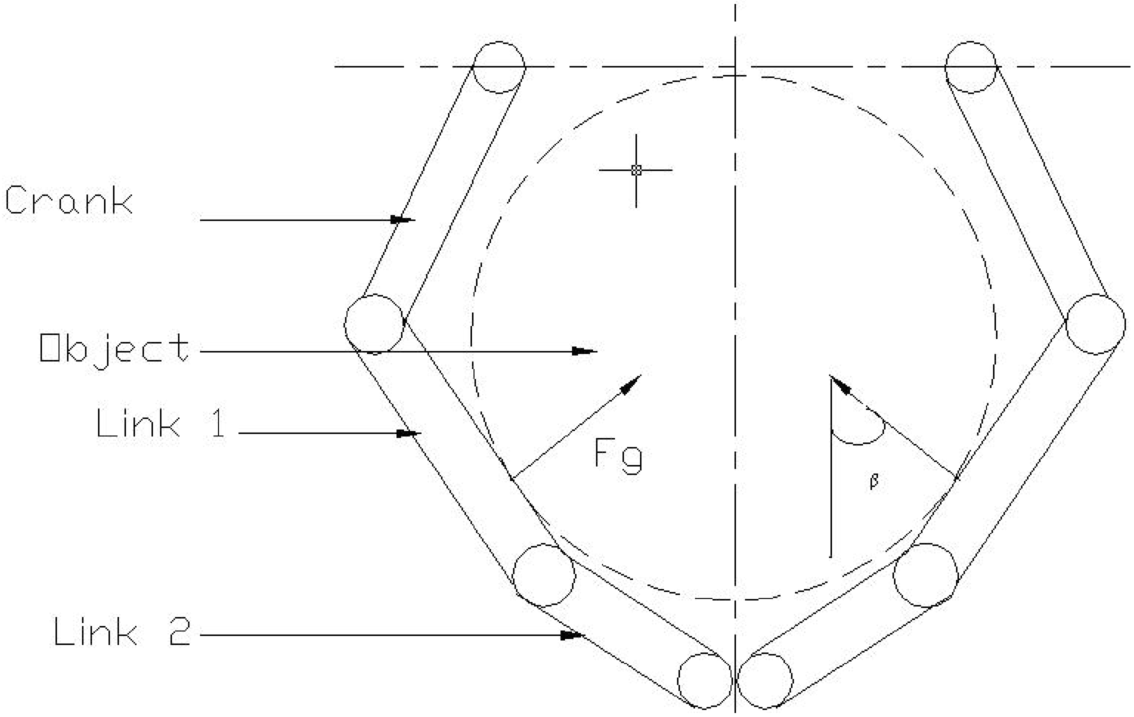


Figure 3.7 Estimation of Gripping Force

$n_f.F_g.\cos\beta = W.g$

$n_f = 3$,

$\beta = 65^\circ$

W=2kg =4.4107 lbf.

F_g= 3.4788 lbf.

Torque on the Finger actuating motor

The point of contact between the object and the finger link is slightly below the center of the lower link .The point of contact is 1.125" away from the motor shaft. Therefore the torque the motor shaft would have to overcome would be,

M_1=Fg *1.125

= 3.91365 lb-inch

To account for friction between moving parts, gears, and a motor with rated torque of 4.8 lb-inch was selected.

Factor of Safety for the Finger Link Motor =4.8/3.91365

= 1.23

Torque on the lead screw

The torque on the lead screw was calculated as

$$M_2 = \frac{Load * Lead}{2 * \pi * \eta}$$

Lead = pitch* No. of starts

For the lead screw selected,

= 1.0”

No. of Starts = 5,

Therefore,

Pitch= 0.2.

η= The efficiency of the lead screw- nut combination. From the data in the user’s manual,

η= 0.84.

$$M_2 = \frac{4.4107 * 1}{2 * \pi * 0.84}$$

= 0.8656 lb-inch.

Factor of Safety for Lead motor = 4.8/0.8656

= 5.542

Another critical component that failed during the stage of development time several times was the power nut. The nut bought earlier was an acetal-acrylic based nut. The maximum force rating at which the grippe occurs was 10 lbf. However because of unbalanced forces, the power nut broke.

A new solid plastic nut with a maximum rating of 19 lbf was purchased. The Factor of Safety for the new nut is calculated as

Factor of safety=19/5=4.8

3.5 Hardware Specifications

Most of the components used in the gripper were made at the College of Engineering Machine Shop. Few components were ordered for the gripper. This section gives an overview of these components.

3.5.1 Motors [15]

12 V DC Gear motors from Merkle-Korff Industries with a rated torque of 4.8 inch-lb. were used as the finger link actuation motors and the lead screw actuation motor. The rated speed of this motor is 8 RPM. The motors are reversible and have an integrated encoder. The motor has an inline shaft gearbox configuration with shaft supported by bronze sintered bearings. The stalling torque for the motor is 18.2 inch-lb.

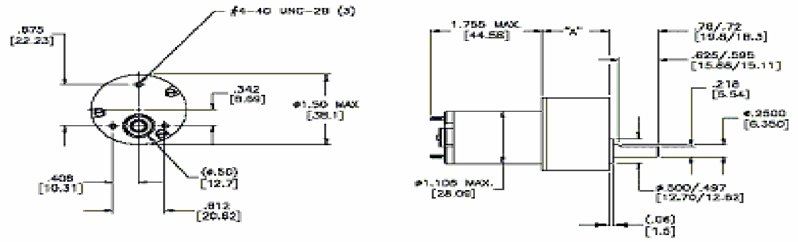


Figure 3.8 Dimensions of the Motor used for Gripper Actuation

3.5.2 Lead Screw [16]

A radially preloaded 303 stainless steel screw with a pitch of 1” from Kerk Motion Products Inc. was used as the lead screw for the gripper. It has a core diameter of 0.375”. The lead screw has 5 starts and comes with a self lubricating acetal flanged nut, as shown in Fig. Five starts on the lead screw ensures a smooth transfer of loads and consistent and repeatable torque.

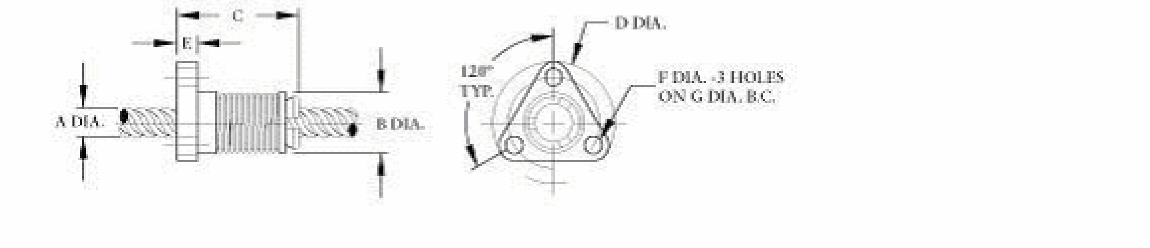


Figure 3.9 Dimensions of the Lead Screw

3.5.3 Gears [17]

Figure 3.10 Gear used for Power Transmission

The constraints of the mechanism demanded that four gears were to be placed between 3”. Hence a spur gear with pitch diameter of 0.75” was selected from Boston Gear Inc. The pressure angle for the gear is 14 1/2 ° and the diametrical pitch is 32.The gear has a bore of 0.3125”.

Chapter Four

Sensors and Control System

The gripping force exerted by the fingers of the grippers is used as a parameter to gauge and compare their performance. The specifications of the force sensor, the Data Acquisition equipment used for force measurement and the Labview code used to program the Data Acquisition Card (DAQ card) is explained in this chapter. The voltage output from the sensors is used to provide a force feedback to stop the motor in case of the force exceeding a pre-defined value. The control system and the circuits are explained in this Chapter.

4.1 Flexiforce Sensors [18]

4.1.1 Construction and Physical Properties

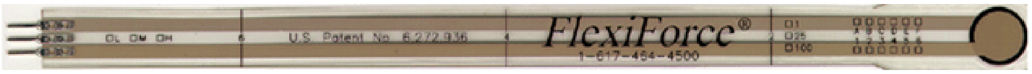


Figure 4.1 Flexiforce Sensor

With its paper-thin construction, flexibility and force measurement ability, the Flexiforce sensor can measure force between almost any two surfaces and is durable enough to stand up to most of the environments. Flexiforce has better sensor properties, linearity, hysteresis, drift and temperature sensitivity than any other thin film force sensor. The A-201 sensor is ultra thin (0.008”), flexible printed circuit. It is 0.55”wide and 2.5” long. The active sensing area is a 0.375” diameter circle at the end of the sensor. The sensors are constructed of the two layers of substrate, such as a polyester film. On each layer, a conductive material (silver) is applied, followed by a layer of pressure sensitive ink. Adhesive is then used to laminate the two layers of the substrate to form a sensor. The silver circle on top of the pressure sensitive ink defines the active sensing area. Silver extends from the sensing area to the connectors at the other end of the sensor, forming conductive leads. A-201 sensors are terminated with a male square pin, which allows them to be incorporated in a circuit. The two outer pins of the connector are active and the sensor pin is inactive.

4.1.2 Sensor Performance

The Flexiforce single element sensor acts as a resistor in an electrical circuit. When the sensor is unloaded, its resistance is very high. When force is applied to the sensor, this resistance decreases. When a constant voltage is applied across the connecting leads of the sensors, the output voltage is proportional to the force applied on the sensor by the relationship as shown in Fig 4.2. The Flexiforce force sensors are available in different ranges between 0-100 lb. The force sensor used for the data measurement has a range of 0-25 lb.

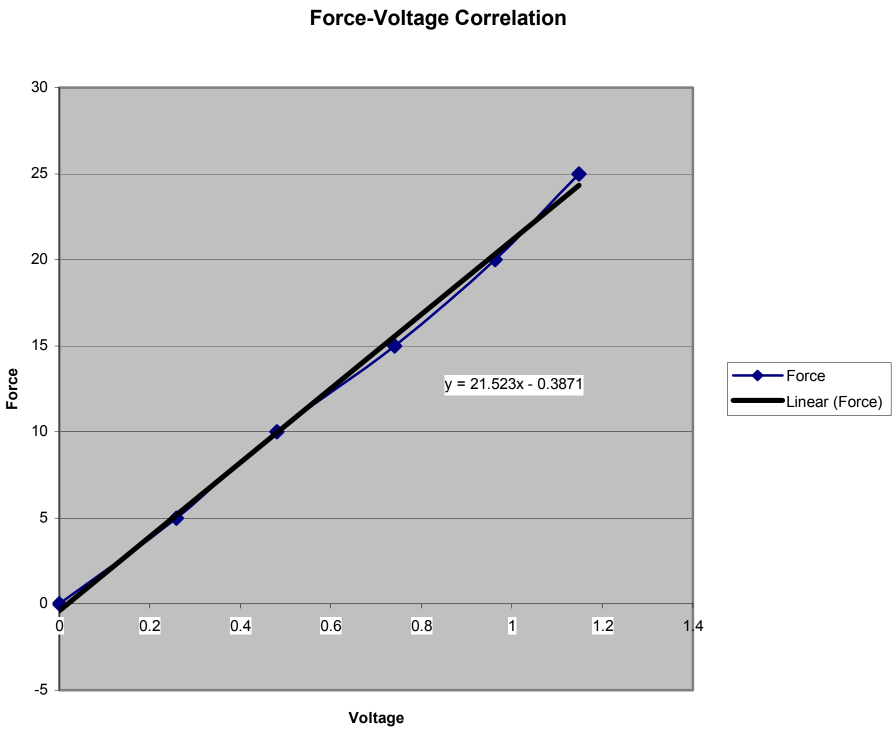


Figure 4.2 Force –Voltage Correlation for the Force Sensor

4.2 Data Acquisition Card [19]

The data for measurement of gripping force exerted by the fingers comes from multiple sensors mounted on the fingers. Three sensors mounted on the three fingers of the prototype provide simultaneous force measurements for analysis. This required a multi-channel input-output system for force measurement.

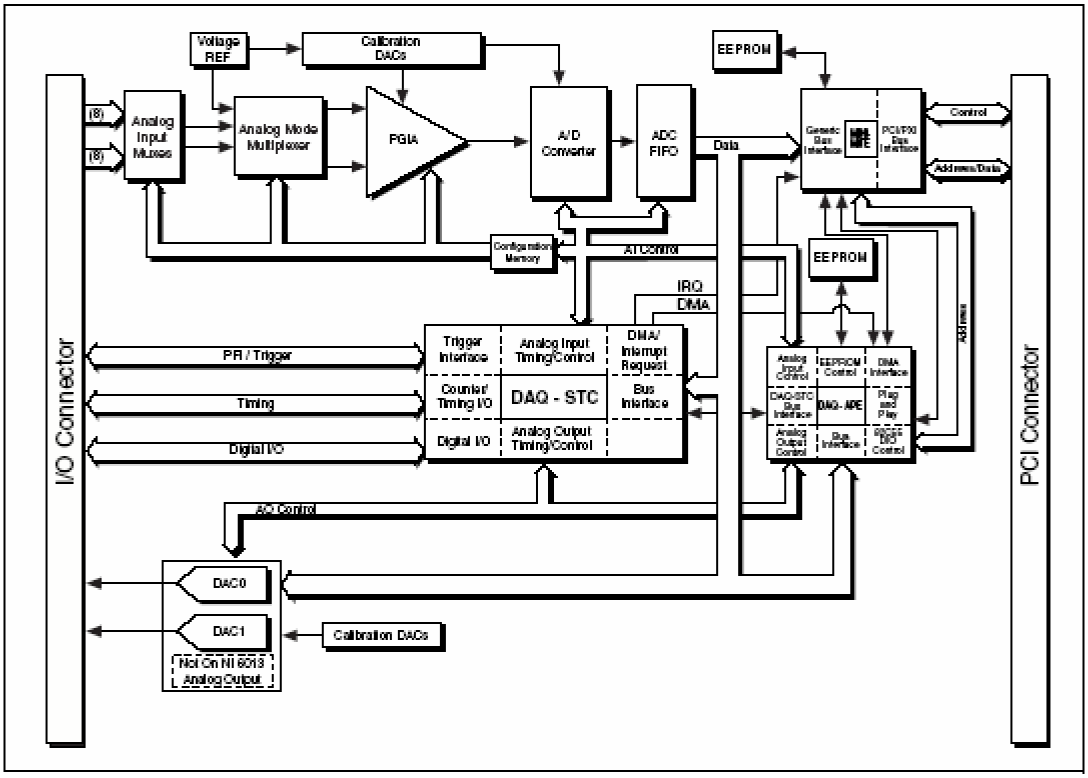


Figure 4.3 Block Diagram of the DAQ Card

A NI PCI 6013 DAQ card is a multifunction analog input –digital output device with 16 channels of 16 bit analog input. It uses a NI DAQ system-timing controller. The DAQ card can function with two modes of input, non-referenced single ended (NRSE) and Differential (DIFF) input. It has a bipolar input range and a programmable gain range depending upon the voltage supplied as shown in the Table 4.1

Table 4.1 Device Gain

Device Gain (Software Selectable)	Voltage
0.5	± 10 V
1	± 5V
10	± 500 mV
100	± 50 mV

It is connected to the connector block using a 68-pin connector cable. The pin assignment for the device is as shown in Fig 4.4

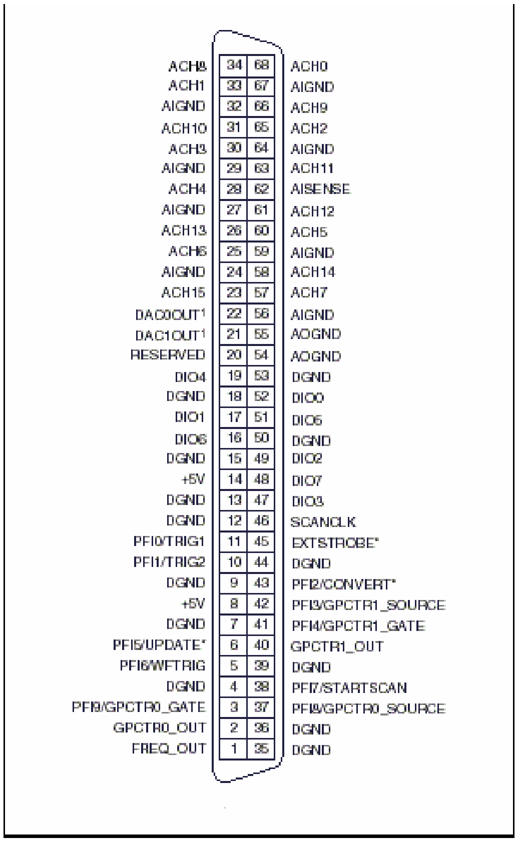


Figure 4.4 I/O Connector Pin Assignment

The other specifications of the DAQ card are as shown in Table 4.2

Table 4.2 DAQ Card Specifications

Input Characteristics	
Number of Channels	16 single ended or 8 differential
Type of ADC	Successive Approximation
Resolution	16 bits, 1 in 65,36
Sampling Rate	200 kS/s guaranteed
Input Signal Ranges	Bipolar Only
Input Coupling	DC

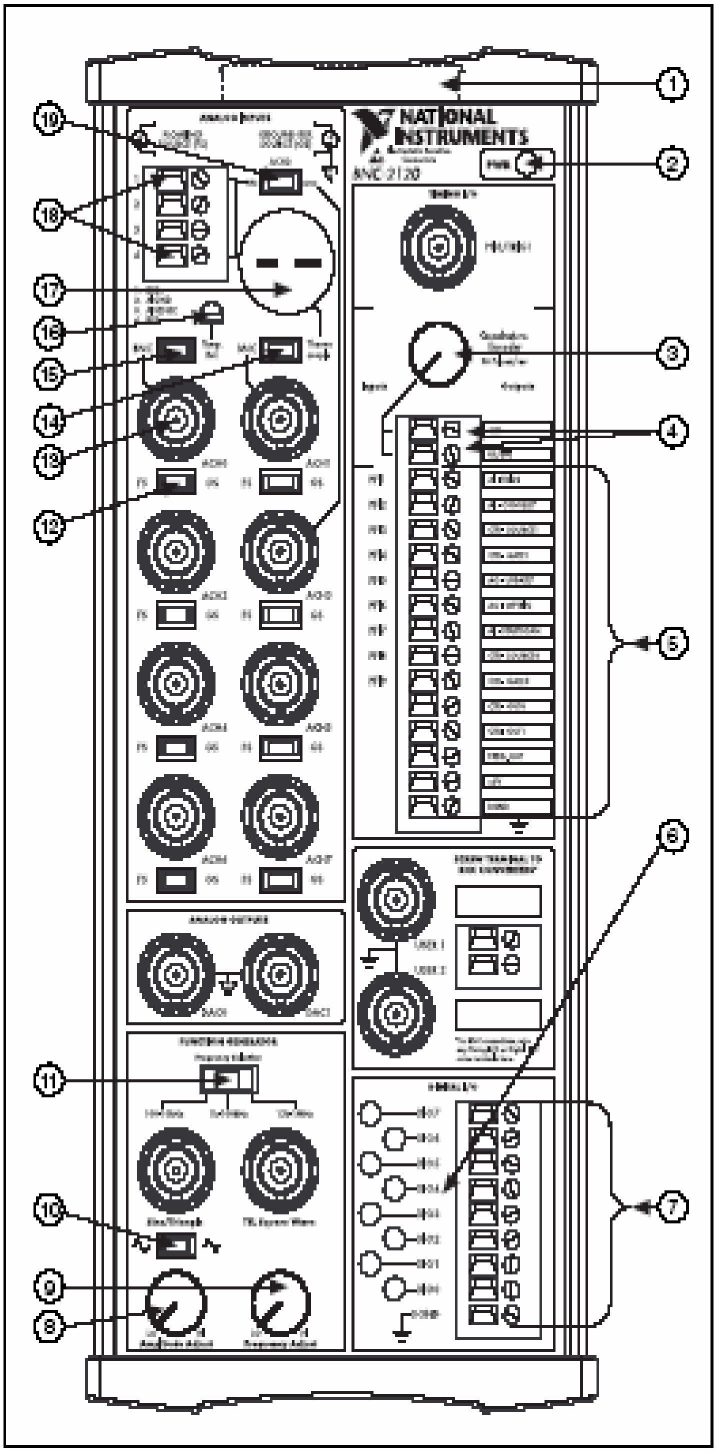
Table 4.2 Continued

Output Characteristics	
Voltage Output	± 10 V
Output Coupling	DC

4.3 Connector Block [20]

The connector block connects the sensors on the gripper fingers with the DAQ card. It has eight BNC connectors for analog input from a variety of sources, depending upon the application. It has two BNC connectors for Analog Outputs. It also has screw terminals for Digital Input- Output communication. A quadrature encoder is supported by the BNC 2120.

In the present application, the BNC would be used to connect the connectors from the sensors with the DAQ card. The input to the DAQ card will be analog input in the form of a voltage across the connectors. Using the Labview code, the force would be computed. The BNC 2120 is shown in Fig. 4.5



1	68-Position I/O Connector
2	Power LED Indicator
3	Quadrature Encoder Knob
4	Quadrature Encoder Output Screw Terminals
5	TIO Screw Terminals
6	DIO LED State Indicators
7	DIO Screw Terminals
8	Function Generator Amplitude Adjust Knob
9	Function Generator Frequency Adjust Knob
10	Sine/Triangle Waveform Selection Switch
11	Frequency Range Selection Switch
12	Floating Source (FS)/ Ground-Referenced Source (GS) Switch
13	BNC Connector
14	BNC/Thermocouple Selection Switch
15	BNC/Temperature Reference Selection Switch
16	Temperature Reference
17	Thermocouple Input Connector
18	Resistor Measurement Screw Terminals
19	Resistor/BNC Selection Switch

Figure 4.5 BNC 2120

4.4 LabView Code [21]

4.4.1 LabView

LabView is a graphical programming language that uses icons instead of lines of text to create applications. In contrast to text-based programming languages, where instructions determine program execution, LabView uses dataflow programming, where the flow of data determines execution.

In Labview, a user interface is built using a set of tools and objects. The user interface is known as the front panel. A code is then added graphical representations of functions to control the front panel objects. The code is contained in the block diagram.

The front panel and the block diagram for the force measurement system are shown respectively in Figure 4.6 and Figure 4.7.

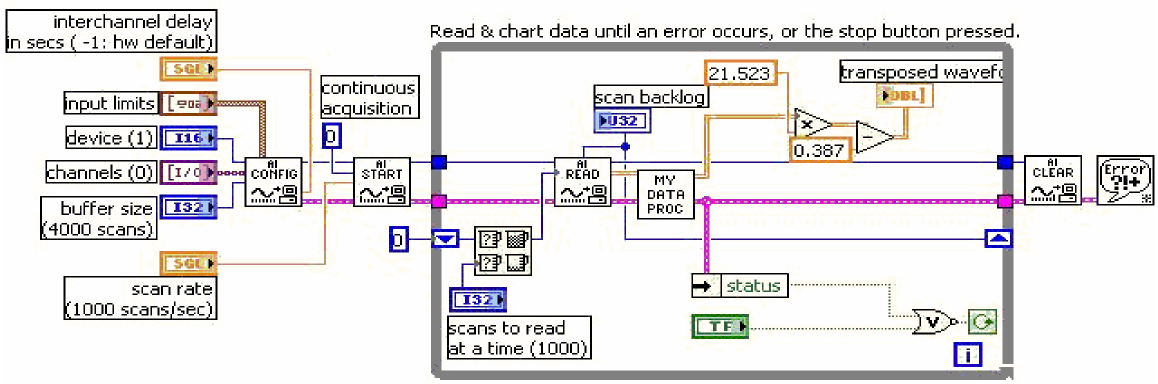
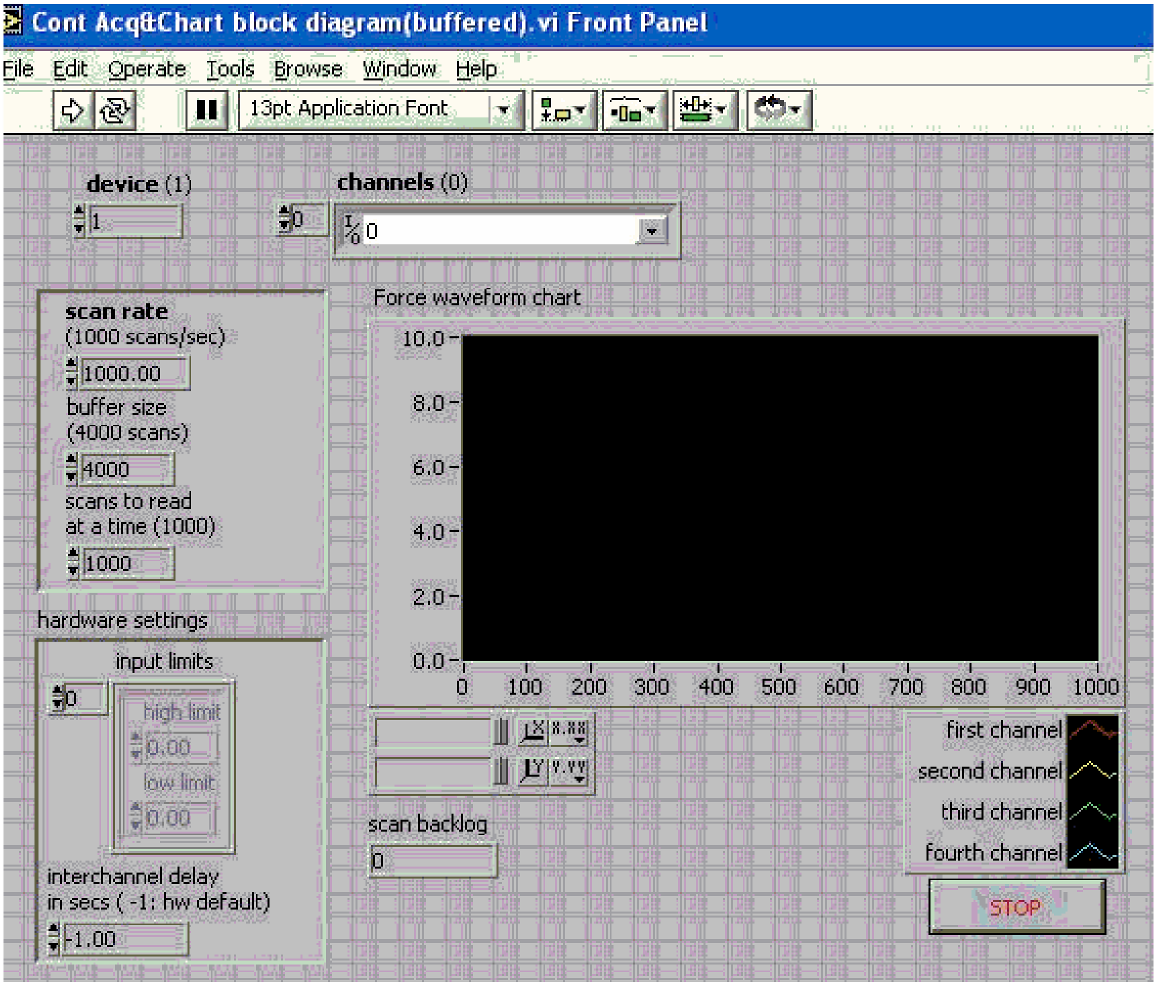


Figure 4.6 Block Diagram for the Force Measurement System



device (1): 1

channels (0): 0

scan rate (1000 scans/sec): 1000.00

buffer size (4000 scans): 4000

scans to read at a time (1000): 1000

hardware settings

input limits: 0

high limit: 0.00

low limit: 0.00

interchannel delay in secs (-1: hw default): -1.00

scan backlog: 0

Figure 4.7 Front Panel for the Force Measurement System

4.4.2 Code Logic

When the gripper grasps an object, a gripping force acts mutually, on the object and the sensor mounted on the finger of the gripper. The resistance of the silver filament Mounted inside the sensor changes and as a result a voltage change takes place across the leads of the sensor. The force and voltage output for the sensor is related by the relationship

$$F=21.523V-0.3871.$$

The change of voltage is fed to the DAQ card via the connector block. The three fingers will provide such data to the DAQ card. Also, the process is a time dependent process. Hence the data processing has to be dynamic. A scan rate of 1000 scans per sec is provided so that the data is continuously monitored. The first output of the loop is a continuous voltage data. To every voltage computed, the relationship is applied and the output is seen as a graph of Force versus Time on the front panel.

4.5 Control Circuit

In order to ensure that the gripper does not damage the object, by the use of excessive force, a circuit was designed to stop the actuating motors when gripping force reaches a predefined value. The control circuit and its components are described in this section.

Circuit Description:

When the gripper holds an object, the sensor attached to the finger of the gripper senses the gripping force and gives out a voltage output. This voltage is used as the controlling parameter to stop the motors when force exceeds a predefined value. However, the sensor output voltage is very feeble and cannot be directly used as the triggering voltage for a relay to stop the motor. Hence an amplifier circuit was designed to amplify the output to the relay triggering voltage of 9 V. The voltage output of each sensor is supplied to an Operational Amplifier, which also acts as an adder. The voltage output is added and amplified by varying the gain of the amplifier circuit. The relay used is a normally closed (NC) relay, which is connected in the motor driving circuit. When the relay encounters the triggering voltage from the sensor, it flips to the open position thereby breaking the circuit and stopping the motors.

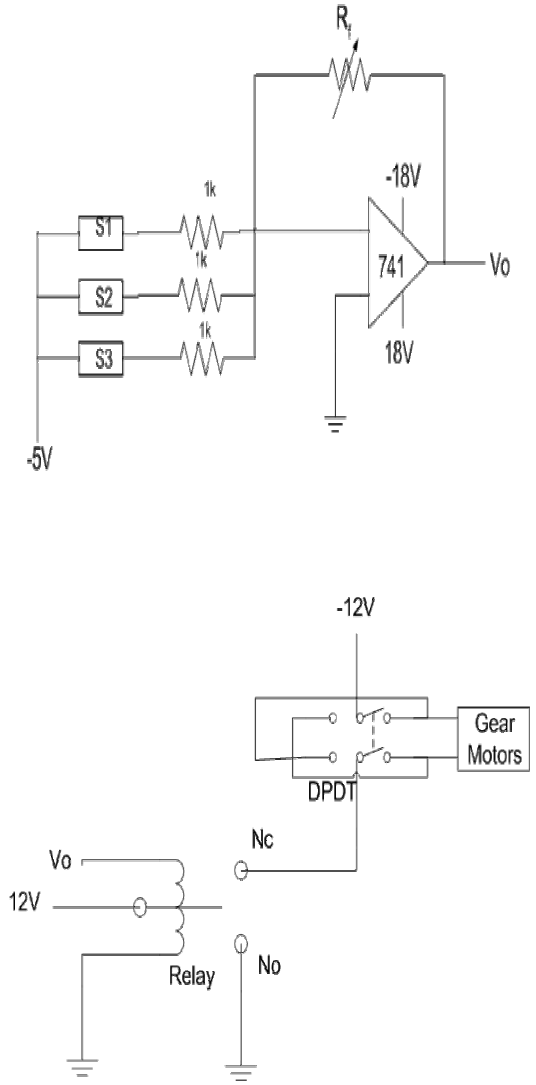
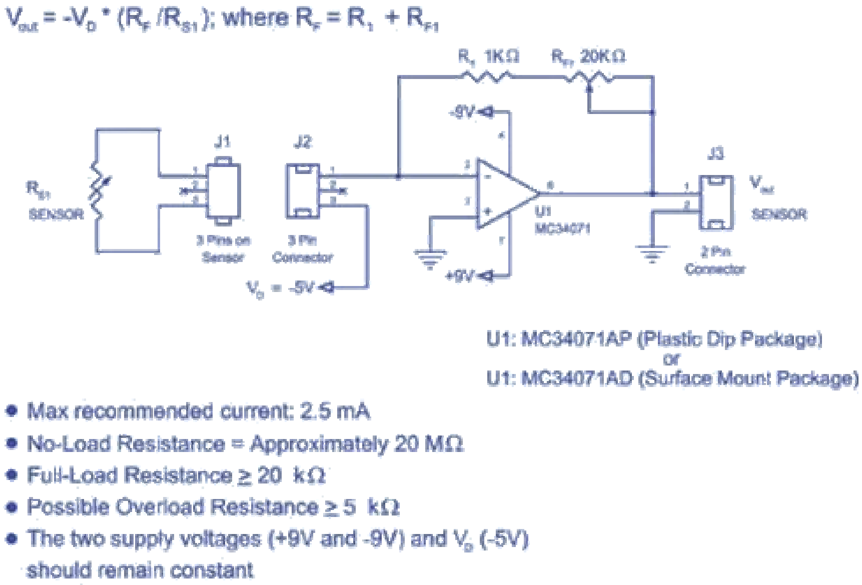


Figure 4.8 Complete Circuit Schematic Diagram

The circuit can be divided into two parts for further explanation.

4.5.1 Op-Amp Adder Circuit [18], [22], [23]

An Op-Amp adder circuit was used to amplify the sensor output. A circuit similar to the one shown in Fig. 4.8



$V_{out} = -V_D * (R_F / R_{S1})$; where $R_F = R_1 + R_{F1}$

U1: MC34071AP (Plastic Dip Package)
or
U1: MC34071AD (Surface Mount Package)

- Max recommended current: 2.5 mA
- No-Load Resistance = Approximately 20 MΩ
- Full-Load Resistance ≥ 20 kΩ
- Possible Overload Resistance ≥ 5 kΩ
- The two supply voltages (+9V and -9V) and V_D (-5V) should remain constant

Figure 4.9 Sensor Actuation Circuit

As is shown in Fig 4.8, an input of –5 V is given to the sensor. The output of each sensor is provided to pin 2 of an 8 pin-inverting amplifier as shown in Fig.4.9.

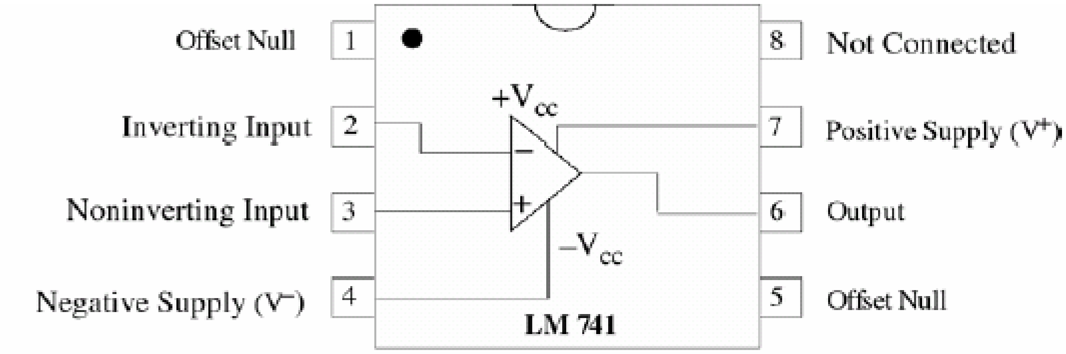


Figure 4.10 Operational Amplifier Pin Assignment

The Amplifier also acts like the adder as is shown in Fig.4.10. It is powered by +/- 18 V. In order to vary the gain of the amplifier circuit, a potentiometer with a range of 0-500 kΩ was used. The output voltage of the op-amp circuit acts like the triggering voltage for the relay.

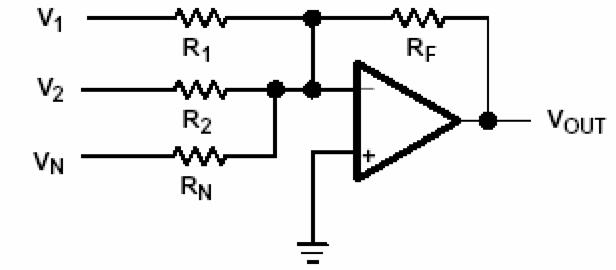


Figure 4.11 Adder Circuit

4.5.2 Relay [24]

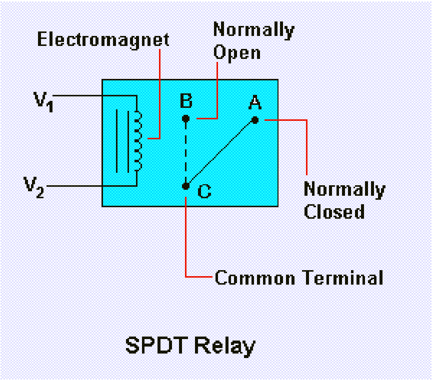


Figure 4.12 SPDT Relay

A relay is essentially an SPDT switch that is controlled by an electromagnet. As is shown in Fig.4.11, when a voltage V_1 and V_2 is applied across the coil of the relay, the electromagnet acts upon the SPDT thereby connecting terminals B and C. The voltage required for the electromagnet in the relay that was used in the circuit is 9 V. The relay is connected as a switch in the motor driving circuit so that the terminals A and C are connected to power supply and the motor lead respectively. When the electromagnet is activated by the amplified sensor voltage, the circuit breaks and the motor stops.

Chapter Five

Results and Discussions

Objects with different shapes, sizes and masses were grasped using the gripper to test its performance. Cylindrical, Spherical and Planar objects were selected to demonstrate the efficiency in grasping different shapes. Objects in everyday use are used to test the gripper, which shows that the gripper can be used as a part of a rehabilitation robot in accomplishing activities of daily living. The gripping forces are measured and the results are analyzed in this chapter.

5.1 Results

5.1.1 Cylindrical Objects

A coffee mug, a soda can and a plastic bottle, representing cylindrical objects in everyday life, were the objects used in testing the gripper. The three objects represent objects of different size and mass. The gripping forces were measured and are represented in Table 5.1.The gripping forces as seen on the force measurement system for the coffee mug, plastic bottle and soda can are shown in figures 5.1, 5.2 and 5.3 respectively.

Table 5.1 Gripping Forces for Cylindrical Objects

Object	Object Mass (oz)	Gripping Force (oz)			
		Trial 1	Trial 2	Trial3	Average Gripping Force
Coffee Mug	8.0	7.77	8.05	10.67	8.83
Plastic Bottle	12.0	11.85	10.6	10.65	11.03
Soda Can	13.5	10.67	14.88	10.01	11.85

Figure 5.1 Gripper Grasping the Coffee Mug

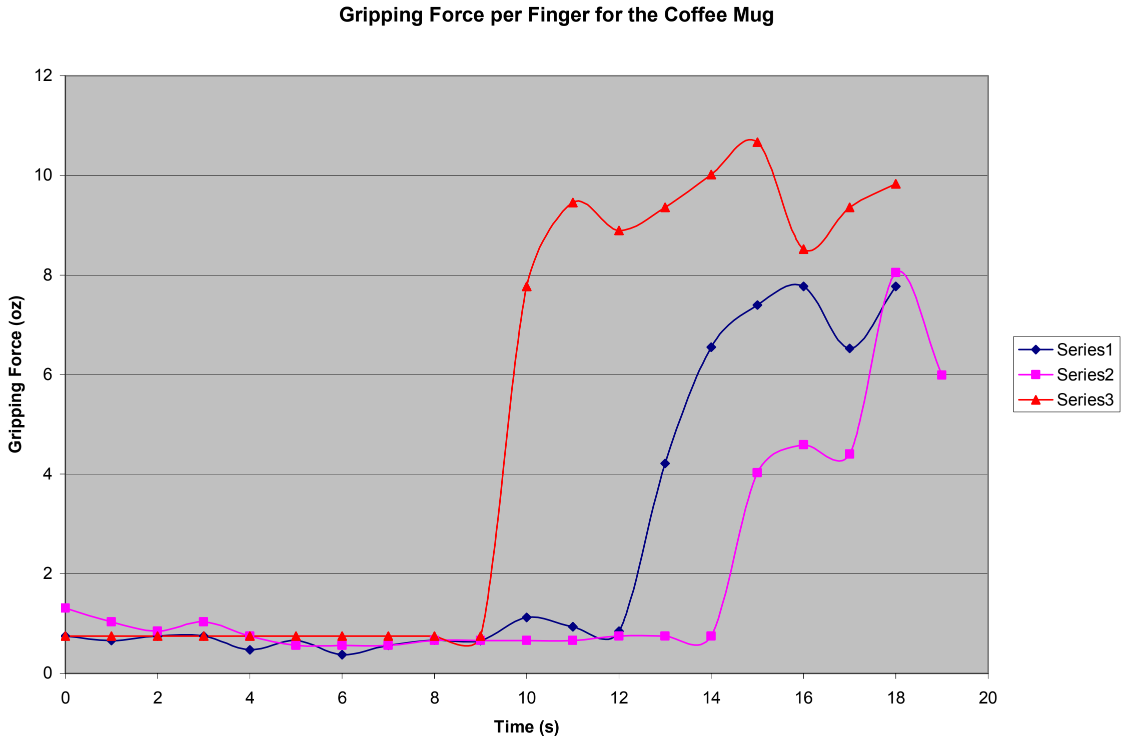


Figure 5.2 Gripping Forces for Coffee Mug

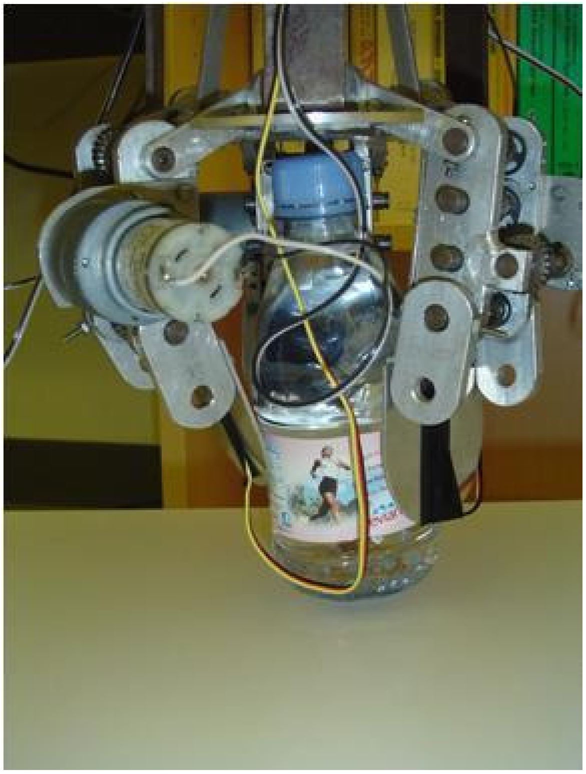


Figure 5.3 Gripper Grasping the Plastic Bottle

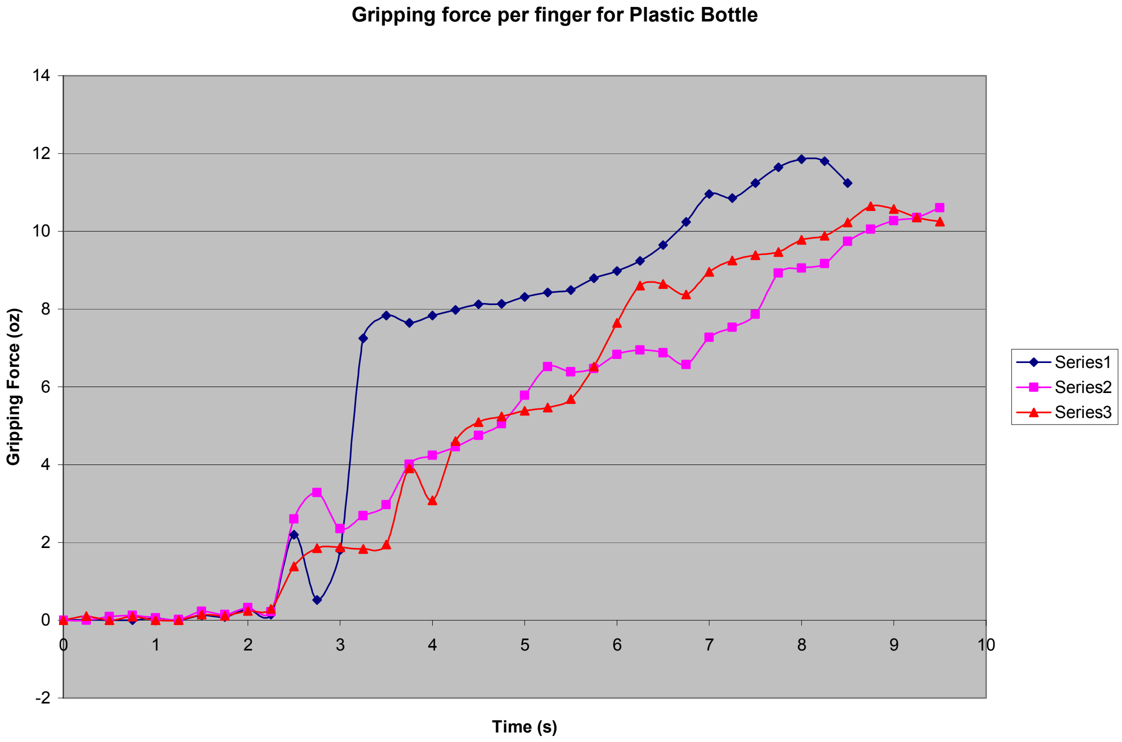


Figure 5.4 Gripping Forces on Plastic Bottle

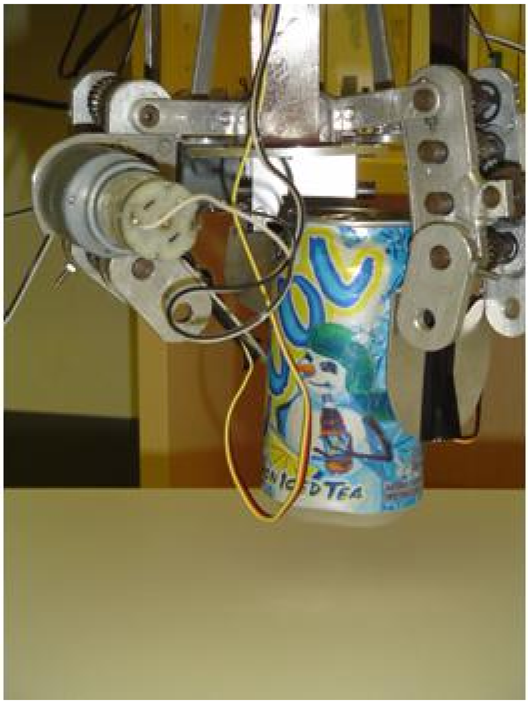


Figure 5.5 Gripper Grasping the Soda Can

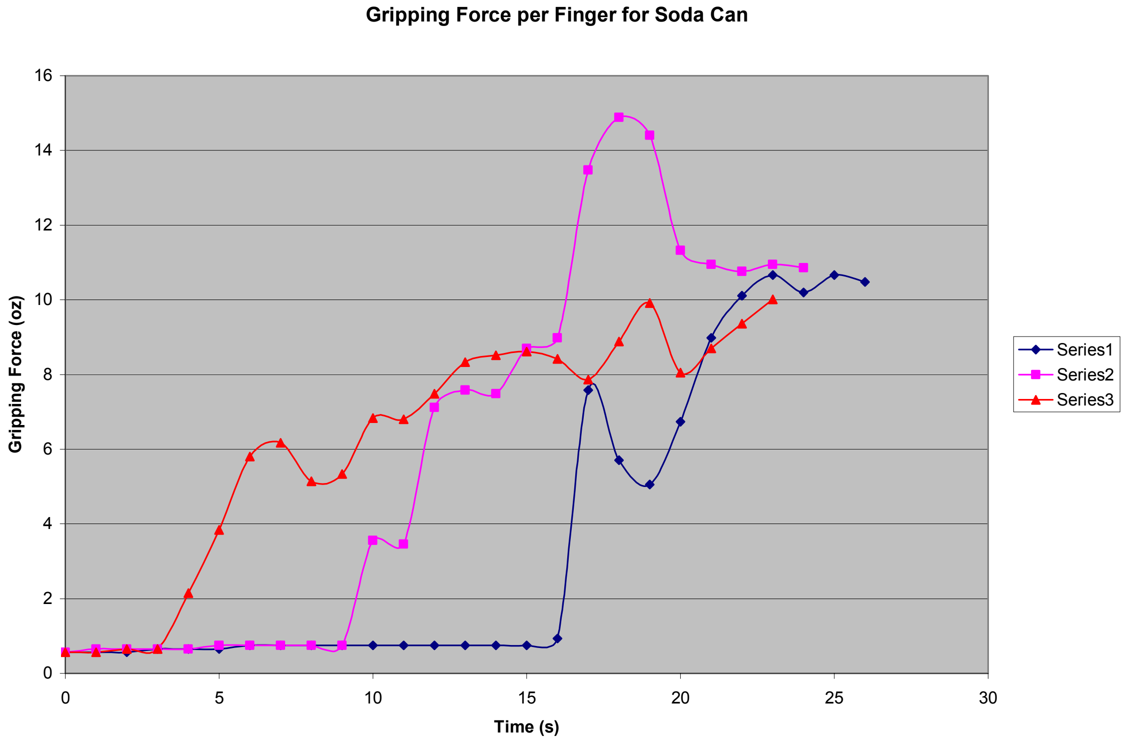


Figure 5.6 Gripping Forces on Soda Can

5.1.2 Spherical Objects

A spherical doorknob, a baseball and a grapefruit were the spherical objects used to test the gripper. While the doorknob and baseball represented exact spheres, the grapefruit was not exactly spherical. Yet, the gripper grasped it successfully. This demonstrated the ability of the gripper to accommodate different shapes. The gripping force measured is shown in Table 5.2.Figures 5.4, 5.5 and 5.6 show the forces on the front panel of the data acquisition system respectively for the door knob, baseball and grapefruit.

Table 5.2 Gripping Forces for Spherical Objects

Object	Object Mass (oz)	Gripping Force (oz)			
		Trial 1	Trial 2	Trial3	Average Gripping Force
Door Knob	8.25	8.05	9.64	8.70	8.80
Baseball	5.0	5.61	5.81	4.64	5.35
Grapefruit	13.5	12.82	12.56	15.23	13.54

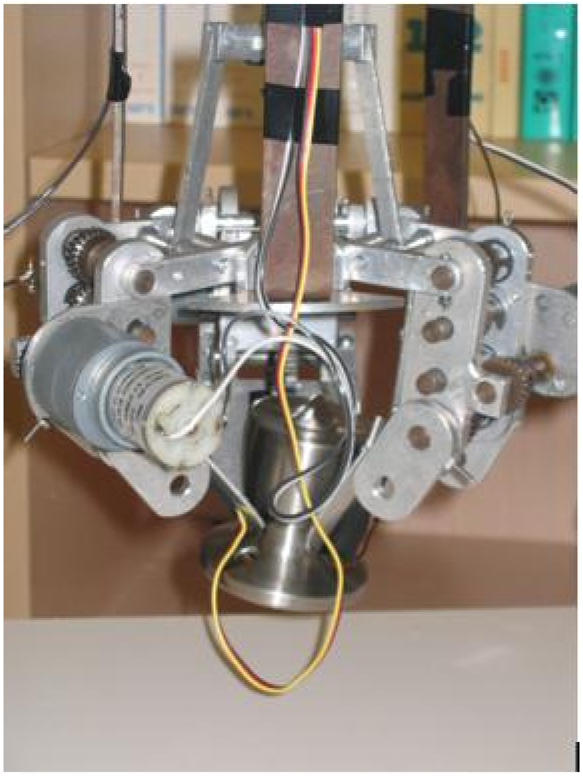


Figure 5.7 Gripper Grasping the Door Knob

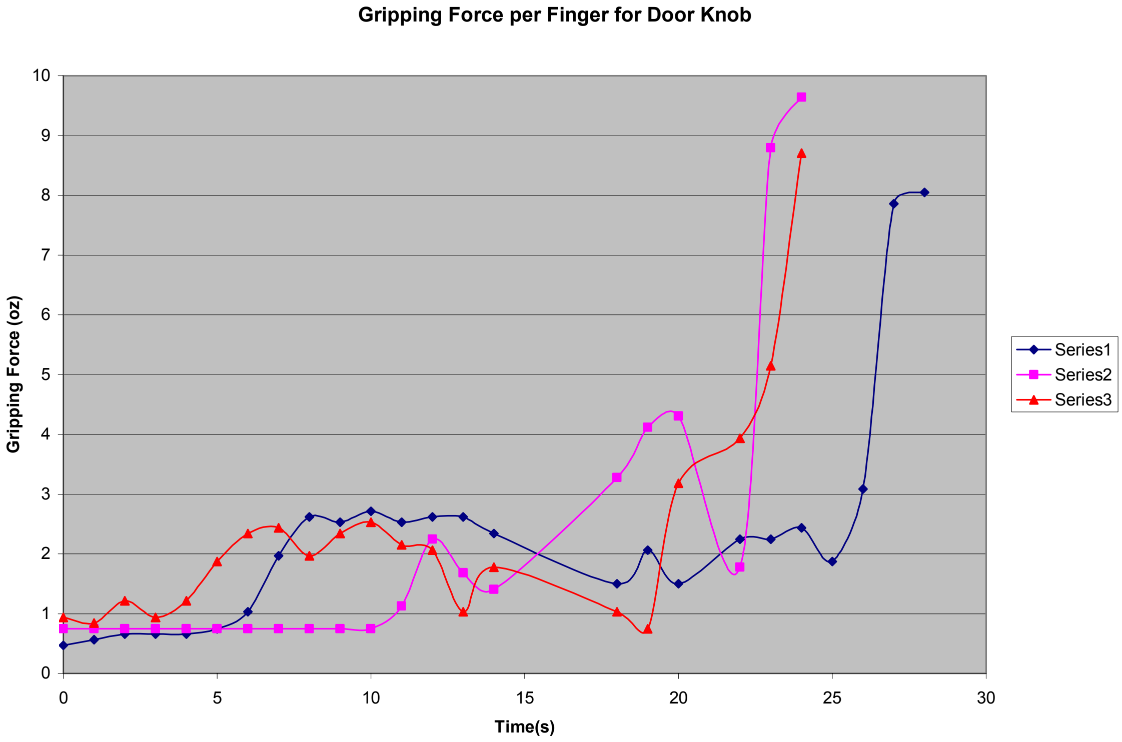


Figure 5.8 Gripping Forces for Door Knob

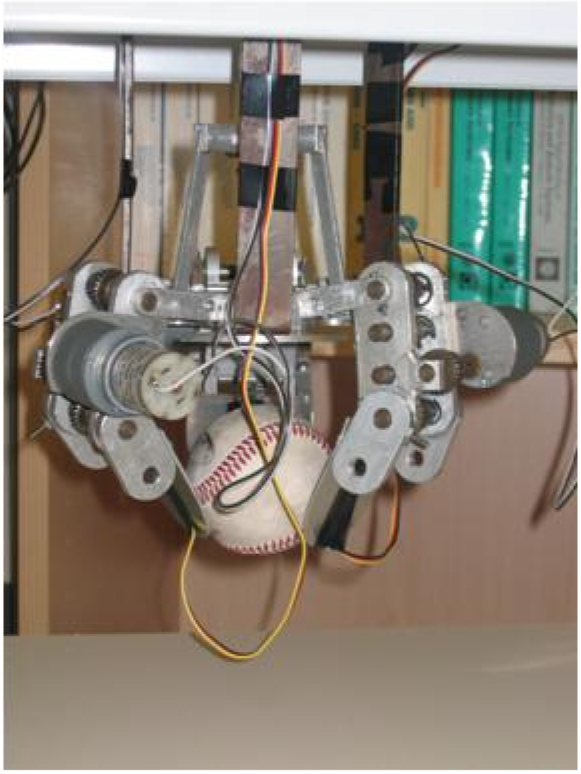


Figure 5.9 Gripper Grasping the Baseball

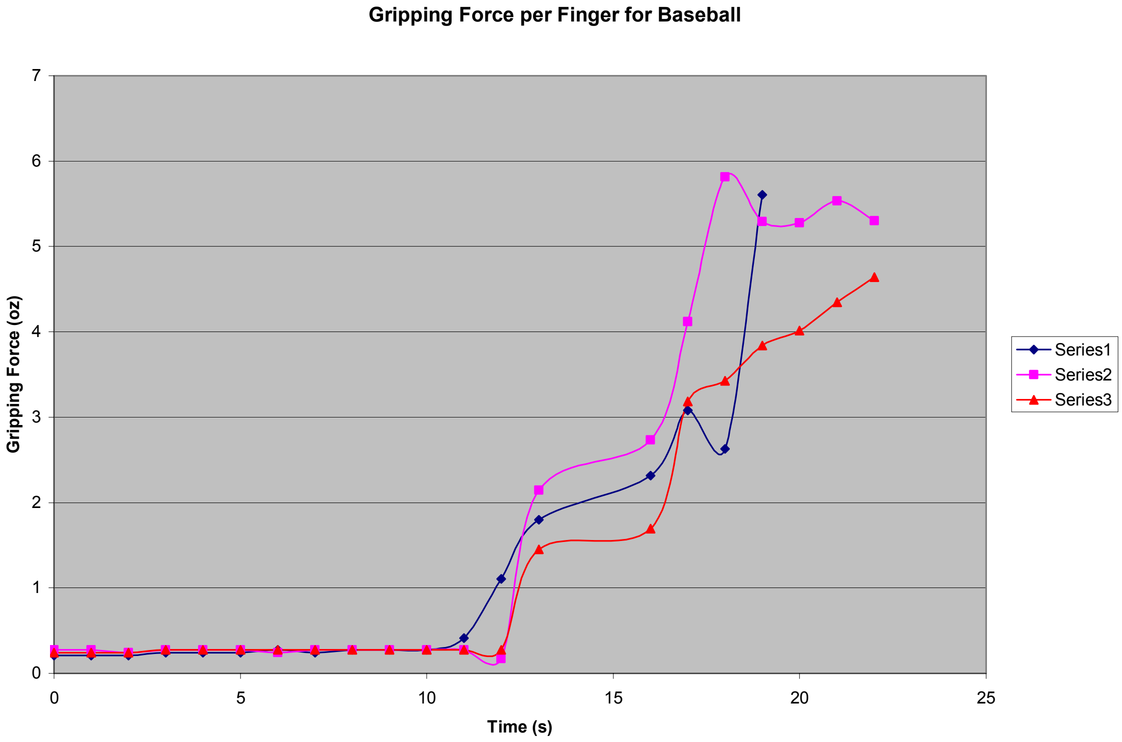


Figure 5.10 Gripping Forces on Baseball

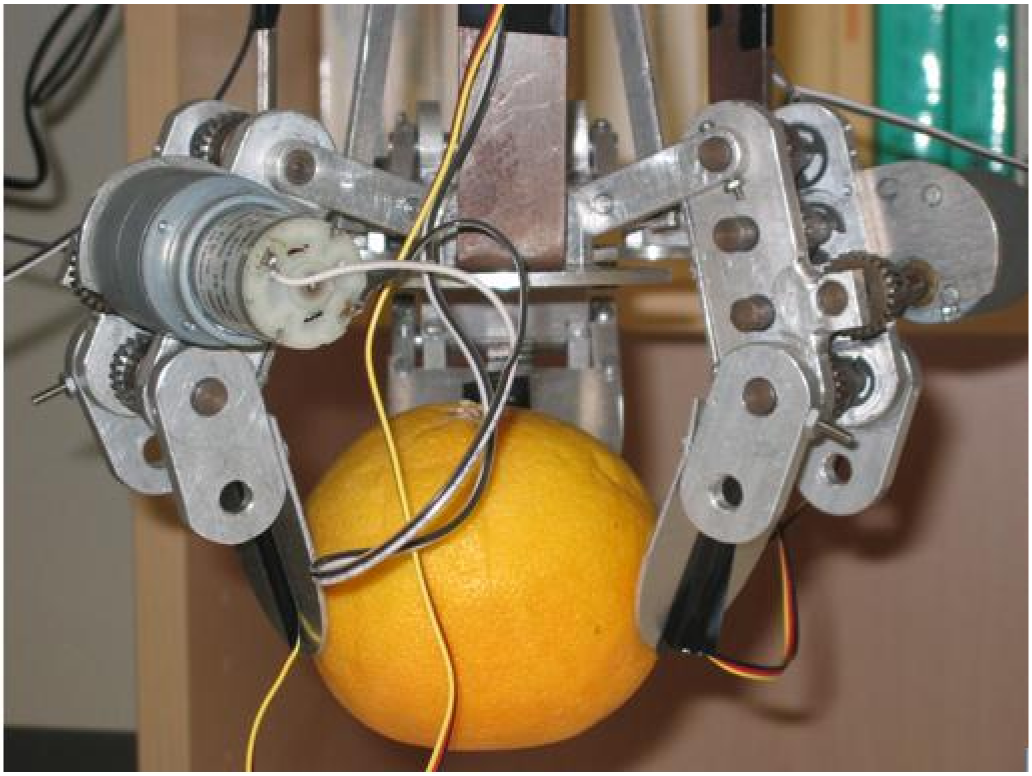


Figure 5.11 Gripper Grasping the Grapefruit

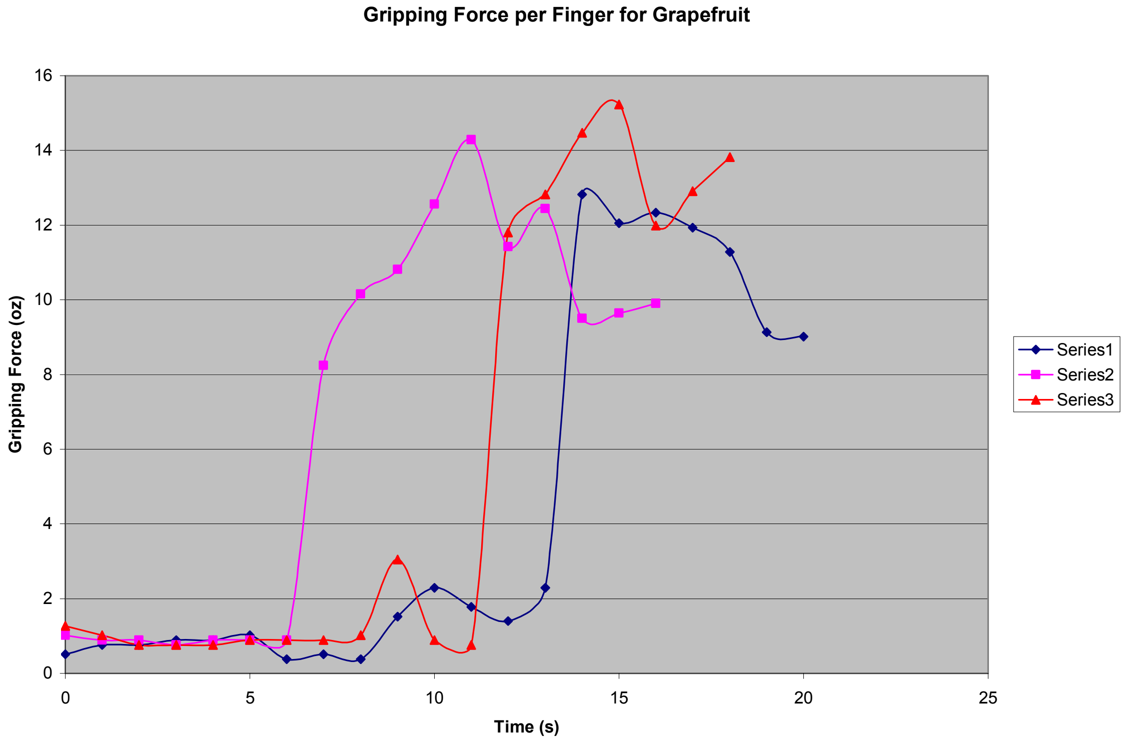


Figure 5.12 Gripping Forces on Grapefruit

5.1.3 Planar Objects

Three objects with planar faces, viz. a cardboard box, a cell phone and a stapler were selected as specimen. The gripping forces measured are as shown in table 5.3. The gripping forces are as shown in Fig. 5.7, 5.8 and 5.9.

Table 5.2 Gripping Forces for Spherical Objects

Object	Object Mass (oz)	Gripping Force (oz)			
		Trial 1	Trial 2	Trial3	Average Gripping Force
Cardboard Box	2	2.2	3.28	1.95	2.48
Cell Phone	4.5	5.13	5.6	5.92	5.55
Stapler	14	14.68	14.23	13.89	14.27

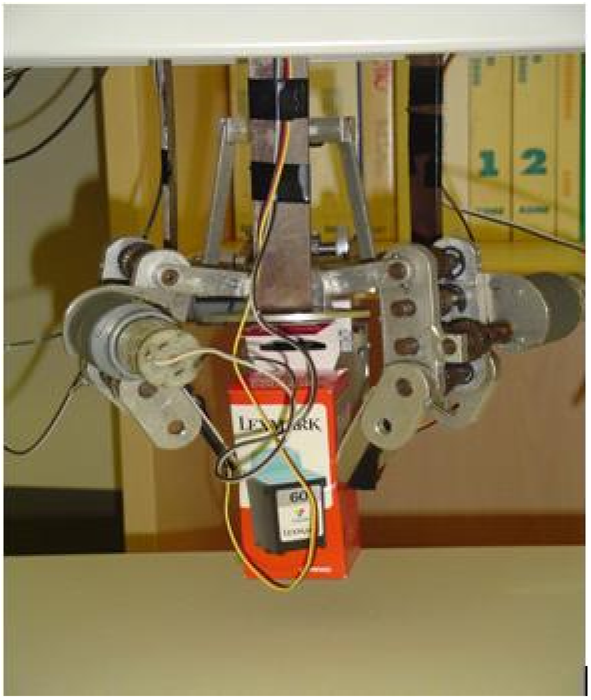


Figure 5.13 Gripper Grasping the Cardboard Box

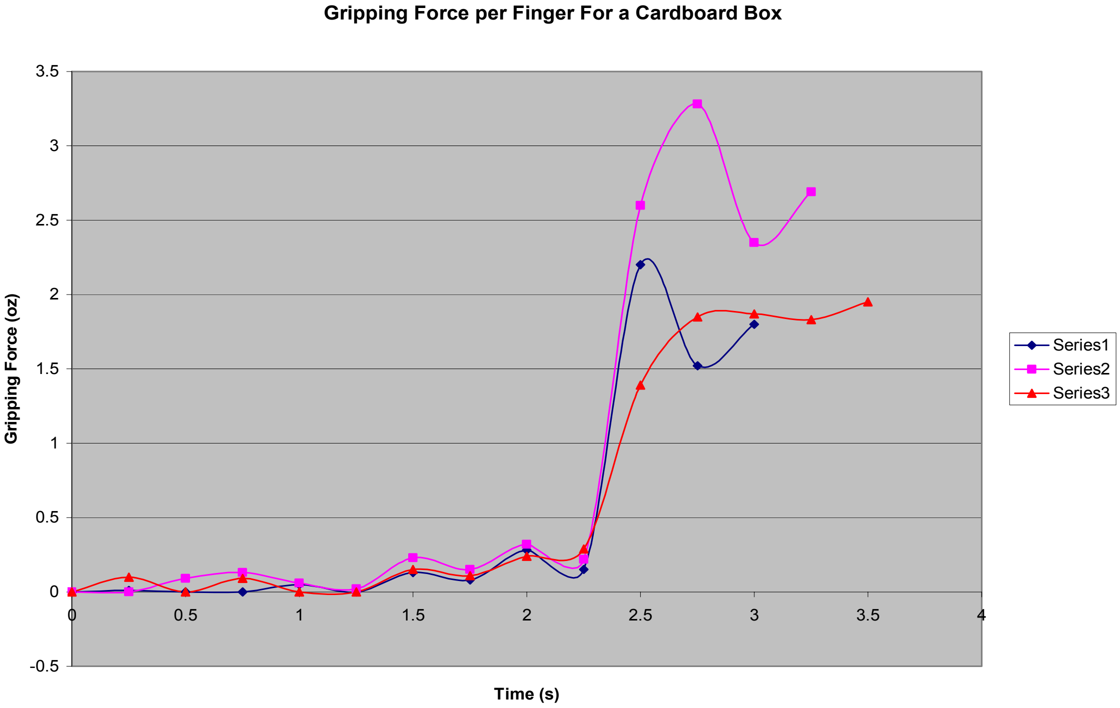


Figure 5.14 Gripping Forces on Cardboard Box

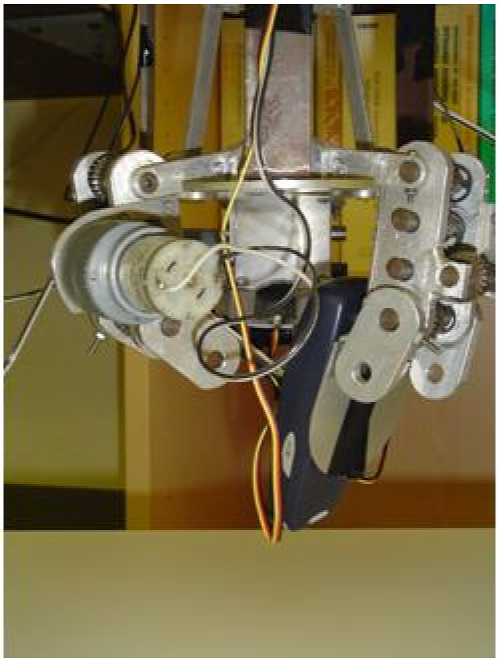


Figure 5.15 Gripper Grasping the Cell phone

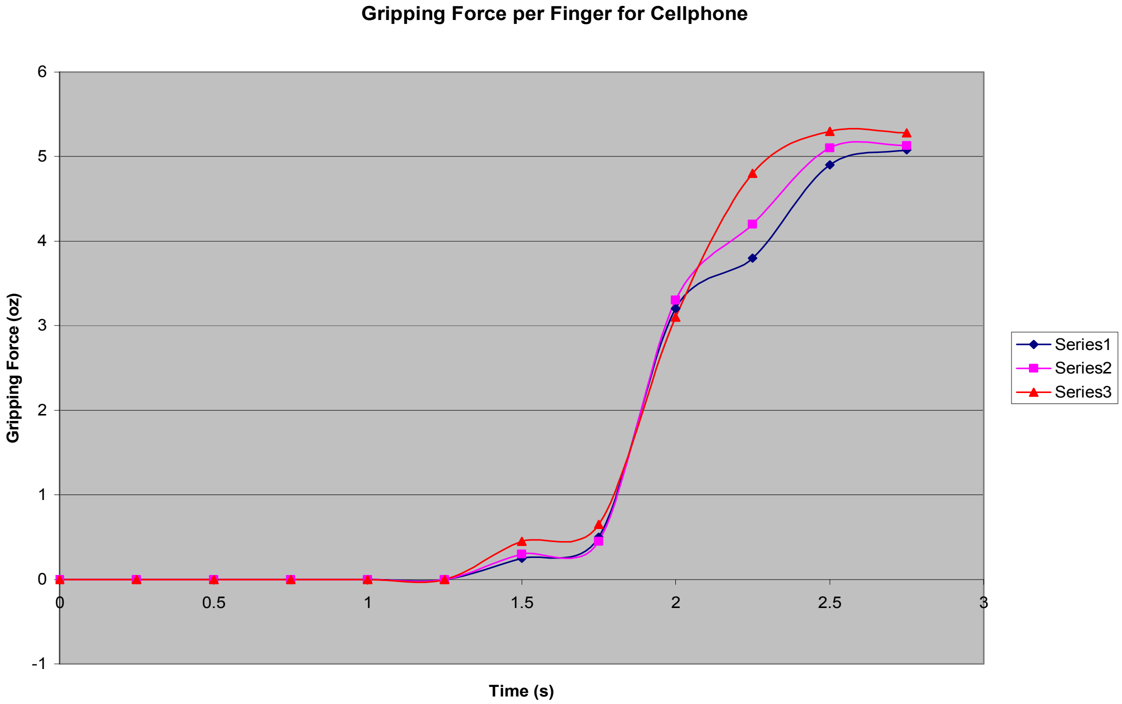


Figure 5.16 Gripping Forces on Cell Phone

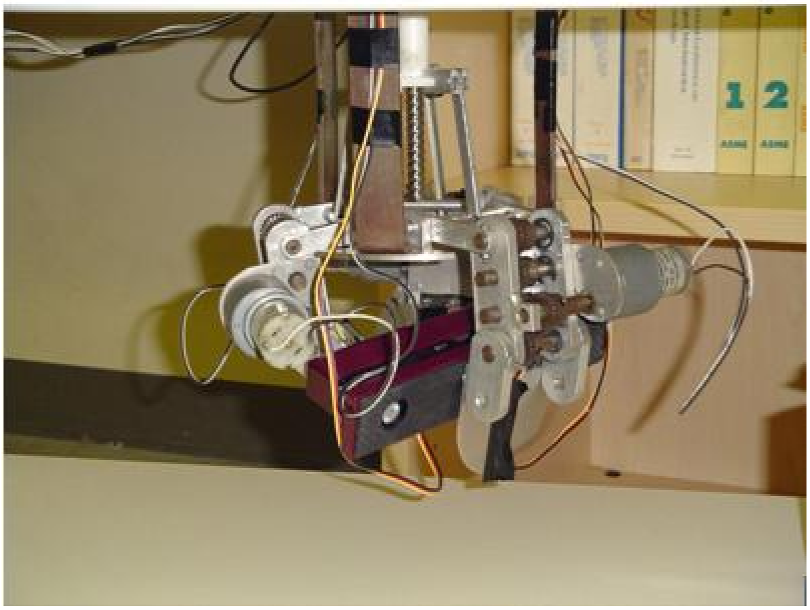


Figure 5.17 Gripper Grasping the Stapler

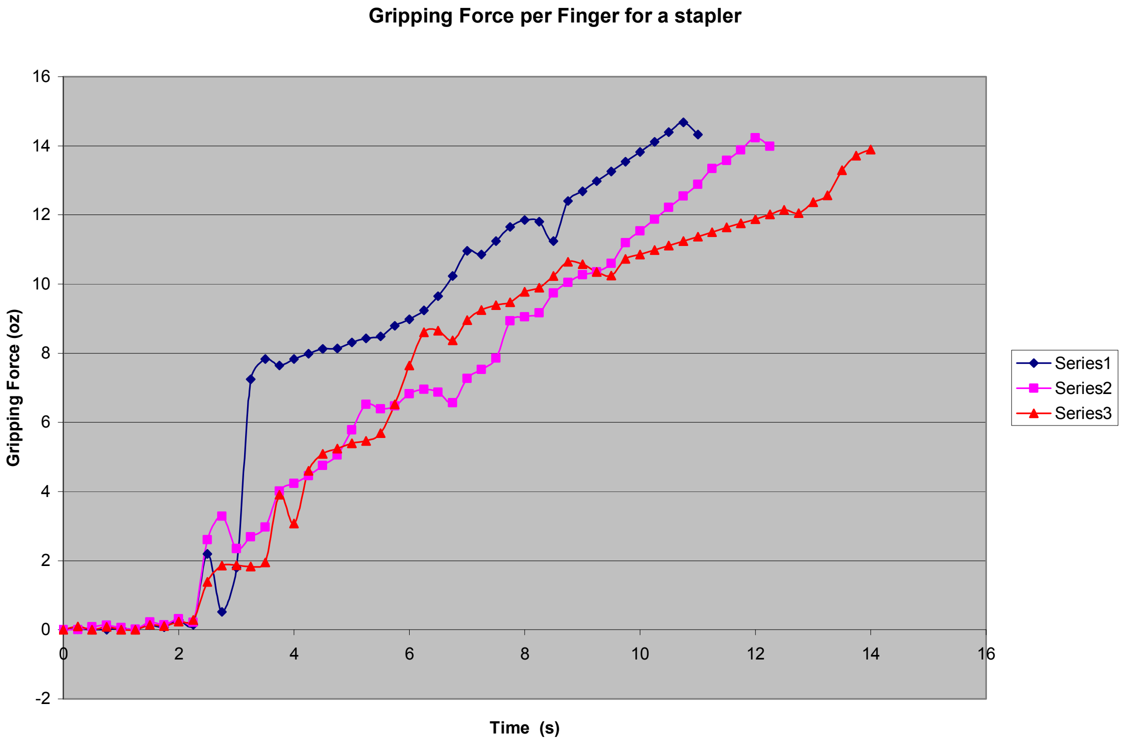


Figure 5.18 Gripping Forces on Stapler

5.2 Analysis of the Results

As is seen from the curves, the plot of gripping force with respect to time follows a uniform pattern.

As the finger moves inwards to grasp the object, there is no force acting on the sensor. As a result, the voltage output of the sensor is zero. This phase continues until some contact between the object and the finger occurs. This is shown by a phase of very low forces on the force plots.

As soon as the contact between the object and the sensor occurs, the resistance of the sensor drops rapidly. This causes a sudden change in the voltage output of the sensors and thereby the force on the sensor as is shown in the plots.

As the contact force level reaches a preset level, the relay is activated thereby breaking the motor activation circuit. This stops the motion of the fingers. The object is now securely held between the fingers and the forces remain constant. This is shown by a drop in the slope of the curve.

The plots show some random variations in the general pattern. This may occur because of a variety of reasons. As the gripper is mounted on a stationary platform, a change in initial placement of the object gives very different results. This may cause a variable force distribution between the fingers. As a result, the force patterns and the cycle time for each trial is not necessarily the same.

The sensor is very sensitive to even slight variations in forces. As a result, an occasional spike occurs even when the object is not grasped. This can be attributed to slight jerks in the finger motion. Also, electrical noise from the circuit can cause the spike.

In cases like grasping the plastic bottle or grapefruit, the object gets slightly deformed upon contact. As a result, the force on each sensor is not necessarily the same. This causes the relay to activate at different times and for different force values. As a result, the peak force value for each trial is not the same.

Chapter Six

Conclusion and Recommendations

6.1 Conclusions

A prototype articulated gripper was developed to improve the overall manipulation capabilities of a wheelchair mounted robot arm. This prototype serves as a gripper, which can handle objects of various shapes and sizes for objects with a mass up to 4 lbs.

Initially, the pre development surveys used in development of robotic assistive devices were studied. The user task priorities were discussed and the role of the gripper in accomplishing those tasks was identified. The features of the grippers on commercially available rehabilitation robots were studied and design parameters were evaluated.

A mechanical design process followed and a prototype was developed based on the design criteria and calculations. The prototype was tested and modified until the mechanical performance of the gripper was found satisfactory.

Force sensors were calibrated to establish the force-voltage relationship. The force sensors were attached to the fingers of the robot. A Data Acquisition System was developed using a Data Acquisition Card from National Instruments Inc. LabView was used to program the DAQ Card for continuous voltage measurement.

A wide variety of objects used in everyday life were selected based on shape, size and the mass of the objects. These objects were picked up using the gripper and the gripping forces were measured using the DAQ system. The results were documented and analyzed.

A force feedback circuit was developed using an inverting amplifier and relay system. Based on the forces required to grip each object, a cut off force was determined. A relay circuit was designed so that upon attainment of the threshold force, the motors would stop. This enabled the gripper to grasp objects reliably and securely without damaging them.

The prototype gripper with some necessary modifications can perform as an effective end -effector for a wheelchair mounted robot. The force feedback and the relay mechanism present an effective safety feature that would enable the gripper to grasp objects without damaging them.

6.2 Future Recommendations

The results and the performance of the gripper while handling objects showed that the gripper could handle objects of complex shapes. The force feedback circuit demonstrated the efficacy of the control feature implemented to ensure the reliability of the grasp. However, the gripper would perform better if some modifications and additional features are added.

The gripper used DC Gear motors as its actuators. The design had to be modified in order to make room for the motors. The links had to be made longer and thicker to accommodate the motors in the assembly. The motors account for more than 50% of the mass of the gripper itself. The size of the motor makes it difficult to mount it close to the centerline of the gripper. As a result, motors are directly attached to the finger link.

This presents a problem of too much mass away from the centerline of the gripper. As a result, the motion of the gripper is not smooth. Also, it causes excessive force and drag on the power nut. Also, the motors do not have encoders. This makes positional feedback a difficult proposition. The gripper cannot be attached to a wheelchair mounted robotic arm owing to its size and bulk.

Servomotors present a better solution to this problem as they can deliver the same torque with a very small size and mass. The smaller size of servomotors would make it possible to mount the motors between the cranks. This would make the gripper more compact and lighter. Also, the servomotor could be programmed using a Basic Stamp that would make provision for positional feedback.

The servomotor should be mounted along the finger instead of being perpendicular to the finger. This would be accomplished by using a bevel gear pair between the motor shaft and the finger gear. Also, plastic gears should be used to replace the metal gears. This would reduce the mass of the gripper.

Two DPDT switches are used to control the motion of the gripper. With the use of an Analog-to- Digital Converter, a single joystick would replace the two switches thereby providing more control over the gripping of the motor.

The gripper presents a practical solution for grasping and shape accommodation. However, the gripper cannot be used to manipulate objects. Providing an active wrist with two degrees of freedom would make it more versatile in handling as well as manipulating objects. With an active wrist, compact size and lightweight and assistance with force and position feedback, the gripper would certainly become a state of the art end- effector.

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Appendices

Appendix A: Source Data

a) Coffee Mug.

Table A.1 Data for the Gripping Forces while Grasping Coffee Mug

Time	Gripping Force (oz)		
(sec.)	Trial 1	Trial 2	Trial 3
0	0.748587	1.310027	0.748587
1	0.655013	1.029307	0.748587
2	0.748587	0.84216	0.748587
3	0.748587	1.029307	0.748587
4	0.467867	0.748587	0.748587
5	0.655013	0.56144	0.748587
6	0.374293	0.56144	0.748587
7	0.56144	0.56144	0.748587
8	0.66438	0.655013	0.748587
9	0.655013	0.655013	0.748587
10	1.12288	0.655013	7.766587
11	0.935733	0.655013	9.450907
12	0.84216	0.748587	8.889467
13	4.2108	0.748587	9.357333
14	6.550133	0.748587	10.01235
15	7.392293	4.023653	10.66736
16	7.766587	4.585093	8.515173
17	6.52674	4.397947	9.357333
18	7.766587	8.047307	9.8252
19		5.988693	

Appendix A (contd.)

b) Plastic Bottle

Table A.2 Data for the Gripping Forces while Grasping a Plastic Bottle

Time (sec.)	Gripping Forces (oz.)		
	Trial 1	Trial 2	Trial 3
0	0	0	0
0.25	0.01	0	0.1
0.5	0	0.09	0
0.75	0	0.13	0.09
1	0.05	0.06	0
1.25	0	0.02	0
1.5	0.13	0.23	0.15
1.75	0.08	0.15	0.11
2	0.28	0.32	0.24
2.25	0.15	0.22	0.29
2.5	2.2	2.6	1.39
2.75	0.52	3.28	1.85
3	1.8	2.35	1.87
3.25	7.25	2.69	1.83
3.5	7.83	2.97	1.95
3.75	7.65	4.01	3.91
4	7.83	4.24	3.08
4.25	7.98	4.46	4.6
4.5	8.12	4.75	5.09
4.75	8.14	5.05	5.24
5	8.31	5.78	5.39
5.25	8.43	6.52	5.47

Appendix A (contd.)

Table A.2 Continued

5.5	8.49	6.39	5.69
5.75	8.79	6.47	6.52
6	8.98	6.83	7.65
6.25	9.24	6.95	8.6
6.5	9.65	6.87	8.65
6.75	10.24	6.57	8.37
7	10.96	7.27	8.96
7.25	10.85	7.53	9.25
7.5	11.24	7.86	9.39
7.75	11.65	8.93	9.47
8	11.85	9.05	9.78
8.25	11.8	9.17	9.89
8.5	11.24	9.74	10.23
8.75		10.05	10.65
9		10.27	10.57
9.25		10.35	10.35
9.5		10.6	10.25
			10.65

Appendix A (contd.)

c) Soda Can

Table A.3 Data for the Gripping Forces while Grasping Soda Can

Time (sec.)	Gripping Forces (oz.)		
	Trial 1	Trial 2	Trial 3
0	0.56144	0.56144	0.56144
1	0.56144	0.655013	0.56144
2	0.56144	0.655013	0.655013
3	0.655013	0.655013	0.655013
4	0.655013	0.655013	2.152187
5	0.655013	0.748587	3.836507
6	0.748587	0.748587	5.801547
7	0.748587	0.748587	6.17584
8	0.748587	0.748587	5.146533
9	0.748587	0.748587	5.33368
10	0.748587	3.555787	6.830853
11	0.748587	3.462213	6.802781
12	0.748587	7.111573	7.485867
13	0.748587	7.57944	8.328027
14	0.748587	7.485867	8.515173
15	0.748587	8.70232	8.608747
16	0.935733	8.98304	8.4216
17	7.57944	13.47456	7.86016
18	5.707973	14.87816	8.889467
19	5.05296	14.41029	9.918773
20	6.73728	11.32237	8.047307
21	8.98304	10.94808	8.70232

Appendix A (contd.)

Table A.3 Continued

22	10.10592	10.76093	9.357333
23	10.66736	10.94808	10.01235
24	10.19949	10.85451	
25	10.66736	14.87816	
26	10.48021		
27	10.66736		

Appendix A (contd.)

d) Door Knob

Table A.4 Data for the Gripping Forces while Grasping Door Knob

Time (sec.)	Gripping Force (oz)		
	Trial 1	Trial 2	Trial 3
0	0.467867	0.748587	0.935733
2	0.655013	0.748587	1.216453
3	0.655013	0.748587	0.935733
4	0.655013	0.748587	1.216453
5	0.748587	0.748587	1.871467
6	1.029307	0.748587	2.339333
7	1.96504	0.748587	2.432907
8	2.620053	0.748587	1.96504
9	2.52648	0.748587	2.339333
10	2.713627	0.748587	2.52648
11	2.52648	1.12288	2.152187
12	2.620053	2.24576	2.058613
13	2.620053	1.68432	1.029307
14	2.339333	1.4036	1.777893
18	1.497173	3.275067	1.029307
19	2.058613	4.117227	0.748587
20	1.497173	4.304373	3.181493
22	2.24576	1.777893	3.93008
23	2.24576	8.795893	5.146533
24	2.432907	9.638053	8.70232
25	1.871467		
26	3.08792		

Appendix A (contd.)

e) Baseball

Table A.5 Data for the Gripping Forces while Grasping a Baseball

Time (sec.)	Gripping Force (oz.)		
	Trial 1	Trial 2	Trial 3
0	0.2076	0.2768	0.2422
1	0.2076	0.2768	0.2422
2	0.2076	0.2422	0.2422
3	0.2422	0.2768	0.2768
4	0.2422	0.2768	0.2768
5	0.2422	0.2768	0.2768
6	0.2768	0.2422	0.2768
7	0.2422	0.2768	0.2768
8	0.2768	0.2768	0.2768
9	0.2768	0.2768	0.2768
10	0.2768	0.2768	0.2768
11	0.4152	0.2768	0.2768
12	1.1072	0.173	0.2768
13	1.7992	2.1452	1.4532
16	2.3182	2.7334	1.6954
17	3.0794	4.1174	3.1832
18	2.6296	5.8128	3.4254
19	5.6052	5.2938	3.8406
20		5.279268	4.0136
21		5.531502	4.348067
22		5.300028	4.642167

Appendix A (contd.)

f) Grapefruit

Table A.6 Data for the Gripping Forces while Grasping Grapefruit

Time (sec.)	Gripping Forces (oz)		
	Trial 1	Trial 2	Trial 3
0	0.507627	1.015253	1.269067
1	0.76144	0.888347	1.015253
2	0.76144	0.888347	0.76144
3	0.888347	0.76144	0.76144
4	0.888347	0.888347	0.76144
5	1.015253	0.888347	0.888347
6	0.38072	0.888347	0.888347
7	0.507627	8.248933	0.888347
8	0.38072	10.1538	1.015253
9	1.52288	10.82006	3.04576
10	2.28432	12.56376	0.888347
11	1.776693	14.28461	0.76144
12	1.395973	11.4216	11.80232
13	2.28432	12.43685	12.81757
14	12.81757	9.502771	14.46736
15	12.0536	9.644907	15.2288
16	12.33533	9.89872	11.98951
17	11.92796		12.90547
18	11.28073		13.82144
19	9.13728		
20	9.010373		

g) Cardboard Box

Table A.7 Data for the Gripping Forces while Grasping Cardboard Box

Time (sec.)	Gripping Forces (oz.)		
	Trial 1	Trial 2	Trial 3
0	0	0	0
0.25	0.01	0	0.1
0.5	0	0.09	0
0.75	0	0.13	0.09
1	0.05	0.06	0
1.25	0	0.02	0
1.5	0.13	0.23	0.15
1.75	0.08	0.15	0.11
2	0.28	0.32	0.24
2.25	0.15	0.22	0.29
2.5	2.2	2.6	1.39
2.75	1.52	3.28	1.85
3	1.8	2.35	1.87
3.25		2.69	1.83
3.5			1.95
3.75			

Appendix A (contd.)

h) Cell Phone

Table A.8 Data for the Gripping Forces while Grasping a Cell Phone

Time (sec.)	Gripping Forces (oz.)		
	Trial 1	Trial 2	Trial 3
0	0	0	0
0.25	0	0	0
0.5	0	0	0
0.75	0	0	0
1	0	0	0
1.25	0	0	0
1.5	0.25	0.3	0.45
1.75	0.5	0.45	0.65
2	3.2	3.3	3.1
2.25	3.8	4.2	4.8
2.5	4.9	5.1	5.3
2.75	5.08	5.13	5.28
3	5.12	5.14	5.42
3.25	5.11	5.08	5.71
3.5	5.09	5.09	5.59
3.75	5.13	5.12	5.63
4	5.12	5.14	5.92
4.25	5.12	5.12	5.38
4.5	5.11	5.09	5.51
4.75	5.08	5.08	5.68
5	5.11	5.13	5.81
5.25	5.09	5.11	5.69

Appendix A (contd.)

Table A.8 Continued

5.5	5.13	5.6	5.13
5.75	5.11	5.4	5.11
6	5.09	5.5	5.09
6.25	5.09	5.6	5.09
6.5	5.12	5.3	5.12
6.75	5.11	5.2	5.71
7	5.09	5.12	5.09
7.25	5.12	5.32	5.12
7.5	5.11	5.12	5.11
7.75	5.09	5.05	5.49
8	5.09	5.06	5.09
8.25	5.13	5.35	5.63

Appendix A (contd.)

i) Stapler

Table A.9 Data for the Gripping Forces while Grasping a Stapler

Time (sec.)	Gripping Forces (oz.)		
	Trial 1	Trial 2	Trial 3
0	0	0	0
0.25	0.01	0	0.1
0.5	0	0.09	0
0.75	0	0.13	0.09
1	0.05	0.06	0
1.25	0	0.02	0
1.5	0.13	0.23	0.15
1.75	0.08	0.15	0.11
2	0.28	0.32	0.24
2.25	0.15	0.22	0.29
2.5	2.2	2.6	1.39
2.75	0.52	3.28	1.85
3	1.8	2.35	1.87
3.25	7.25	2.69	1.83
3.5	7.83	2.97	1.95
3.75	7.65	4.01	3.91
4	7.83	4.24	3.08
4.25	7.98	4.46	4.6
4.5	8.12	4.75	5.09
4.75	8.14	5.05	5.24
5	8.31	5.78	5.39
5.25	8.43	6.52	5.47

Table A.9 Continued

5.5	8.49	6.39	5.69
5.75	8.79	6.47	6.52
6	8.98	6.83	7.65
6.25	9.24	6.95	8.6
6.5	9.65	6.87	8.65
6.75	10.24	6.57	8.37
7	10.96	7.27	8.96
7.25	10.85	7.53	9.25
7.5	11.24	7.86	9.39
7.75	11.65	8.93	9.47
8	11.85	9.05	9.78
8.25	11.8	9.17	9.89
8.5	11.24	9.74	10.23
8.75	12.404	10.05	10.65
9	12.688	10.27	10.57
9.25	12.972	10.35	10.35
9.5	13.256	10.6	10.25
9.75	13.54	11.19	10.73
10	13.82	11.54	10.86
10.25	14.11	11.87	10.99
10.5	14.39	12.21	11.11
10.75	14.68	12.54	11.24
11	14.32	12.88	11.37
11.25		13.34	11.5
11.5		13.57	11.64

Appendix A (contd.)

Table A.9 Continued

11.75		13.88	11.76
12		14.23	11.88
12.25		13.98	12.01
12.5			12.14
12.75			12.05
13			12.37
13.25			12.57
13.5			13.29
13.75			13.71
14			13.89
14.25			13.62