DEVELOPMENT OF A TWO-FINGERED AND A FOUR-FINGERED ROBOTIC GRIPPER

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ABSTRACT

DEVELOPMENT OF A TWO-FINGERED AND
A FOUR-FINGERED ROBOTIC GRIPPER

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In this thesis study, a two-fingered gripper and a four-fingered multipurpose gripper are developed and manufactured. In addition to development of robotic hands, computer control hardware and software are also developed for computer control of both hands. The two-fingered gripper is designed for a specially defined pick and place operation. Its task is to pick a cylindrical work piece and place it in the appropriate position in a flexible manufacturing cell. Pneumatic actuator is used for power generation and mechanical links are used for power transmission. Four-fingered gripper is designed as a multipurpose gripper. The task is not predefined for this gripper, so, human hand and previous dexterous hands are taken as model during design. It consists of 3 fingers and a thumb. It has 1 degree of freedom for every finger and thumb. Pneumatic actuators are also used for this gripper. Rope and pulley system is used for the power transmission mechanism. Structures of both hands are manufactured from 5083 series aluminum. Gripping force can be controlled by the pressure regulator of the pneumatic system for both hands. Computer software is developed for the control of open and close motion of the fingers. Also, a motion control card is designed and manufactured for control of the pneumatic valves.

Keywords: Robot Hands, Robot Grippers, Robotics, Robotic End-Effectors.

ÖZ

İKİ PARMAKLI VE DÖRT PARMAKLI ROBOT TUTUCU GELİŞTİRİLMESİ

Doğan, Burak
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Bu tez çalışmasında, iki parmaklı robot tutucu ve çok amaçlı dört parmaklı robot tutucu geliştirilmiş ve üretilmiştir. Geliştirilen robot ellere ek olarak, her iki elin bilgisayar kontrolünde kullanılacak olan donanım ve yazılım da geliştirilmiştir. İki parmaklı el; özel olarak tanımlanan tutma ve konumlama işi için tasarlanmıştır. Görevi silindirik nesneyi kavrayarak esnek üretim hücresinde uygun yere yerleştirmektir. Güç üretimi için pnömatik tahrik elemanı, güç iletimi için ise mekanik bağlantı sistemi kullanılmıştır. Dört parmaklı tutucu; genel amaçlı olarak tasarlanmıştır. Bu tutucu için öngörülebilen bir görev belirlenmediğin için, tutucu tasarımında, insan eli ve daha önceki becerikli robot el uygulamaları model olarak kullanılmıştır. Tutucu üç parmak ve bir başparmaktan oluşmaktadır. Her bir parmak ve başparmak için bir serbestlik derecesine sahiptir. Bu tutucu için de pnömatik tahrik elemanı kullanılmıştır. Güç iletim mekanizması olarak ip ve makara sistemi kullanılmıştır. Her iki el 5083 serisi alüminyumdan imal edilmiştir. Tutma kuvveti, iki el için de, pnömatik sistemde yer alan basınç regülatörü aracılığıyla kontrol edilebilir. Bilgisayar yazılımı parmakların açma-kapama hareketini kontrol etmek için geliştirilmiştir. Ayrıca, pnömatik valfleri kontrol etmek için hareket kontrol kartı tasarlanmış ve üretilmiştir.

Anahtar Kelimeler: Robot Eller, Robot Tutucular, Robotik, Robotik Uç İşlemciler.

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SYMBOLS

A	Cylinder internal cross sectional surface area [mm^2]
a	Cross-sectional area of the shaft [mm^2]
a_1	Length of $\overrightarrow{OA}$ [mm]
a_2	Length of $\overrightarrow{OC}$ [mm]
C_x	x-component of tip point displacement vector
C_y	y-component of tip point displacement vector
D_2	Length of link 2 for the two fingered gripper [mm]
D_3	Length of link 3 for the two fingered gripper [mm]
D_4	Length of link 4 for the two fingered gripper [mm]
d_{min}	Minimum diameter of rope [mm]
F	Finger tip point force [N]
F_A	Actuator force [N]
F_G	Gripping force applied by one finger of the two fingered gripper [N]
F_J	Force applied by jaw of the gripper [N]
F_P	Piston force [N]
F_T	Thumb tip point force [N]
F_{ij}	Force applied by link i to link j [N]
g	Gravitational acceleration [m/s^2]
k	Length from joint1 to axis of symmetry [mm]
k_R	Stiffness of the Rope
L_1	Length of link 1 for the four fingered gripper [mm]
L_2	Length of link 2 for the four fingered gripper [mm]
L_3	Length of link 3 for the four fingered gripper [mm]
m	mass [kg]
M	Reaction moment for finger [N.mm]
M_i	Moment about joint *i* for finger [N.mm]

M_{ij} Reaction moment link *i* to link *j* [N.mm]

M_O Moment about point O [N.mm]

M_T Reaction moment for thumb [N.mm]

M_{Ti} Moment about joint *i* for thumb [N.mm]

O_G Gripper center point

P System pressure [N/mm^2]

p_1 Pressure in the shaft side [N/mm^2]

p_2 Pressure in the piston side [N/mm^2]

p_{amb} Atmospheric pressure [bar]

p_{abs} Absolute pressure [bar]

p_e Working pressure [bar]

r Radius of piston [mm]

r_a Radius of actuator pulley [mm]

r_p Radius of pulley for finger [mm]

r_T Radius of pulley for thumb [mm]

r_{Ta} Radius of actuator pulley for thumb [mm]

$\overrightarrow{r_f}$ Position vector of finger tip for four fingered gripper

$\overrightarrow{r_t}$ Position vector of thumb tip for four fingered gripper

RF Reserve factor for the rope

S Safety factor for the two fingered gripper

T Tension force on rope of finger [N]

T_a Torque applied by actuator [N.m]

T_T Tension force on rope of thumb [N]

T_{Ta} Torque value for actuator [N.m]

V_{tx} Velocity component of thumb tip point in x-direction

V_{ty} Velocity component of thumb tip point in y-direction

V_x Velocity component of finger tip point in x-direction

V_y Velocity component of finger tip point in y-direction

x Parallel distance from joint1 to joint2 [mm]

y Perpendicular distance from joint1 to joint2 [mm]

α Angle between link normal and line of action of the gripping force [degree]

β Angle from jaw to link normal [degree]

θ_1 Rotation angle of link 1 for four fingered gripper [degree]

θ_2 Rotation angle of link 2 for four fingered gripper [degree]

θ_3 Rotation angle of link 3 for four fingered gripper [degree]

θ_{1T} Rotation angle of link 2 for two fingered gripper [degree]

θ_{2T} Rotation angle of link 3 for two fingered gripper [degree]

$\dot{\theta}_1$ Angular velocity of Link 1 [°/s]

$\dot{\theta}_2$ Angular velocity of Link 2 [°/s]

$\dot{\theta}_3$ Angular velocity of Link 3 [°/s]

μ Coefficient of friction

η Efficiency

σ_{all} Allowable stress value for the rope

σ_{app} Applied stress value on the rope

δ Displacement [mm]

CAD Computer Aided Design

CAM Computer Aided Manufacturing

FMC Flexible Manufacturing Cell

PCB Printed Circuit Board

CHAPTER 1

INTRODUCTION

An industrial robot can be defined as a reprogrammable multifunctional manipulator designed to move material, parts, tools, and specialized devices through variable programmed motions for the performance of a variety of tasks [1].

This definition states that robots are reprogrammable manipulators that are able to operate on their own, according to previously given instructions. Their instructions must also be changed easily. This implies that a facility for storing instructions that can be changed at a later time must be provided. This facility can range in complexity from the basic mechanical stops, used on the most primitive non-servo controlled robots, to advanced electronic memories used in computer controlled robots.

Robots consist of a robot manipulator and an end-effector. The role of the end-effector is critical since it is the part of a robot in direct contact with the object. Although usually a manipulator is thought as a robot, a robot cannot do anything without end-effector. The end-effectors serving to handle the work pieces are called grippers. Although the grippers are one type of robot end-effectors, unlike the other end-effectors they are very diverse due to their fields of usage.

1.1. History and Background

Inventors of mechanical devices have often tried to produce mechanical devices which resemble living creatures. People have always been affected by mechanical devices that emulate human or animal behavior. For example archeologists discovered an Egyptian toy mechanical dog that was made in 2000 BC.

In the seventieth and eighteenth centuries, some mechanical devices were invented showing some of the features of today's robots. Two examples of these inventions are the human-sized musicians built by Jacques de Vaucanson in the mid-1700s and mechanical doll built by Henry Maillardet in the year 1805, which is capable of drawing pictures using a series of cams as the program.

18th century also saw a series of devices used in the textile industry. These were Hargreaves' Spinning Jenny in 1770, Crompton's Mule Spinner in 1779 and Eli Whitney's Cotton Gin in 1794, which separated the cotton fibers from the seed. In 1804, Joseph Marie Jacquard constructed a loom that is controlled by punched cards to produce highly complex patterns.

One of the important fields in the development of robotics is the power. In this field, hydraulic power was widely applied in the first years on the 19th century. In 1829, air compressor was patented followed by the beginning of the usage of pneumatic power in industrial applications. The usage of today's most popular drive for industrial robots, electricity was not started until the introduction of electric motor by Moritz Jacobi in 1834.

The quality and accuracy of the components produced by machine tools advance steadily. However, the greatest advance was the invention of a fully automatic lathe in 1873 by Christopher Spencer. The instructions required by the lathe were contained in the form of adjustable cams mounted on two large drums that are beneath the lathe bed.

In 1904, another important step was set in the field of robotics as the triode was invented by De Forest which made it possible to amplify signals electronically.

Robot is a term derived from the Czech word "robata" which means "forced labor" [2]. This word was first used in 1921, in Karel Capek's play "Rossum's Universal Robots" which was about human like machines that was called robots.

Modern industrial robots essentially evolved from teleoperators. A teleoperator is an articulated mechanism that is directly and often remotely controlled by a human operator. Teleoperators were first introduced during World War II to handle radioactive materials. The first robot end-effector was a gripper and it was used in these teleoperators. On the other hand, these grippers were rigid grippers without any relative motion. They were called as passive grippers and the only gripper motion was the motion of the wrist. Teleoperators are still used in hazardous areas with active grippers and human viewing is achieved via a protective window or a remote camera.

In 1937, Howard Aiken thought of utilizing the principles used in card controlled machines to produce a fully automatic calculating machine. By 1944 the automatic calculator was completed by IBM.

The ENIAC, an acronym for Electronic Numerical Integrator and Calculator was completed in 1946 in USA. This machine had been designed for military purposes such as calculating shell trajectories.

The transistor, which was invented by Shockley, Bardeen and Brittain acted as the catalyst for further progress. This electronic component was many times smaller than a valve, had no moving parts, was reliable and could be used as a switch or a solid-state amplifier.

In more recent times, numerical control and telecherics played important parts in the development of robotics.

Numerical Control (NC) was developed for machine tools in the late 1940s and early 1950s. As its name suggests, numerical control involves the control of the actions of a machine tool by means of numbers.

By the 1960's, industrial robots were becoming a reality due in large part to the development of relatively low cost digital computers, the element necessary to coordinate the control functions associated with the various links and the end-effector. The design of the first industrial robot built in the United States was based on the efforts of George Dewal. The first industrial robot was actually built at Unimation Inc. in Danbury, in 1961. Although industrial robots could have been employed immediately in the 1960's in a variety of industrial applications, especially to replace human workers in certain types of hazardous and mundane occupations, their initial use was hampered by both economics and hardware.

The development of microprocessor has played an important role in the rapid growth of industrial robotics as stated before. Although the robots that were available prior to 1970 had a remarkable versatility, the continual development of the microprocessors since 1970s has provided current industrial robots with far more "intelligence" at a much lower cost, and this trend will probably continue with concurrent advances in microprocessor technology. Other technological advances such as rare earth magnets for electric motors, high power transistors for motor control, improved bearings and transmission elements has improved both the performance and reliability of the industrial robots.

Robot manipulators were developed with end-effectors. Grippers are one type of the robot manipulator's end-effectors. The end-effectors serving to handle the work pieces are called grippers. The grippers are the most developable end-effectors since they have the widest application areas. However, enough effort was not spent for development. Until 1980's, the grippers were developed and produced for a single task that they will perform. Although a multipurpose gripper has always been the aim, real researches on such grippers started in 1980's in few countries which are Japan, U.S.A. and West Germany, mostly in universities. The main reason for this is the high cost of these researches. Multipurpose grippers developed as the actuators, mechanisms, sensors were developed. In the development of multipurpose grippers the examples are taken from the nature (especially human hand) as a model. On the other hand, until now, the imperfect technical model of biological examples so far developed is heavy, clumsy and expensive due to technological obstacles.

1.2. Industrial Robots

The industrial robot is a machine with significant characteristics of versatility and flexibility. According to the widely accepted definition of the Robot Institute of America, a robot is a reprogrammable multifunctional manipulator designed to move materials, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks. Such a definition, dating back to 1980, reflects the current status of robotics technology. By virtue of its programmability, the industrial robot is a typical component of programmable automated systems. Nonetheless, robots can be entrusted with tasks in both rigid and flexible automated systems.

According to the International Federation of Robotics report, up to 2006 nearly one million industrial robots are in use worldwide, half of which are in Asia, one third in Europe, and 16% in North America. The four countries with the largest number of robots are Japan, Germany, United States and Italy. The figures for robot installations in the last 15 years are summarized in the graph in Figure 1.1; by the end of 2007, an increase of 10% in sales with respect to the previous year is foreseen, with milder increase rates in the following years, reaching a worldwide figure of 1,200,000 units at work by the end of 2010.

In the same report it is shown how the average service life of an industrial robot is about 12 years, which may increase to 15 in a few years from now.

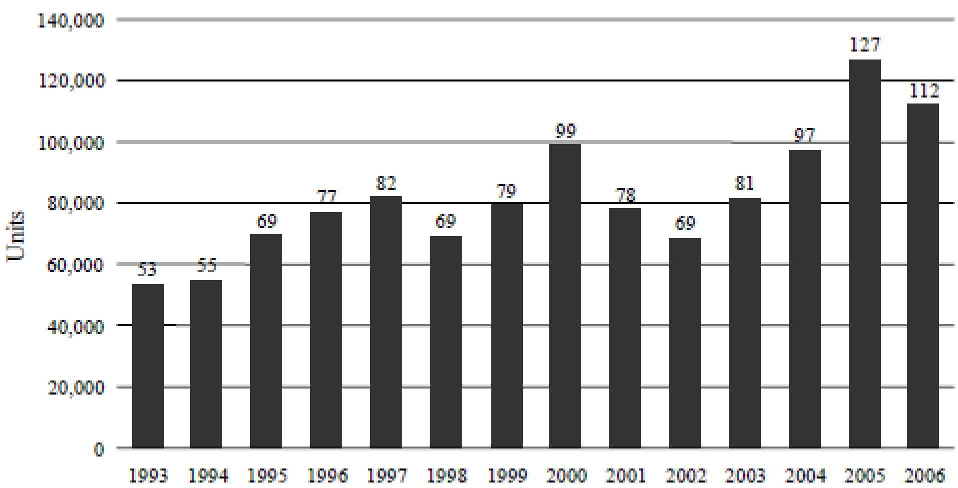


Figure 1.1: Yearly Installations of Industrial Robots Worldwide. [3]

Figure 1.2 shows the usage of industrial robots in main industries. In the graph, the automotive industry is still the predominant user of industrial robots. The graph referring to 2005 and 2006, however, reveals how both the chemical industry and the electrical/electronics industry are gaining in importance, and new industrial applications, such as metal products, constitute an area with a high potential investment.

Finally, industrial robot usage of Europe in manufacturing is shown in Figure 1.3.

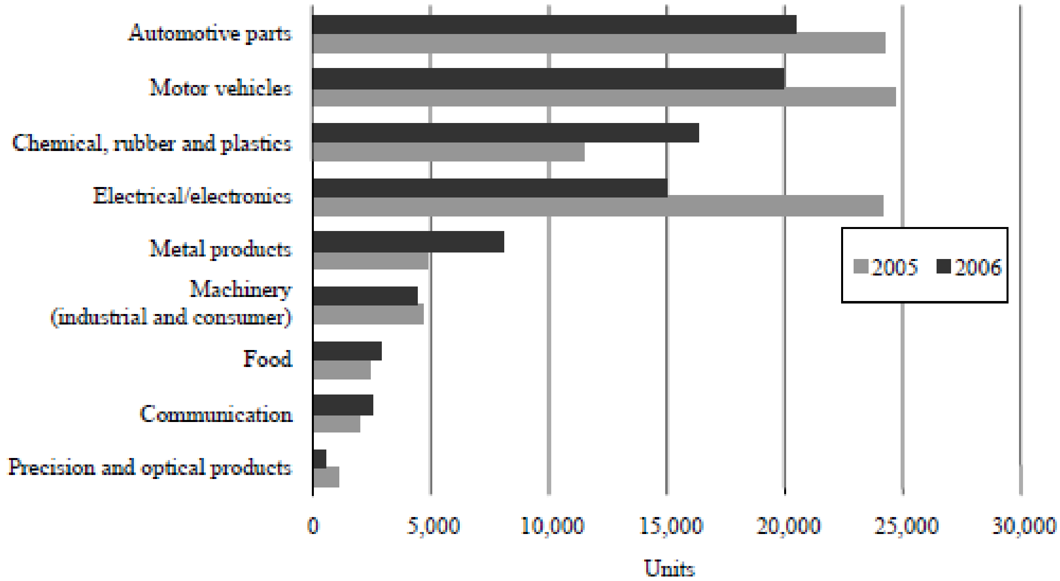


Figure 1.2: Yearly Supply of Industrial Robots by Main Industries. [3]

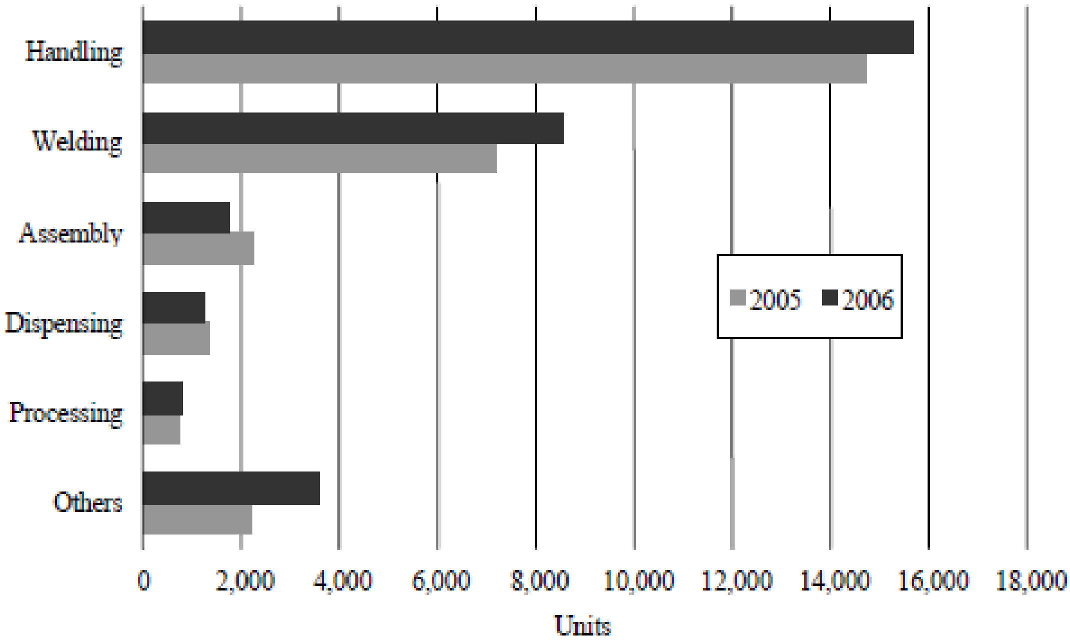


Figure 1.3: Yearly Supply of Industrial Robots in Europe for Manufacturing Operations. [3]

1.3. Robot Grippers

Grippers are subsystems of handling mechanisms which provide temporary contact with the object to be grasped. They ensure the position and orientation when carrying and mating the object to the handling equipment. Prehension is achieved by force producing and form matching elements. The term "*gripper*" is also used in cases where no actual grasping, but rather holding of the object as e.g. in vacuum suction where the retention force can act on a point, line or surface.

There are many types of work pieces with different shapes and sizes to be handled. So, it is impossible to design a universal gripper suitable for all work pieces. The majority of the researches in the area of grippers utilize electric or pneumatic actuators and two parallel fingers. Electrically actuated grippers generally utilize DC or stepper motors to provide the motive force. Transmission systems like ball screws, gears, pulleys or other mechanical linkages are necessary to convert the motion of the actuator to the finger motion, adding to the complexity, size and weight of the gripper assembly. A gripper can be considered more important than the robot, because without a gripper robot cannot handle anything.

Grippers vary by form and task that they can perform. The grippers used in industry are generally task oriented grippers. They are manufactured for a single task and they can only handle the objects which have similar properties like geometry, weight etc. The task oriented grippers are preferred because they are used in mass production where handled objects do not vary; the cost and the reliability of the gripper are of vital importance in industrial use. The usage area of a robot in industry is increased by using a single gripper with modular fingers or using multiple grippers which can be replaced easily.

In past, the grippers had been developed and produced for a single task to be performed. But, the latest technological developments gave opportunity for more developed universal gripping devices. These are called dexterous robot hands. Generally these hands were not used in industry now because of the high cost and complexity. Compared to the dexterous hands, usage of a task oriented gripper is much more feasible. They are cheap and more reliable. Also, multipurpose grippers (dexterous hands) are not preferred in industries with mass production and handled work pieces do not change. Although the capability of handling different shaped object is higher for multipurpose grippers, the handling capacity is very low compared to task oriented grippers.

1.4. Objective of Present Investigation.

In this thesis work, the aim is to make the design and construction two new robotic grippers. One of the grippers is specialized to work in a flexible manufacturing cell (FMC) while the other one is designed as a multipurpose robotic gripper. Specialized gripper has two fingers to grip cylindrically shaped work piece and transfer the work piece between the stations of the FMC. Multipurpose gripper is developed for general purposes and has four fingers. The shape of this gripper is similar to human hand like other dexterous grippers. Both of the grippers are designed to work with commercial robot manipulator in METU CAD/CAM Robotics Center.[4]

The second part of the thesis study covers the computer control of developed grippers. For computer control of the grippers, a motion control card, is developed and produced to drive the actuators. This motion control card can be connected to any computer with RS232 serial interface. Also computer software is developed for control of the fingers of the grippers. This software transmits the data with serial interface to the motion control card and ensures the movement of the fingers for gripping action.

1.5. Outline of the Thesis

In Chapter 1, an introduction is presented and the brief history about robotics is given. Usage areas of industrial robots and the multi-purpose gripper researches around the world are introduced. The grippers used in industry today are explained and their properties, limitations, usage areas are investigated. The robotic grippers developed in this thesis study are introduced. The outline of the thesis is specified.

In Chapter 2, literature survey about robotic grippers is given. Robotic grippers are classified due to their several properties. The dexterous robot hand researches are introduced. Their tasks, properties, capabilities and limitations are detailed.

In Chapter 3, the components of the grippers such as actuators, power transmissions systems, joints and linkages used in robotic grippers are investigated, their advantages and disadvantages are pointed out.

In Chapter 4, the design procedure of the two fingered gripper is explained. Selections of the elements that are used in the design are discussed. Development of power transmission mechanism is clarified. The kinematic analysis, position analysis and force analysis of the gripper are carried out. The technical specifications of the gripper are described.

In Chapter 5, the design procedure of the four fingered multipurpose robotic gripper is explained. Selection of the elements used as actuators, construction materials, covering material etc. are discussed. The development of the transmission mechanism used in the gripper is explained. The manufacturing machines which are used in production are explained. The technical specifications of the gripper are described. The kinematic analysis, position analysis and force analysis of the gripper are carried out.

In Chapter 6, development of the motion control card and computer softwares are described. Also functionality of the softwares developed are described and user manual for the computer softwares are given.

Finally, discussion of results, conclusion and suggestions for further works are given in separate chapters.

CHAPTER 2

LITERATURE SURVEY

2.1. Introduction

Human labor has always been associated with the acquisition of specific skills, methods, and tools making the work and its environment easier and more effective. Increasing competition from industrial robots for tasks normally carried out by human hands has led to the need for more effective handling equipment, especially prehension tools (more commonly called grippers). However, industrial robots are not simply as a substitute for people. Their relevance is more often in applications beyond the normal ability (physical or temporal) of conventional manpower. Examples include, dirty, hazardous and repetitive work. Just as human hands are the organs of human manipulation, so are robot grippers usually the only parts in direct contact with the work piece. For this reason they deserve special attention

2.2. Robotic Grippers

Grippers are one type of the robot manipulator's end-effectors. Grippers are active links between the handling equipment and the work piece or, in a more general sense, between the grasping organ (normally the gripper fingers) and the object to be acquired. [5] Their functions depend on specific applications and include:

- Temporary maintenance of a definite position and orientation of the work piece relative to the gripper and the handling equipment.
- Retaining of static (weight), dynamic (motion, acceleration or deceleration) or process specific forces and moments.
- Determination and change of position and orientation of the object relative to the handling equipment by means of wrist axes.

- Specific technical operations performed with, or in conjunction with, the gripper.

Grippers are not only required for use with industrial robots but also they are universal components in automation. Grippers operate with:

- Industrial robots (handling and manipulation of objects).
- Hard automation (assembling, micro assembling, machining, and packaging).
- NC machines (tool change) and special purpose machines.
- Hand-guided manipulators (remote prehension, medical, aerospace, nautical).
- Work piece turret devices in manufacturing technology.
- Rope and chain lifting tools (load-carrying equipment).
- Service robots (prehension tools potentially similar to prosthetic hands).

In robotics technology, grippers belong to the functional units having the greatest variety of designs. This is due to the fact that, although the robot is a flexible machine, the gripper performs a much more specific task. Nevertheless, these tasks are not limited to prehension alone which is why the more generic term "end-effector" is often used.

The majority of robotic end-effectors used today are simple open and close type two fingered grippers, magnetic devices or vacuum cups. Obviously magnetic devices and vacuum grippers are useful only under very specific operating conditions such as sheet metal gripping. The conventional jaw-type grippers are also usually targeted to a specific task. Often the gripper design is such that the object to be handled must be presented in a specific orientation at a precisely defined location and only that particular object and very similar ones can be properly handled.

The great number of different requirements, diverse work pieces and the desire for well adapted and reliable systems will continue to stimulate further developments in future gripper design. Many experts consider the capabilities of the gripper as an essential factor for the economic effectiveness of automatic assembly systems. Experience indicates that in the future it will only be possible to respond to practical demands if flexible designs for assembly equipment are available. Consequently, grippers must become ever more flexible. Assembly relates not only to prehension and manipulation of objects but also to pressing, fitting and joining operations. Many grippers are employed for the loading of manufacturing lines, in packaging and storage as well as the handling of objects in laboratory test and inspection systems.

More recently, miniaturized grippers have been developed in order to handle delicate components in microtechnology. This has gone hand in hand with the emergence of many novel prehension methods. The number of grippers used in nonindustrial areas, e.g. in civil engineering, space research, handicraft, medical and pharaceutical engineering is steadily increasing. Hand-guided (teleoperation) or automatic manipulators are used in these areas primarily as handling machines. In addition to conventional grippers, for which, the gripper jaws are shaped according to the work piece profile, there exist numerous application specific grippers. This explains why an overwhelming proportion of corresponding patent literature is devoted to prehension concepts of unconventional design. In general, end-effectors are not normally within the delivery responsibility of robot manufacturers. Depending on the specific requirements, they are selected as accessories from tooling manufacturers or specially designed for the given purpose.

2.3. Gripper Classification

In manufacturing technology the term "active pairs" of interacting components, e.g. gripper jaw and work piece, is often used. However, the types of the contact are also important. There are many definitions to be found in the literature. In the past the classification was limited to three gripping methods: clamping, suction, and magnetic adhesion. [6] Another categorization distinguishes between single-sided contact (vacuum suction, adhesion), double sided contact, and multilateral contact as in the case of shape adaptive gripper jaws [7]. In addition, other physical (adhesion, interaction) forces may also be considered.

Grippers may be categorized (in the broadest manner) in four main groups:

1. Impactive: A direct mechanical force from two or more directions is applied to the object.

2. Ingressive: Prehension of the object is achieved through permeation of the object surface.
3. Astrictive: A binding force is applied in a single direction
4. Contigutive: Nonimpactive methods whereby a direct contact is required to provide a prehension force in a single direction.

These four categories, together with typical examples, are listed in Table 2.1. This table shows the classification comprising four gripping categories [8].

Table 2.1: Gripper Classification According to Physical Principle of Operation. [8]

Prehension Method	Gripper Type	Typical Examples
Impactive		Clamps (external fingers, internal fingers, chucks, spring clamps), tongs (parallel, shear, angle, radial)
Ingressive	Intrusive	Pins, needles, hackles
	Non-intrusive	Hook and loop
Asrictive	Vacuum Suction	Vacuum suction cup/bellows
	Magnetoadhesion	Permanent magnet, electromagnet
	Electroadhesion	Electrostatic field
Contigutive	Thermal	Freezing, melting
	Chemical	Permatack adhesives
	Fluid	Capillary action, surface tension

The majority of industrial grippers is either of the impactive kind or of an astrictive nature (particularly vacuum suction). Nevertheless, many other designs using the methods given above do exist.

The ingressive grippers may be subdivided into a further two categories: those which permeate the material (intrusive) and those which do not. Most needle based grippers are deliberately designed to penetrate the materials surface. Other methods, for example those based on hook and loop (Velcro) techniques do not. The specific choice of design depends largely on the material to be handled.

Similarly, there are three sub-groups for astrictive prehension. Although electro-adhesion is suitable with almost all materials, both electrically conducting and non-conducting, it is limited to relatively light objects. Vacuum suction is also usable with almost any material and provides a much larger gripping force. However, a near perfect pneumatic contact is necessary. Magnetoadhesion also provides a very usable prehension force but is strictly limited to magnetically susceptible materials such as Iron, Steel, Nickel and Cobalt

Other classification schemes are proposed but what is absent from most classifications are such everyday methods as spoon or hook. Whether these really constitute robot grippers in the conventional sense is debatable. However, for completeness they will be included. Table 2.2 lists methods and applications for such grippers.

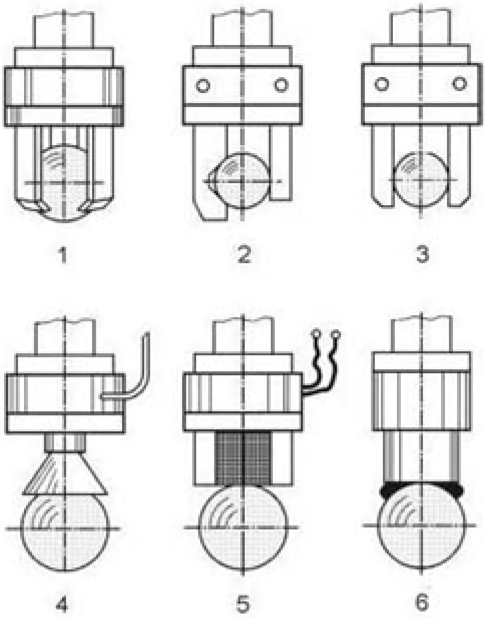
Table 2.2: Other Prehension Methods not Normally Categorized. [8]

Gripper	**Material Type**	**Example application**
Spoon	Rigid	Loose materials such as nuts and bolts
	Flexible	Powders and viscous fluids.
Hook	Rigid	Determinate topology for example castings
	Flexible	Waste materials sorting

2.4. Definitions and Conceptual Basics

Grasping organs or tools constitute the end of the kinematic chain in the joint system of an industrial robot and facilitate interaction with the work environment. Although universal grippers with wide clamping ranges can be used for diverse object shapes, in many cases they must be adapted to the specific work piece shape.

Three of the most usual forms (impactive, astrictive and contigutive) of object prehension are depicted in six different examples in Figure 2.1.



1. Pure enclosing without damping.
2. Partial form fit combined with damping force.
3. Pure force closure
4. Holding with vacuum air (pneumatic force closure)
5. Retention using magnetic field. (force field)
6. Retention using adhesive media.

Figure 2.1: Possibilities for Prehension of a Spherical Object. [5]

One should differentiate between grasping (prehension) and holding (retention) forces. While the grasping force is applied at the initial point of prehension (during the grasping process), the holding force maintains the grip thereafter (until object release). In many cases the retention force may be weaker than the prehension force. The grasping force is determined by the energy required for the mechanical motion leading to a static prehension force. The functional chain $drive \rightarrow kinematics \rightarrow holding\ system$ is given, however, only for mechanical grippers. Astrictive vacuum suction grippers require no such kinematics.

There are some characteristic terms that are often used in prehension technology. Grippers consist mostly of several modules and components, in the following, the most essential terms used will be explained considering as an example a mechanical gripper such as the one shown in Figure 2.2.

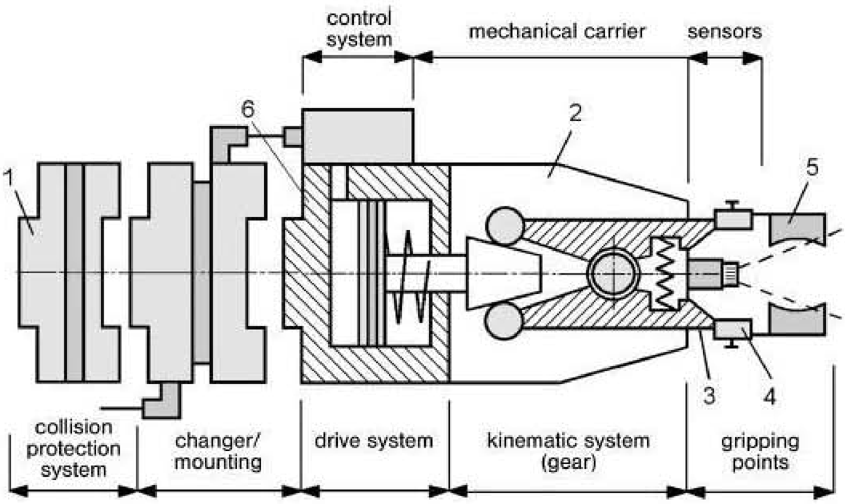


Figure 2.2: Subsystems of a Mechanical Gripper. [5]

1. Remote Center Compliance, 2. Carrier, 3.Gripper Finger,

4. Basic Jaw, 5. Extended Jaw, 6. Flange.

A short glossary of further important terms used in gripper technology is briefly explained in Appendix A. [5]

2.5. Requirements and Gripper Characteristics

The choice of a gripper depends mainly on the work it has to perform. Every prehension task is characterized by the following factors and requirements:

- *Technological requirements;* these include prehension time, gripping path, time dependence of the prehension force and the number of the object acquisitions per gripping cycle.
- *The effects of the prehended objects;* these include the mass, design, dimensions, tolerances, position of the center of gravity, stability, surface, material, strength, and temperature. The correlations between gripper and object can be summarized as listed below:

Object shape	⇔	gripping surface
Object size	⇔	gripping range
Object mass	⇔	gripping force

Object position ⇔ gripping point

- *Factors related to handling equipment;* such as the positional accuracy, axial accelerations and connection specifications (mechanical, electrical, etc.).
- *Factors related to environmental parameters;* these include process forces, feeding conditions and damps, storage conditions, contaminations, humidity and vibration.

The choice of gripping principle is based on the requirements and their analysis. There are many effects with complicated interrelationships and it is difficult to obtain a complete overview. The selection of them is presented in Figure 2.3 as a semantic network.

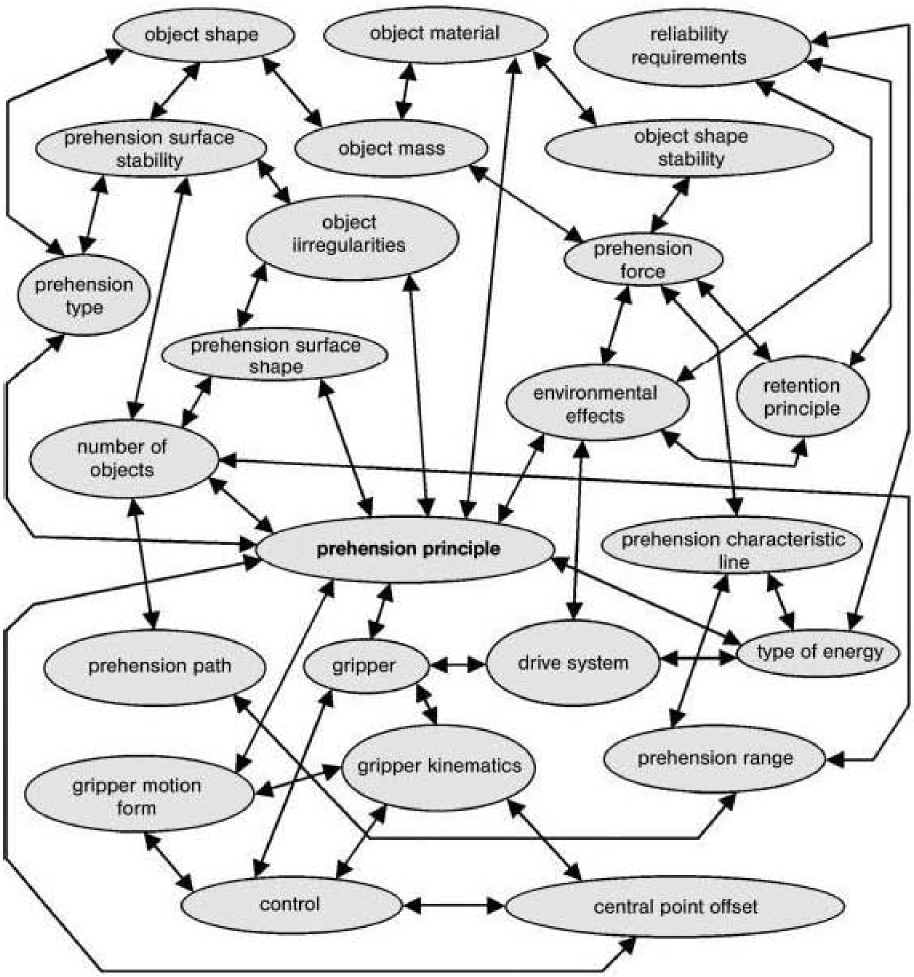


Figure 2.3: Semantic Network Illustrating Interdependences Relevant to Prehension Principle Selection. [5]

A semantic network is formalism for representation of knowledge in the form of a structure reflecting the interrelations among objects, which consists of nodes connected by directed paths. The nodes represent specific aspects of the gripper.

A high quality gripper should possess the following properties:

- Optimum adjustment of the gripper structure to the operations performed.
- Large adjustment range and options to prehend parts of different shape and size.
- Reliability with respect to dislocations of the object (stability of the object position and orientation).
- Optimum gripping force path characteristics.
- Low number of links and joints (where applicable).
- Small installation space and mass, robustness.
- High reliability combined with easy service.
- Avoidance of damage and deformation to the object during prehension.
- Sufficiently high object positional accuracy.
- Good wear resistance.
- Simple control and short action times.

Some rather specific requirements include:

- Variation of prehension possibilities depending on object mass, shape and size.
- Possibility to selectively acquire objects in close proximity to one another.
- Rapid gripper exchange.
- Variation of the holding force dependent on the object mass.

Table 2.3 summarizes the most important gripper parameters:

Table 2.3: Gripper Specifications for Technical Characterization. [5]

<table>
<tr><th>Primary characteristics</th><th>Secondary characteristics</th></tr>
<tr><td>Active principle
mechanical
fluidic
compressed air
vacuum
magnetic
permanent magnet
electromagnetic
adhesive
Prehension force [N]
Prehension force time dependence
Prehension force diagram
Prehension range per jaw [mm] or angle of spread [°]
Gripping range settings
Load bearing capacity max. [N]
Closing (prehension) time [s]
Opening (release) time [s]
Load limits
forces
moments of force
finger length
Number of grasping organs
Overall dimensions [mm]
Deadweight [kg]</td><td>Environmental factors (cleanroom class)
exhaust air
abrasion
Bearing and guideway design
Model range selection
Operating temperature
Operation type
single-acting
double-acting
Power/mass ratio
Mass moment of inertia [kgm^2]
Reproducibility and accuracy [mm]
Operational pressure range [bar]
Maintenance cycle
Installation position
Maximum operational frequency [Hz]
Energy type and consumption
Retention force backup in case of energy failure
Monitoring of prehension range
Material specifications
Interface specifications
mechanical
fluidic
electric
Service life</td></tr>
</table>

2.6. Dexterous Hands

Multi-finger grippers with moving finger links are designed mainly for manipulation tasks requiring a certain amount of dexterity similar to that of the human hand. Hence, these grippers are often called dexterous hands. Such hands have been studied since the early 1980s. Examples include the three-finger hand (thumb and two jointed fingers) developed at the University of Bologna (Italy) [9] or the MIT/Utah-Hand. Some of the designs have been developed further for industrial use, e.g. in remote-controlled manipulators for service tasks in dangerous environments or the accomplishment of special medical tasks [10]. Much research has been devoted to the development of such hands over the past two decades [11, 12]. Perhaps their most valuable contribution to technology lies not with the prehension itself but with the development of the necessary micro mechanisms and actuators.

For industrial purposes, grippers tend to be more tasks specific. Usually, the wide flexibility of the human hand is sacrificed in order to produce a gripper deliberately designed to achieve a limited range of tasks better and/or quicker.

Hand prostheses are in many details similar to industrial grippers as can be seen from the artificial hand shown in Figure 2.4. [13] The actuation of the 3-link fingers and that of the thumb are integrated into the hand.

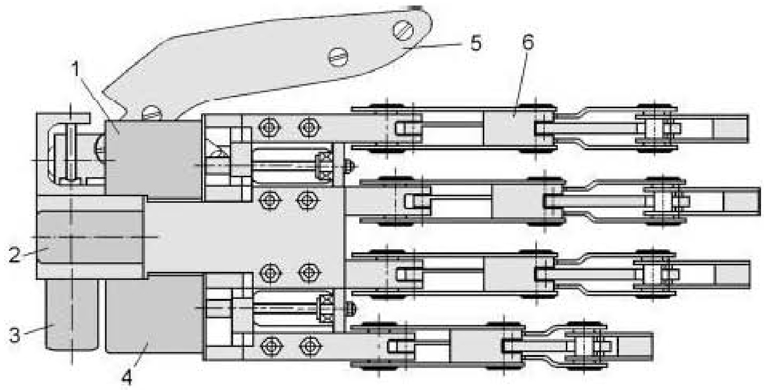


Figure 2.4: Construction of a 5-Finger Artificial Hand. [13]
1. Index finger drive, 2. Thumb on and off, 3. Thumb actuation,
4. Actuation of fingers 3 to 5, 5. Thumb, 6. Jointed fingers.

Constriction and relaxing of the hand are controlled through electromyograms (EMG) which are taken from the remaining nerve endings of the corresponding hand muscle. Secure prehension of an object requires force reflection. The adjustment of the gripping force can be realized by two control-loops which monitor the corresponding gripper position and prehension force. The gripping force is set by slip sensors at the gripping surfaces. The EMG signals allow corrections to be made to the corresponding coordinate elements (gripping motion of the thumb and the fingers). Figure 2.5 shows a control flow scheme.

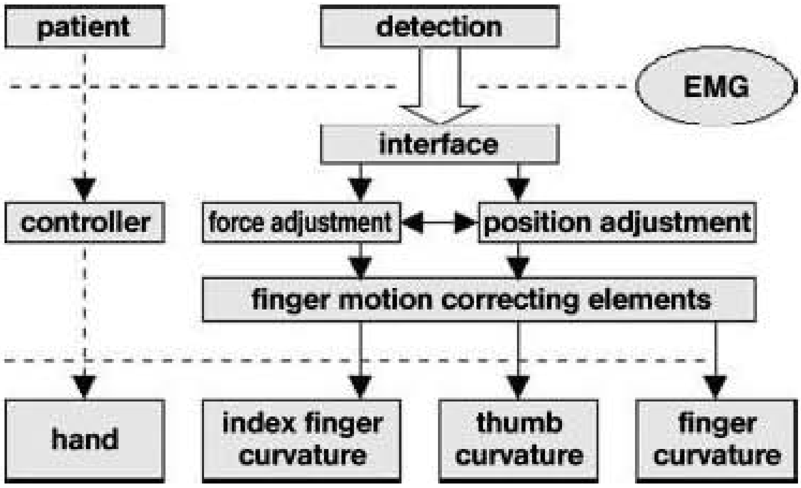


Figure 2.5: Force Adjustment of an Artificial Hand. [13]

Belgrade Hand

A five-fingered hand modeled on the natural hand (1962), though the finger joints are not independently controllable (Figure 2.6). When the hand closes, initially each consecutive finger joint moves in the same manner until the finger makes contact with the object. Despite blocked motion of the inner (proximal) finger joints, the outer joints continue to close thus achieving complete enclosure of the object. Problems associated with control of the Belgrade Hand have been drastically simplified and several different versions of this hand have been developed over the years.

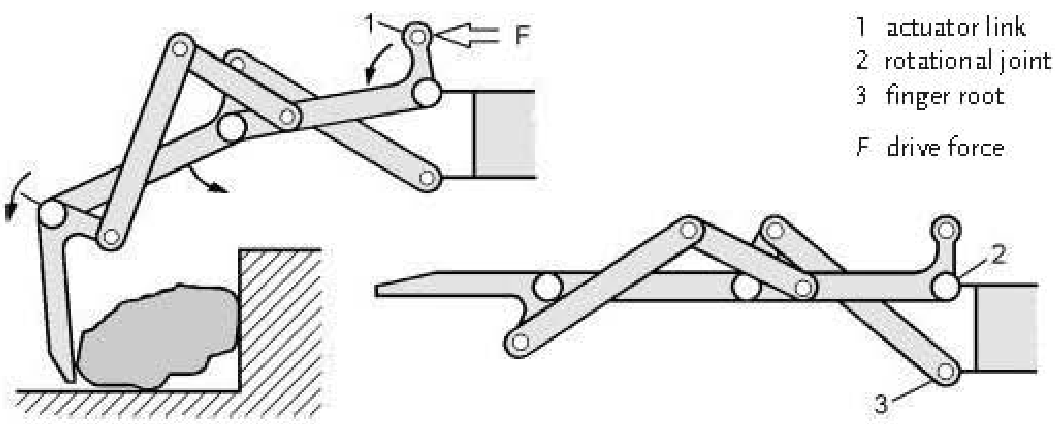


Figure 2.6: Gripper Finger of the Belgrade Hand. [5]

Skinner Hand

This hand is a good example for a 3-finger design which enables, the embracing prehension, the spread (internal) prehension, and the two-finger tip prehension (Figure 2.7). Each finger possesses three joints and in addition can be rotated in the phalanx base. A total of 4 electric motors are employed as prime movers.

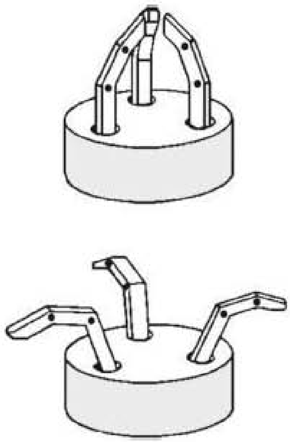


Figure 2.7: Grip Capabilities of Skinner Hand. (1974) [5]

Okada Hand

Three-fingered hand (Figure 2.8) developed by a Japanese research laboratory [14] possessing 11 joint angle degrees of freedom. The finger positions are reassigned and stored in electronic memory. Intermediate positions are linearly interpolated.

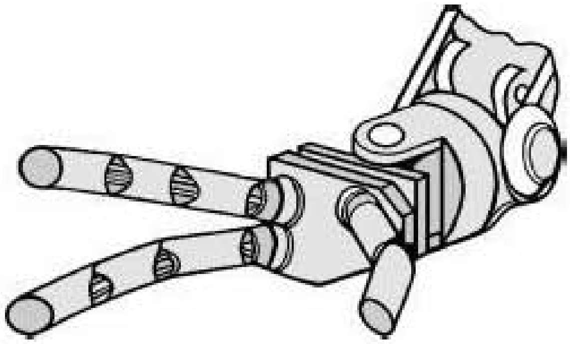
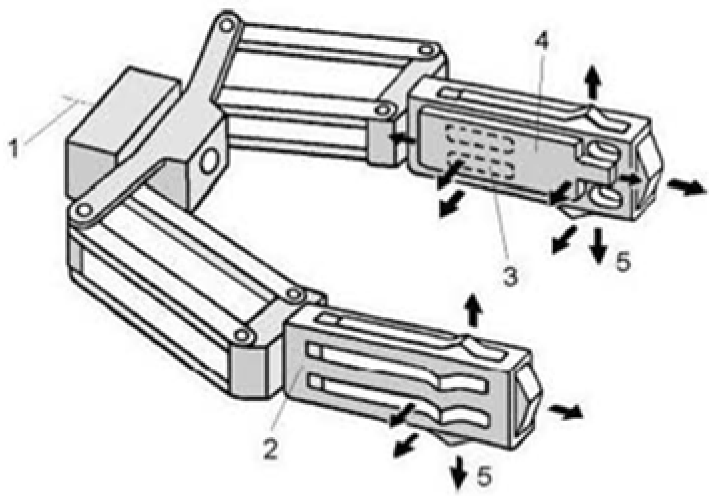


Figure 2.8: Okada hand. [5]

HI-T Hand

This abbreviation stands for the *Hitachi tactile controlled hand*, a gripper designed by the Hitachi Company for assembly work by an industrial robot (Figure 2.9). This dexterous hand which was developed in 1978 had an elastic hand joint and was capable of completing hole drilling tasks with a tip clearance within 7 to 20 µm in fewer than 3 seconds. 14 contact, 4 pressure, and 6 force sensors were employed. Fine corrective movements were performed by electronically controlled stepping motors. Subsequently (1984), Hitachi developed a 3-finger hand with 3 analogous designs [15]. Each finger had 3 links and 4 joints but there was no thumb. Actuation was realized using shape memory alloy (SMA) wires which, when electrically heated, contracted against a return spring. This resulted in a relatively high force to weight ratio but, due to the basic thermal principle (heating and cooling sequences) of the actuator, had a somewhat delayed response. Furthermore, it soon became clear that the lifetime of the SMA wire was too short for industrial applications.



1. hand rotation axis
2. gripper finger
3. pressure sensor (pressure sensitive electro conductive rubber)
4. extended sensor plate with limit switch
5. contact sensor

Figure 2.9: HI-T Hand. [5]

Utah/MIT Dexterous Hand

The development of this 4-fingered hand began in 1982 [16]. It possesses three fingers and an opposing thumb modeled on the human hand (Figure 2.10). The finger enjoys 16 degrees of freedom.

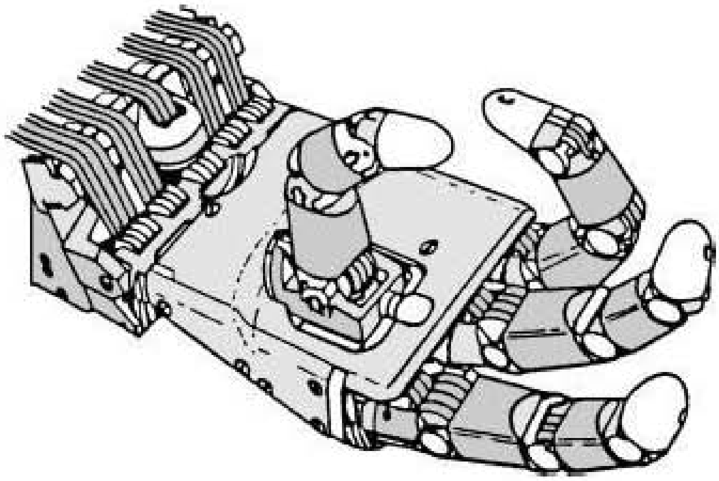


Figure 2.10: Version IV of UTAH / MIT Hand. [5]

The finger links are actuated by tension bands. The finger designs are shown in Figure 2.11. Since ropes and bands can transmit only tension, two bands were necessary for each finger link. This makes a total of 32 tension bands (“sinews") for the 3 fingers and the thumb, which must be guided through a correspondingly large number of pulleys. The pneumatic drive cylinders are not integrated with the hand but housed externally in the forearm, which leads to some limitations. The fingers are electrically controlled by means of relatively computationally intensive software.

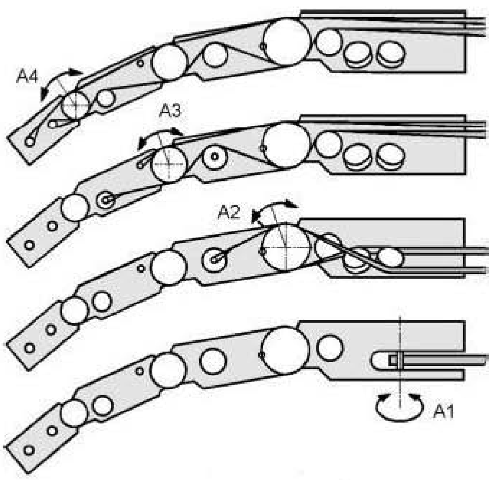


Figure 2.11: Guiding of the Tension Bands (Super Hard Plastics) in a Finger with 4 Degrees of Freedom (Utah/MIT Dexterous Hand)
“A” Motion Axis. [5]

Stanford / JPL Hand

The Stanford Hand was built in 1983 and is equipped with tactile sense contacts on the fingers which are to imitate the human sense of touch. The gripper was equipped with just three fingers but could still manipulate the work piece in its hand.

The three-fingered hand, (Figure 2.12) with opposing thumb, comprises 9 degrees of freedom for the three joints per finger. Finger motion is based on 12 Teflon covered cables driven from 12 miniaturized DC motors with microprocessor control mounted in the robot forearm. Sensors determine driving force from the cables and encoders the rotation angle. The finger tip joints are augmented with 8 x 8 tactile sensor arrays.

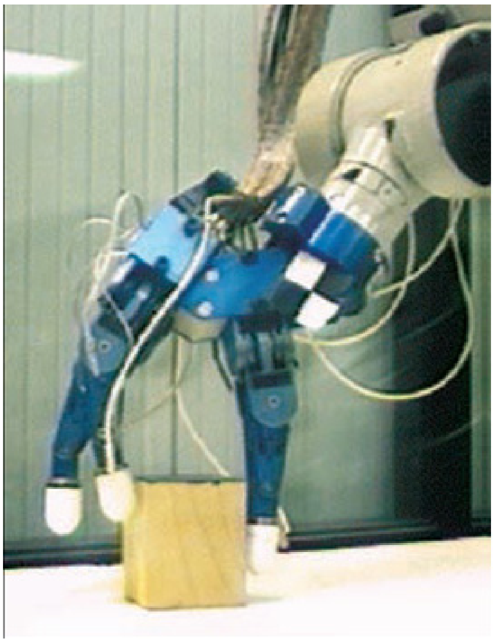


Figure 2.12: Stanford / JPL Hand. [17]

Robonaut Hand

The word robonaut stands for robotic astronaut which is a telepresence-robot with a height of 1.9m and a mass of 182kg, designed for space missions [18]. This robot is expected to support future astronauts in maintenance and repair work in space. For this purpose it was necessary to develop a hand, the size and appearance of which mimics the human hand. The Robonaut Hand (NASA) is a five-jointed finger hand with 22 degrees of freedom. 14 joints can be independently activated.

The Robonaut Hand (Figure 2.13) is one of the first to be designed for applications in space. According to NASA, the highest demands on the materials used, such as extreme temperature resistance, distinguish this hand from all hands produced so far. Even eventual gas emissions by the hand and their influence on other space systems were taken into consideration.

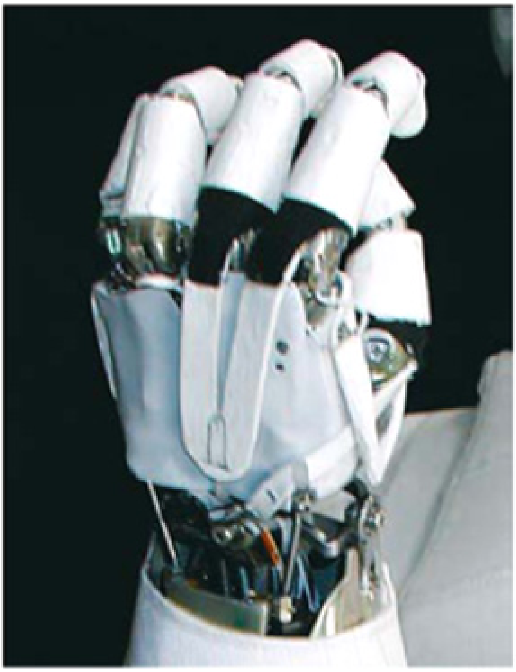


Figure 2.13: Robonaut Hand. [17]

Further dexterous hand implementations of varying complexity [19] are still being developed for educational and investigative purposes, mainly in research institutions, colleges and universities: some examples include the five-finger hand of the Technical University Berlin, Germany, the Gifu 5-jointed finger hand of the Gifu University (Japan), the IPA Hand (/PA, Stuttgart, Germany) with fixed thumb and two movable fingers, a hand with tactile sensors on rounded finger ends in order to produce a "finger tip feeling" (University Bielefeld, Germany) and several variations of hand from ETH Zurich, Switzerland, and other institutes.

CHAPTER 3

GRIPPER COMPONENTS

Grippers are the commonly used end effectors and mainly composed of four components that directly affect the physical properties of the gripper. These components also affect the performance of the gripper. The components can be classified as;

1. Transmission Systems.
2. Actuators.
3. Joints and Links.
4. Sensors.

3.1. Transmission Systems

Transmissions systems are used in any mechanical system where power must be transmitted from actuator over a distance. Transmission systems employed in gripper mechanism can be classified as;

1. Chain – Belt Mechanism.
2. Mechanical Link.
3. Gear Train System.
4. Rope – Pulley System.
5. Rack – Pinion Drive.
6. Harmonic Drive.

3.1.1. Chain - Belt Mechanism

The links of each finger unit is driven by using time belts. The rotations of the joints are achieved by installing a chain mechanism, inside the finger unit. A main torque is given to the first link of the finger than the whole finger is supposed to work in a single degree of freedom.

There are some advantages and disadvantages of using such a mechanism:

Advantages:

- The system is durable due to its rigidity.
- Transmission of the torque is powerful.
- Deflections are prevented.
- The maintenance is easy.

Disadvantages:

- The number of chains for the system is too much.
- The problem of backlashes makes positioning inaccurate.
- Assembly of the system is not easy.
- The cost becomes too high.
- The standards for the chains are not suitable for small size applications.

3.1.2. Mechanical Link

It can be a good system for the sake of classical mechanical engineering application. The system consists of crank and rockers. Most of the time, it is enough to make four bar mechanism analysis. The first link of the finger unit is actuated by a motor and the rest of the motion is transmitted by the help of a slider crank mechanism.

Advantages:

- The mechanism is much more reliable and durable than the chain - belt mechanism.
- Deflections are not permitted.
- Kinematic analyses are easy.

Disadvantages:

- Manufacturing of the system is not easy.
- The mechanism to operate the fingers occupies more space.
- The appearance deviates from natural hand shape concept.
- The system does not return its initial position easily, there may occur a locking problem.

3.1.3. Gear Train System

The system consists of the gear trains assembled in each unit of the finger that make up links. The whole motion is supplied by gear couplings. The diameter ratios of the gears in the joints are in special importance to give the hand gripping motion.

Advantages:

- The position analysis of each point on the links is easy.
- The rigid body assumption is valid.
- Natural hand appearance is possible

Disadvantages:

- There are number of gears for each finger unit, which increases the cost of the system.
- The assembly of the gears is difficult.
- Wear will arise due to power reducing units which causes the system to fail, so system is not reliable.
- Overall weight is increased due to the gears.
- There will be a maintenance problem in the future; the worn part should be replaced only by disassembling the whole system.

3.1.4. Rope – Pulley System

Rope – Pulley transmission mechanism is the cheapest system for the grippers. It transmits the rotary motion of the actuator to a joint without any change in motion type. Each link is controlled by aid of separate ropes which are attached on the pulleys. The pulleys are mounted on the main shaft having proper diameters so that the ropes are ever in tension and the movements of the links are synchronized. These are mostly used is dexterous hands where the transmitted force is low, limited rotary motion is needed and small space for transmission systems.

Advantages:

- System is easy to manufacture.
- Maintenance is simple, since all important machine elements are outside the finger.
- It is easy to assemble.
- The production cost is low.
- The system is not heavy.
- It provides high accuracy.

Disadvantages:

- There may occur deflection on the wires due to environmental effects such as temperature changes or tension forces in the wires.
- The rope should be replaced in short time periods
- Rigidity is low.

3.1.5. Rack and Pinion Drive

Rack and Pinion mechanism changes the translational mechanism to rotary motion. It is used where limited rotary motion is needed. The rotary motion angle depends on the length of translational motion and teeth number of pinion.

Advantages:

- Is is relatively inexpensive.

Disadvantages:

- The system suffers from friction.
- There may occur backlash in long term use.

3.1.6. Harmonic Drive

A harmonic drive is an innovative type of transmission system that basically employs three concentric mechanical elements, namely, a rigid external ring with internal teeth called the circular spline, a non rigid internal flexspline with fewer teeth that rotates within the circular spline in response to the motion of a rotating input drive element which is called "wave generator". Since harmonic drives have high torque capacities with nearly zero hysteresis, they are increasingly used in robotics applications.

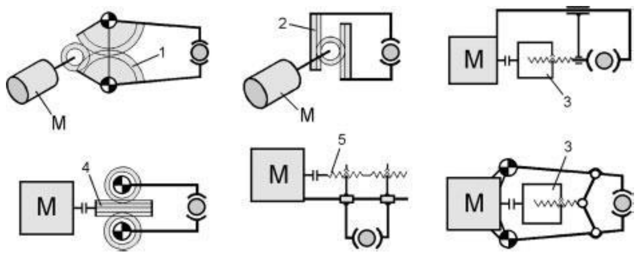
3.2. Actuators.

Finger motion can be realized by a number of possible prime movers. This is accomplished by converting some form of energy into mechanical energy which corresponds to the required form of motion. There are mainly three types of actuators used in grippers. These are;

1. Electromechanical Actuators.
2. Hydraulic Actuators.
3. Pneumatic Actuators.

3.2.1. Electromechanical Actuators.

Most electromechanical drives used in grippers are based on spindle or rack and pinion gears as force converters. Although their part on the market is not large compared to the other types of drive, there are several different designs in common use as seen on figure 3.1.



1 tooth segment,
2 toothed rack and pinion gear,
3 spindle nut,
4 toothed rack,
5 right-left handed threaded spindle,
M motor

Figure 3.1: Basic Design Strategies for Grippers Driven by Electric Motors. [5]

Spindle driven gripper jaws normally enjoy a relatively large stroke not normally achievable with other gear types. As a prime mover almost any form of electrically commutated DC servo motor is suitable.

The main advantages of electrical energy are:

1. It is non-polluting.
2. It is a familiar source of energy.
3. Supplies are easily connected using flexible cables.
4. Most of all, controllers are compact, lightweight and easy to design.

It also has some disadvantages as;

1. Electrical motors rotate at high speeds with low torque so they are always used in conduction with step down gears which results in an increase both in weight and cost.
2. Direct current motors cannot maintain a large torque during prolonged standstill operation and the torque decreases if speed increases. On the other hand, these motors cannot be used in standstill for a long time, because of the overheating problem.
3. In step motors torque depends on the position (angle).

DC servo and stepper motors are the main types of electric actuators used in robotics applications. DC motors are essentially transducers that convert electrical energy to mechanical energy. The magnitude and direction of current flow in a rotating armature produces a corresponding, proportional torque. Unlike DC motors which generally require some form of feedback or closed loop control, stepper motors are essentially driven by a sequence of electric pulses, with the number of pulses directly controlling the position of the motor. A stepper motor is capable of moving in small incremental steps each time when the signal comes. So the control is simpler than DC motors. Stepper motors are generally used in less sophisticated robotics applications, such as pick and place operations, where moderately precise, open loop control is acceptable and the torque requirements are small.

3.2.2. Hydraulic Actuators.

Advantages of this hydraulic energy are;

1. High power to weight ratio (20 times better than electrical energy ratio).
2. No need for gear reduction.
3. Ease of design.

On the other hand, there are some disadvantages as;

1. It is expensive due to the need for local generation of energy, high cost components, short-term maintenance and high energy losses.
2. There may occur leakage and burst problems.
3. Heavy, bulky chambers and pipes.
4. Adequate fluid filtration.

Hydraulic actuators which employ various oils under high pressure (2000 psi) can be operated in either an open loop or a closed loop manner. In the latter case, an electrical servo amplifier controls the position of an electromechanical servo valve located in the hydraulic fluid system which in turn, regulates the primary oil flow [7].

3.2.3. Pneumatic Actuators.

The most frequently used impactive grippers are pneumatically driven. Actuation is realized either by pneumatic cylinders integrated within the gripper housing or by externally mounted cylinders. Such prime movers are robust and resistant to overload. Both single-acting cylinders with spring return or double-acting devices are available. The piston force F_P can be obtained from the following equation:

$$F_P = p_e \cdot A \cdot \eta \tag{3.1}$$

p_e = working pressure ($p_e = p_{abs} - p_{amb}$; $p_{amb} \approx 1$ bar)

A = Cylinder internal cross sectional surface area

η = Efficiency

p_{amb} is often taken as 1.1 or 1.2 Bar as a safety margin to allow for changes in atmospheric pressure.

Typical values for the efficiency (depend on air leakage, friction etc.) are:

- for high quality single-acting and double-acting cylinders $\eta > 0.9$
- for cheaper double-acting cylinders with lip seals $\eta = 0.7$ to 0.9

In double-acting pneumatic and hydraulic actuators, Figure 3.2, the force F_P is proportional to differences in pressure, p_2-p_1, in static mode as;

$$F_P = p_2 \cdot A - p_1 \cdot (A - a) \tag{3.2}$$

p_1 = Pressure in the shaft side

p_2 = Pressure in the piston side

A = Cross-sectional area of the piston

a = Cross-sectional area of the shaft

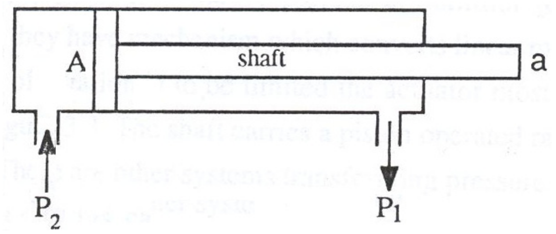


Figure 3.2: Schematic View of Double Acting Cylinder.

There are also advantages and disadvantages for pneumatic energy. The main advantages are;

1. Relatively high power to weight ratio (more powerful than electrical, weaker than hydraulic actuators).
2. No necessity for gear reduction.
3. Simple in design.
4. Low cost.
5. No environmental or safety problems because of leakage.

On the other hand there are some disadvantages as;

1. Very difficult to control (as air is compressible fluid).
2. Necessity for compressed air supply system.
3. Necessity for piping.

Some of the most often used pneumatic actuators on grippers are as follows; linear pistons, rotary pistons, motors and pneumatic muscles.

Linear pistons: These systems are generally on-off controlled and the speed of the movement is not precisely controlled. Figure 3.3 shows a standard linear dual action piston. To overcome friction and avoid any juddering movement it is important that the maximum theoretical pressure in the section of pipe should be greater than any opposing pressure. There is asymmetry in the forces developed in the pulling and pushing movements of the actuator. If a pneumatic piston is to be used over its full stroke it is useful to employ a damped piston.

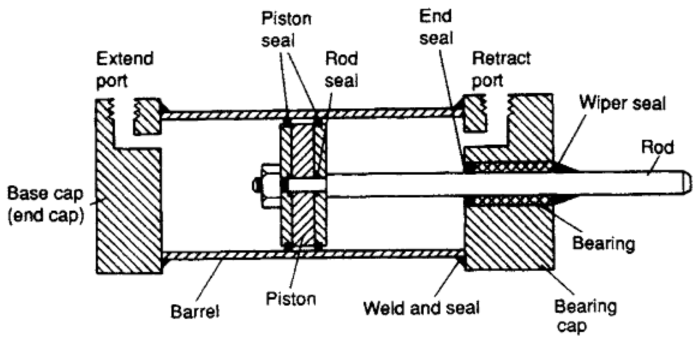


Figure 3.3: Elements of Standard Double-Action Linear Piston.

Rotary pistons: These pistons are similar to linear pistons; the only difference is that they have mechanism which converts linear motion to rotational motion. If the amplitude of rotation is to be limited the actuator most frequently used is of the type shown in Figure 3.4. The shaft carries a piston operated rack that drives a pinion on the output axis. There are other systems transforming pressure to a rotational movement such as screw-nut systems, cams.

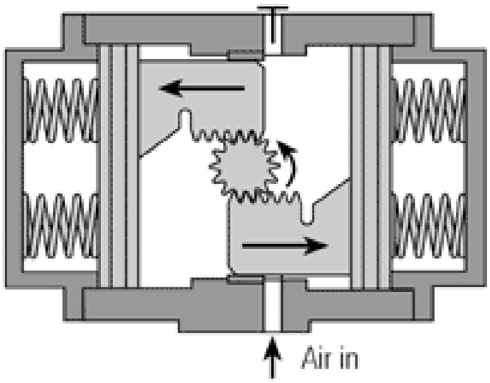


Figure 3.4: Spring Return Rotary Pneumatic Actuator. [20]

Motors: Devices which transform pneumatic energy into mechanical rotary movement with possibility of continuous motion are known as pneumatic motors. The pneumatic motors with unlimited angle of rotation are one of the most widely used working elements operating on compressed air. Pneumatic motors are categorized into four groups; Piston motors, sliding-vane motors, gear motors and turbines.

Pneumatic Muscles: Pneumatic artificial muscles are contractile or extensional devices operated by pressurized air. Similarly to human muscles, pneumatic muscles are usually grouped in pairs as one agonist and one antagonist.

Pneumatic artificial muscles were first developed (under the name of McKibben Artificial Muscles) in the 1950s for use in artificial limbs. The Bridgestone rubber company (Japan) commercialized the idea in the 1980s under the name of Rubbertuators.

The retraction strength of the pneumatic artificial muscle is limited by the sum total strength of individual fibers in the woven shell. The exertion distance is limited by the tightness of the weave; a very loose weave allows greater bulging, which further twists individual fibers in the weave.

Pneumatic artificial muscle actuator (Figure 3.5) is formed from a two-layered cylinder consisting of an inner containment liner usually formed from rubber and an outer woven braid material. These are clamped to end caps that seal the open ends of the muscle and allow the input of compressed air. When pressurized the muscles become fatter and due to the weave pattern of the braided material they reduce in length and it is this motion that can be used to move robotic limbs.

Figure 3.5: Pneumatic Muscle. (Festo Pneumatics) [21]

The functional similarity between natural and pneumatic muscles suggests they are well suited to the field of biologically inspired robots and particularly anthropomorphic robots.

Pneumatic actuators are perhaps the simplest in design and the lowest in cost to employ in robotics applications. Unfortunately, pneumatic drives are the most difficult to control, as air pressure is simply not forceful enough to alter quickly the inertia of a moving piston, because air is compressible. Therefore, pneumatic actuators are usually employed in simpler pick and place applications.

3.3. Sensors.

3.3.1. Piezoelectric sensors

Piezoelectric sensors are either made of silicon or quartz. At the present time quartz is widely used. Quartz is connected to an electric circuit. When any pressure is applied on quartz material, it slightly deforms for a while and at this time the potential difference between the terminals of the quartz changes; therefore a voltage signal is generated. As soon as the pressure exerted on quartz is released it deforms back to its original position immediately.

Advantages:

- Sensor is dynamic so that, the result can be got and processed immediately as the pressure is exerted.

Disadvantages:

- It occupies a large space so that at the fingertip it would create serious kinematic problems.
- High cost.

3.3.2. Fiber optic sensing devices.

This system works on the principle that as the washer like structure around the finger moves, the optical beams passing all inside along the finger are disturbed. According to the extent of this disturbance, the receiver will receive less light beam. There occurs a signal proportional to the extent of the disturbance.

Advantages:

- More sensitive than piezoelectric sensors.
- Long life

Disadvantages;

- Very expensive
- Manufactured for cases where very small weights are to be held.

3.3.3. Force sensing resistors:

This sensor's structure is very similar to a strain gage. When, pressure applies on the sensor, its resistance decreases and the current passing through the sensor increases. Then the analog signal created is sent to the control unit and processed there.

Advantages:

- Occupies very small space on the finger.

- Very cheap

Disadvantages:

- Not very sensitive

CHAPTER 4

DESIGN OF THE TWO-FINGERED GRIPPER

4.1. Introduction

Robotic grippers are the most important parts in most of the robotics applications as they are in contact with work pieces. Design of the robot gripping mechanism always becomes the key element for the entitled project. In order to achieve its requirements and to do its job, a gripper must suit the shape, mass, physical properties and other special demands of the work piece being handled. Also the parameters of the handling and environment have to be satisfied. Generally these requirements can be met by low-cost grippers designed for series production.

Design of the gripper has to match the capabilities of the robot to the requirements of the task. The prehension principles should be synthesized from independent solutions to these considerations shown in Figure 2.3. After synthesis suitable gripper design must be selected and implemented.

If handling or assembling problem in complicated, then the use of a special gripper is needed. When designing grippers, the assurance of the required capabilities with minimum weight is a must, because the dynamic behavior of robots is affected adversely by the mass moved as the gripper is attached to tip of the robot arm.

The features, as general saying requirements that a perfect gripper design should have can be listed as; [22]

1. Low cost,
2. Light Weight,
3. Simple, rugged and compact design,

4. High grip force to weight ratio,
5. Controllable grip force,
6. Controllable finger position,
7. Minimal backlash and friction,
8. High speed finger motion,
9. Sensor ready (tactile, proximity, slip, force),
10. Interface to robot or microcomputer controller.

As well as the requirements of a perfect gripper are proved, it is not possible to have design that satisfies all of them. Because of the fact, the designer should select major requirements that are suitable for the task and ignore others.

4.2. Design

The first step of design of the gripper is to define its task. The grippers differ from one application to another, so, it is important to define the task clearly. Only by doing this definition, the requirements used for the design can be determined. This gripper will be used with robot in METU CAD/CAM Robotics Center to develop a flexible manufacturing cell (FMC) which will be composed of a robot, conveyor systems, a furnace and a hydraulic press. The function of the gripper is to transfer work piece from furnace to press and after operation of press, it will transfer the work piece from press to conveyor. The main purpose of the FMC is to compress a hot 3 inch diameter Aluminum billet for hot thixo-forming operation. Because of the simplicity of the task (pick and place), it was decided to design a two fingered gripper which can easily and quickly grasp the cylindrical work piece.

Second step is to investigate the working conditions of the gripper. These conditions do not directly affect the prehension itself, but they have effects on it. As defined before, this gripper will be used in the METU CAD/CAM Robotics Center which can be taken as machine shop conditions. In addition to these conditions, gripper will take place in a flexible manufacturing cell which includes industrial furnace. The resultants of them are oily, dirty, hot and hard conditions. As a result, the actuators, power transmission elements and construction materials must be insensitive to oil, dust, metal filings and high temperature. Another condition which is an effect on design is the power source available on machine shop. There is pressurized air available which affected the selection of power system used in gripper.

After the definition of the task and environmental conditions the design steps can be categorized as follows;

1. Selection of actuation type.
2. Selection of transmission system.
3. Selection of material.
4. Selection of sensors.
5. Manufacturability and Feasibility analysis.

4.2.1. Selection of Actuation type.

As previously explained in section 3.2, three types of actuation can be used in grippers. These are electromechanical actuators, hydraulic actuators and pneumatic actuators. Their advantages and disadvantages are described in depth. In comparison, electromechanical actuators are best for computer control, hydraulic actuators are best for strength and pneumatic actuators are best for ease of use, simpler design and low cost.

It is a fact that; actuator of the gripper must be on it since mounting the actuator to robot arm avoids the gripper to be demountable. Also this prevents the robot to work with different end effectors which is not preferred for multipurpose robots. So, the actuator must be small with high power to weight ratio.

The gripper will be used for pick and place applications, so it will remain in gripping position during its travel. This condition is not suitable for electromechanical actuators since the temperature of actuator will increase if it continuously applies torque in standstill mode for a long time. Also electromechanical actuators are quite expensive

Hydraulic actuators which have very high power to weight ratio and have no drawback for force application during a long time in standstill mode can be other alternative. But, such systems are very expensive and more importantly hydraulic actuators needs external power generation for work. Also, the task defined does not need such a big power to pin down the usage of hydraulic actuators.

Considering these facts, pneumatic actuator is chosen for gripper. Pneumatic actuators are smaller in size and have sufficiently high power to weight ratio. These actuators have no drawback in the standstill mode and cheaper against electromechanical and hydraulic actuators. Also, as mentioned in section 4.2, pressurized air is available in the METU CAD/CAM Robotics Center, so there is no need for external power generation. Double Acting Linear Pneumatic Cylinder is used in the gripper as actuator. The pneumatic circuit diagram of the two-fingered gripper is given in Appendix B.

Figure 4.1: Linear Pneumatic Cylinder Used in the Two-Fingered Gripper. [21]

4.2.2. Selection of Transmission System,

As soon as the linear pneumatic cylinder is selected as actuator, the actuator cannot carry out the gripping action itself. There is a need for transmission mechanism to convert the linear movement of the actuator to a useful action of the fingers. The eligible systems for transmission are explained in section 3.1. For the task that gripper will be used, it will work with cylindrical objects only. So, angular motion of the fingers is required for both ease of gripping and work piece centering. For this reason selected transmission system for this gripper is a mechanical link. The mechanism for converting the linear actuator movement to an angular finger movement can be seen on Figure 4.2.

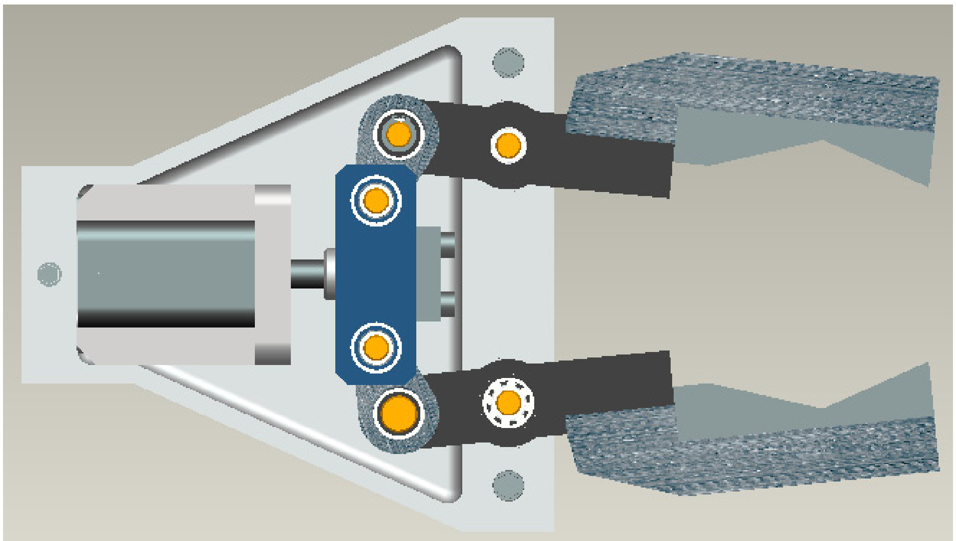


Figure 4.2: Transmission System for Linear to Angular Motion Conversion.

Mechanism is composed of 6 links, 6 revolute and 1 prismatic joints. This mechanism gives the gripper working range of jaw opening from 50mm to 100mm.

4.2.3. Selection of Material

In a general manner, material selection for similar designs is as follows; if the weight is in the forefront then the selection is aluminum, if corrosion resistance is under discussion then the selection is stainless steel and if the high temperatures are working conditions then selection is nickel.

In the design of the gripper, the major preference is the lightness of the gripper. The robot's, which the gripper will be attached, carrying capacity is 10 kilograms. So, it is needed to make the gripper as light as possible in order to leave the remaining capacity for the work piece. On the other hand, the work piece to be picked by the gripper is hot, so, there is a requirement for temperature resistance. In order to satisfy these requirements, finger tips are made from stainless steel. There is no need for nickel alloy since; the operating temperature (660ºC) does not pass over the melting point of stainless steel (1455ºC).

Aluminum available on the Turkish market is not sufficient for the design. It has relatively low mechanical properties. For this reason special aluminum magnesium alloy (5083), which physical properties are given in Table 4.1, is used.

Table 4.1: Typical Mechanical Properties for Aluminum Alloy 5083. [23]

Temper	**H32**
Proof Stress 0.2% (MPa)	240
Tensile Strength (MPa)	330
Shear Strength (MPa)	185
Elongation A5 (%)	17
Hardness Vickers (HV)	95

4.2.4. Selection of Sensors

It is important to have force, position and safety sensors on the gripper but these sensors are quite expensive. On the other hand, this gripper is pneumatically controlled so the gripping force can be adjusted by the means of the pressure regulator used for the system. There exists computer controlled pressure regulators on the market but these pneumatic equipments are very expensive. Since this thesis study is not financially supported, usage of the equipment is cancelled and postponed for future studies.

4.2.5. Manufacturability and Feasibility Analysis.

This is the last but most important step of the design. Till now, the actuation type to drive the gripper, transmission system for the power transfer, materials for production and sensors to be used on gripper are determined. But these are not enough. All these determined variables can be assembled in various ways. In this step, the geometry that uses the determined systems and best fits the required task with the minimum investment has to be studied.

There may be different alternative solutions for the design. But as the gripper will be produced in the METU CAD/CAM Robotics Center, it is necessary to design the parts to be manufactured using the Machine Park capability of the Center. Simple shaped parts are preferred rather than complex parts. Very complex 3D parts may be needed during the design, but manufacturing of this type of parts are expensive, time consuming and requires special machines. So instead of using complex shaped parts, simpler parts with necessary sub assemblies are used during the design phase.

4.3. Computer Aided Design

Computer Aided Design (CAD) is the most important phase of the design process. Solid modeling programs take place in this phase. Solid modeling programs are used to visualize the idea of the designer on the computer screen. Geometries of the components and assemblies can be modeled using these softwares. There are many different programs for solid modeling. Some of the most famous ones are Catia, Pro/Engineer, Unigraphics and I-Deas. All these softwares are same in logic but their usage is different. Also the areas of applications can be different. For example, while automobile and aerospace industries prefer to use Catia to take advantage of the surface modeling power, most of the defense industry uses Pro/E or Unigraphics.

The help of solid modeling is not only to see what you think. It also enables easy and early detection of the clashes, overlapping and non-fittings parts. This means the problems can be seen during the design phase and necessary changes can be implemented. The parts constructing the total assembly are adapted to each other for providing proper matches. Element sizes, component positions and assembly hole positions can be given with parametric relations. If this type of design is used than all the components can be reconstructed and repositioned according to any change in the global sizes of the linkage or component sizes for any requirements.

For the design phase of the two fingered gripper, Pro/Engineer wildfire 2.0 is used as the Computer Aided Design application. All of the parts and assemblies developed for the gripper are modeled using this software. Pro/E gives opportunity for parametric design. Also it has features for simulation of mechanisms. Some pictures from 3D design and manufactured gripper and also from gripping action of the work object are given in Appendix C.

The steps of the computer aided design of two-fingered gripper are;

1. 3D modeling of each elements that are used in gripper,
2. Definition of materials for each element.
3. Construction of sub assemblies,
4. Construction of main assembly that forms the gripper.
5. Clash analysis for early detection (before manufacturing)
6. Definition of the mechanism used in gripper.
7. Simulation of the mechanism to ensure it meets the requirements.

4.4. Computer Aided Manufacturing

Computer Aided Manufacturing (CAM) is the other important technology used in development and production. Computer aided manufacturing is the real time simulation of the manufacturing process. It simulates the manufacturing conditions as machine tools, fixtures, tool paths, etc. By the help of CAM, automated production which will be done by appropriate machine can be seen on computer screen and mistakes or maladjustments can easily be removed from program if any.

Most of the CAD programs include their own CAM modules. CAM modules work with the data coming from CAD program. Usage of the CAM programs is nearly same as CAD programs. In fact, the main difference is that, the part is modeled in CAD programs while, tools, fixtures and tool paths are modeled in CAM programs. The usage of CAM programs eliminates the need for engineering drawings for production. But for quality assurance these drawings are necessary unless there exists no Coordinate Measuring Machine (CMM). For manufacturing of two-fingered gripper Pro/E CAM module is used.

The steps of the computer aided manufacturing of two-fingered gripper are;

1. Data received from CAD program.
2. Definitions of the machine tools and fixtures that are used.
3. Modeling the program that will manufacture the required geometry.
4. Simulate the manufacturing program in order to detect faults.
5. Post process the modeled program for machine tool language
6. Transfer processed program to machine tool.
7. Insert necessary fixtures in the machine tool.

By following these successive steps, parts composing the gripper are manufactured one by one. Engineering drawings of all parts used in two-fingered gripper can be found in Appendix D.

4.5. Manufacturing of Gripper.

Gripper is composed of 63 elements (excluding the pneumatic equipments), where 40 of them are standard parts readily purchased. Remaining 23 parts are designed and produced. As defined in the previous sections, all these parts are modeled using the Pro/E CAD program. After modeling the parts, they are delivered to the machine shop for production. As the machine shop uses Pro/E for post processing of parts, there is no need to model the part using new program. NC programs for the necessary parts are prepared using the Pro/E CAM module and transferred to the appropriate machine for production.

Most of the parts are produced using the CNC wire-cut Electric Discharge Machine. Main profiles of the parts are cut using this machine and after the profiles are ready they transferred to the CNC Vertical-Milling Machine where the remaining operations as drilling holes, slot cutting etc are realized. Universal lathe is used for the production of the pins which are used as joints. After the production, manual deburring is applied for all of the parts to clear the chips away.

4.6. Kinematic Analysis.

In this section, kinematic analysis of the gripper has been performed. Both fingers are same in structure and symmetrical. So, analyses are performed for only one finger. Also tip point displacement vector is derived inside the section.

At the beginning of the kinematic analysis, coordinate axes and the origin of the system is determined. Since the fingers are fixed at the gripper's palm, the center of joint 1 is defined as the coordinate axis origin and coordinate axis is placed as shown on Figure 4.3.

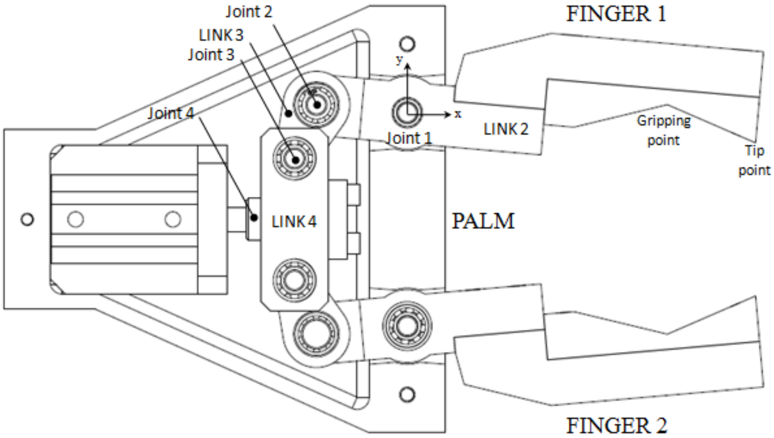


Figure 4.3: Schematic View of the Two-Fingered Gripper.

The rotations of the links are always about the z-axis since rotations about other axes are blocked by the geometry. So, the kinematic model of one finger can be shown as Figure 4.4.

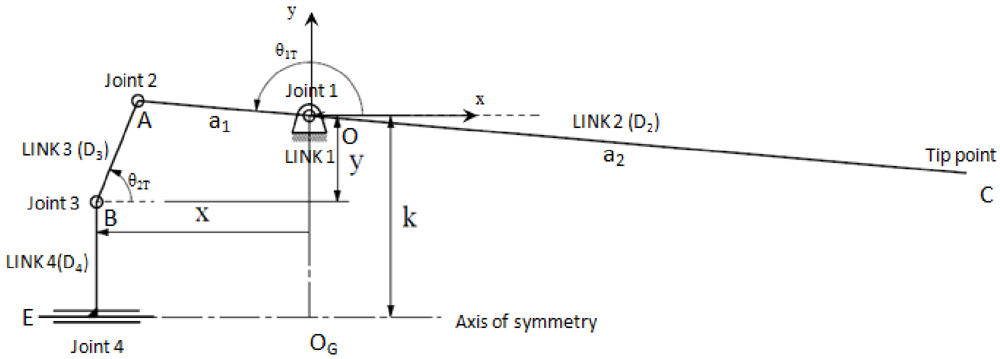


Figure 4.4: Kinematic Model Representation of One Finger.

In this kinematic representation link 4 is modeled as a welded joint to simulate the actual connection. As a result, the motion of joint 3 is directly affected from this link.

Since joint 4 is a prismatic joint, the mechanism is simulating the slider crank mechanism. From Figure 4.4, the loop closure equation for the system can be written as;

$$\overrightarrow{OA} = \overrightarrow{OB} + \overrightarrow{BA} \tag{4.1}$$

Using equation 4.1, the x and y components of the loop closure equation is;

x direction; $a_1 \cos \theta_{1T} = -x + D_3 \cos \theta_{2T}$ (4.2a)

y direction; $a_1 \sin \theta_{1T} = -y + D_3 \sin \theta_{2T}$ (4.2b)

after determination of x and y components of the loop closure equation, the known and unknown variables are to be defined. Equations 4.2a and 4.2b define 3 variables which are x, θ_{1T} and θ_{2T} where y and D_3 are constants. Then, as there are two equations, definition for one unknown is needed in order to calculate other unknowns. Since actuator have 10 mm stroke and initial position is known, the values for θ_{1T} and θ_{2T} can be determined for corresponding x values. Using equation 4.2b, θ_{1T} can be written as;

$$\theta_{1T} = \sin^{-1}\left(\frac{D_3 \sin \theta_{2T} - y}{a_1}\right) \tag{4.3}$$

Also, equation 4.2a can be written in new form in order to use known values of x as;

$$x = D_3 \cos \theta_{2T} - a_1 \cos \theta_{1T} \tag{4.4}$$

by substituting equation 4.3 in equation 4.4, θ_{2T} values can be determined for corresponding x values by using numerical values a_1=30mm, D_3=19 mm and y=15mm. The x values for the gripper vary between 33.5mm and 43.5mm. The calculations yield two solution sets for θ_{2T} values. But, from the geometry of the gripper only first quarter results are used. By using the calculated θ_{2T} in equation 4.3, θ_{1T} values are calculated. Then calculated values of θ_{1T} are used for tip point displacement.

For the tip point displacement, components of the vector are written as;

x direction; $\overrightarrow{C_x} = a_2 \cos(\pi - \theta_{1T})$ (4.5a)

y direction; $\overrightarrow{C_y} = a_2 \sin(\pi - \theta_{1T})$ (4.5b)

using numerical value for a_2=115mm; the components of the position vector is;

$$\overrightarrow{C_x} = 115 \cos(\pi - \theta_{1T}) \tag{4.6a}$$

$$\overrightarrow{C_y} = 115 \sin(\pi - \theta_{1T}) \tag{4.6b}$$

After definition of tip point vector components, displacement graph is constructed for finger with the varying values for 33.5mm < x < 43.5mm.

Displacement of finger tip wrt. finger coordinate system is given in figure 4.5.

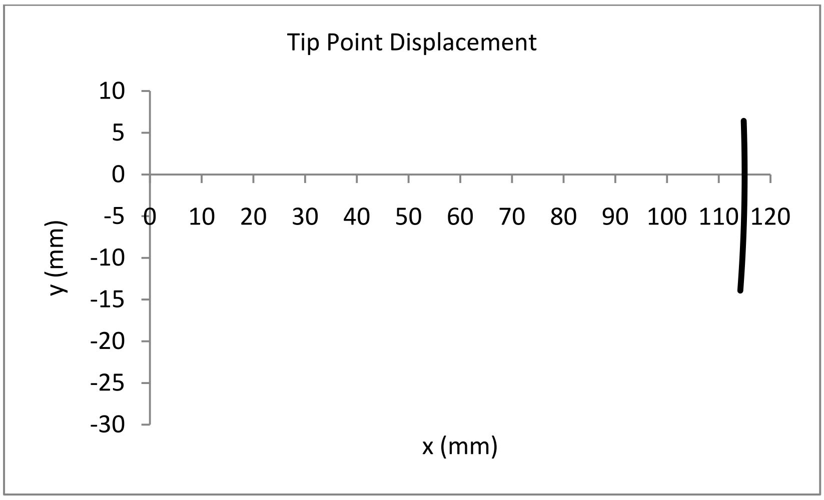


Figure 4.5: Tip Point Displacement of Finger Tip wrt. Finger Coordinate Frame.

The other finger of the gripper is symmetrical and the symmetry axis is shown on figure 4.4. If displacement of finger 1 is translated to gripper origin (O_G) (where k=35mm) and displacement of finger 2 is taken as symmetrical to the axis of symmetry then figure 4.6 can be constructed showing the motion of two fingers.

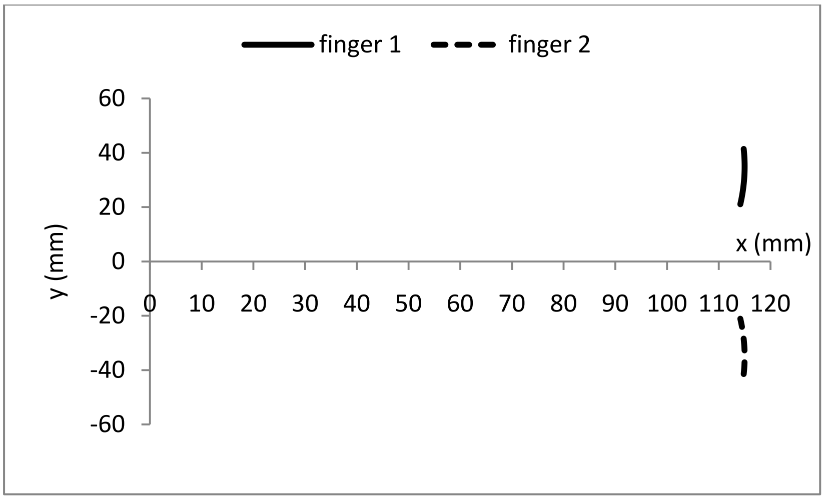


Figure 4.6: Combined Displacements of Finger Tips wrt. Gripper Coordinate Frame.

4.7. Force Analysis

In order to carry out force analysis, it is needed to calculate gripping force for gripping point. So, instead of tip point, gripping point shown on figure 4.3 is used for calculations. For analysis, simplified free body diagrams of all links are given. Following the free body diagram construction, static equilibrium conditions are applied and gripping force is calculated.

The developed gripper is pneumatically controlled. So, gripping force exerted by the gripper is directly related to the pressure applied on the actuator of the system. For that reason, instead of giving exact values for gripping force, relation between gripping force and pressure of the system is derived inside the section.

For analysis, gravitational forces and frictional forces are neglected as they are small when compared to gripping forces.

Free body diagrams for link 2, 3 and 4 are given in figure 4.7, 4.8 and 4.9 respectively.

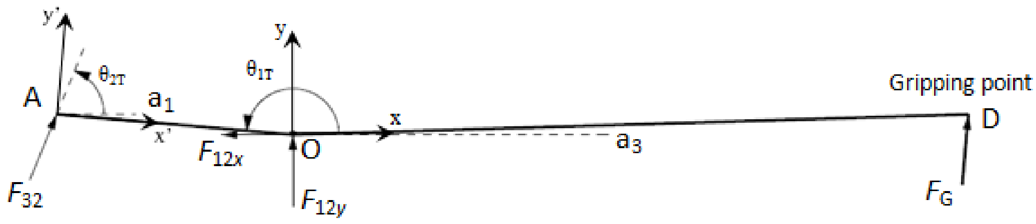


Figure 4.7: Simplified Free Body Diagram for Link 2.

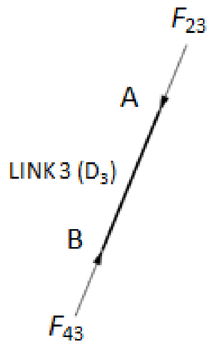


Figure 4.8: Simplified Free Body Diagram for Link 3.

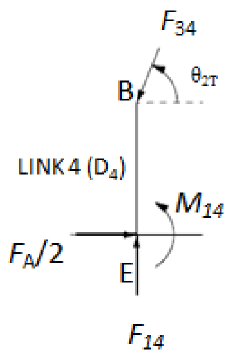


Figure 4.9: Simplified Free Body Diagram for Link 4.

In figures 4.7, 4.8 and 4.9, used nomenclature is defined as;

F_G: Gripping force applied by one finger of the gripper.

F_{ij}: Force applied by link *i* to link *j*.

F_A: Force applied by actuator.

M_{ij}: Reaction moment from link i to link j.

Because of the symmetric solution half of actuator force is used in calculations.

From free body diagram of link 3, figure 4.8, it is seen that link 3 is a two force member. Then;

$$\overrightarrow{F_{43}} = -\overrightarrow{F_{23}} \tag{4.7}$$

From free body diagram of link 4, figure 4.9;

$$\sum F_x = 0, \qquad F_A / 2 - F_{34} \cos \theta_{2T} = 0 \tag{4.8a}$$

$$\sum F_y = 0, \qquad F_{14} - F_{34} \sin \theta_{2T} = 0 \tag{4.8b}$$

$$\sum M_E = 0, \qquad F_{34} \cos \theta_{2T} * D_4 + M_{14} = 0 \tag{4.8c}$$

From figures 4.7, 4.8 and 4.9;

$$\overrightarrow{F_{34}} = -\overrightarrow{F_{43}} \tag{4.9a}$$

$$\overrightarrow{F_{43}} = -\overrightarrow{F_{23}} \tag{4.9b}$$

$$\overrightarrow{F_{23}} = -\overrightarrow{F_{32}} \tag{4.9c}$$

It is now needed to define the line of action for gripping force to use in calculations. For cylindrical workpieces, the line of action for gripping force can be found from the gripper geometry. Link 2 and the gripper jaw geometry is shown on Figure 4.10.

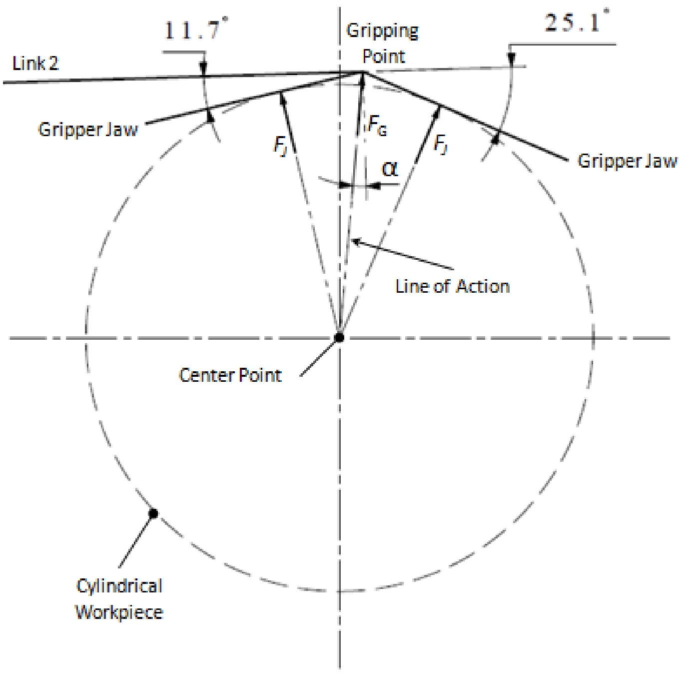


Figure 4.10: Line of Action for the Gripping Force on Cylindrical Workpiece.

On Figure 4.10;

F_G: Gripping force applied by one finger of the gripper.
F_J: Force applied by jaw of the finger.
α: Angle between link normal and line of action of the gripping force.

Because of the geometry of the gripper, force applied by jaw of the finger is always perpendicular to jaw at contact point and towards the center of the workpiece. From the geometry shown on Figure 4.10, α, which is defined as angle between link normal and line of action of the gripping force, is found as;

$$\alpha = (25.1° - 11.7°) / 2 \qquad \alpha = 6.7° \tag{4.10}$$

From free body diagram of link 2 (Figure 4.7);

$$\sum M_O = 0 \tag{4.11}$$

It is required to decompose F_{32} into its components in the x'-y' frame;

$$F_{32x'} = F_{32} \cos(\pi - \theta_{1T} + \theta_{2T}) \tag{4.12a}$$

$$F_{32y'} = F_{32} \sin(\pi - \theta_{1T} + \theta_{2T}) \tag{4.12b}$$

Also, it is required to define normal and parallel components of the gripping force

$$\text{Normal Component: } F_{Gn} = F_G \operatorname{Cos} \alpha \tag{4.13a}$$

$$\text{Parallel Component: } F_{Gp} = F_G \operatorname{Sin} \alpha \tag{4.13b}$$

After definitions in equations 4.12 and 4.13, the moment about point O can be written as;

$$-F_{32y'} a_1 + F_{Gn} a_3 = 0 \tag{4.14}$$

using equations 4.7, 4.8a, 4.9, 4.12, 4.13 and 4.14, gripping force is defined as;

$$F_G = \frac{-F_A \sin(\pi - \theta_{1T} + \theta_{2T}) a_1}{2 a_3 \cos\theta_{2T} \cos\alpha} \tag{4.15}$$

Since F_A, actuator force, is the pressure force, it is related to system pressure and calculated using equation 3.2,

$$F_A = P\,A - P_1\,(A - a) \tag{4.16}$$

where, P is the system pressure, P_1 is the atmospheric pressure (taken as 1.1 bar for safety), A is cross sectional area of the piston and a is the cross sectional area of the shaft of pneumatic cylinder. The piston has circular cross section and r=8mm and shaft has square cross section with l=7mm edge length. Using these values;

$$A = \pi\, r^2 = 201.1 \text{ mm}^2 \tag{4.17a}$$

$$a = l^2 = 7^2 = 49 \text{ mm}^2 \tag{4.17b}$$

Finally, using numerical values for $P_1 = 0.11$ [N/mm^2], $a_1 = 30$mm and $a_3 = 85{,}6$mm gripping force – pressure relationship is given as;

$$F_G = \frac{-(201.1\,P - 16.731)\sin(\pi - \theta_{1T} + \theta_{2T})30}{171{,}2\ \cos\theta_{1T}\ \cos\alpha} \tag{4.18}$$

where, the unit of P is [N / mm^2].

From the gripping force calculated using equation 4.18, gripping capacity of the gripper can be calculated using equation 4.19 [5] which is given as;

$$F_G = \frac{m(g + a)}{2\mu}\sin\beta \cdot S \tag{4.19}$$

In this formula;

F_G : Gripping Force
m : Mass
g : Gravitational Acceleration
a : Acceleration
μ : Coefficient of friction
2β : Angle between Jaws of the gripper
S : Safety Factor.

For the developed gripper the values are;

μ = 0.35 (Finger Surface: Steel, Workpiece Surface: Aluminum.) [5]

S = 1.2

a = 0

β = 71.5º

4.8. Specifications of Gripper.

4.8.1. Mechanical Specifications

Weight of the gripper: 1.989 kg

Weight of the gripper without pneumatic equipments: 1.894 kg

Width of the gripper: 140mm

Length of the gripper: 250mm

Height of the gripper: 50mm

Construction material for main body and links: 5083 Aluminum (Magnesium alloy).

Construction material for finger tips: 304 Stainless Steel.

Number of fingers: 2 fingers

Degrees of freedom: 1

Finger force range at 6 bars: 19.8N - 108.7 N

Maximum rotation of fingers: 20.4º

Maximum jaw opening: 82.8mm

Minimum jaw opening: 42mm

4.8.2. Pneumatic System Specifications

Actuator Specifications:

Actuator Type: Double Acting Linear Cylinder ADVULQ-016-10-A-P-A (FESTO)

Piston Diameter: 16mm

Stroke: 10mm

Theoretical pushing force at 6 bars: 121 N.

Theoretical pulling force at 6 bars: 90 N

Operating pressure range: 1.3-10 bar.

Valve Specifications:

Valve Type: Directional Control Valve MLH-5-1/8-B (FESTO)
Function: 5/2 way, monostable (single solenoid)
Type of return: Mechanical Spring.
Operating pressure range: 2-8 bars.
Solenoid working voltage: 24 V.

Pressure Regulator Specifications:

Regulator Type: Filtered Regulator LFTR-D-MINI (FESTO)
Input Pressure: 1-16 bars.
Output Pressure: 0.5-12 bars.
Hysteresis: 0.2 bars.

All other pneumatic equipments as connection elements, silencers, solenoids and pipes are purchased from Festo Pneumatics.

CHAPTER 5

DESIGN OF THE FOUR-FINGERED GRIPPER

5.1. Introduction

A detailed introduction about the design of robotic grippers is given in section 4.1. In this chapter, the second part of the thesis which is the design of four-fingered robotic gripper will be examined.

Two-fingered gripper was specially designed for pick and place task defined in Chapter 4. But this four-fingered gripper is designed to be a multipurpose gripper.

The requirements of the perfect gripper design still remains the same and given as;

1. Low cost,
2. Light Weight,
3. Simple, rugged and compact design,
4. High grip force to weight ratio,
5. Controllable grip force,
6. Controllable finger position,
7. Minimal backlash and friction,
8. High speed finger motion,
9. Sensor ready (tactile, proximity, slip, force),
10. Interface to robot or microcomputer controller.

However, major requirements suitable for the task must be selected as for the design and remaining ones should be ignored.

5.2. Design.

As stated before, starting point for design of the gripper is to define its task. Otherwise, the requirements will be used for the design cannot be determined and this can be resulted as redundant complex gripper for a simple task or inadequate design for a complex task. Force distribution of the gripper must be decided and work piece characteristics have to be known. Compared with the two-fingered gripper, which is developed for a special task, this four-fingered gripper is not designed for a predefined task. It designed to be a multipurpose gripper. Since the task is not predefined, no specific conditions can be considered during design. So, as a general approach, human hand and previous dexterous hands are taken as a model for dimensioning. This gripper is ideal for light objects. All the fingers can be controlled individually and this gives the gripper ability to grasp complex shaped objects.

For the second step, environmental conditions must be defined clearly. Like in the two-fingered one, this gripper will be used in the METU CAD/CAM Robotics Center too. So, oily and dirty machine shop conditions are also valid for this gripper. The only difference is that, this gripper will not work in high temperature environment. As a result, the actuators, power transmission elements and construction materials must be insensitive to oil, dust and metal filings. Coating material is needed for this gripper in order to increase the coefficient of friction of the contact surfaces of the gripper. Also, the pressurized air source availability on machine shop is already has an effect on design.

After the definition of the task and environmental conditions for four-fingered gripper, the design steps can be listed as follows like two-fingered one;

1. Definition of kinematic structure
2. Selection of actuation type.
3. Selection of transmission system.
4. Selection of material.
5. Selection of sensors.
6. Manufacturability and Feasibility analysis.

5.2.1. Definition of Kinematic Structure.

In design of the gripper, since there is no data about the work piece, human hand has been taken as a model. For determination of the number of joints, number of links and their geometrical configuration, human hand is used as model being the perfect multipurpose gripper. Although number of joints in the fingers of the gripper is equal to number of joints in human hand, the degrees of freedom are different. In human hand there are 4 joints with 3 degrees of freedom for each finger [24], but in the developed gripper, there are 3 joints and degree of freedom is limited to 1. Each finger has one actuator for movement. The working principle is to transfer the movement of actuator from one link to another simultaneously. By this way, this gripper can make partially wrap-around grasp. On the other hand, human hand has an intrinsic muscle that modifies the palm's shape; however, the developed gripper has no such ability for this type of movement.

5.2.2. Selection of Actuation Type.

In the four-fingered gripper, because of the finger geometry and used transmission system a powerful actuator is required. On the other hand, because of the actuators will be on gripper to maintain detachability, the selected actuators must be lightest as possible. Taking these two conditions into account electromechanical actuators are eliminated because, pneumatic actuators have higher power to weight ratio than electromechanical actuators. Also, application of higher torques in standstill mode causes temperature increases in electromechanical actuators. This condition also has an effect on elimination of electromechanical actuators.

The hydraulic actuators are stronger than pneumatic actuators but they have some disadvantages as leakage, high cost and external power generation requirement. As previously described in environmental conditions, pressurized air source is available in the Robotics Center. So, the requirement of external power generation for hydraulic actuators results in the elimination of this actuation type.

The preceding conditions resulted as selection of pneumatic actuators for the gripper. But, these types of actuators have some disadvantages too. The pneumatic actuators are very fast in action, but in prehension study fast movement of fingers is not wanted as such movements can be harmful for some types of work pieces and gripper. There may be special tasks that require high speed but as a multipurpose gripper, this four-fingered gripper has control mechanism for speed of the fingers.

In gripper design semi-rotary drive pneumatic actuator is selected for actuation. Torque and force values of the actuator are listed in Table 5.1. [21]

Table 5.1: Force and Torque Values for Actuator.

Forces and Torques		
Torque at 6 bar	[Nm]	2
Maximum swiveling frequency	[Hz]	3
Maximum permissible radial load	[N]	75
Maximum permissible axial load	[N]	30

As seen from the table 5.1 actuator exerts 2 N.m torque at 6 bar pressure. However, maximum permissible radial load for this actuator is 75 N. In design, it is needed to use the correct vales for limitation in calculations.

Besides the pneumatic actuator, there are many types of pneumatic equipments used in the gripper. These are pressure regulator for system pressure and gripping force control, flow control valves for speed adjustment, 5/2 solenoid valves for direction control and finally pipes and fittings that connects all system together. The flow control valves controls the speed of airflow in both direction. The pneumatic circuit diagram of the four-fingered gripper is given in Appendix B.

5.2.3. Selection of Transmission System.

In selection of transmission system, there are several points. First of all, the pneumatic actuators have to be placed on the nearest position to the arm to shorten the moment arm that affects the precision of the gripper. Placing actuators on links cannot be possible until there is no space for actuators between fingers. Because of these requirements power transmission system has to be used in design.

It is described that there are 6 methods for power transmission. These are;

1. Chain – Belt Mechanism.
2. Mechanical Link.
3. Gear Train System.
4. Rope – Pulley System.
5. Rack – Pinion Drive.
6. Harmonic Drive.

The chain-belt mechanism is not effective for design because of its disadvantages as the problem of backlashes, complexity of assembly and the standards for the chains are not suitable for small size applications.

Mechanical link transmission system is useful and powerful but the problem is that, the gripping force is non-linear as the moment arm at joints changes by rotation. (Figure 5.1)

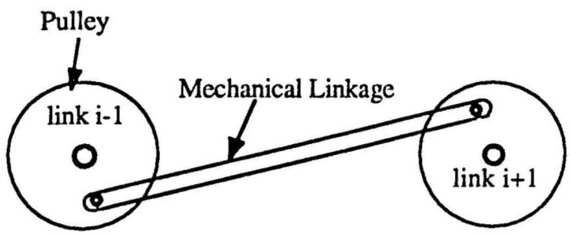


Figure 5.1: Schematic View of USC/Belgrade Hand Transmission Mechanism.

Gear train system is not effective for this design until the joints are separate from each other. It is possible to design such a transmission system but this design results as unnecessary weight and high cost.

The rack and pinion drive can be used for the first joint of the fingers but is not suitable for transmission between the limbs of finger.

Harmonic drives are not used for finger transmission as they are difficult to manufacture.

Between these 6 options, the more effective and useful mechanism is rope and pulley mechanism. Similar to the tendons in a human hand, this mechanism have tendon like ropes to transfer the actuator movement to finger joints. Most the highly developed robotic hands as the Utah/MIT hand and Anthrobot use this mechanism as well. In this transmission system the moment arm does not changes by rotation of joints which is declared as a disadvantage of mechanical link transmission system.

In the four-fingered gripper, the actuator power is transmitted to the joints of fingers by rope-pulley drives. Used pulleys must be small because of the free space in the fingers. As the pulleys have size limitation, this also limits the size of the ropes used for transmission. Also, ropes must be flexible as it will wound around the pulleys.

5.2.4. Selection of Material

In the design of the gripper, the major preference is the lightness of the gripper, because this four fingered gripper is designed for dexterity, not for heavy loads. For lightness best choice is Aluminum for construction. As in the two-fingered gripper, 5083 series aluminum is used for production of the gripper elements. As soon as the aluminum on Turkish market has enough strength for structural elements, its manufacturability is very weak. To overcome this situation a stronger material having high manufacturability is used for construction. This material has values for shear strength = 250 MPa, tensile strength = 330 MPa, Vickers hardness=95 and density = 2.65 g/cm^3. [23]

For selection of material for rope and pulley system, the main idea is having a strong rope, as it will have a small cross section, and a suitable pulley that does not damage the rope. In the selection of rope material, there are several aspects as;

1. Ropes must be flexible,
2. Ropes must have very high tensile strength
3. Ropes must have large modulus of elasticity.
4. Ropes must not have springback effect.

In design of the gripper, 2mm diameter static ropes are used as tendon material. the ease of reach for this material have a role on selection of the material. It has a tensile strength of 191 MPa [25].

Pulley material is selected as brass unless not to be deformed during the application with the gripper.

The last material that has to be defined for the design is the covering material. Covering material is required to protect finger structures and also to increase coefficient of friction between the finger and work piece. Use of covering material helps to decrease the gripping force required to grasp the work piece and to increase the area of contact in non flat work piece surfaces. To maintain these requirements, a soft material with high coefficient of friction has to be selected. For these, soft rubber having 2mm thickness is selected and proved by gripping experiments.

5.2.5. Selection of Sensors

Same as the two-fingered gripper, this gripper is also pneumatically controlled so the gripping force can be adjusted by the means of pressure regulator used for system. As the thesis study is not financially supported, usage of computer controlled pressure regulators is cancelled and postponed for future studies.

5.2.6. Manufacturability and Feasibility Analysis.

Till now, kinematic structure, the actuation type to drive the gripper, transmission system for power transfer, materials for production and sensors to be used on gripper are determined. But as in the two-fingered gripper, these are not enough. All these determined variables can be assembled variously. In this step, the geometry that uses the determined systems and best fits the required task with minimum investment has to be studied.

The gripper is produced in Hasaş Makina Ind. & Trd. Ltd. Co. So, design is optimized to be manufactured using the Machine Park capability of the company. As in the two-fingered gripper, simpler parts with necessary sub assemblies are used during the design phase.

5.3. Computer Aided Design

The importance of computer aided design is explained in Section 4.3. For the design phase of the four-fingered gripper, CATIA Computer Aided Design software is used. All of the parts and assemblies developed for the gripper are modeled using this software. Like Pro/E, CATIA gives opportunity for parametric design too. Also it has features for simulation of mechanisms. Some of the pictures from 3D design and manufactured gripper and also pictures from gripping action of various objects are given in Appendix E.

5.4. Computer Aided Manufacturing

Computer Aided Manufacturing is explained in depth in Section 4.4. The parts are produced using Unigraphics CAM module and MasterCAM programs for the four-fingered gripper. Engineering drawings of all parts used in four-fingered gripper can be found in Appendix F.

5.5. Manufacturing of Gripper.

Gripper is composed of 150 elements (excluding the pneumatic equipments), where 85 of them are standard parts readily purchased. Remaining 65 parts are designed and produced. All these parts are modeled using CATIA software. After the modeling of parts, they are delivered to machine shop for production. The machine shop uses Unigraphics and MasterCAM for programming and post processing of the parts, so, all models converted to universal file type STP. This file type is used for data transfer between various CAD and CAM programs. NC programs for necessary parts are prepared using Unigraphics and MasterCAM programs and transferred to appropriate machine tool for production.

Most of the parts are produced using CNC Vertical Milling Center and CNC Lathe Also, CNC wire-cut Electric Discharge Machine is used for grooves on parts. After the production, manual deburring is applied for all of parts to clear chips away.

5.6. Kinematic Analysis.

In this section, kinematic analyses of the gripper are performed. The analyses are performed as two separate parts. First one is the kinematic analysis for the fingers and the second is the kinematic analysis for thumb. Displacement vectors are derived inside this section. Also velocity vectors for fingers and thumb are derived and given in Appendix G in order to be available for dynamic analyses.

Three fingers of the gripper are similar in joint numbers and link dimensions. So, their kinematic structure is the same as well. But the thumb of the gripper and also the kinematic structure is different than fingers. As a result analyses are performed for one finger, representing the others, and for thumb.

5.6.1. Kinematic Analysis for Fingers.

At the beginning of the kinematic analysis, coordinate axes and origin of the system is determined. Since the fingers are fixed at the gripper's palm, center of the joint 1 is defined as coordinate axis origin and axis is placed as shown on Figure 5.2.

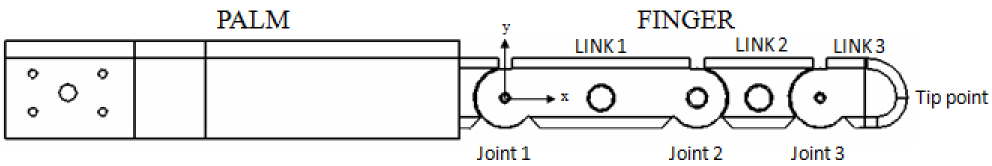


Figure 5.2: Schematic View of Palm and Finger of the Gripper.

The rotations of the links are always about z-axis till rotations about other axes are locked by geometry. The kinematic model of the finger is shown as figure 5.3.

Because of the transmission system used in gripper, rotation angle between link (i-1) and link (i) is always equal to angle between link (i) and link (i+1).

From Figure 5.3, the position vector $\vec{r_f}$ of the tip point is derived as;

$$\vec{r_f} = [L_1 \cos \theta_1 + L_2 \cos (\theta_1 + \theta_2) + L_3 \cos (\theta_1 + \theta_2 + \theta_3)]\vec{\imath} + [L_1 \sin \theta_1 + L_2 \sin (\theta_1 + \theta_2) + L_3 \sin (\theta_1 + \theta_2 + \theta_3)]\vec{\jmath} \quad (5.1)$$

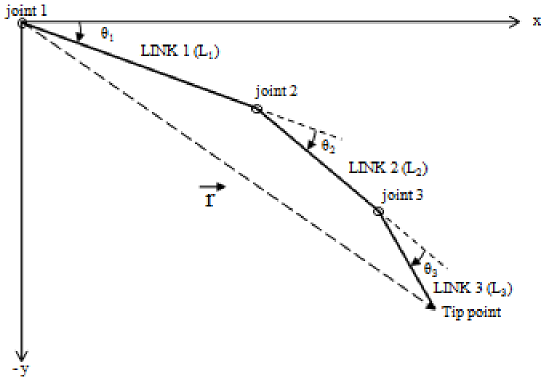


Figure 5.3: Kinematic Model Representation of Finger.

5.6.2. Kinematic Analysis for Thumb.

As for fingers, coordinate axes and origin of the system is determined as starting point. Thumb is fixed at the grippers' palm. So, center of the joint 1 is defined as coordinate axis origin and coordinate axis is placed as shown on figure 5.4. Thumb is different than fingers as having 2 limbs; also dimensions are different than fingers.

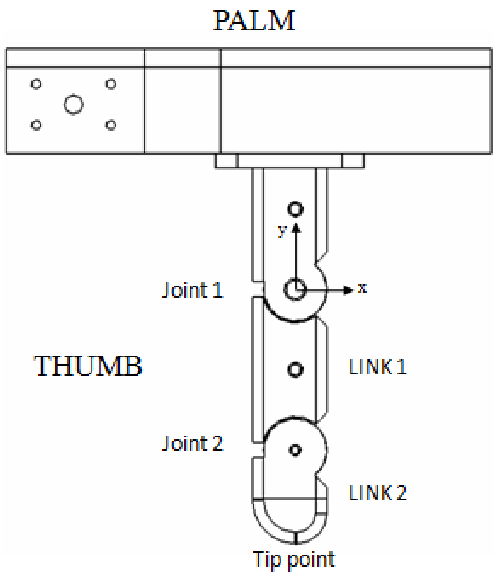


Figure 5.4: Schematic View of Palm and Thumb of the Gripper.

The rotations of the links are always about z-axis like fingers. The kinematic model of the thumb is shown in figure 5.5.

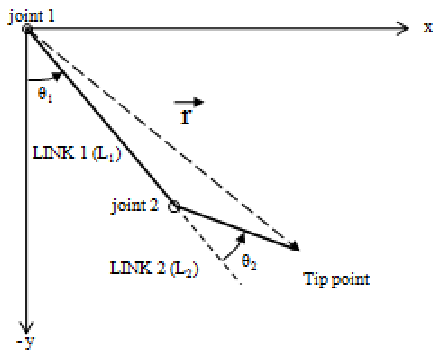


Figure 5.5: Kinematic Model Representation of Thumb.

Components of the position vector of tip point for thumb are written as;

$r_{tx} = L_1 \cos(90 - \theta_1) + L_2 \cos(90 - (\theta_1 + \theta_2))$ (5.2a)

$r_{ty} = L_1 \sin(90 - \theta_1) + L_2 \sin(90 - (\theta_1 + \theta_2))$ (5.2b)

From equations 5.2a and 5.2b position vector is obtained as;

$\vec{r_t} = [L_1 \sin\theta_1 + L_2 \sin(\theta_1 + \theta_2)]\vec{\imath} - [L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2)]\vec{\jmath}$ (5.3)

5.6.3. Position Analysis for Fingers

In this section position analysis of the fingers is done by using the position vector derived in section 5.6.1. The displacement results are given as graphical form.

Equation 5.1 can be written as; using $\theta_1 = \theta_2 = \theta_3 = \theta$.

$\vec{r_f} = [L_1 \cos\theta + L_2 \cos 2\theta + L_3 \cos 3\theta]\vec{\imath} + [L_1 \sin\theta + L_2 \sin 2\theta + L_3 \sin 3\theta]\vec{\jmath}$ (5.4)

using numerical values from geometry L_1 = 55mm, L_2=35mm, L_3=25; the components of the position vector are;

$\overrightarrow{r_{fx}} = 55 \cos\theta + 35 \cos 2\theta + 25 \cos 3\theta$ (5.5)

$\overrightarrow{r_{fy}} = 55 \sin\theta + 35 \sin 2\theta + 25 \sin 3\theta$ (5.6)

After determination of tip point vector components, displacement graphs are constructed for finger. The following graphs are drawn from θ=0º to θ=90º.

X and Y displacement of finger versus rotation of joint 1 is given in figure 5.6. Displacement of finger tip with respect to finger coordinate system is given in figure 5.7.

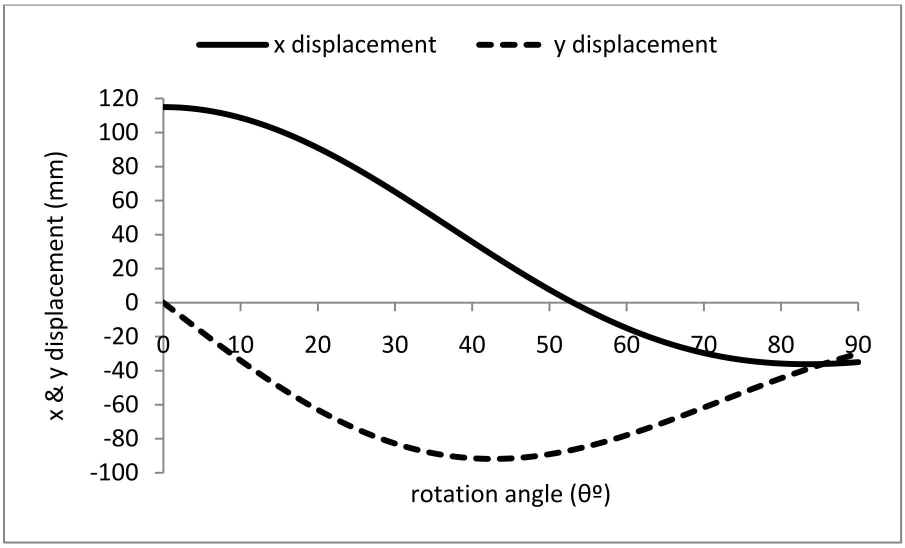


Figure 5.6: X and Y Displacements of Finger versus Rotation Angle.

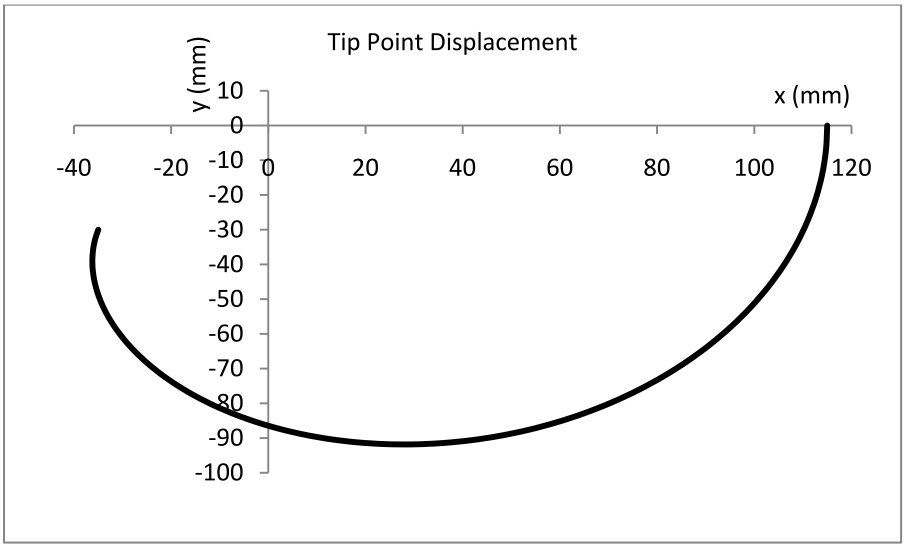


Figure 5.7: Finger Tip Point Displacement wrt. Finger Coordinate Frame.

5.6.4. Position Analysis of Thumb.

In this section position analysis of the thumb is done by using the position vector derived in section 5.6.2. The displacement results are given as graphical form as for fingers.

Equation 5.3 can be written as; using $\theta_1 = \theta_2 = \theta$.

$$\vec{r_t} = [L_1 \sin\theta + L_2 \sin 2\theta]\vec{\imath} - [L_1 \cos\theta + L_2 \cos 2\theta]\vec{\jmath} \quad (5.7)$$

using numerical values from geometry L1 = 43mm, L2=25mm; the components of the position vector are;

$$\overrightarrow{r_{tx}} = 43 \sin\theta + 25 \sin 2\theta \quad (5.8)$$

$$\overrightarrow{r_{ty}} = -43 \cos\theta - 25 \cos 2\theta \quad (5.9)$$

After determination of tip point vector components, displacement graphs are constructed for thumb. The following graphs are drawn from θ=0º to θ=90º . X and Y displacement of thumb versus rotation of joint 1 is given in figure 5.8. Displacement of thumb tip wrt. finger coordinate system is given in figure 5.9.

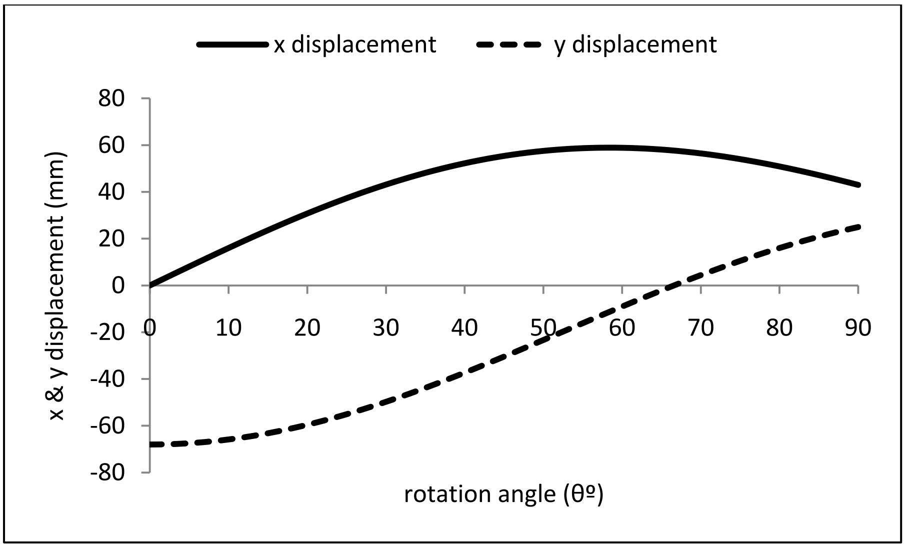


Figure 5.8: X and Y Displacements of Thumb versus Rotation Angle.

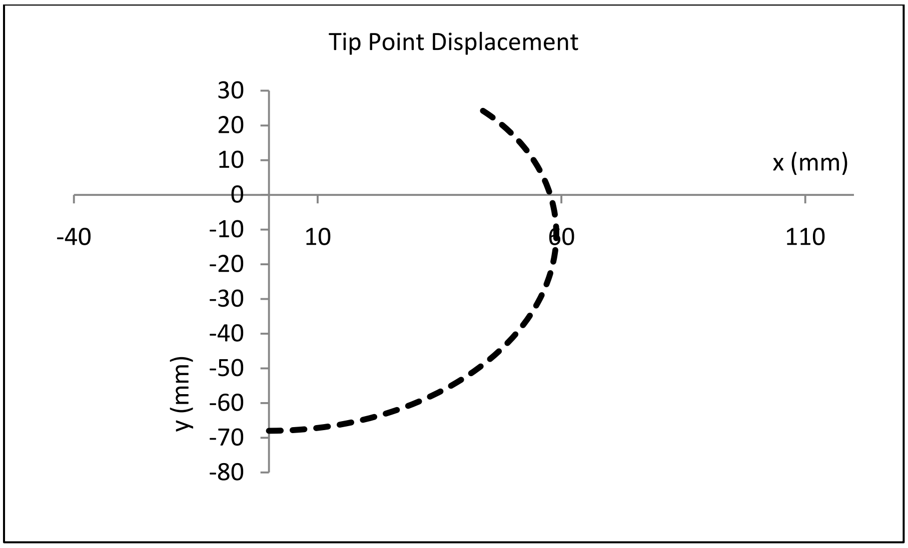


Figure 5.9: Thumb Tip Point Displacement wrt. Thumb Coordinate Frame.

After these calculations, the transformation of the calculated values of thumb tip from thumb coordinate system to finger coordinate is required in order to obtain combined results for both thumb and finger.

Figure 5.10 represents the translated x and y displacement of thumb with respect to finger coordinate frame. Figure 5.11 represents the translated displacement of thumb tip with respect to finger coordinate frame.

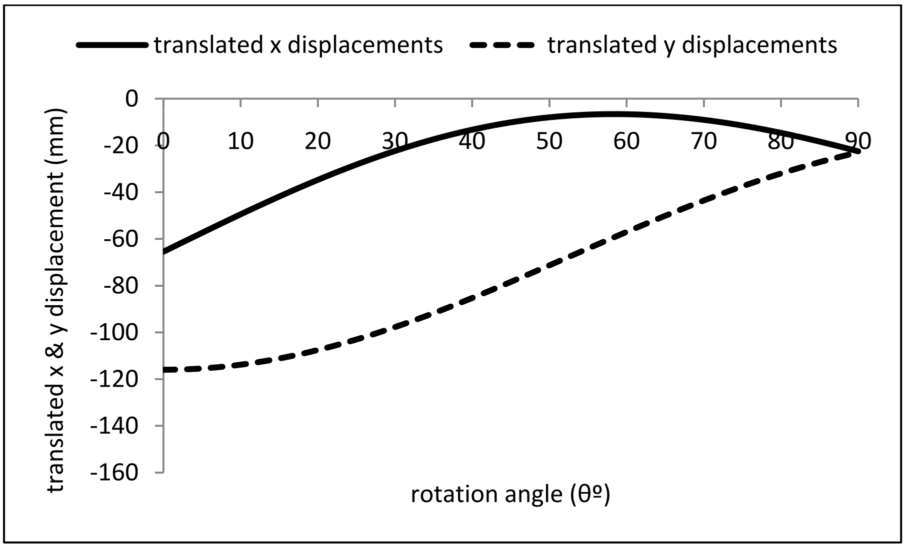


Figure 5.10: Translated X and Y Displacements of Thumb versus Rotation Angle wrt. Finger Coordinate Frame.

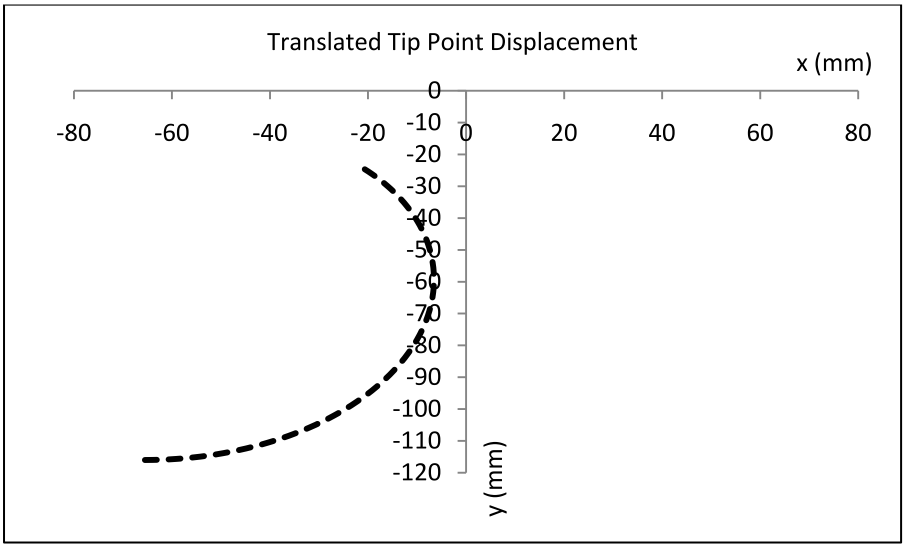


Figure 5.11: Translated Displacement of Thumb Tip wrt. Finger Coordinate Frame.

After necessary transformations, finger tip and thumb tip displacements can be shown in a single graph on figure 5.12. This graph is constructed for finger coordinate system as all values are transferred. This graph shows the position of finger tip and thumb tip positions at any rotation angle. Using Figure 5.12 with 5.6 and 5.10 respectively for finger and thumb, it is possible to find rotation angle of finger and thumb. As an example, the rotation of the thumb and finger at the point that tip point of finger and thumb are coincide, can be calculated as follows. From chart on Figure 5.12 it is found that both curves intersect at x = -11mm. This point is the most closes point of gripper where gripper can grasp thinnest object. Then, Figure 5.6 is used for finding finger rotation. For x = -11mm corresponding rotation angle of finger is found as 58º and similarly from chart in Figure 5.10, corresponding rotation angle for thumb is found as 43º.

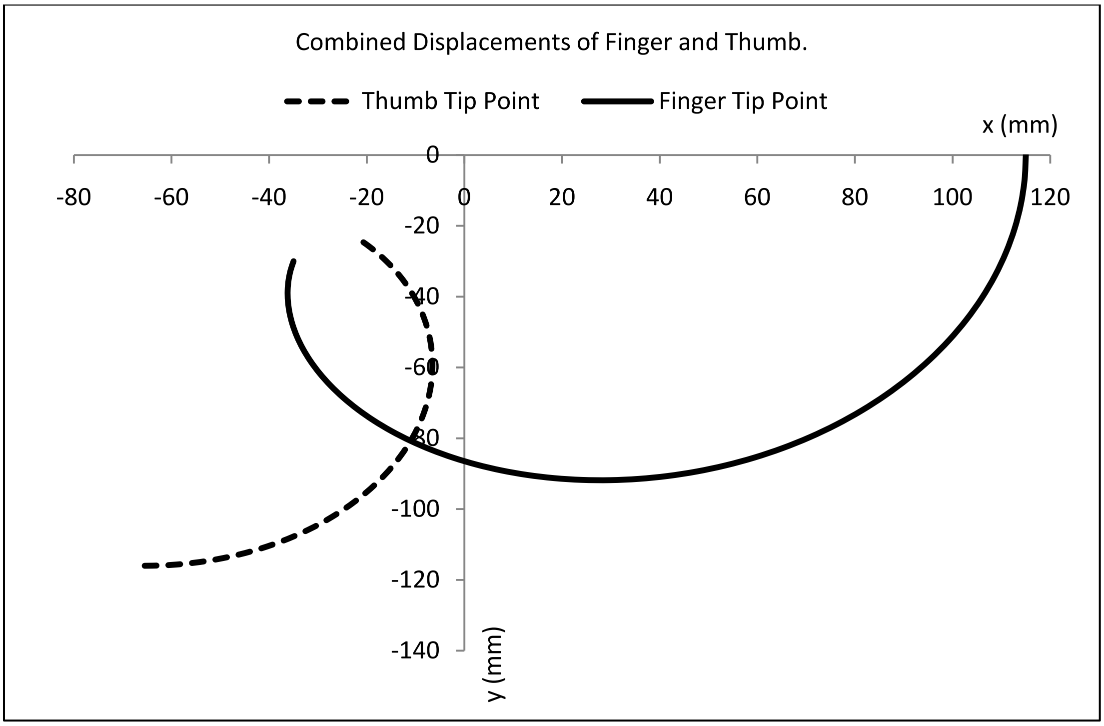


Figure 5.12: Combined Displacements of Finger Tip and Thumb Tip wrt. Finger Coordinate Frame.

5.7. Force analysis

In this section, force analyses of the gripper are performed. As the structure of fingers and thumb are different, calculations are carried out in two sections like in kinematic analysis. Force analysis of the fingers and force analysis of the thumb are given in separate subsections.

The developed gripper is pneumatically controlled. So, gripping force exerted by the gripper is related to the pressure applied to the actuators of the system. So, only tip point force is derived inside the section.

During the analysis, gravitational forces and frictional forces are neglected as they are small when compared to gripping forces.

5.7.1. Force Analysis for fingers.

Force analysis for fingers are done for one finger as other two have the same design. In order to carry out force analysis, first step is to draw the schematic representation of the finger. The representation is given in figure 5.13.

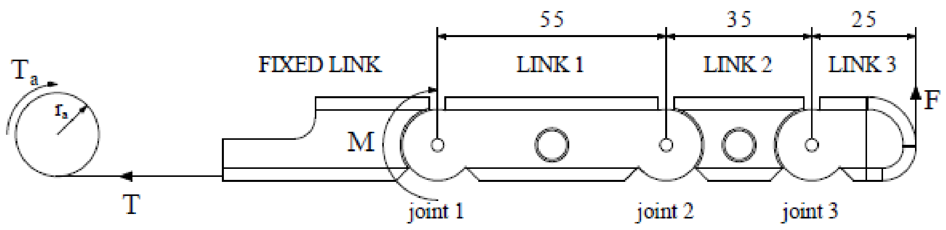


Figure 5.13: Schematic Representation of Finger.

It is seen from figure 5.13; the moments about joints are;

$$M_1 = F * (L_1 + L_2 + L_3) \qquad M_1 = 115F \qquad (5.10a)$$

$$M_2 = F * (L_2 + L_3) \qquad M_2 = 60F \qquad (5.10b)$$

$$M_3 = F * (L_3) \qquad M_3 = 25F \qquad (5.10c)$$

The critical moment that creates the tension is M_1. After definition of M as reaction moment on joint 1 then it is written as;

$$M_1 = M \qquad (5.11)$$

Where,

$$M = T * r_p \qquad (5.12)$$

Here, T is the tension force on rope and r_p is the radius of pulley at joint 1. From equations 5.11 and 5.12,

$$115\,F = T * 6 \qquad T = 19.167\,F \qquad (5.13)$$

is found. After determination of tension force on rope the torque value of the actuator is calculated from;

$$T_a = T * r_a \tag{5.14}$$

Where r_a is radius of actuator pulley and r_a=10.5mm

$$T_a = 19.167\,F * 10.5 \quad T_a = 201\,F \text{ [N.mm]} \tag{5.15a}$$

$$T_a = 0.201\,F \text{ [N.m]} \tag{5.15b}$$

From Table 5.1 it is seen that for 6 bar pressure, torque value for actuator is 2 [N.m]. Then; using this value and equation 5.15b, maximum gripping force for the tip point of the finger is calculated as;

$$F = 9.95 \text{ [N]} \tag{5.16}$$

By taking the coefficient of friction as 0.5 [26] (covering material), Maximum carrying capacity of one finger can be calculated as;

$$m = F * \mu / g \qquad m = 9.95 * 0.5 / 9.81 \quad m = 0,507 \text{ [kg]} \tag{5.17}$$

from the result calculated in equation 5.17, the gripping capacity of the hand for three fingers and palm can be calculated as;

$$m_G = 3 * m \qquad m_G = 1,521 \text{ [kg]} \tag{5.18}$$

Finally, it is necessary to define an equation for torque-pressure relation for the actuator of the gripper in order to determine finger force for an open loop gripping force control.

The actuators used in the gripper are rotary vane type pneumatic actuators. So, torque value of the actuator is linearly proportional to applied pressure and defined as;

$$\text{Torque Factor x Pressure = Torque Output} \tag{5.19}$$

Using equation 5.19 and values from Table 5.1 torque factor for actuator is found as;

$$\text{Torque Factor} = 2 \text{ [N.m]} / 600000 \text{ [N/m}^2\text{]} = 0.334\text{x}10^{-5} \text{ [m]} \tag{5.20}$$

Then, torque-pressure relation for the actuator is defined as;

$$T\text{a} = 0.334\text{x}10^{-5}\,P \tag{5.21}$$

In this equation, unit of T_a is [N.m] and P is [N/m^2]. Using equations 5.15b and 5.21, the relationship between pressure and the gripping force is obtained as;

$$F = 1.662 \text{x} 10^{-5}\, P \qquad (5.22)$$

Here, unit of F is [N] and P is [N/m^2]. Equation 5.22 is valid for pressure ranges between 2 and 8 bars which is the operating range of the actuator.

5.7.2. Force Analysis for Thumb.

For force calculations of the thumb, same procedure is followed as fingers. Starting point of the analysis is to draw Schematic Representation of thumb which is given in Figure 5.14.

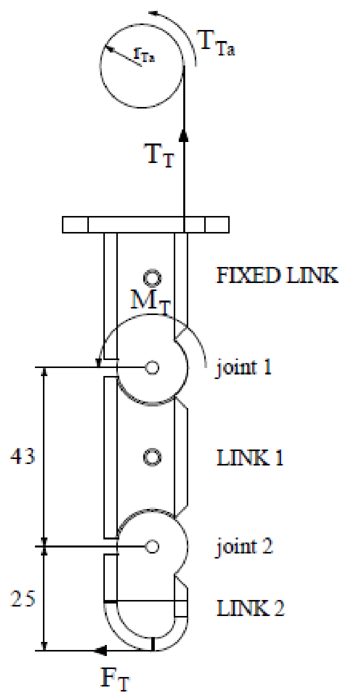


Figure 5.14: Schematic Representation of Thumb.

From Figure 5.14, the moments about joints are;

$$M_{T1} = F_T * (L_1 + L_2) \qquad M_{T1} = 78F_T \qquad (5.23a)$$

$$M_{T2} = F_T * (L_2) \qquad M_{T2} = 25F_T \qquad (5.23b)$$

Here the critical moment that creates the tension is M_{T1}. After definition of M_T as reaction moment on joint 1 then it can written as;

$$M_{T1} = M_T \tag{5.24}$$

Where,

$$M_T = T_T * r_T \tag{5.25}$$

Here, T_T is the tension force on rope and r_T is the radius of pulley at joint 1. From equations 5.23a, 5.24 and 5.25,

$$78\, F_T = T_T * 6 \qquad T_T = 13\, F_T \tag{5.26}$$

is found. After determination of tension force on rope the torque value of the actuator is calculated from;

$$T_{Ta} = T_T * r_{Ta} \tag{5.27}$$

Where r_{Ta} is radius of actuator pulley and r_{Ta}=10.5mm

$$T_{Ta} = 13\, F_T * 10.5 \qquad T_{Ta} = 136.5 F_T \text{ [N.mm]} \tag{5.28a}$$

$$T_{Ta} = 0.1365\, F_T \text{ [N.m]} \tag{5.28b}$$

From Table 5.1 it is seen that for 6 bar pressure, torque value for actuator is 2 [N.m]. Then; using this value and equation 5.28b, maximum gripping force for the tip point of thumb is calculated as;

$$F = 14.652\text{[N]} \tag{5.29}$$

The actuator of the thumb is same as actuator used for finger. So, torque-pressure relation for actuator of thumb is given as;

$$T_{Ta} = 0.334\text{x}10^{-5}\, P_T \tag{5.30}$$

Using equations 5.28b and 5.30, the relationship between pressure and the gripping force of the thumb is obtained as;

$$F_T = 2.447\text{x}10^{-5}\, P_T \tag{5.31}$$

Here, units of F_T is [N] and P_T is [N/m^2]. Equation 5.31 is also valid for pressure ranges between 2 and 8 bars which is the operating range of the actuator.

5.7.3. Stress Calculation for the Rope.

After the calculations for applied forces of fingers and thumb, it is necessary to check the strength of the rope. The loading for the rope is larger on fingers than thumb, so, maximum force applied on fingers is used for calculations. Using equation 5.13 tension force on rope is calculated as

$$T = 19.167\,F \qquad \mathrm{T}=190.7\ [\mathrm{N}] \tag{5.32}$$

where, maximum F for finger is 9.95 [N]. This tension force is the maximum force applied on the rope. Defining the allowable stress equation as;

$$\sigma_{all} = \frac{T}{A} \tag{5.33}$$

where, $A=\pi d^2/4$ and σ_{all}=191Mpa for 2mm diameter rope [25]. Minimum diameter equation for the rope is defined as;

$$d_{min} = \sqrt{\frac{4T}{\pi\sigma_{all}}} \tag{5.34}$$

Using equation 5.34 minimum diameter is found as;

$$d_{min} = 1.127\ [\mathrm{mm}] \tag{5.35}$$

As seen from equation 5.35, diameter of the rope used in the design (2mm) is larger than minimum required diameter. Finally, reserve factor is defined as;

$$RF = \frac{\sigma_{all}}{\sigma_{app}} \tag{5.36}$$

where, σ_{all}=191Mpa and σ_{app}=60.7Mpa. Then, the reserve factor is calculated as;

$$RF = 3.15 \tag{5.37}$$

5.7.4. Stiffness of the Rope

For the stiffness value of the rope, tensile test have been carried out in order to find force and displacement curve of the rope. The curve is given in Figure 5.15.

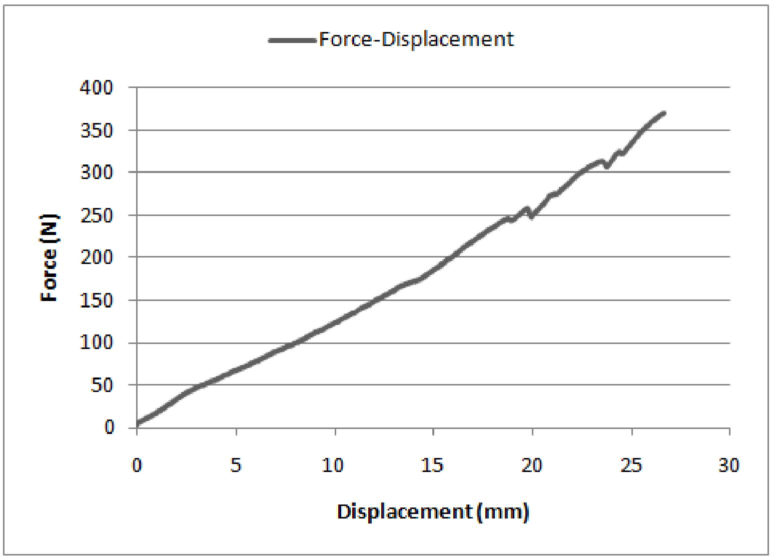


Figure 5.15: Force – Displacement Curve of the Rope.

Non-Linear behavior of the rope above 250N force is the result of the fibered structure of the rope. Applied maximum forces for fingers and thumb are 191 N. So, stiffness value of the rope is calculated from:

$$k_R = \frac{F}{\delta} \tag{5.38}$$

Using equation 5.38 and values from curve F = 191N and δ = 15.3mm, stiffness value is calculated as:

$$k_R = 12.48 \text{ N/mm} \tag{5.39}$$

Fingers and thumb completes full motion with 90º rotation of the actuator. On the other hand, actuators used in gripper are capable of 180º rotation. So, the displacement value under applied force which is 15.3mm can be tolerated by the 90º extra rotation of the actuators which is calculated as $\pi d_a/4$=16.5mm.

Maximum applied force of the tensile test is calculated as 370N which is smaller than ultimate limit of the rope which is 600N. This is the result of the gripping method of the rope during test. Because of the fixture, rope is compressed between the jaws of the machine and this compression deforms the rope and forms a notch effect on the rope. So, the rope breaks before the ultimate limit.

5.8. Specifications of Gripper.

5.8.1. Mechanical Specifications

Weight of the gripper: 3.068 kg
Weight of the gripper without pneumatic equipments: 1.838 kg
Width of the gripper: 198.6mm
Length of the gripper: 358mm
Height of the gripper: 207
Construction material for main body and links: 5083 Aluminum (Magnesium alloy).
Construction material for pulleys: Brass.
Construction material for rope: Static Rope

5.8.2. Gripper Specifications

Number of fingers: 4 fingers (3 fingers, 1 thumb)
Degree of freedom for fingers: 1
Degree of freedom for thumb: 1
Number of joint for finger: 3
Number of joints for thumb: 2
Maximum rotation of fingers: 270º
Maximum rotation of thumb: 180º

5.8.3. Pneumatic System Specifications

Actuator Specifications:

Actuator Type: Semi-rotary drive DSRL-16-180-P (FESTO)
Number of Actuators: 4
Piston Diameter: 16mm

Swivel angle: 180º

Torque at 6 bar: 2 N.m

Operating pressure range: 2-8 bar.

Maximum permissible radial load: 75 N

Maximum permissible axial load: 30 N

Valve Specifications:

Valve Type: Directional Control Valve MLH-5-1/8-B (FESTO)

Function: 5/2 way, monostable (single solenoid)

Type of return: Mechanical Spring.

Operating pressure range: 2-8 bars.

Solenoid working voltage: 24 V.

Air Flow Regulator Specifications:

Regulator Type: Flow Control Valve GRO-QS-4 (FESTO)

Number of regulators: 4 (1 for each actuator)

Pressure Regulator Specifications:

Regulator Type: Filtered Regulator LFTR-D-MINI (FESTO)

Input Pressure: 1-16 bars.

Output Pressure: 0.5-12 bars.

Hysteresis: 0.2 bars.

All other pneumatic equipments as connection elements, silencers, solenoids, pipes and valve block are purchased from Festo Pneumatics.

CHAPTER 6

COMPUTER CONTROL OF THE DEVELOPED HANDS

In this section, computer control of the developed hands is to be explained. Computer control of the gripper is a very important task in automation. In order to use a gripper with suitable industrial robot, gripper must have computer control as an industrial robot does. It is also preferred that, control of the gripper is provided by the control software of the robot to avoid complexity and errors.

In the thesis study, control softwares for two fingered and four fingered grippers are developed separately. These softwares are used for the motion control of the fingers. Both grippers will be used with the industrial robot in the METU CAD/CAM Robotics Center. By the way, both hands can be controlled independently from robot with the developed softwares. These softwares gives opportunity to use the grippers with any industrial robot.

The motion control card is also developed for computer connection of the grippers. On contrary to having two different softwares for grippers, the motion control card is designed as combined to use same electronic components in control of both hands.

6.1. Motion Control Card

In the previous sections of the thesis study, it is defined that both grippers use pneumatic actuators for motion. Pneumatic actuators are controlled with pneumatic valves which controls the flow direction of air. For both grippers, 5/2 way directional control valves are used with actuators. Used valves for motion are MLH-5-1/4-B by Festo [27] (Figure 6.1). The valve is electrical piloted controlled and has a spring return mechanism. This valve provides two way air flow by a solenoid and spring mechanism. Air goes through the input channel of the valve and passes to second output channel. This flow is always set as open by the spring mechanism. If the solenoid of the valve is triggered by 24V electrical energy, the way for the pilot air supply opens and the mechanism inside the valve moves against the spring. This movement changes the output flow direction from second channel to first channel. By the change of this air flow the actuator connected to valve moves. If the energy triggering the valve is cut off, spring inside the valve returns the mechanism into its initial position.

Figure 6.1: Directional Control Valve MLH-5-1/4-B (Festo) [27]

Following the definition of the working principle, the requirement for motion control card is determined. The task of the motion control card is defined as the distribution of 24V electrical energy to the related pneumatic valve which provides the movement of the finger. In order to perform the defined task a PIC controlled relay circuit is developed. The relays used in the circuit provide two way current control. The relay changes the direction of the current and passes the 24V energy to the pneumatic valve when triggered from a signal produced by the PIC microcontroller. If the signal from the PIC microcontroller cuts off, relay goes back to the initial state and blocks the transition of electrical current. The developed motion control card uses RS232 serial interface for computer connection. Also, some led indicators are used on the motion control card to give information about the status. Red leds shows that the output is idle and actuator is not working. Green leds used to show the output is active and actuator is working. Finally, blue led gives information about the electrical connection of the motion control card.

Proteus Isis electronic design software is used for circuit design and simulation. This program gives opportunity to virtually simulate the control card. By the help of this simulation, short circuits and misconnections are avoided. So, the risk for damaging the electronic components is minimized.

Proteus Ares software is used for the designation of printed circuit board. All electronic components used in the circuit designed in Isis are transferred automatically to Ares and placement of these components is completed in this software. The design of the routing that connects the components is also done by this software. The electronic circuit diagram, PCB layout and PIC program for motion control card is given in Appendix H.

A photo of the developed motion control card is given in Figure 6.2.

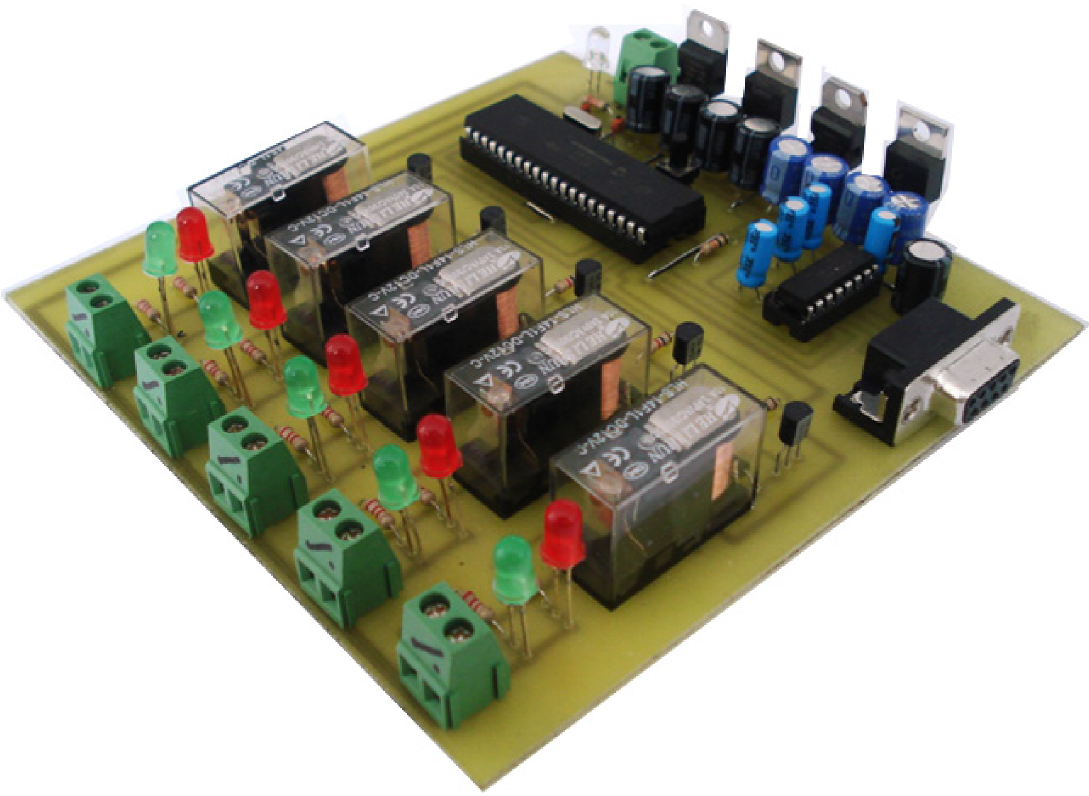


Figure 6.2: Motion Control Card.

6.2. Computer Software for the Two-Fingered Gripper

The software used for computer control of the two-fingered gripper is developed by using Microsoft Visual Basic. The software is used for the motion control of fingers of the gripper. A screenshot from the developed software is shown in Figure 6.3.

Figure 6.3: Screenshot of Computer Software for the Two-Fingered Gripper.

The software scans and lists available communication ports on the personal computer that the software runs. After scanning is completed software enables related option in the communication port frame. This frame is used for the selection of the serial port used for communication with the motion control card. This frame is also used for giving information about the status of the communication port. At the program startup, software informs the user for selection of communication port. (Figure 6.4)

Figure 6.4: Communication Port Frame.

If user proceeds without selecting suitable port software leads the user to select communication port. (Figure 6.5)

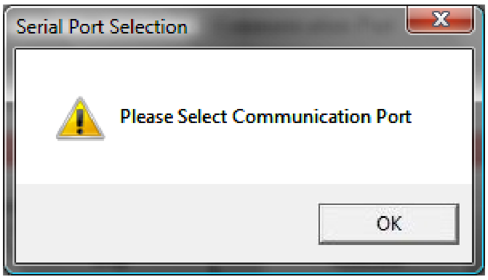


Figure 6.5: Warning Message about Communication Port Selection.

During the selection of communication port process, software scans for the motion control card and gives feedback about the connection status. On Figure 6.6 a screenshot of the software when a wrong port is selected is shown.

Figure 6.6: Notification about Communication Port Selection.

If the correct communication port is selected from options then software detects the motion control card and enables the control of gripper. (Figure 6.7)

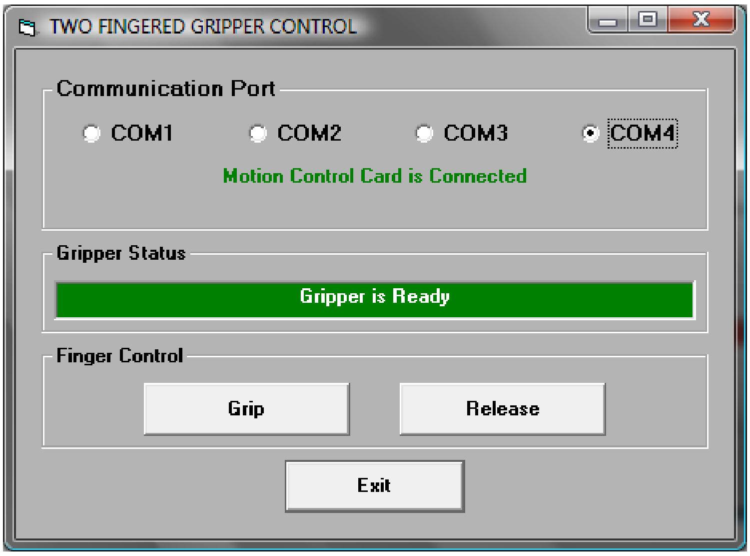


Figure 6.7: Motion Control Card Connection on COM4

Gripper Status frame is used for giving information about the gripper. The connection status of the gripper and the motion of the fingers are directly reflected to status bar. Figure 6.8 shows various screenshots for gripper status.

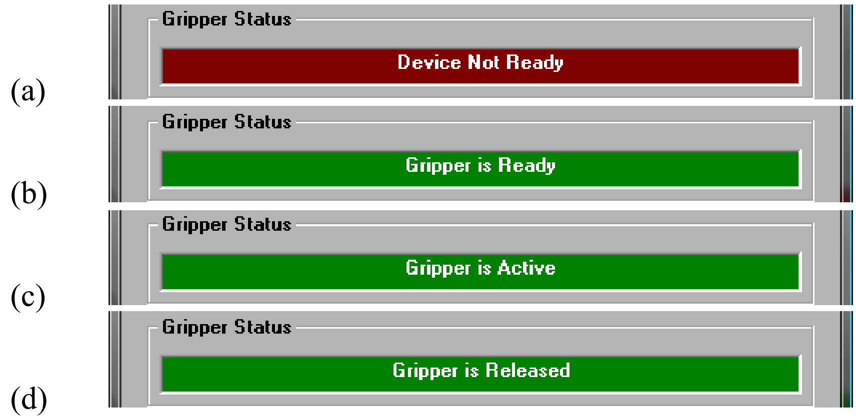


Figure 6.8: Gripper Status for Different Conditions.
(a) Disconnected Device. (b) Connected Device.
(c) Fingers Activated. (d) Fingers Deactivated.

The finger control frame is used for control the movement of the fingers of the gripper. Grip button is used for activation of the fingers of the gripper. Release button in the frame is used for deactivation of the fingers.

Finally, the exit button is used for deactivation of the fingers and termination of the program. Software gives a warning about the cancellation of gripping action and gives an opportunity to cancel program termination. (Figure 6.9) If "Ok" button is selected software terminates the gripping and ends the program. If "Cancel" button is selected program proceed its operation. The programming codes for the developed software are given in Appendix H.

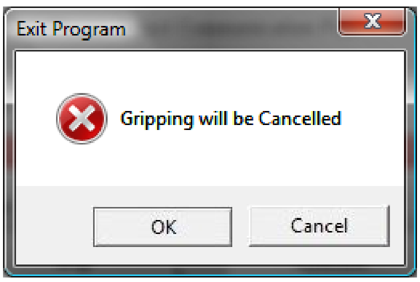


Figure 6.9: Exit Program Dialog Box.

6.3. Computer Software for the Four-Fingered Gripper

The software used for computer control of four-fingered gripper is also developed by using Microsoft Visual Basic. Function of the software is to control the fingers of the gripper. A screenshot from the developed software is shown in Figure 6.10.

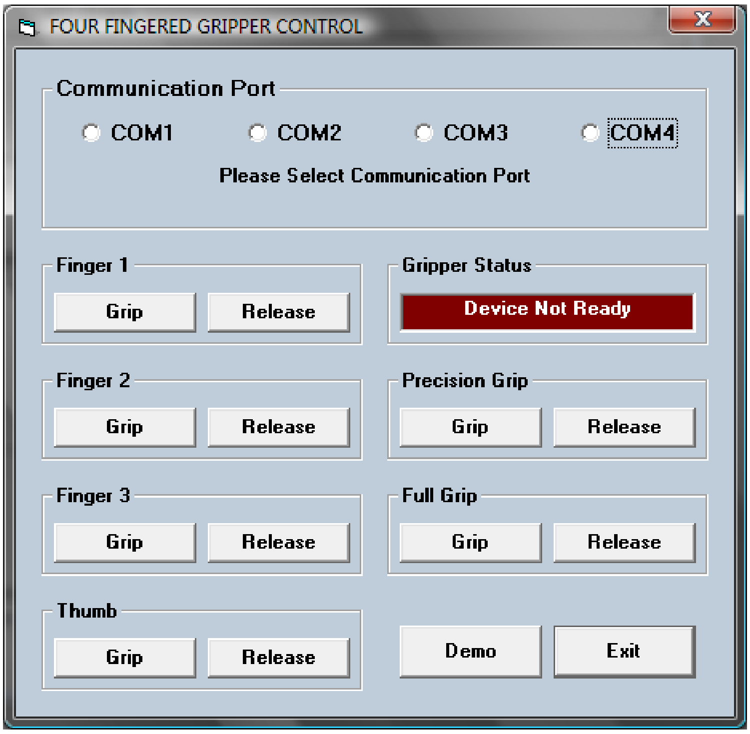


Figure 6.10: Screenshot of Computer Software for the Four-fingered Gripper.

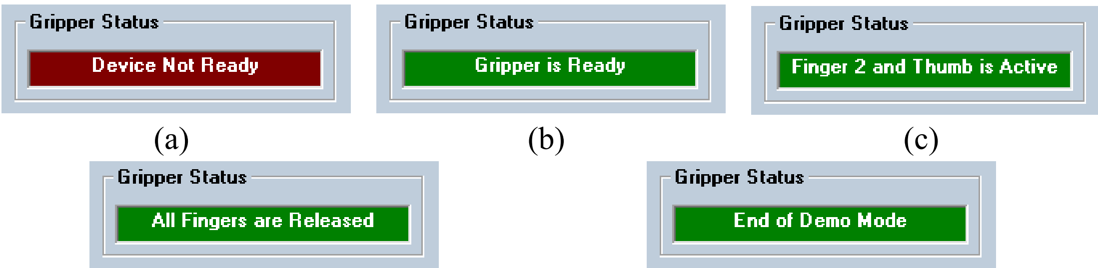
This software also uses RS232 serial interface to communicate with the motion control card. It transmits necessary data from the computer to the microprocessor of the card. After the motion control card receives the data, it processes the data and generates signals required for the pneumatic valves. Frames of the software can be described as follows;

The Communication Frame is used for selection of the serial port number used for communication with the motion control card. Working principle of this frame is same as the software for two fingered gripper explained in section 6.2. After successful connection with motion control card, software enables the access to finger control frames.

Finger1, Finger 2 and Finger 3 frames of the software are used for control the movement of fingers of the gripper. Grip command is used for activation of the related finger for gripping motion. Release command is used for deactivation of related finger.

Thumb frame of the software is used for control the movement of the thumb of the gripper. Grip command is used for activation of the thumb for gripping motion. Release command is used for deactivation of the thumb.

Gripper Status frame is used for information about the gripper. The connection status of the gripper and motion of the fingers is directly reflected to the status bar. Figure 6.11 shows various screenshots for the gripper status.



(a) (b) (c) (d) (e)

Figure 6.11: Gripper Status for Different Conditions.
(a) Disconnected Device. (b) Connected Device. (c) Precision Gripping Activated.
(d) Full Gripping Cancelled. (e) End of Demo Mode.

Precision Grip frame of the software is used for precision gripping. Grip button is used for activation of finger 2 and thumb of the gripper in order. Release button is used for deactivation of them.

Full Grip frame of the software is used for regular gripping with all fingers Grip button is used for activation of fingers and thumb of the gripper. Release button in this frame is used for deactivation of all active fingers and thumb.

Demo button is used for demonstration. This button activates and deactivates the fingers of the gripper in a pre-defined order. Before entering the demo mode, software gives a warning about demo mode in order to inform user. Screenshot for this warning message is shown on figure 6.12.

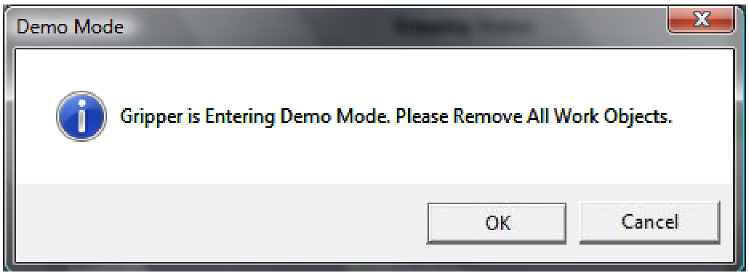


Figure 6.12: Warning Message about Demo Mode.

Ok button proceed the gripper for the demo mode. Cancel button deactivates the demo mode and returns back to software. If demo mode is activated, software inform user at the end of the demo mode. (Figure 6.13)

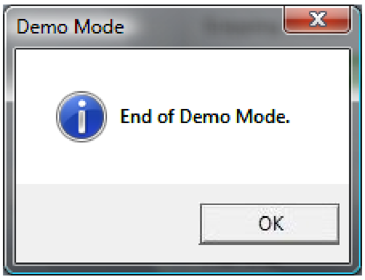


Figure 6.13: End of Demo Mode Message.

Finally, the exit button is used for deactivation of the fingers and termination of the program. Software gives a warning about the cancellation of gripping action and gives opportunity to cancel termination. (Figure 6.14) If “Ok” button is selected software terminates the gripping and ends the program. If “Cancel” button is selected program proceeds its operation. Programming codes are given in Appendix H.

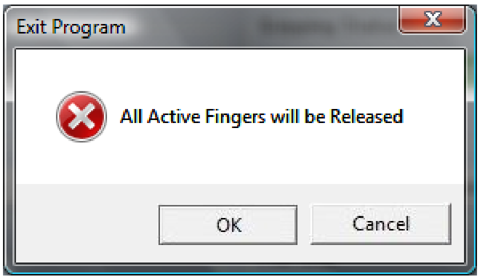


Figure 6.14: Exit Program Dialog Box.

CHAPTER 7

DISCUSSION OF RESULTS

The objective of the thesis study is to develop one two-fingered and one four fingered robotic gripper and to develop the control system needed to drive these two grippers.

The two-fingered gripper is designed for a special task as defined in the previous sections. This gripper has two opposing fingers. It has 6 revolute and 1 prismatic joints with 6 links. Prismatic joint is common for both fingers and the actuator of the gripper drives the mechanism through this joint. The degree of freedom for the gripper is 1. Maximum jaw opening for the gripper is 82,8mm and minimum is 42mm. The maximum value means that gripper cannot hold work pieces having radius bigger than 82,8mm if it approaches the work piece from sides. If work piece diameter increases than usage of the gripper becomes impossible. Also because of the jaw geometry, gripper can hold work pieces having minimum diameter of 66,2mm. The jaw opening range of the gripper can be changed by design changes but the values used in the thesis study satisfies required space for the work piece defined in the task which has 76,2mm diameter.

The gripper is driven by a pneumatic actuator. So, the gripping force changes according to the pressure applied on the actuator. But, for analyses, properties of actuator under 6 bar pressure are taken into account. Maximum force applied by the actuator for 6 bar pressure is given as 121N.[21] Using this value for calculations it is observed that, the maximum and minimum gripping force exerted by the gripper is 19,8N and 108,7N respectively. This change of the gripping force is the result of the mechanism of the gripper. Gripping force increases by the actuator movement. The gripper grasps the work piece with 4,3mm actuator movement resulting with 39N gripping force. This calculated gripping force gives the gripper a holding capacity of 2,4kg work piece.

The four-fingered gripper is designed as a multi-purpose gripper. It has three fingers and one thumb. Thumb is placed opposite to middle finger in order to obtain precision gripping. It has totally eleven joints (three revolute for each finger and two revolute for the thumb) but because of the power transmission mechanism, total degree of freedom is 4, 1 for each finger and 1 for thumb. The working principle of this gripper is similar to human hand and it has ability to handle various shaped work pieces.

This gripper is pneumatically driven too. The rotary actuators exert rotary motion and this motion is transmitted to the fingers with the rope and pulley mechanism. Maximum torque value for the actuator is 2N.m. Using this value for calculations results as approximately 10 N gripping force for each finger and 14.6 N gripping force for thumb.

Both of the developed grippers use pneumatic actuators. Whether it is a linear actuator or a rotary actuator, the position control of pneumatic actuator is very difficult. As the air is compressible, advanced close loop control is required for position control. Force control is quite easy compared to position control but still remains difficult. One way to adjust the force is to regulate the pressure of the system. But, this does not give exact gripping force values. Exact values for position and force can be obtained by using position and force sensors. But, both grippers do not have any sensors installed on them.

The actuators of both grippers are located onto the grippers' body. This property makes them replaceable and compact gripper which can easily be replaced from the robot manipulator easily. But installation of actuators on gripper results as heavier end effectors. Also, since there is not much space available on the gripper, this property limits the number of actuators that can be used in grippers. This condition does not cause any problem for the two-fingered gripper as its task is simply pick and place task where one actuator is quite enough. But, for the four fingered gripper, limited number of actuators results with limited degrees of freedom. Although it has

11 joints on it, only four of them can be driven by the actuator. Remaining joints have to follow the movement of the driven joint. This condition decreases the dexterity of the gripper and also makes the transmission mechanism complex. If it is possible to mount the actuators of the gripper on the robot arm or wrist, then the degrees of freedom and therefore the dexterity of the gripper can be increased and the transmission system can be simplified.

Both of the grippers are manufactured from a strong aluminum magnesium alloy which is used in defense industry. But, some of the parts are not manufactured from this material. For the two fingered gripper, finger jaws are manufactured from stainless steel which have higher temperature resistance than aluminum. For the four fingered gripper, pulleys are manufactured from brass and tendon material is used as static rope. It can be possible to use different materials for both hands. For example, composite technology which is mainly used in aerospace industry is very developed in present time. These developments give opportunity for small part manufacturing. The advantages of composite are its strength and low weight. On the other hand, the manufacturing of composites is quite hard and expensive. In this thesis study, the strength and lightness of aluminum is enough for the developed grippers. The weights of the grippers are sufficiently low. Moreover, in design, materials are changed for the parts where aluminum material is inadequate such as pins, finger jaws, pulleys and ropes.

Finger surfaces of four fingered gripper are covered with rubber to increase the coefficient of friction between finger and work piece. But for two fingered gripper since it will be in touch with hot work pieces no covering material is used. The friction values of steel with aluminum, μ=0,35 [5] ensures the required gripping force for task, also the channels of finger jaw helps for the prehension.

Both grippers are controlled by the softwares developed during the thesis study. These softwares are standalone and simply control the movement of the fingers. Since there are no sensors installed on grippers, the software only sends the required data to motion control card and counts the action is done as there is no feedback. This is an open loop control and seems to be a disadvantage of software but close loop control is quite expensive and complex to apply.

CHAPTER 8

CONCLUSION

In robotic applications usage of end-effectors are very important since they are the parts of the robots in direct contact with objects. Grippers are one type of the end-effectors which are used to handle work pieces. There are many types of grippers and the choice of correct type for relative task is very important. The main selection is to decide whether a special task gripper or multi-purpose gripper is needed. The multi-purpose grippers are useful for undefined tasks where work pieces are not defined or in the tasks where work pieces generally change. On the other hand, special purpose grippers are more stable and reliable compared to multi-purpose grippers. Multi-purpose grippers have higher dexterity than others but carrying capacity of these type of grippers are quite low.

In the thesis study, both special task gripper and multi-purpose gripper are developed. Special task gripper is designed to have 2 fingers as its task is defined at the beginning of the design process. So, requirements are defined easily and design process developed faster. On the other hand, there was no predefined task for multi-purpose gripper. So, previous examples and human hand are used for reference. This gripper is designed to have 4 fingers one opposing the other three.

During the studies it is seen that both grippers have advantages and disadvantages when compared to other. The two fingered gripper is simpler in design and creates more gripping force than the four fingered one. On the other hand, the four fingered gripper is very complex in design but it is capable of handling complex shaped objects which cannot be done with the two fingered gripper. Also working ranges of the grippers are quite different. Since, the four fingered gripper can grasp objects having thickness of paper, the two fingered one is only capable of holding objects having diameter between 66mm to 82mm.

The other critical issue of the gripper design is sensors. Their price are high and they are also complex to use. In fact, usage of sensors is very important to have information about gripping properties. In this topic, usage of pneumatic drives has useful advantage when compared with electrical motors. If electrical motor is used to drive the fingers, force sensors must be used with the system. Otherwise, electrical motor will apply the force until it reaches its maximum. But, in pneumatic drives force is proportional to the pressure of the system. So, it can be calculated and adjusted before handling. By this way application of higher forces can be avoided. In other words it is not an obligation to have force sensors for pneumatic actuator because the system can overcome unnecessary force application problem.

During the thesis studies, a two-fingered gripper and four fingered gripper is designed and manufactured. The study on two different types of grippers is quite different from each other and forces the designer for different point of views. Also, computer control software and hardware which are used for the control of developed grippers are also designed. This section of the study provides to have multi disciplinary view.

CHAPTER 9

SUGGESTIONS FOR FURTHER WORK

During the thesis study, a special task two-fingered gripper and a multi-purpose four-fingered gripper are developed. These grippers are manufactured and assembled. Also, computer control softwares and hardwares for these grippers are developed.

At the present time;

- Both of the grippers are working and can be controlled by computer using the developed motion control card.
- The degree of freedom for the four-fingered gripper is limited to four because of the actuator quantity installed on the gripper..
- There are no sensors on the grippers
- Motion control card uses RS232 Interface to communicate with computer.
- Two different softwares are developed for computer control of the grippers.

For the future works, that can be implemented on the study, it is suggested that;

- The degree of freedom for four-fingered gripper can be increased by increasing the number of actuators used for the gripper. This can be done by transferring the actuators out of the gripper and advancing the power transmission mechanism. Other way is to have smaller actuators directly connected to joints of the gripper.
- Force and position sensors can be placed on both grippers.
- Motion control card can be redesigned to use Universal Serial Bus (USB) interface for computer communication because the usage of RS232 interface is slowly decreasing and support for this port is terminating.

- The softwares used for control of the grippers can be integrated to robot control software in order to use single software for full motion control of the robot.
- Computer controlled pneumatic regulators, pressure sensors and proportional directional control valves can be integrated into pneumatic system in order to have fully computerized pneumatic system control.

  The pneumatic circuit diagrams including this hardware are given in Figure 9.1 and 9.2 for the two fingered gripper and the four fingered gripper respectively. Pneumatic equipments suggested for computer controlled pneumatic system are:

  – Pressure Sensor – SDE-10-10V/20MA (Festo)

  – Proportional Pressure Regulator – MPPE-3-1/8-10-010-B (Festo)

  – Proportional Directional Control Valve – MPYE-5-1/8-LF-010-B (Festo)

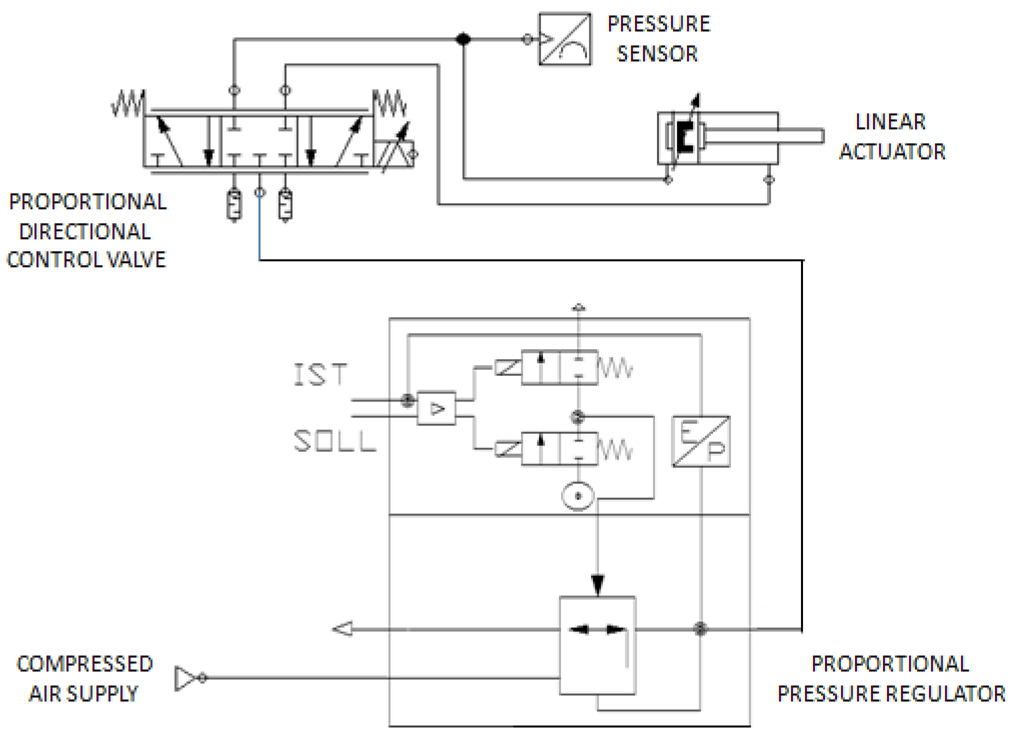


Figure 9.1: Computer Controlled Pneumatic System for the Two Fingered Gripper

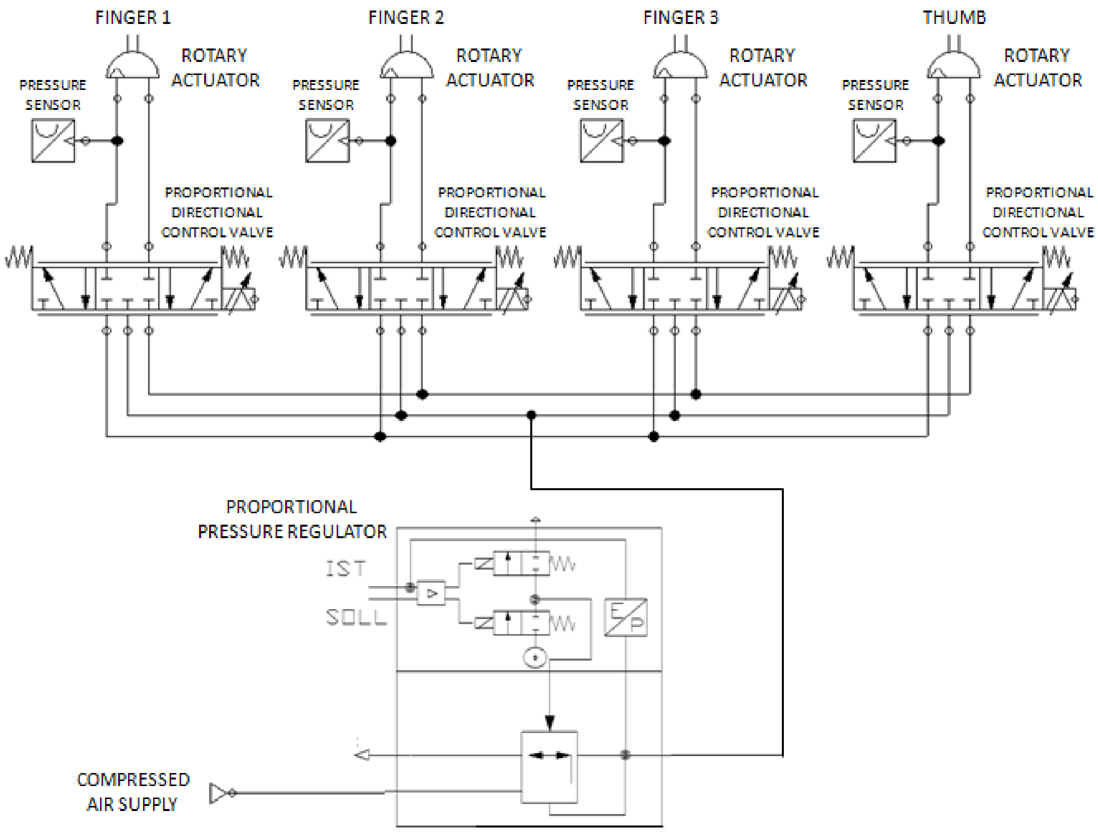


Figure 9.2: Computer Controlled Pneumatic System for the Four Fingered Gripper.

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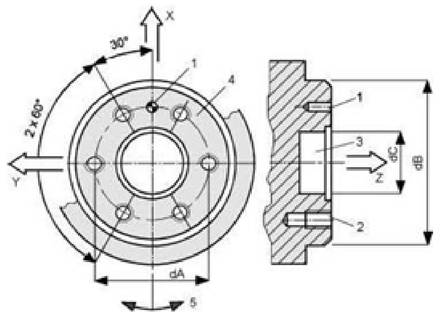
APPENDIX A

GLOSSARY OF THE TERMS USED IN GRIPPER TECHNOLOGY

Astrictive gripper: A binding force produced by a field is astrictive. This field may take the form of air movement (vacuum suction), magnetism or electrostatic charge displacement.

Basic jaw (Universal Jaw): The part of an impactive gripper subjected to movement. An integral part of the gripper mechanics, the basic jaw is not usually replaceable. However, the basic jaws may be fitted with additional fingers in accordance with specific requirements.

Basic unit: Bask module containing all gripper components which is equipped for connecting (flange, hole pattern.) the gripper to the manipulator The connecting capability implies a mechanical, power, and information interface. Figure A.1 shows a flange design in accordance with DIN ISO 9409. This German industrial standard and its subsequent amendments contain design requirements concerning the different overall size, pitch circle diameter, centering cylinder dimensions, number of threaded holes and respective thread pitch as well as some position tolerances. The flange can also be drilled to allow feeding of power and control cables.



1. mating hole for locating pin.
2. threaded security hole.
3. centering cylinder.
4. flange body
5. flange rotation

dA pitch circle diameter
dB centering cylinder diameter
dC inner cylinder diameter

Figure A.1: Example of Flange Design and Mounting in Accordance with German Standard DIN ISO 9409.

Chemoadhesion: Contigutive prehension force by means of chemical effects. Usually, in the form of an adhesive (permatack or single use).

Contigutive gripper: Contigutive means touching. Grippers whose surface must make direct contact with the objects surface in order to produce prehension are termed contigutive. Examples include chemical and thermal adhesion.

Control system: In most of the cases a relatively simple control component for analyzing or pre-processing sensor information for regulation and/or automatic adjustment of prehension forces.

Dexterous hand: Anthropoidal artificial hand (rarely for industrial use), which is equipped with three or more jointed fingers and may be capable of sophisticated, programmed or remote controlled operations.

Double grippers: Two grippers mounted on the same substrate, intended for the temporal and functional prehension of two objects independently.

Drive system: A component assembly which transforms the applied (electrical, pneumatic, hydraulic) energy into rotary or translational motion in a given kinematic system.

Dual grippers: Two grippers mounted on the same substrate, intended for the simultaneously prehension of two objects.

Electro adhesion: Prehension force by means of an electrostatic field.

End effector (end-of-arm tooling): Generic term for all functional units involved in direct interaction of the robot system with the environment or with a given object. These include grippers, robot tools, inspection equipment and other parts at the end of a kinematic chain.

Extended jaw: An (optional) additional jaw situated at the end of an impactive gripper finger. It may, in preference to the finger itself, be modified to fit the profile of the object and it may be replaceable.

Gripper: The generic term for all prehension devices whether robotic or otherwise. Loosely defined in four categories: Impactive, Astrictive, Ingressive and Contigutive.

Gripper axis: A frame with its origin in the TCP (Tool Center Point). This coordinate system is used to specify the gripper orientation. Figure A.2 shows a gripper with three translational and three rotational degrees of freedom. The gripper frame is normally defined relative to the flange frame of the industrial robot.

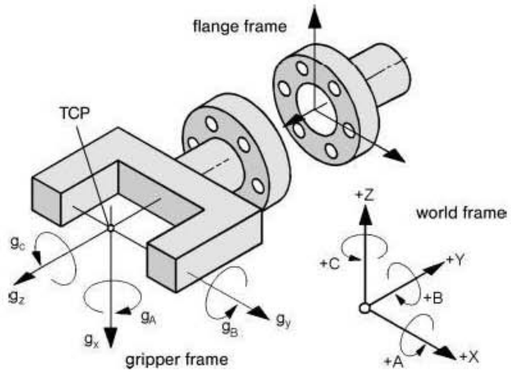


Figure A.2: Gripper Frame.

Gripper changing system: A module for rapid manual, but in most cases automatic, exchange of an end-effector using a standard mechanical interface. In doing so, all power and control cables must be disconnected and reconnected.

Gripper finger: Rigid, elastic, or multi-link grasping organ to enclose or clasp the object to be handled. Fingers are often equipped with extended gripper jaws at their ends. The grip-per finger is usually (though not always) the active part mating contact between the gripper and the object.

Gripper hand (hand unit): Grippers with multiple jointed fingers, each of them representing an open kinematic chain and possessing a high degree of freedom with joints, e.g. f=9.

Gripper jaw: The part of the gripper to which the fingers are normally attached. The jaw does not necessarily come into contact with the object to be gripped. Note: in some cases gripper fingers may be fitted with an additional small (extended) jaw at their ends.

Gripping area: Area of the prehension (gripper jaw) across which the force is transmitted to the object surface. The larger the contact surface area of an impactive gripper, the smaller the pressure on the object surface.

Gripping surface: The passive contact surface between object and gripper, i.e. the surface which is subjected to prehension forces.

Holding system: A term often used for an active prehension system including gripper, jaws and fingers. It may also apply to a passive temporary retaining device.

Impactive gripper: A mechanical gripper whereby prehension is achieved by impactive forces, i.e. forces which impact against the surface of the object to be acquired.

Ingressive gripper: Ingression refers to the permeation of an object surface by the prehension means. Ingression can be intrusive (pins) or non intrusive (e.g. hook and loop).

Kinematic system: Mechanical unit (gear) converting drive motion of the prime mover into prehension action (jaw motion) with characteristic transmission rates for velocities and forces. The most often used kinematic components are lever, screw, and toggle lever gears. The gear determines the final velocity of the jaw movement, and the gripping force characteristics. Grippers without moving elements require no kinematics. Some examples of gears are shown in Figure A.3.

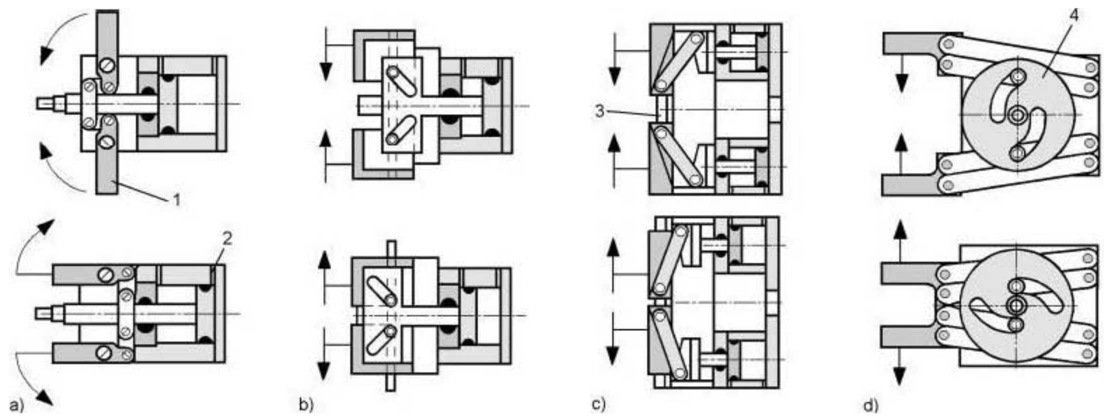


Figure A.3: Pneumatically Driven Gripper with Kinematic System for Transmission of Motion. (Sommer_Automatic)
1 Basic jaw or linger, 2 Pneumatic cylinder, 3 Straight guide way, 4 Cam disc
a) Angle gripper with toggle lever mechanics. b) Parallel gripper with roller link.
c) Parallel gripper with two pneumatic cylinders. d) Parallel gripper with cam disc.

Magnetoadhesion: Prehension force by means of a magnetic field (permanent or electrically generated).

Multiple grippers: Several grippers mounted on the same substrate, intended for the simultaneously prehension of more man two objects.

Prehendability: The suitability of an object to be automatically gripped. It is dependant on the surface properties, weight and strength when exposed to prehension forces. This property can sometimes be enhanced by applying such surfaces or elements (handling adapters) which are required only for a particular procedure.

Prehension: The act of acquiring an object in or onto the gripper.

Prehension planning: Deals with the problem of how to ensure stable mating between robot gripper and work piece. A prehension strategy must be chosen in such a way that it can be accomplished in a stable manner and collision free. Post prehension misalignment of the object is undesirable. In many circumstances, special constraints must be observed in order to avoid contact with certain parts of the object (forbidden zones).

Prehension systems: Complete systems including grippers supplemented with additional units (subsystems), e.g. rotation, pivot and short-travel units, changing systems, joining (adjustment) tools, collision and overload protection mechanisms, measuring devices and other sensors.

Protection system: These are elements attached to the inner or outer part of the gripper which are activated in case of overload or collision in order to protect the robot and gripper from damage (warning signal, emergency stop activation, passive or active evasive movement).

Retention: Pertains to the post prehension status of an object already held in the gripper. Note: prehension and retention forces are not always equal.

Sensor system: Sensors pertinent to the task of prehension. This may include sensors built into the end-effector, possibly with integrated data pre-processing, for position detection, registration of object approach, determination of gripping force, path and angle measurements, slippage detection etc.

Sucker: Normally refers to a passive suction element (disk, cap or cup) which does not require active vacuum suction but relies on the evacuation of air by distortion of the element against the object surface.

Suction head: A form of astrictive gripper which may consist of one or more vacuum suction elements (discs, caps or cups) from which air is actively evacuated by means of externally generated negative pressure.

Synchronization: In the majority of 2 and 3 finger grippers it is intended that the fingers close in a uniform manner towards the center of the gripper. In order to achieve this, the motion of the fingers must be synchronized. Pneumatic cylinders, as can be seen from the example in Figure A.4, can be moved synchronously by means of a shaft with both right and left handed threads.

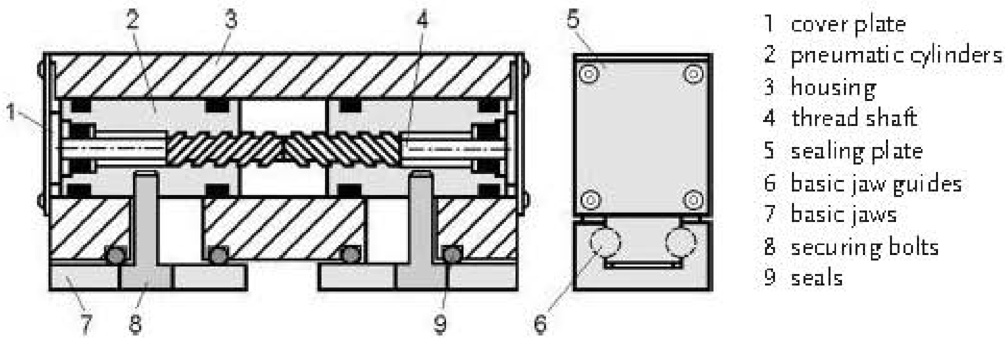


Figure A.4: Synchronization of the Gripper Lingers By Means of a Right and Left Hand Threaded Shaft.

Such movement may also be realized by a gear comprising only links and levers (double swing mechanism), as shown in Figure A.5. The basic jaws are again pneumatically driven by means of cylinders integrated within the gripper housing.

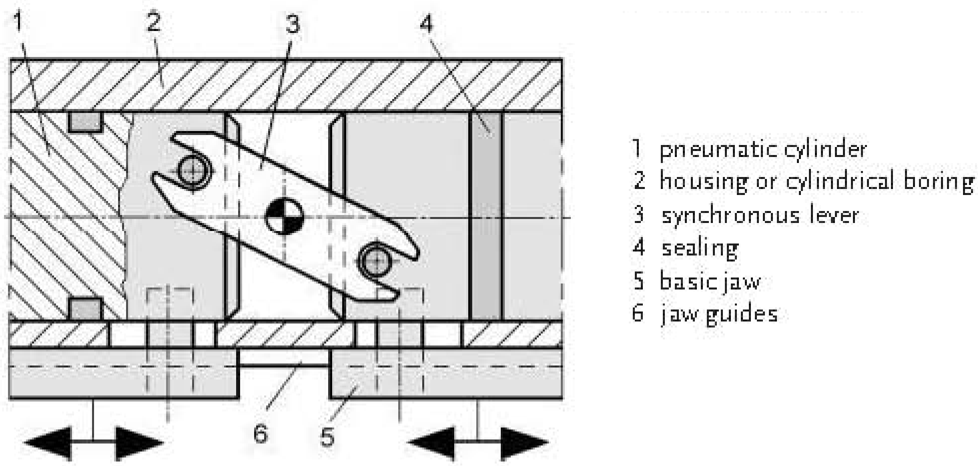


Figure A.5: Synchronization by Means of a Double Swing-Yoke-Drive.

TCP (Tool Center Point): Working point at the end of a kinematic chain. The TCP serves also as a programmed reference point for an end effect or and as a rule determines the origin of the tool frame. A coordinate system whose origin coincides with the TCP is called *tool frame*. Multiple gripper heads may possess several TCPs (Figure A.6) or one main TCP with the rest being defined relative to the main TCP by tool offsets.

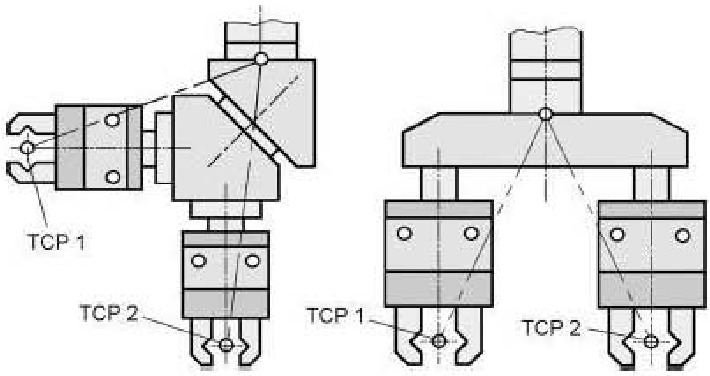


Figure A.6: TCPs of Multiple Grippers.

Thermoadhesion: Contigutive prehension force by means of thermal effects. Usually in the form of freezing or melting.

Work piece or object: A general term which refers to the component or object to be prehended or which is already under prehension by the gripper.

APPENDIX B

PNEUMATIC CIRCUIT DIAGRAMS

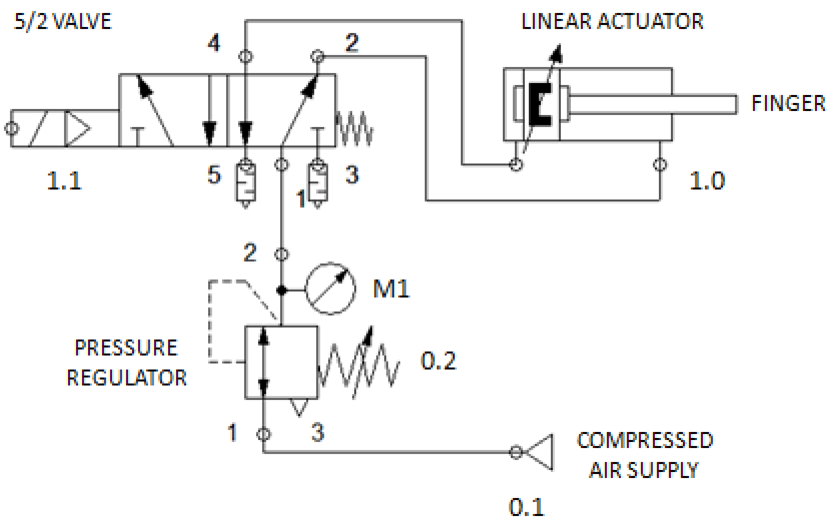


Figure B.1: Schematic Diagram of Pneumatic Circuit for the Two-Fingered Gripper.

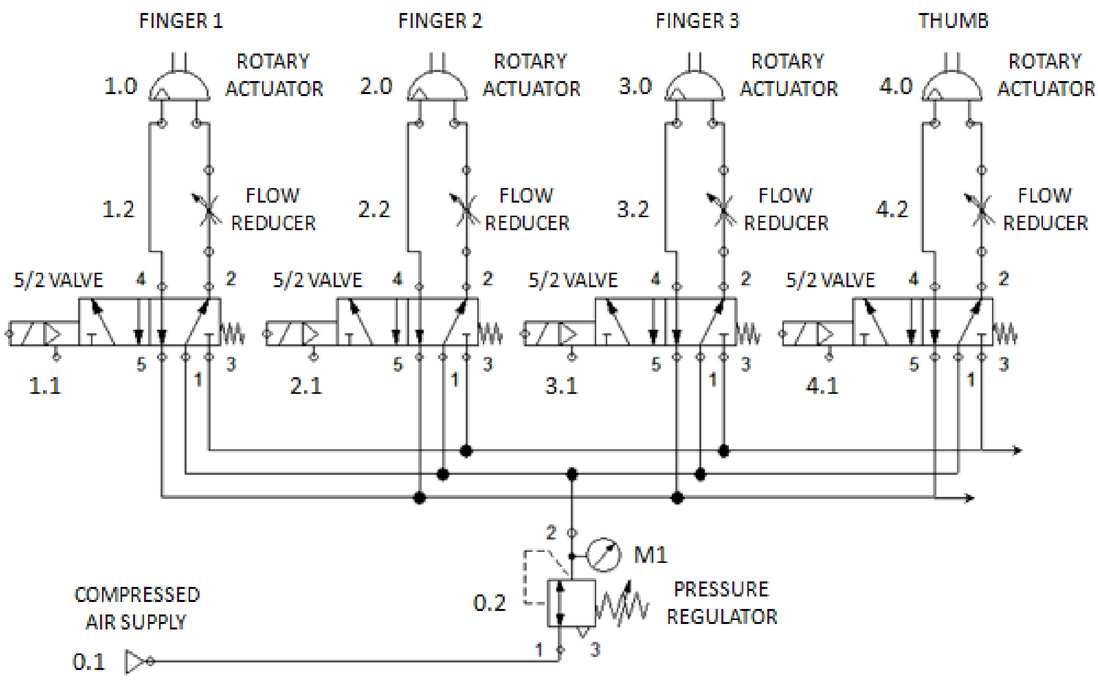


Figure B.2: Schematic Diagram of Pneumatic Circuit for the Four-Fingered Gripper.

APPENDIX C

THE TWO FINGERED GRIPPER

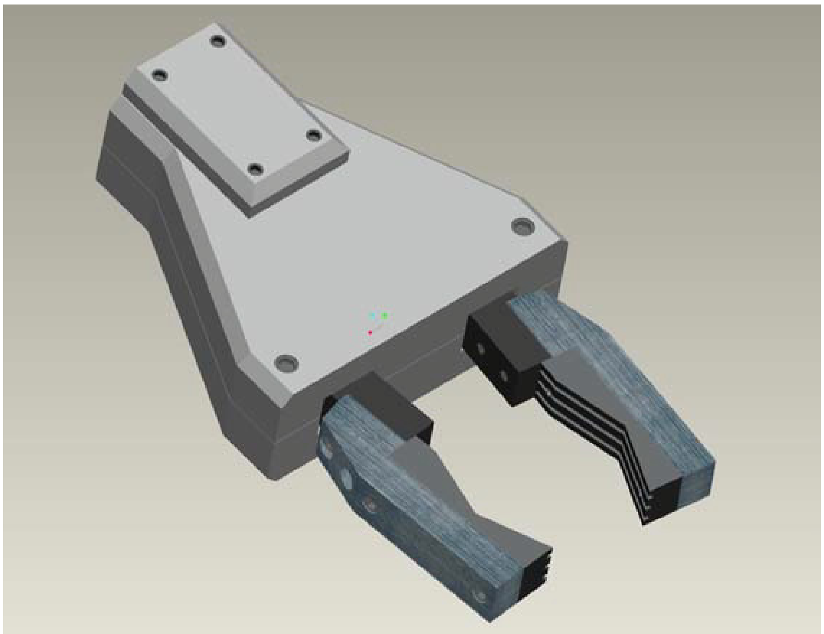


Figure C.1: 3D CAD Representation of the Two Fingered Gripper.

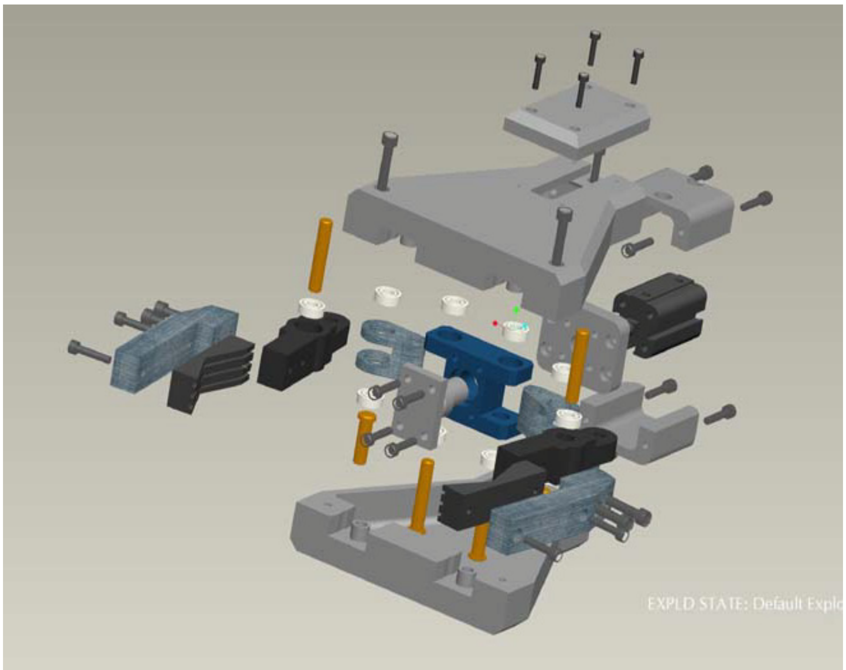


Figure C.2: Expanded View of the Two Fingered Gripper.

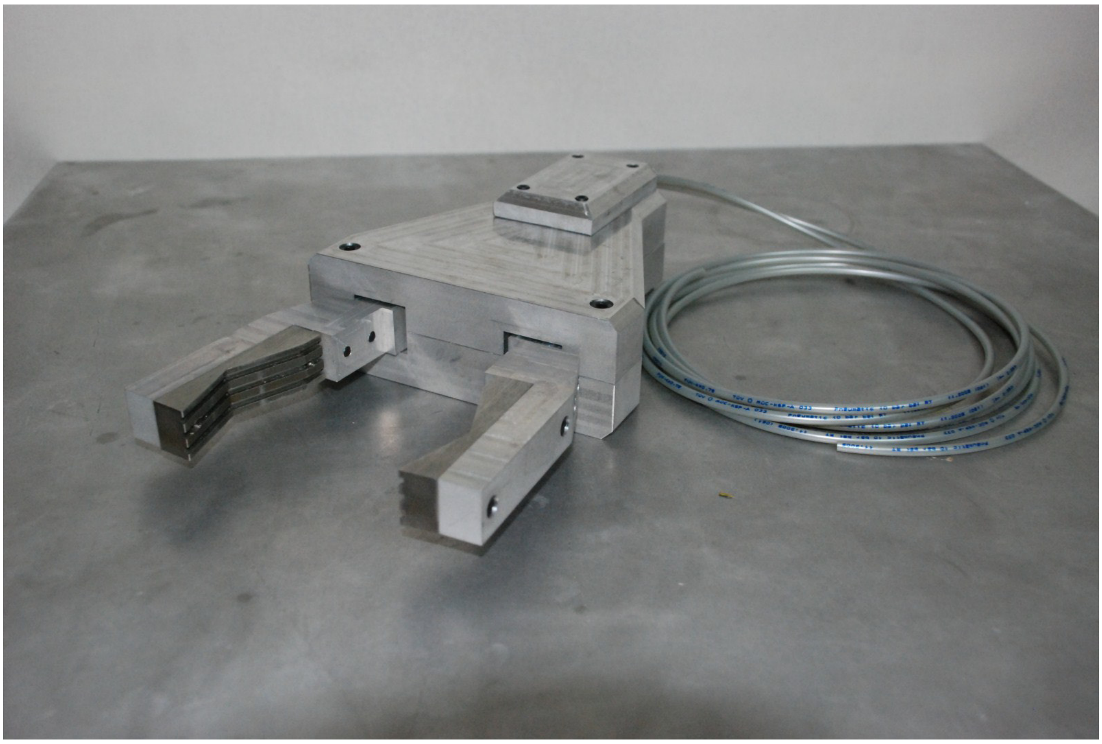


Figure C.3: View of the Manufactured Two-Fingered Gripper.

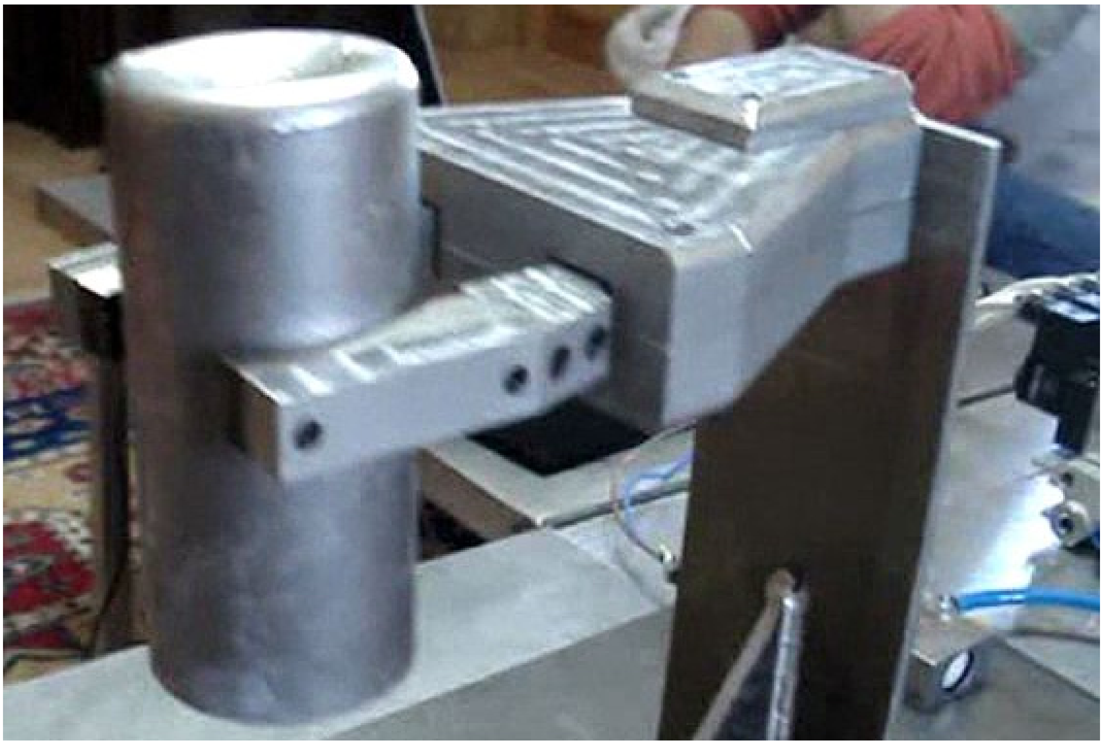
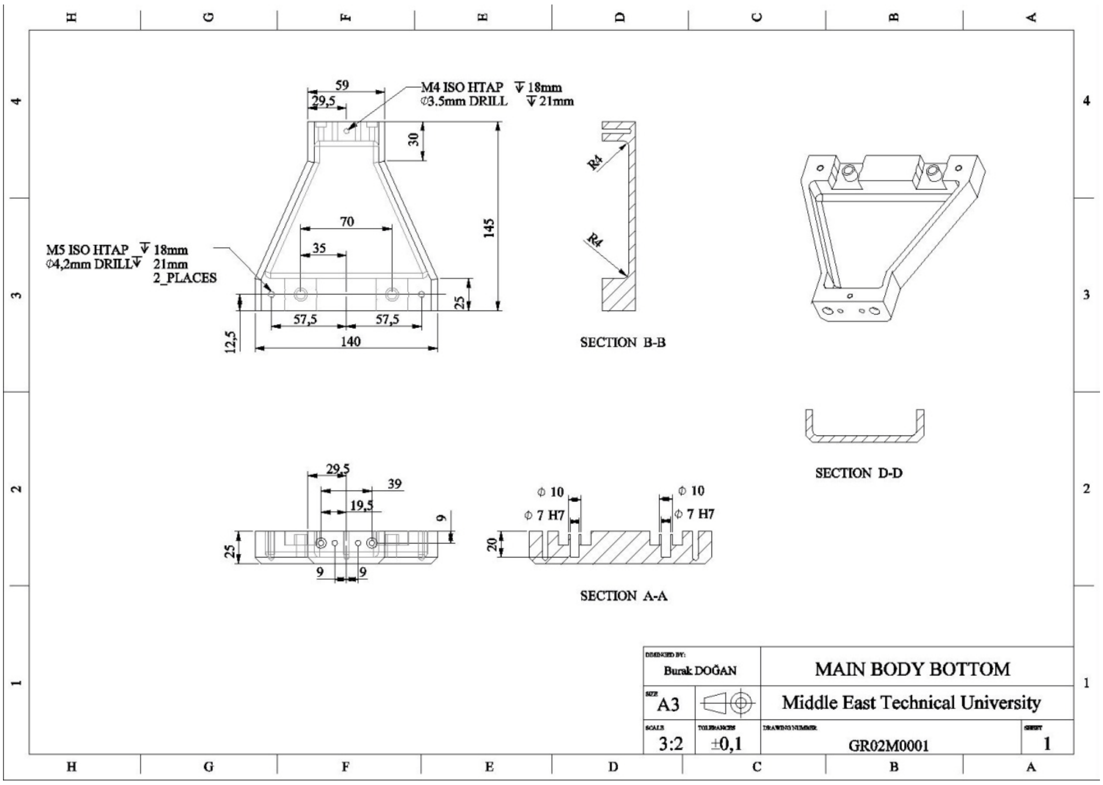
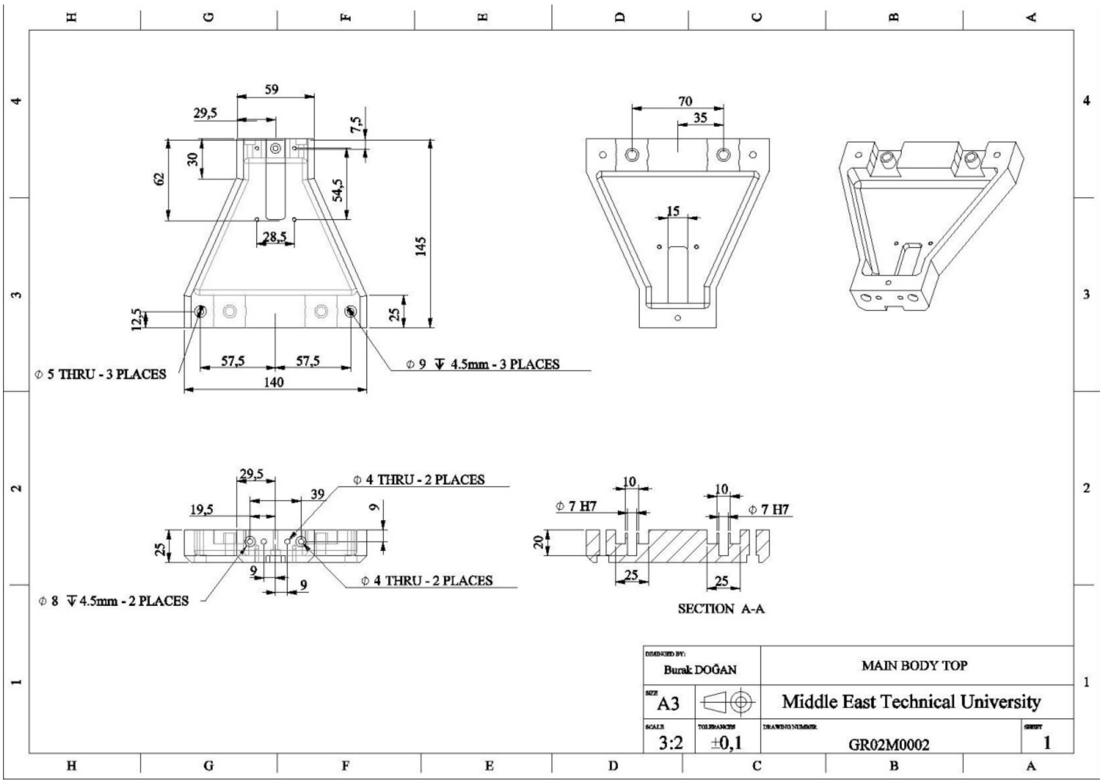


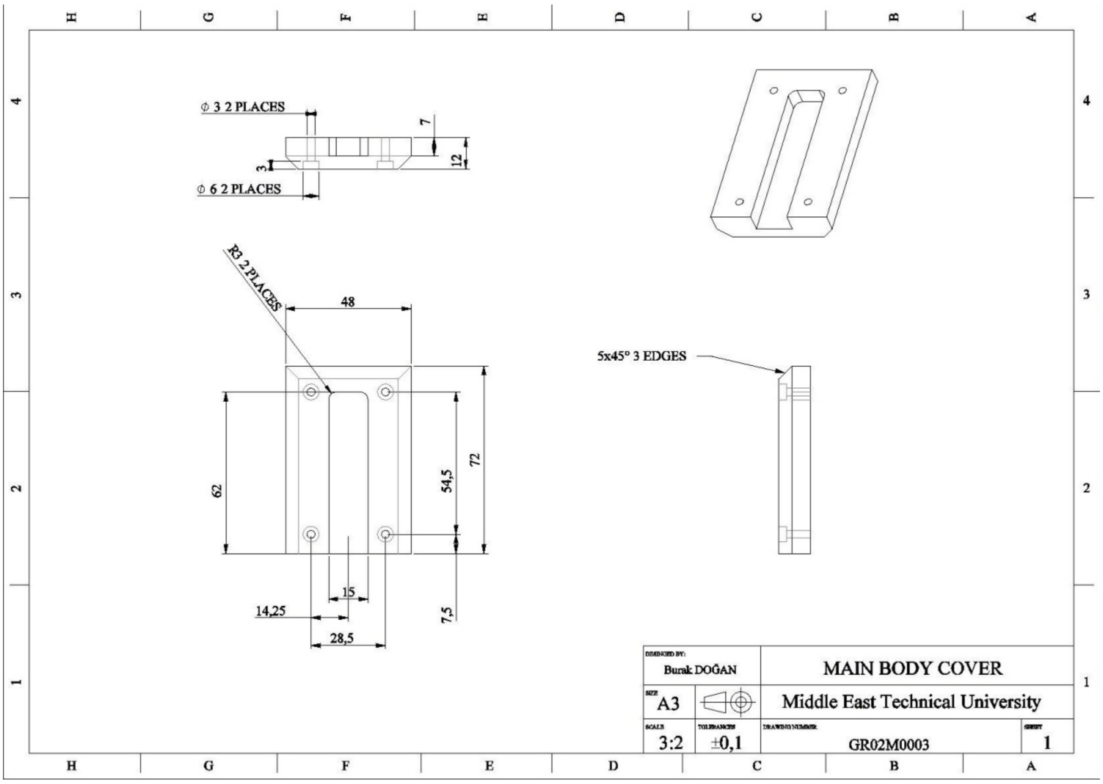
Figure C.4: Gripping of the Work Object.

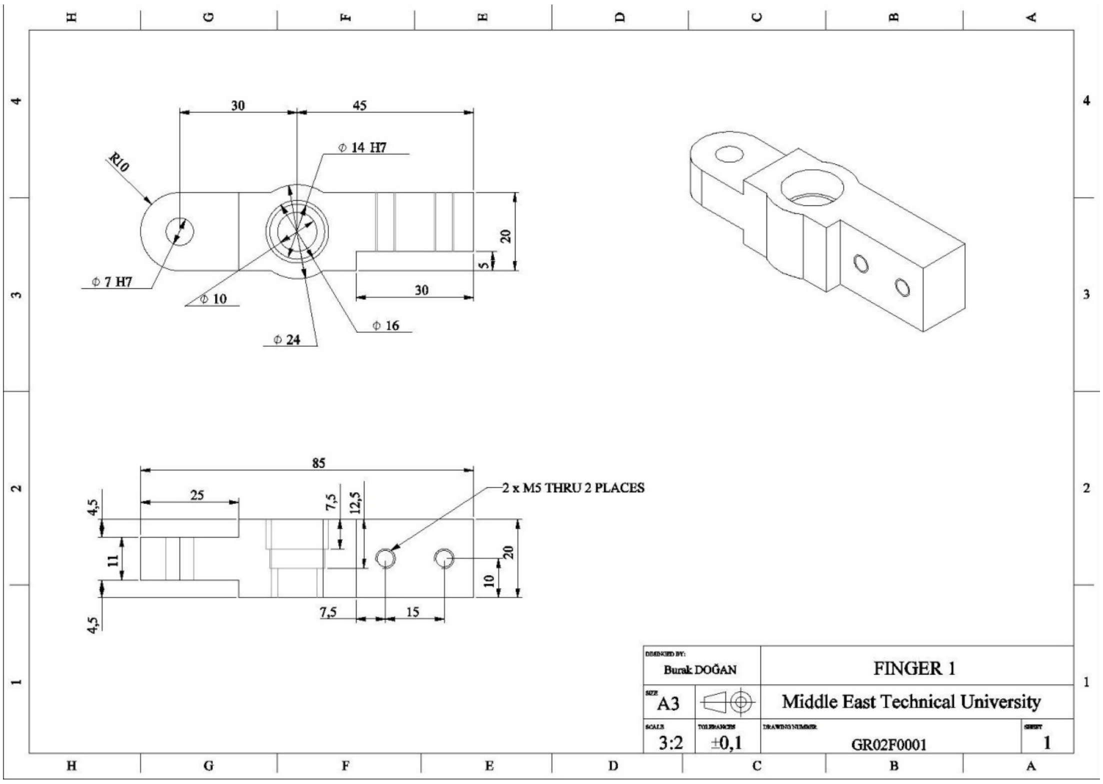
APPENDIX D

ENGINEERING DRAWINGS FOR THE TWO-FINGERED GRIPPER




59
29,5
7,5
30
62
54,5
28,5
145
12,5
25
Φ 5 THRU - 3 PLACES
57,5
57,5
140
Φ 9 ↧ 4.5mm - 3 PLACES
70
35
15
29,5
39
Φ 4 THRU - 2 PLACES
19,5
9
25
9
9
Φ 4 THRU - 2 PLACES
Φ 8 ↧ 4.5mm - 2 PLACES
10
10
Φ 7 H7
Φ 7 H7
20
25
25
SECTION A-A
Burak DOĞAN
MAIN BODY TOP
A3
Middle East Technical University
3:2
±0,1
GR02M0002
1


Φ 3 2 PLACES
7
3
12
Φ 6 2 PLACES
R3 2 PLACES
48
62
54,5
72
15
14,25
7,5
28,5
5x45° 3 EDGES
Burak DOĞAN
MAIN BODY COVER
A3
Middle East Technical University
3:2
±0,1
GR02M0003
1



R10
30
45
Φ 14 H7
20
5
30
Φ 7 H7
Φ 10
Φ 16
Φ 24
85
25
7,5
12,5
2 x M5 THRU 2 PLACES
4,5
11
20
10
4,5
7,5
15
DESIGNED BY:
Burak DOĞAN
FINGER 1
SIZE
A3
Middle East Technical University
SCALE
3:2
TOLERANCES
±0,1
DRAWING NUMBER
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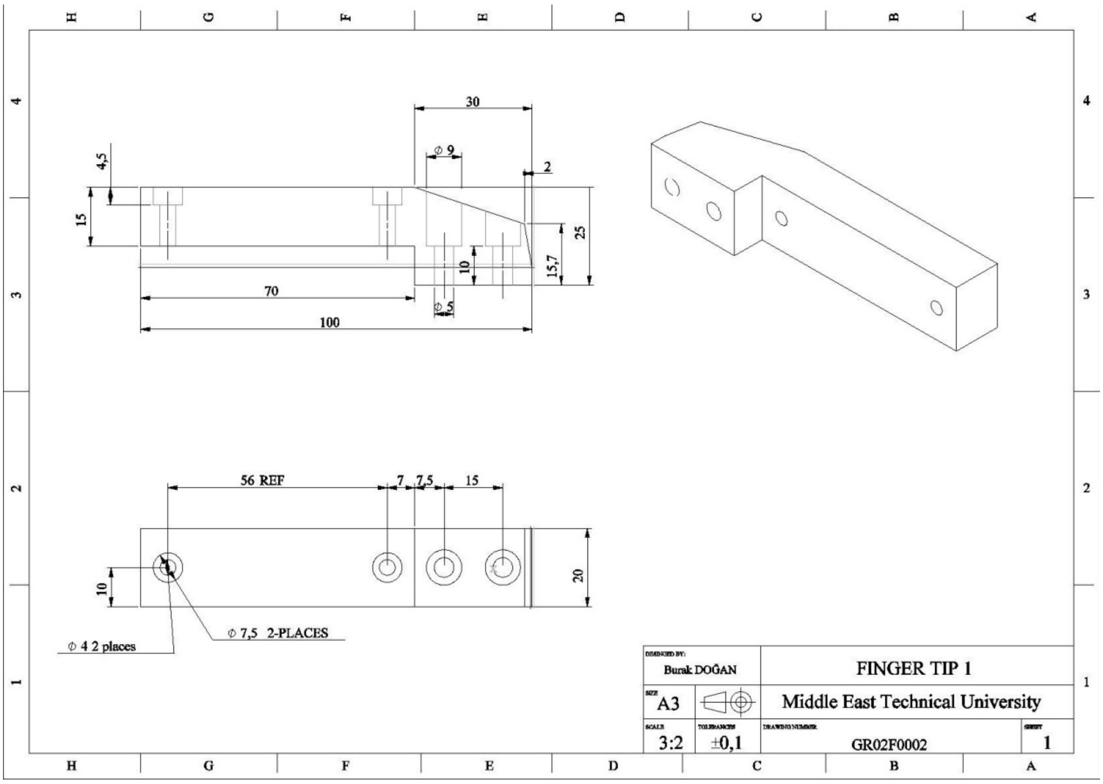
1



30
Φ 9
2
4,5
15
25
10
15,7
70
100
Φ 5
56 REF
7
7,5
15
10
20
Φ 4 2 places
Φ 7,5 2-PLACES
DESIGNED BY:
Burak DOĞAN
FINGER TIP 1
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SCALE
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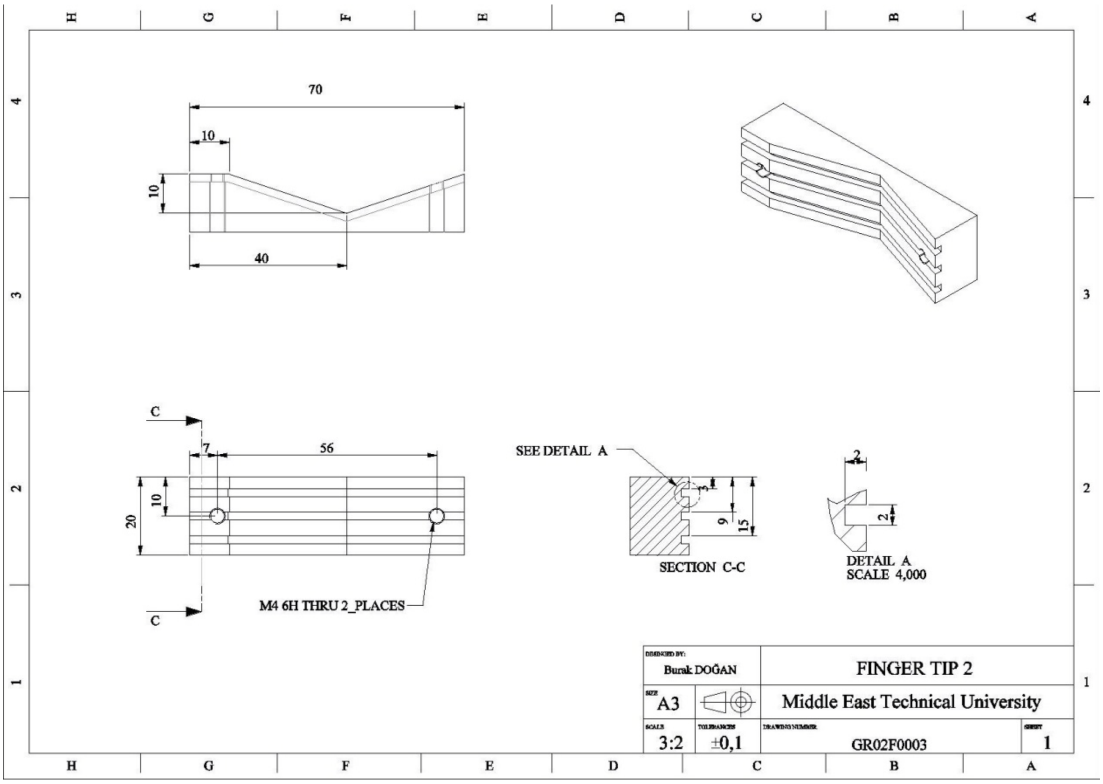
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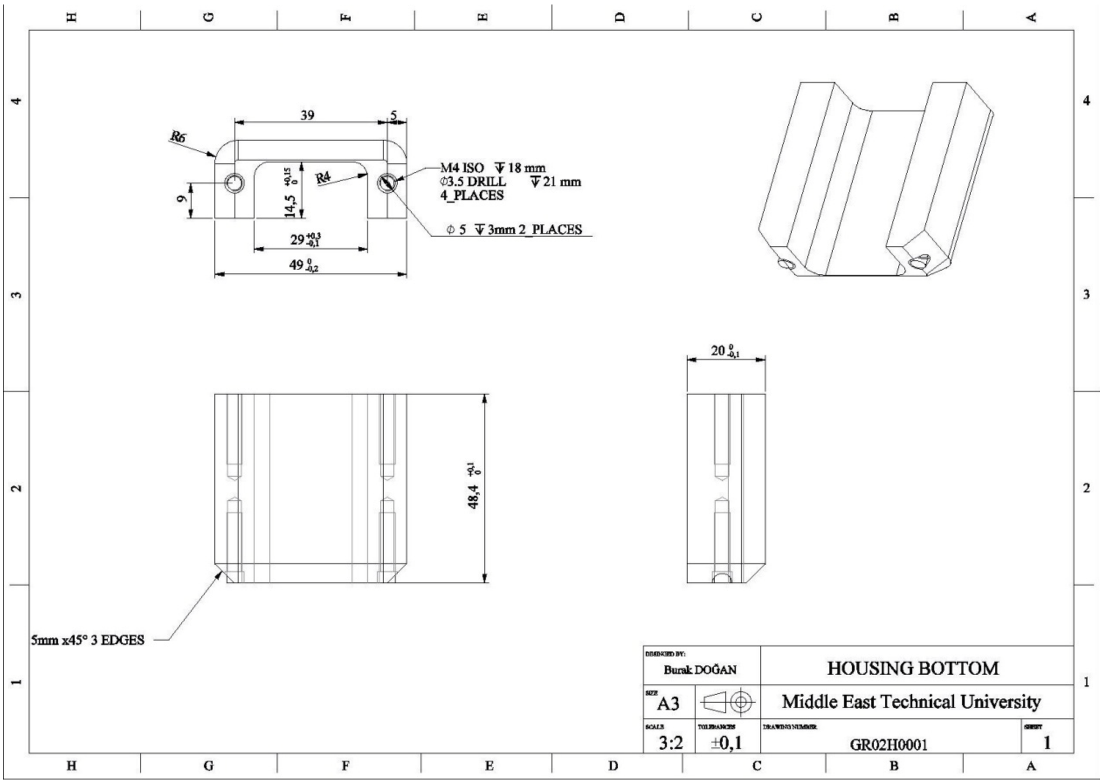
10
10
40
C
7
56
10
20
M4 6H THRU 2_PLACES
SEE DETAIL A
3
9
15
SECTION C-C
2
2
DETAIL A
SCALE 4,000
Burak DOĞAN
FINGER TIP 2
A3
Middle East Technical University
3:2
±0,1
GR02F0003
1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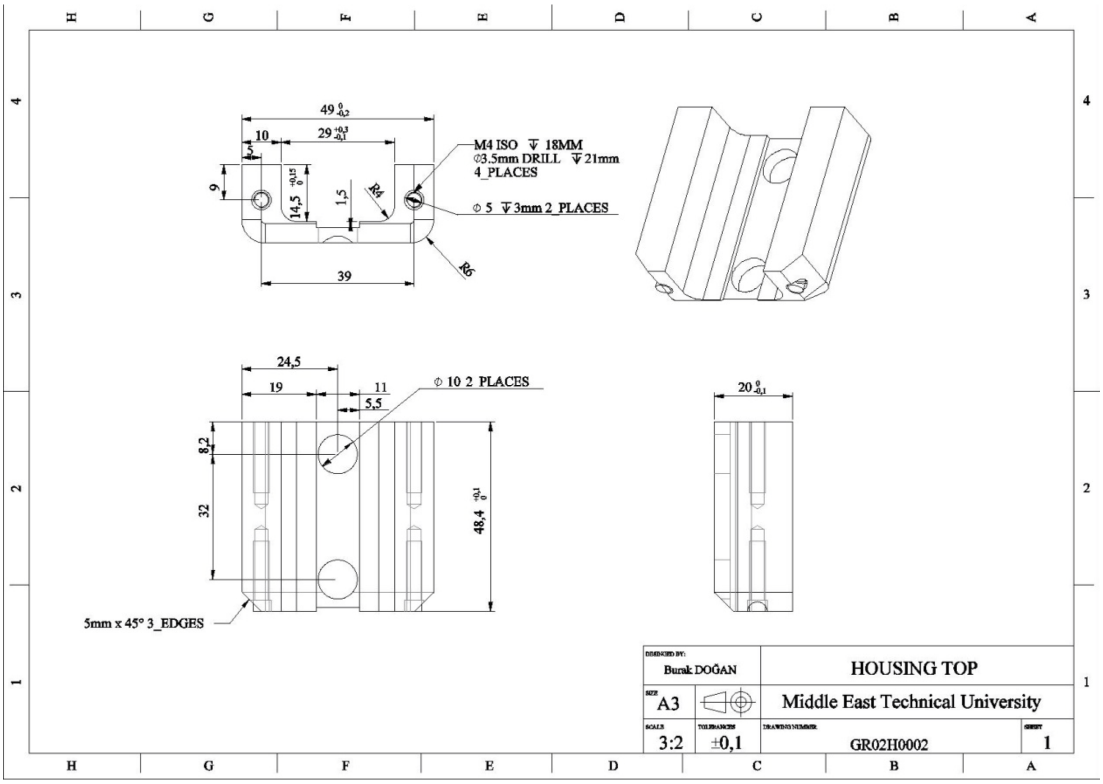
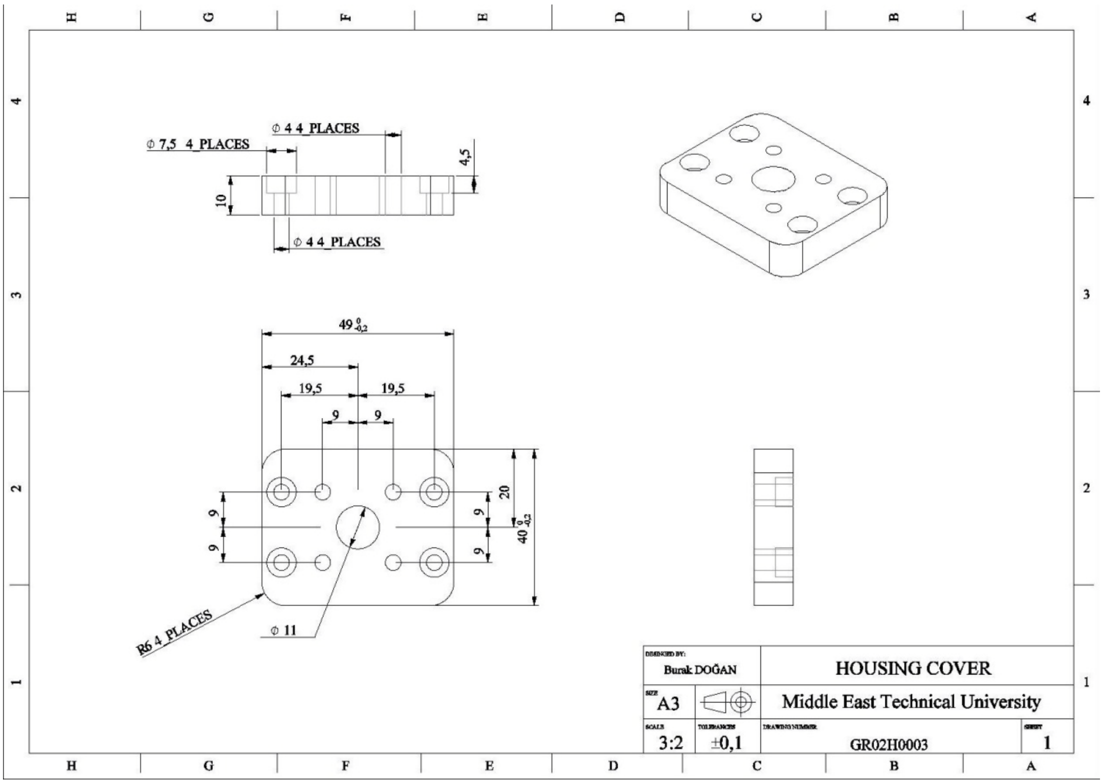
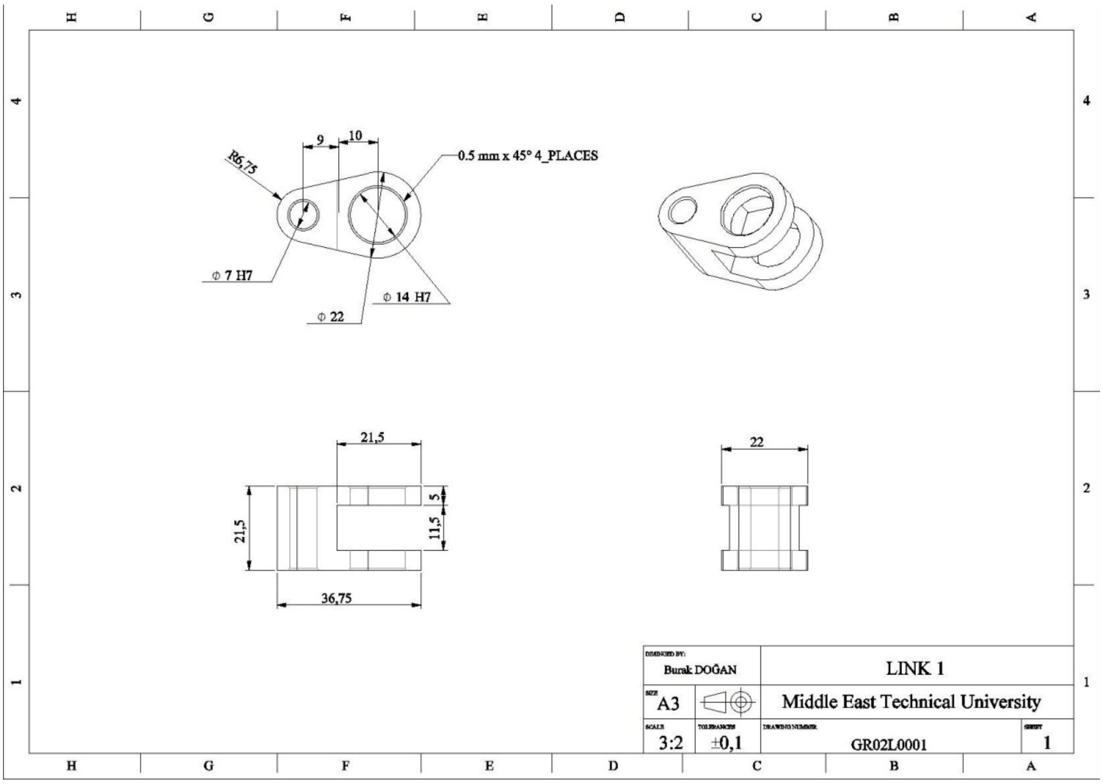
5
R6
R4
M4 ISO ↧18 mm
Ø3.5 DRILL ↧21 mm
4_PLACES
9
14,5
29
49
Ø 5 ↧3mm 2_PLACES
20
48,4
5mm x45° 3 EDGES
Burak DOĞAN
HOUSING BOTTOM
A3
Middle East Technical University
3:2
±0,1
GR02H0001
1


M4 ISO ↧ 18MM
Ø3.5mm DRILL ↧ 21mm
4_PLACES
Φ 5 ↧ 3mm 2_PLACES
Φ 10 2_PLACES
5mm x 45° 3_EDGES
Burak DOĞAN
HOUSING TOP
A3
Middle East Technical University
3:2
±0,1
GR02H0002
1


Φ 7,5 4_PLACES
Φ 4 4_PLACES
Φ 4 4_PLACES
R6 4_PLACES
Φ 11
Burak DOĞAN
HOUSING COVER
A3
Middle East Technical University
3:2
±0,1
GR02H0003
1


R6,75
9
10
0.5 mm x 45° 4_PLACES
Φ 7 H7
Φ 14 H7
Φ 22
21,5
21,5
5
11,5
36,75
22
DESIGNED BY:
Burak DOĞAN
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SCALE
3:2
TOLERANCES
±0,1
DRAWING NUMBER
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SHEET
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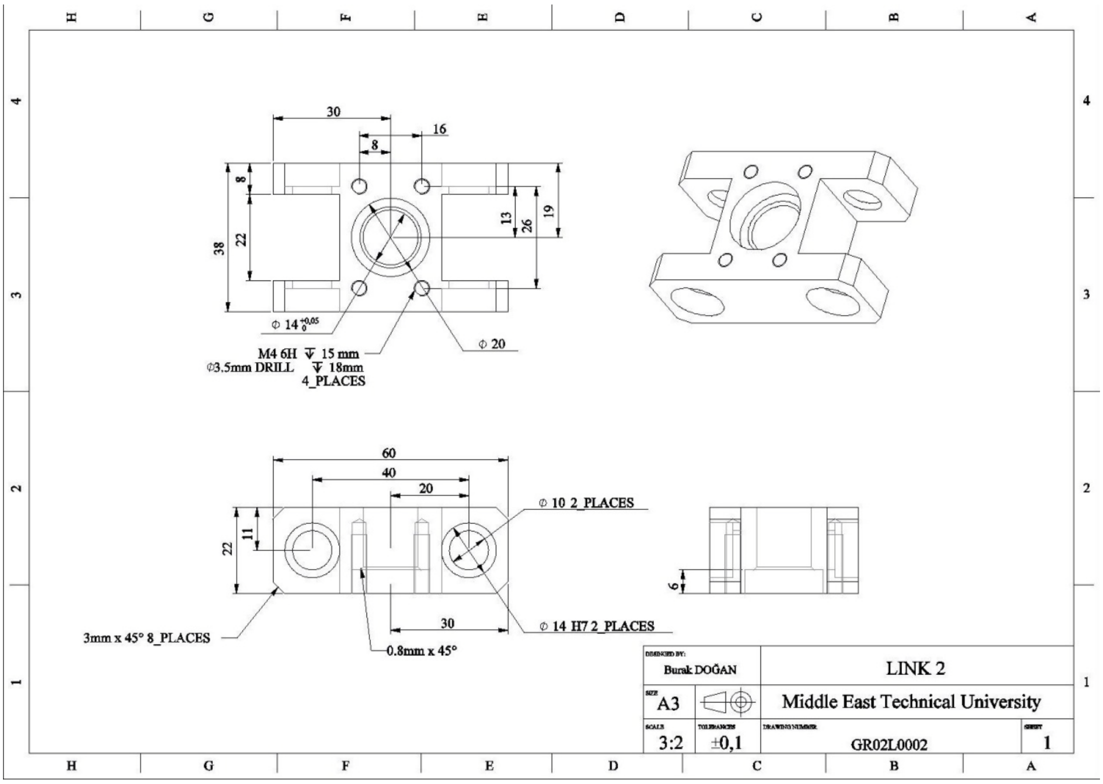
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8
16
8
22
38
13
26
19
Φ 14 +0,05 0
M4 6H ↧ 15 mm
Φ3.5mm DRILL ↧ 18mm
4_PLACES
Φ 20
60
40
20
Φ 10 2_PLACES
11
22
6
30
Φ 14 H7 2_PLACES
3mm x 45° 8_PLACES
0.8mm x 45°
DESIGNED BY:
Burak DOĞAN
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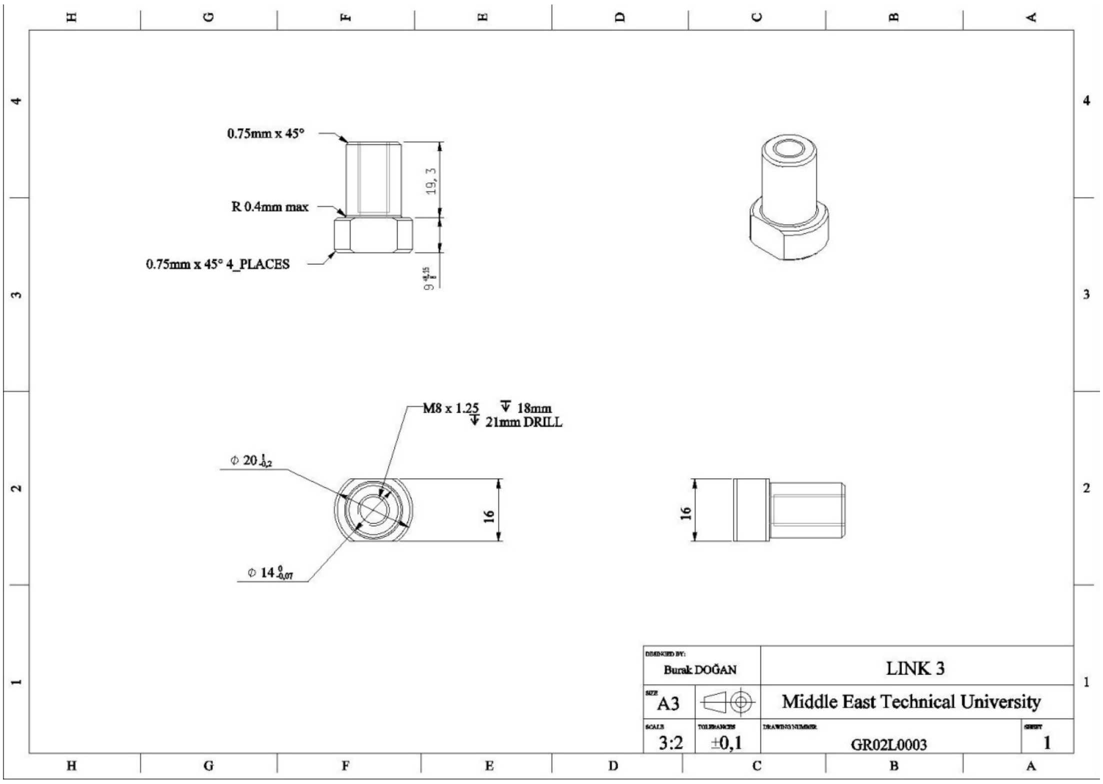
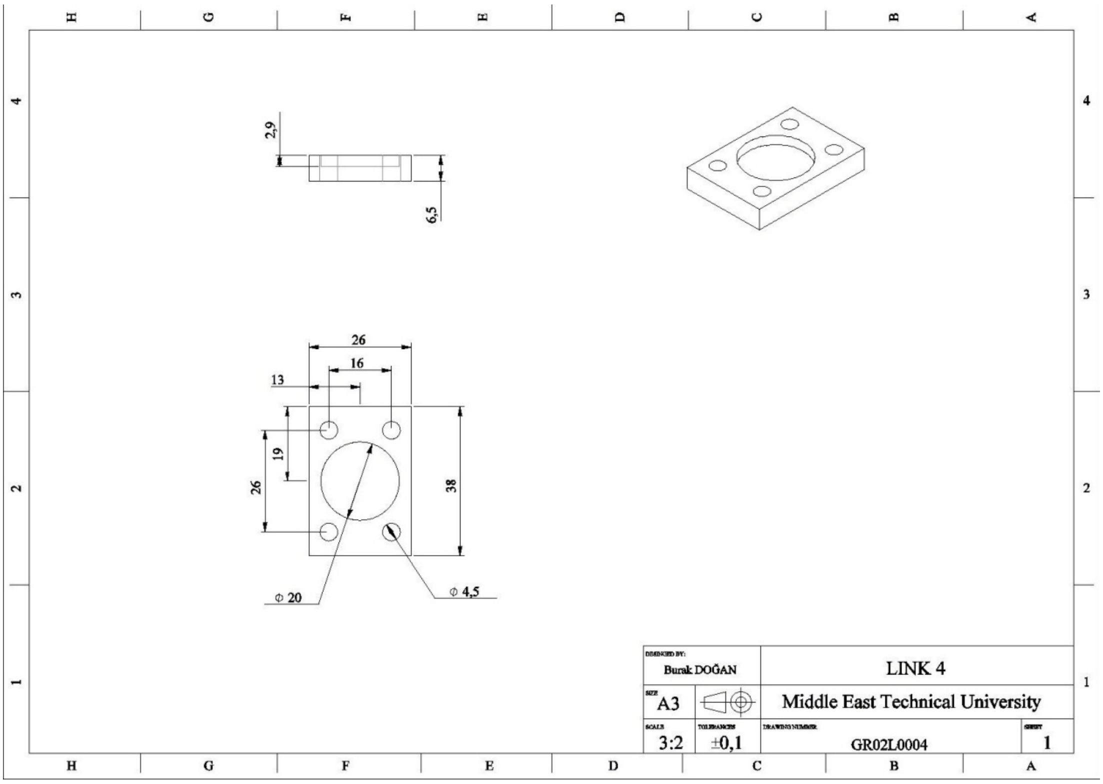

0.75mm x 45°
R 0.4mm max
0.75mm x 45° 4_PLACES
19, 3
M8 x 1.25 ↧ 18mm
↧ 21mm DRILL
16
16
Burak DOĞAN
LINK 3
A3
Middle East Technical University
3:2
±0,1
GR02L0003
1


2,9
6,5
26
16
13
19
26
38
Φ 20
Φ 4,5
Burak DOĞAN
LINK 4
A3
Middle East Technical University
3:2
±0,1
GR02L0004
1

APPENDIX E

THE FOUR FINGERED GRIPPER

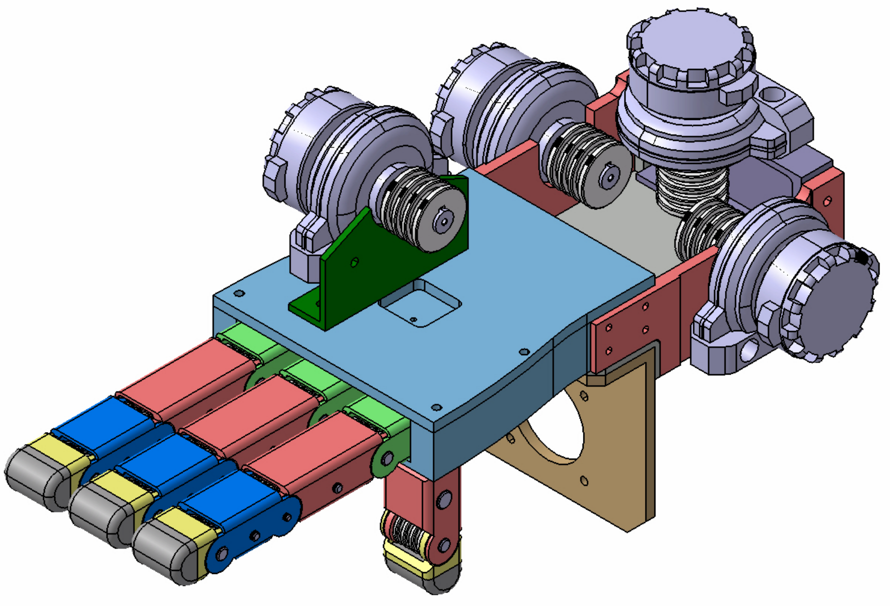


Figure E.1: 3D CAD Representation of the Four Fingered Gripper.

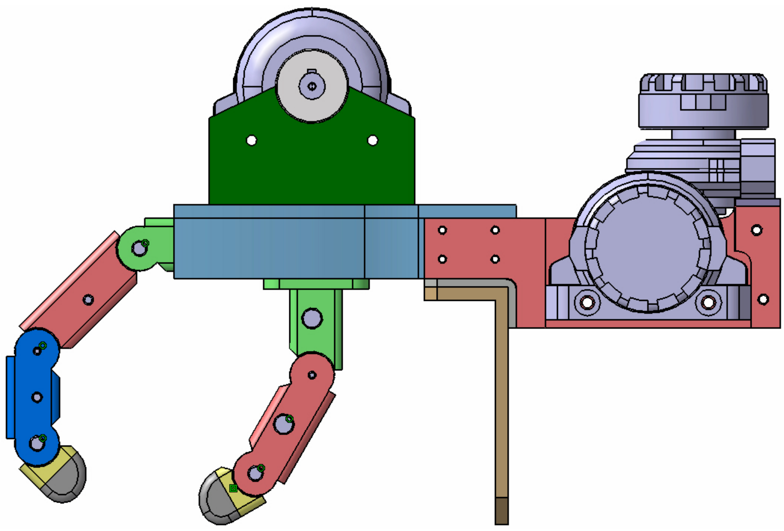


Figure E.2: Left View of the Four Fingered Gripper in Action.

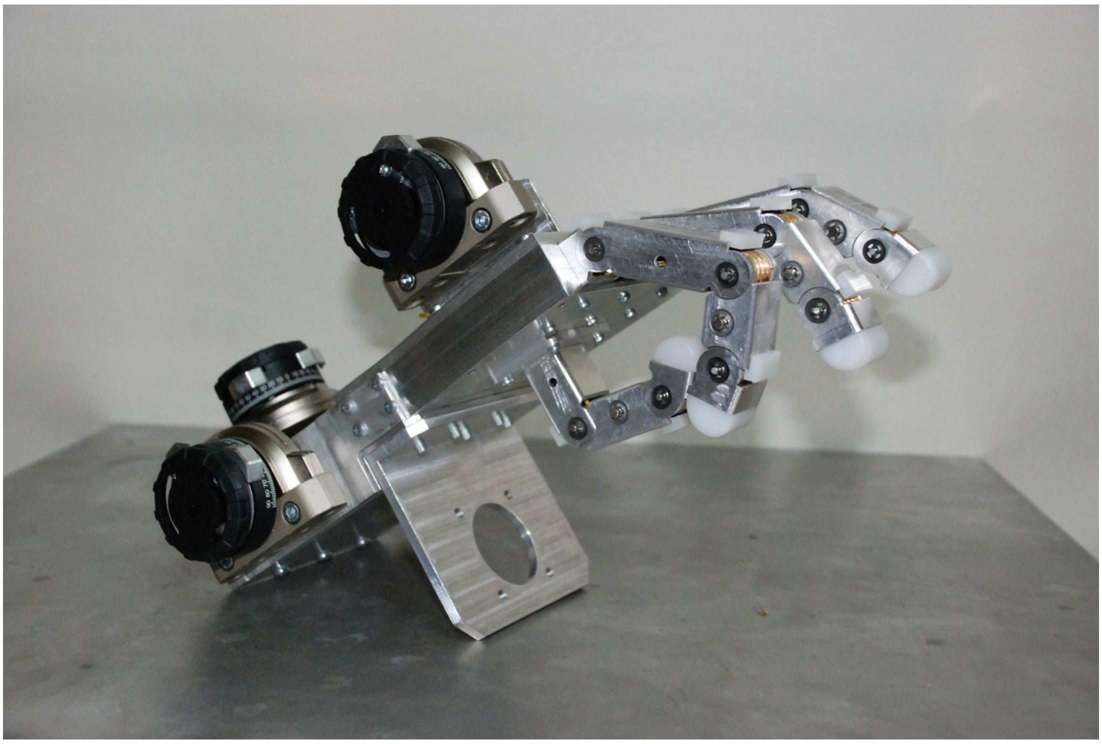


Figure E.3: 3D View of the Manufactured Four-Fingered Gripper - 1.

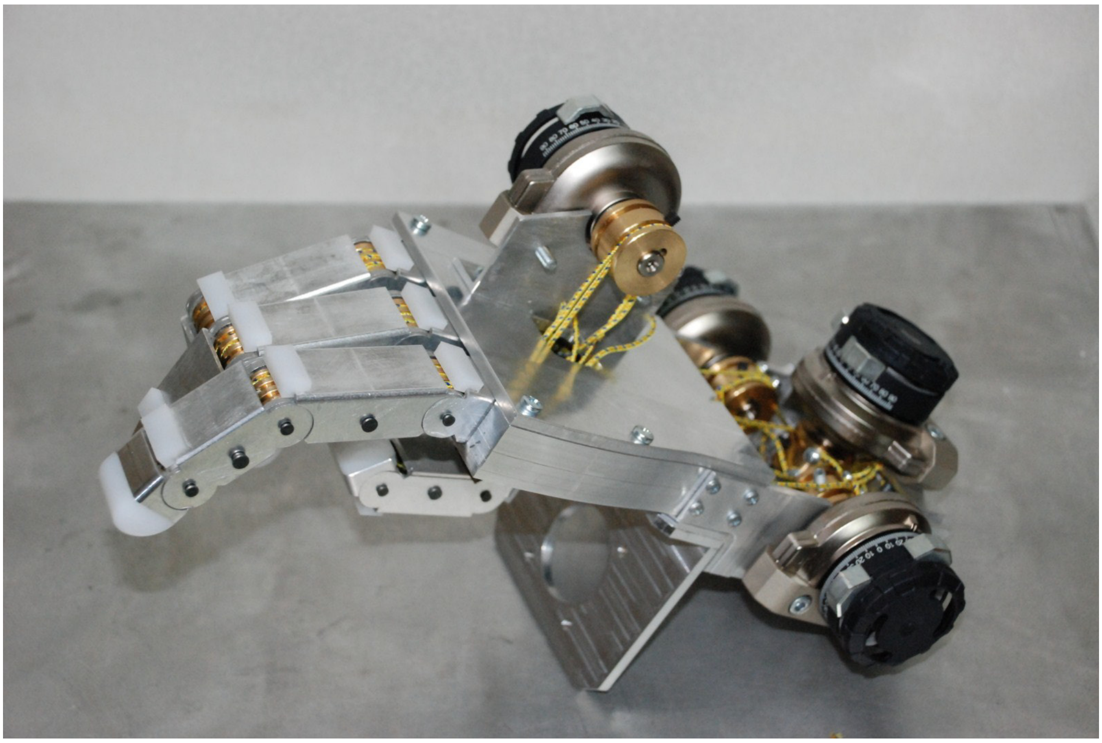


Figure E.4: 3D View of the Manufactured Four-Fingered Gripper - 2.

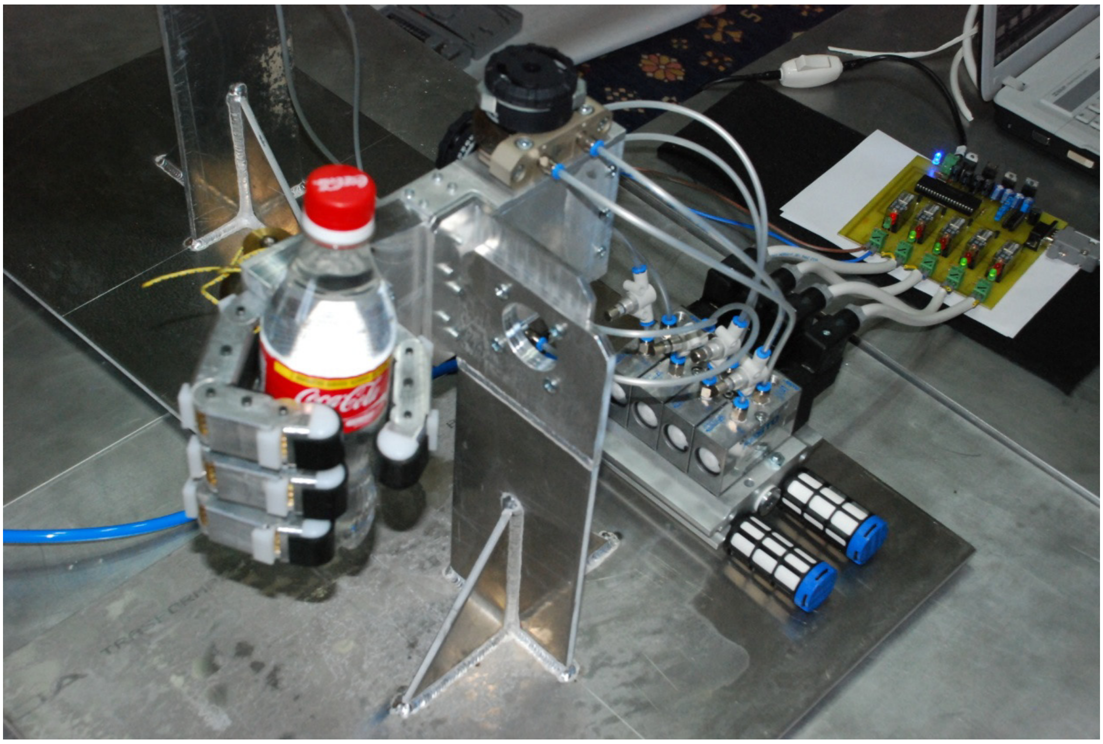


Figure E.5: Gripping of a Cylindrical Object.

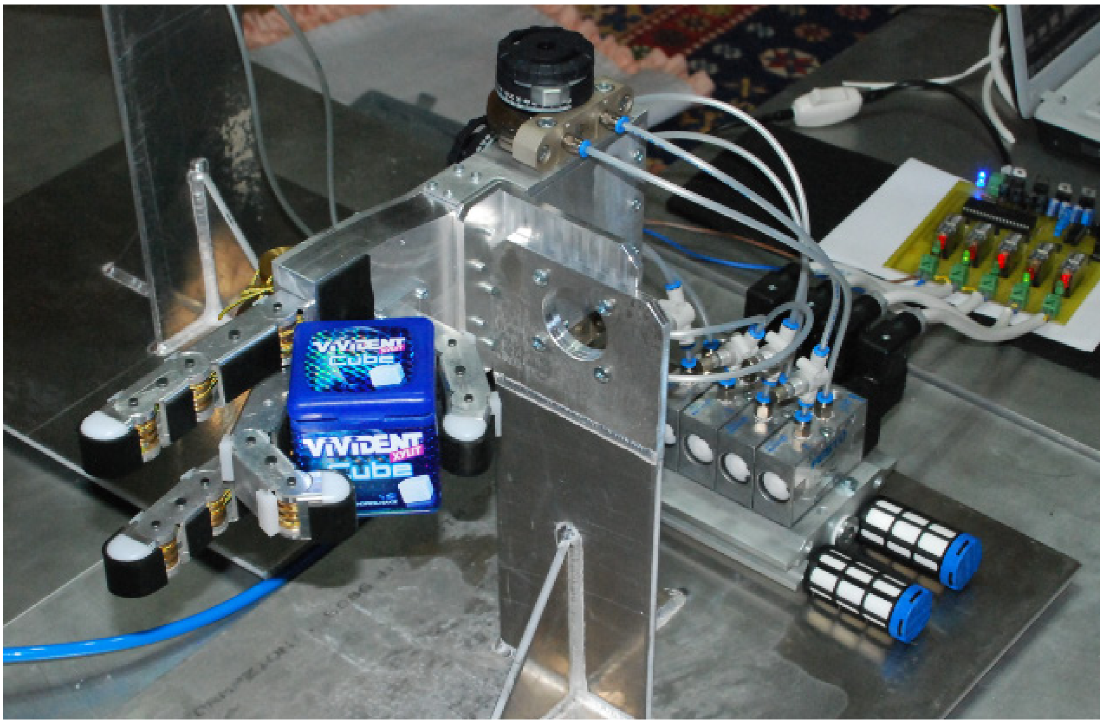


Figure E.6: Gripping of a Square Object.

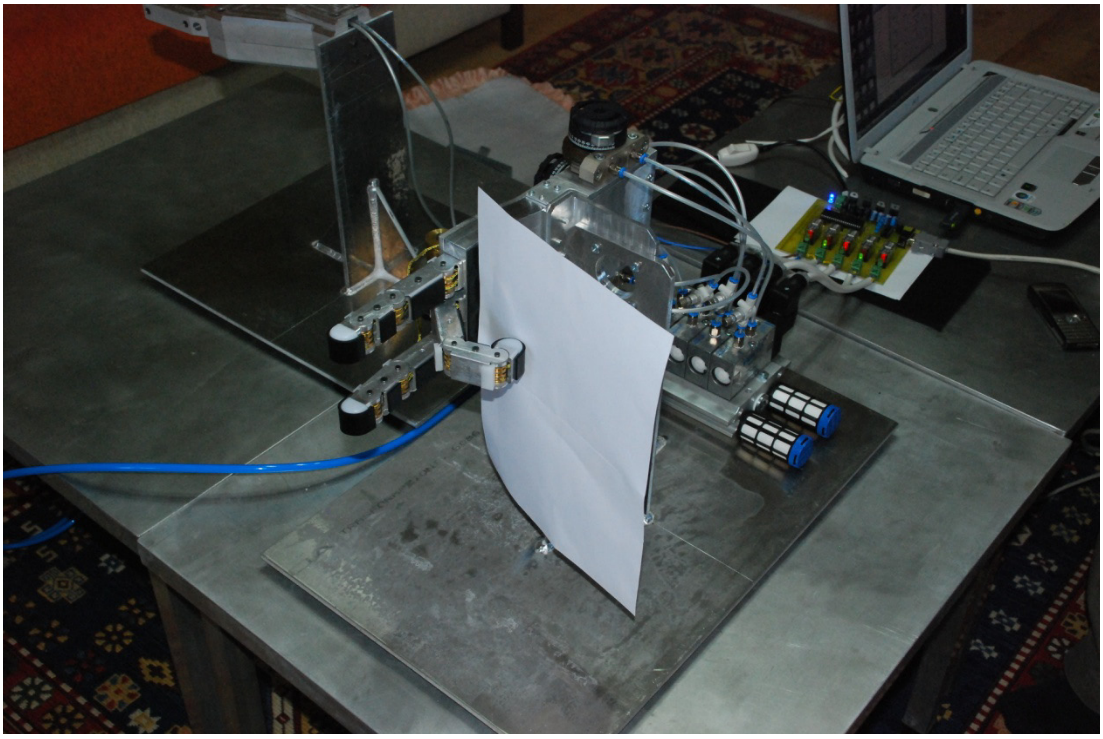


Figure E.7: Precision Gripping of a Sheet of Paper.

Figure E.8: Holding of a Complex Shaped Object.

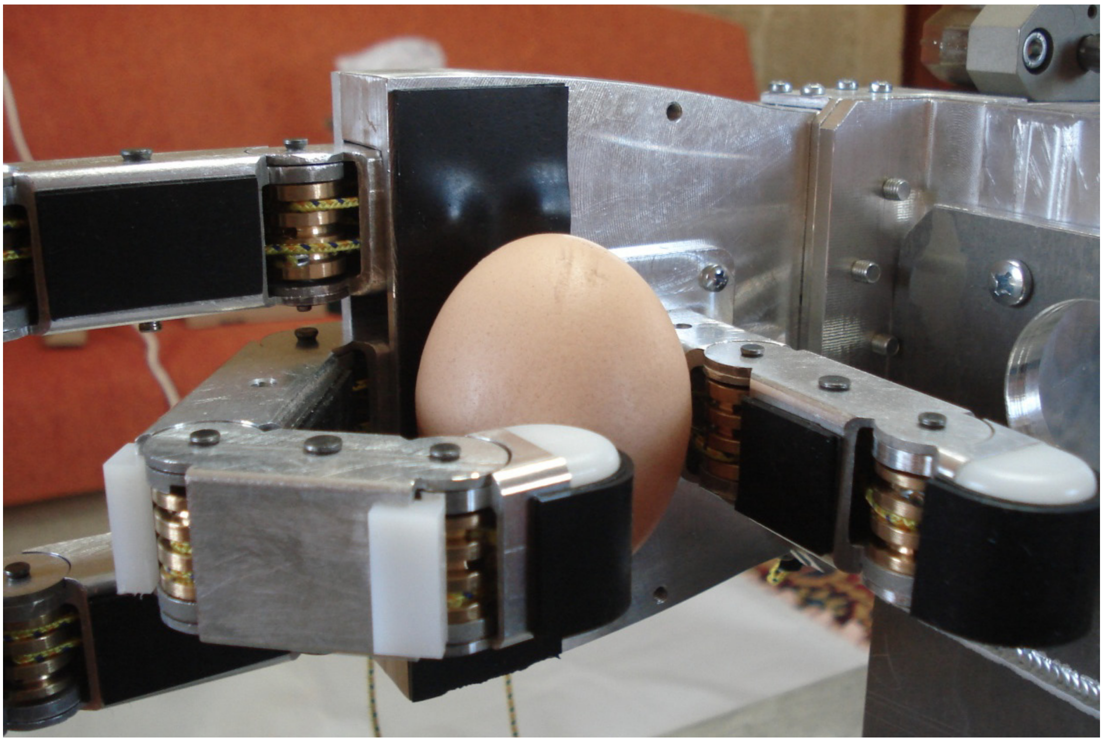
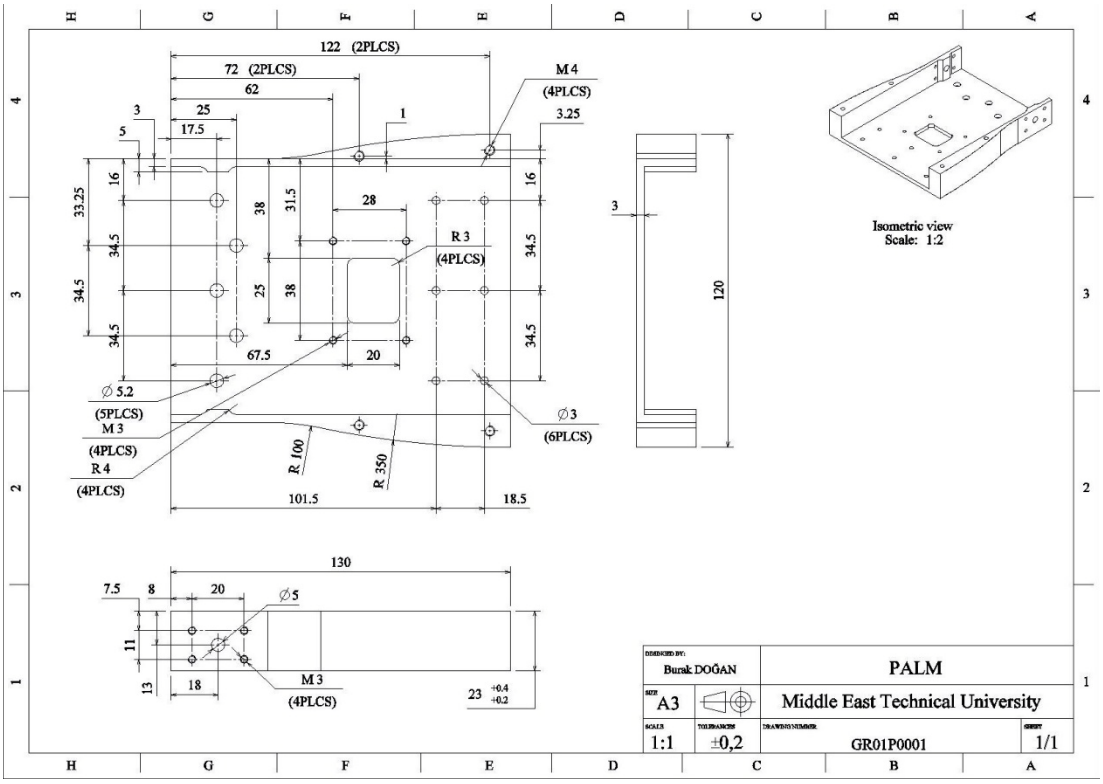
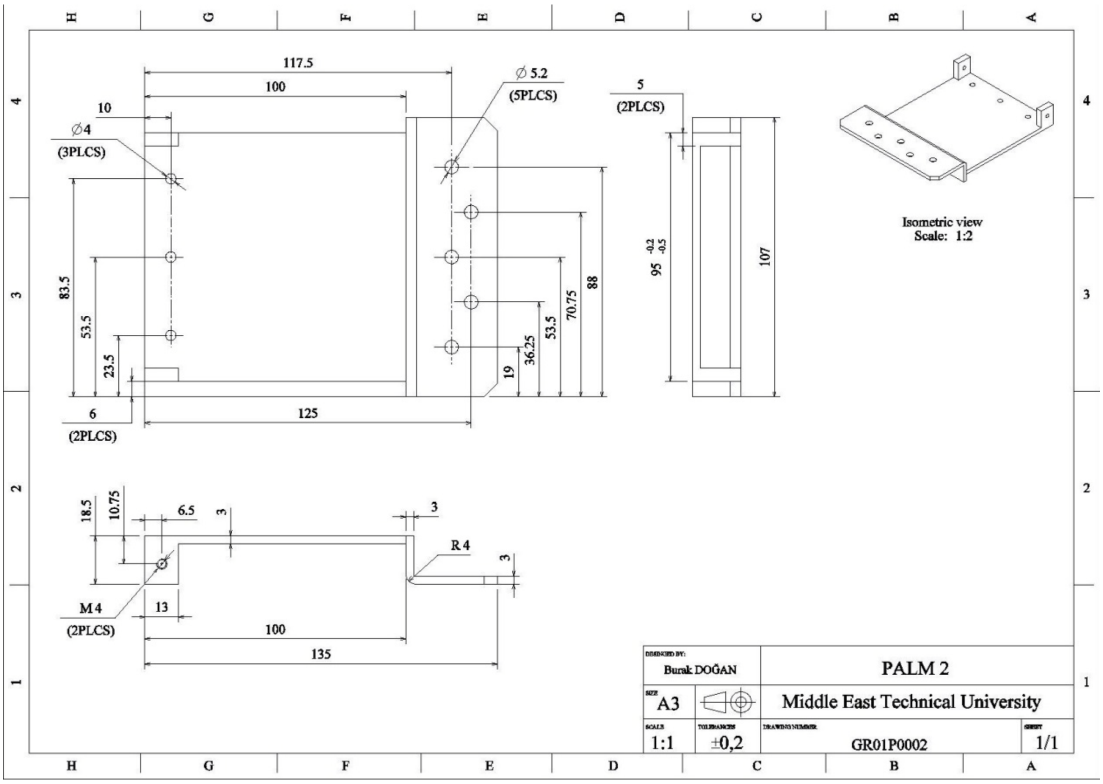


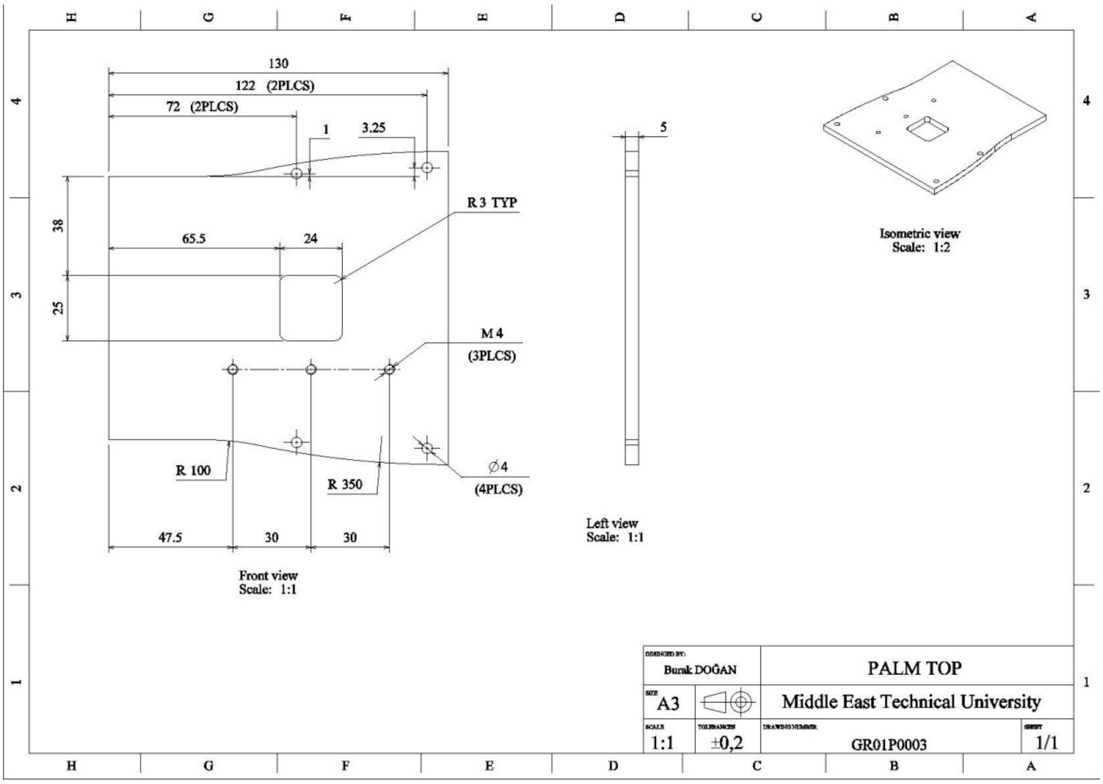
Figure E.9: Precision Gripping of a Fragile Object.

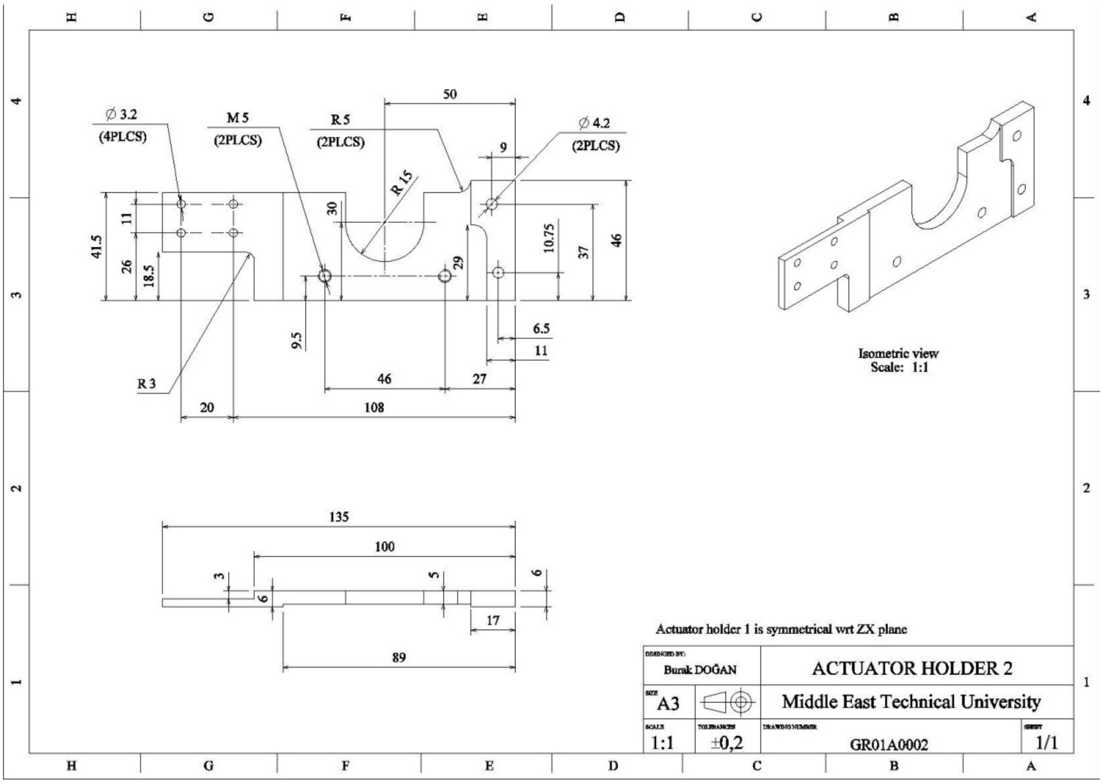
APPENDIX F

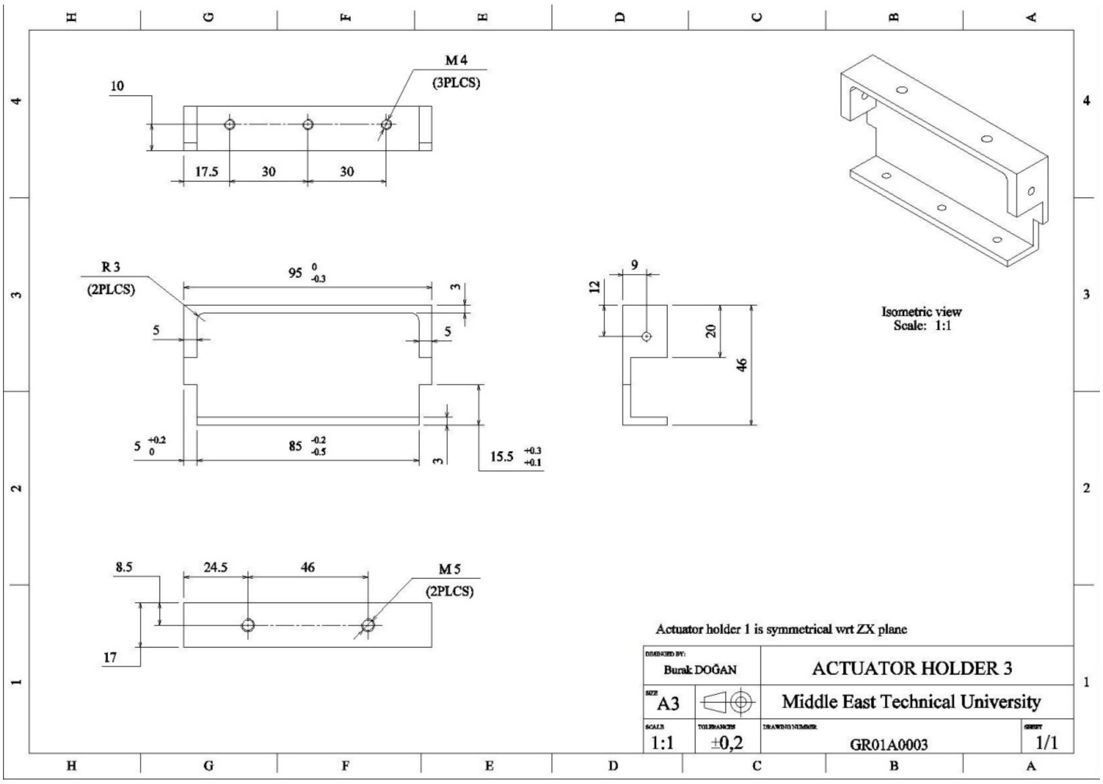
ENGINEERING DRAWINGS FOR THE FOUR-FINGERED GRIPPER

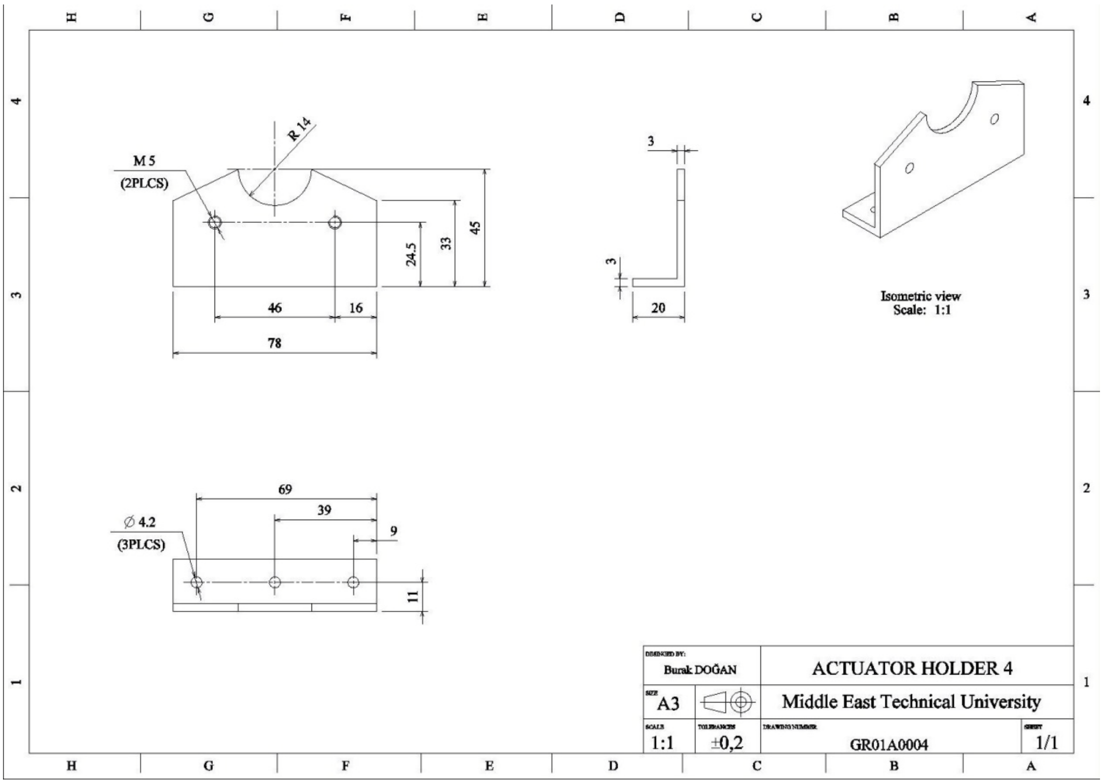



PALM 2
Middle East Technical University
Burak DOĞAN
A3
1:1
±0,2
GR01P0002
1/1
Isometric view
Scale: 1:2

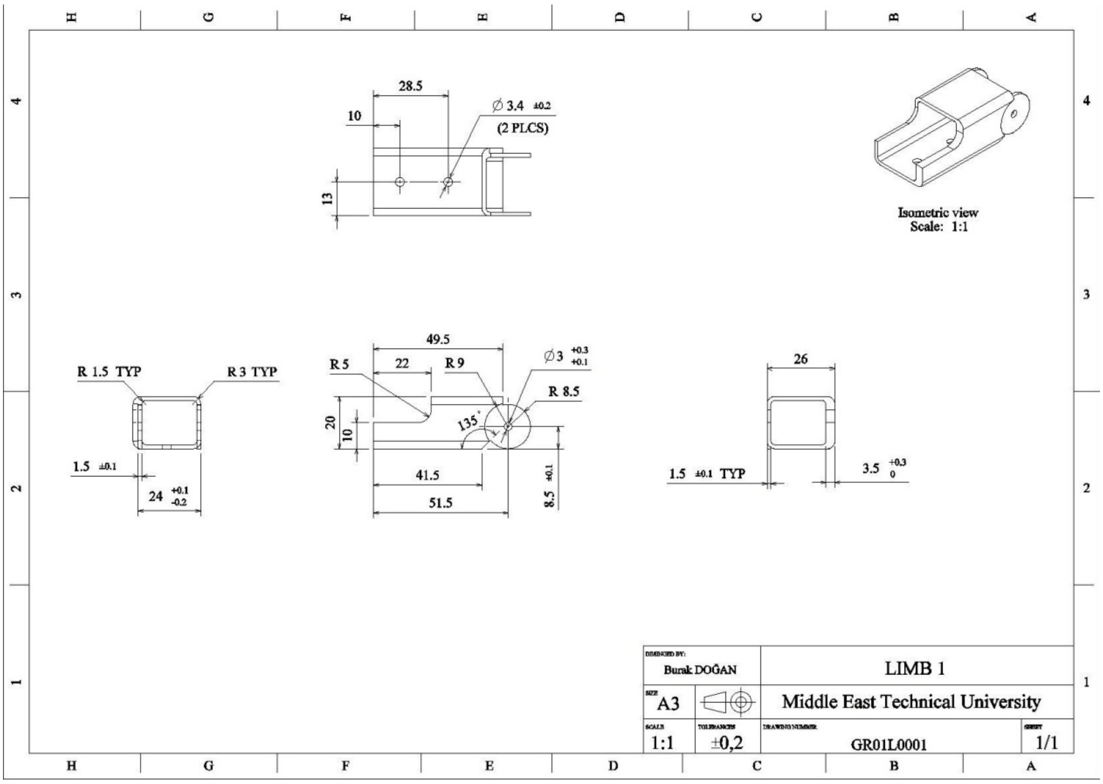

PALM TOP
Middle East Technical University
Burak DOĞAN
A3
1:1
±0,2
GR01P0003
1/1
Front view
Scale: 1:1
Left view
Scale: 1:1
Isometric view
Scale: 1:2


Actuator holder 1 is symmetrical wrt ZX plane
Isometric view
Scale: 1:1
Burak DOĞAN
ACTUATOR HOLDER 2
A3
Middle East Technical University
1:1
±0,2
GR01A0002
1/1

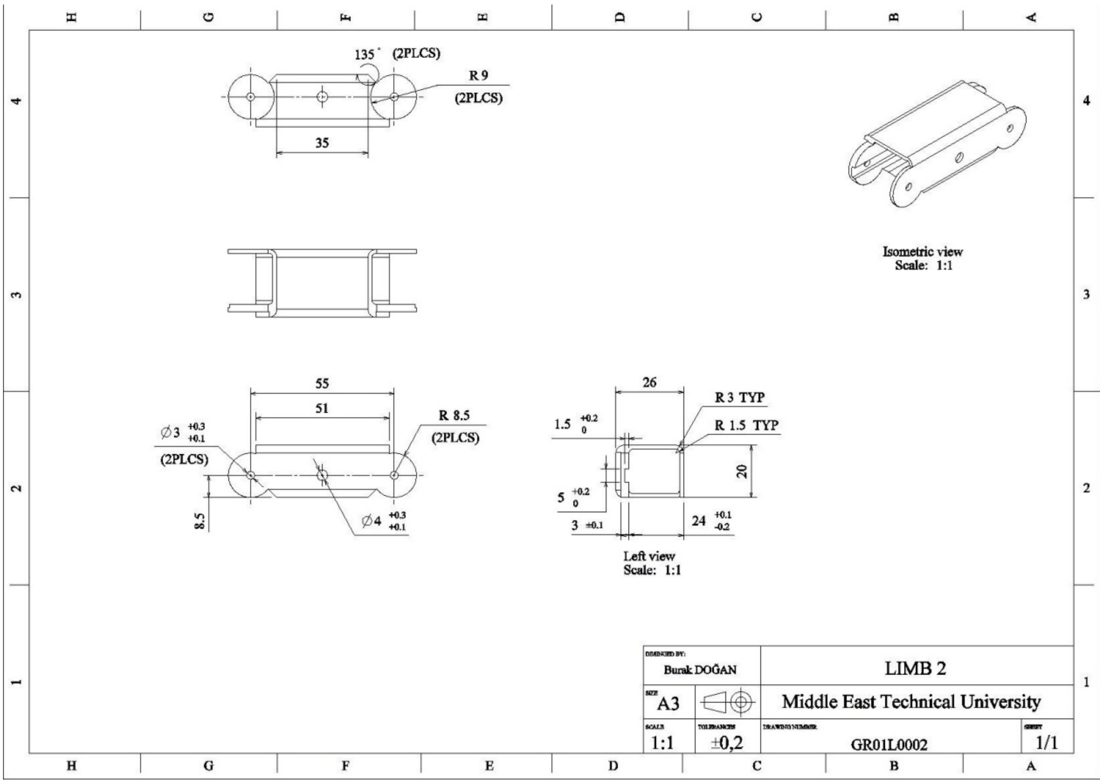

Actuator holder 1 is symmetrical wrt ZX plane
Isometric view
Scale: 1:1
Burak DOĞAN
ACTUATOR HOLDER 3
A3
Middle East Technical University
1:1
±0,2
GR01A0003
1/1

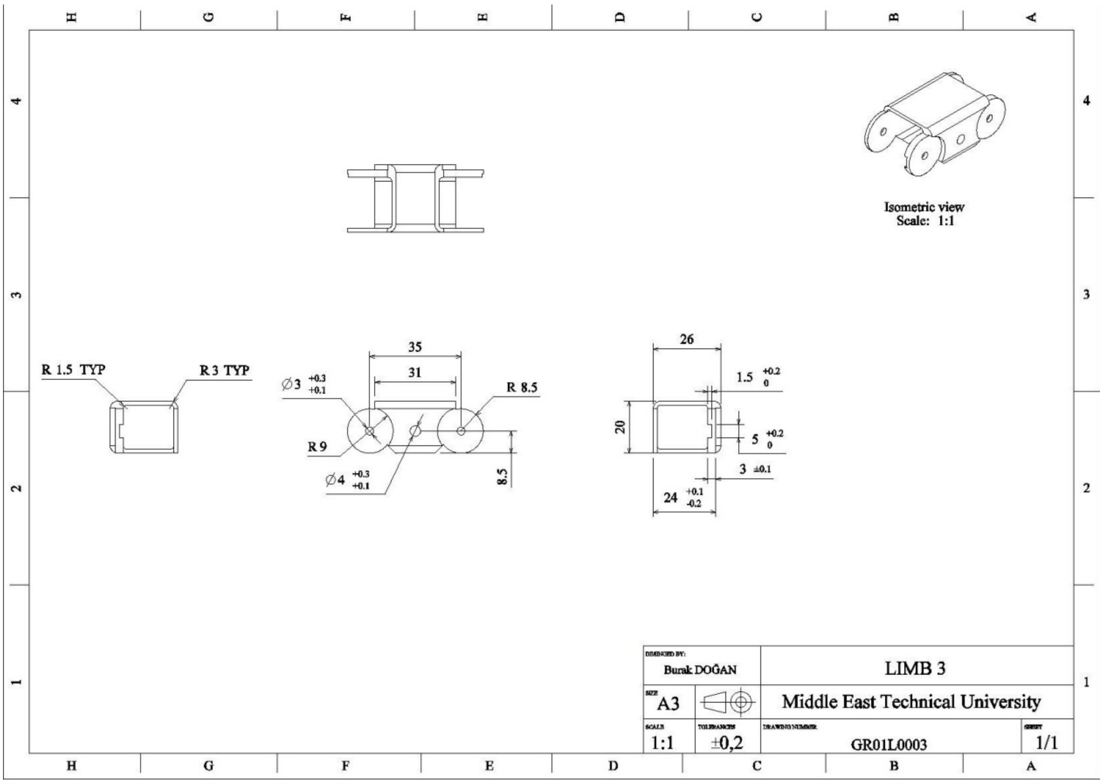


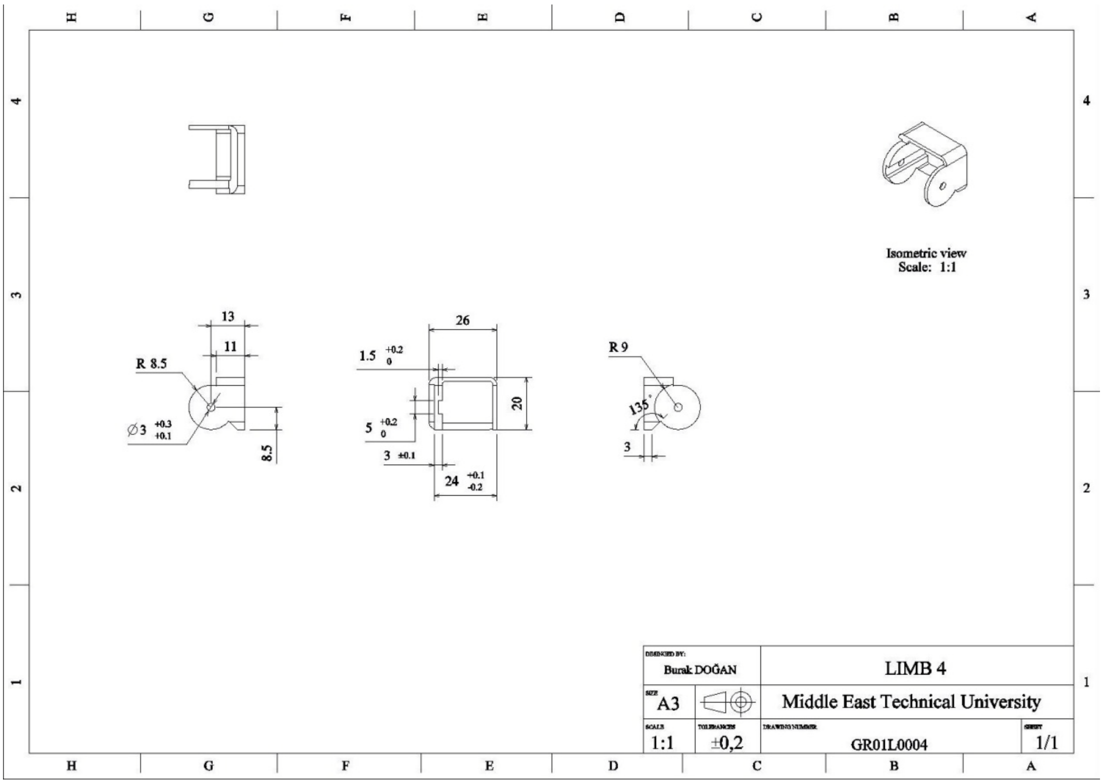
M 5
(2PLCS)
R 14
46
16
78
24.5
33
45
3
3
20
Isometric view
Scale: 1:1
69
39
9
∅ 4.2
(3PLCS)
11
DESIGNED BY:
Burak DOĞAN
ACTUATOR HOLDER 4
A3
Middle East Technical University
1:1
±0,2
GR01A0004
1/1

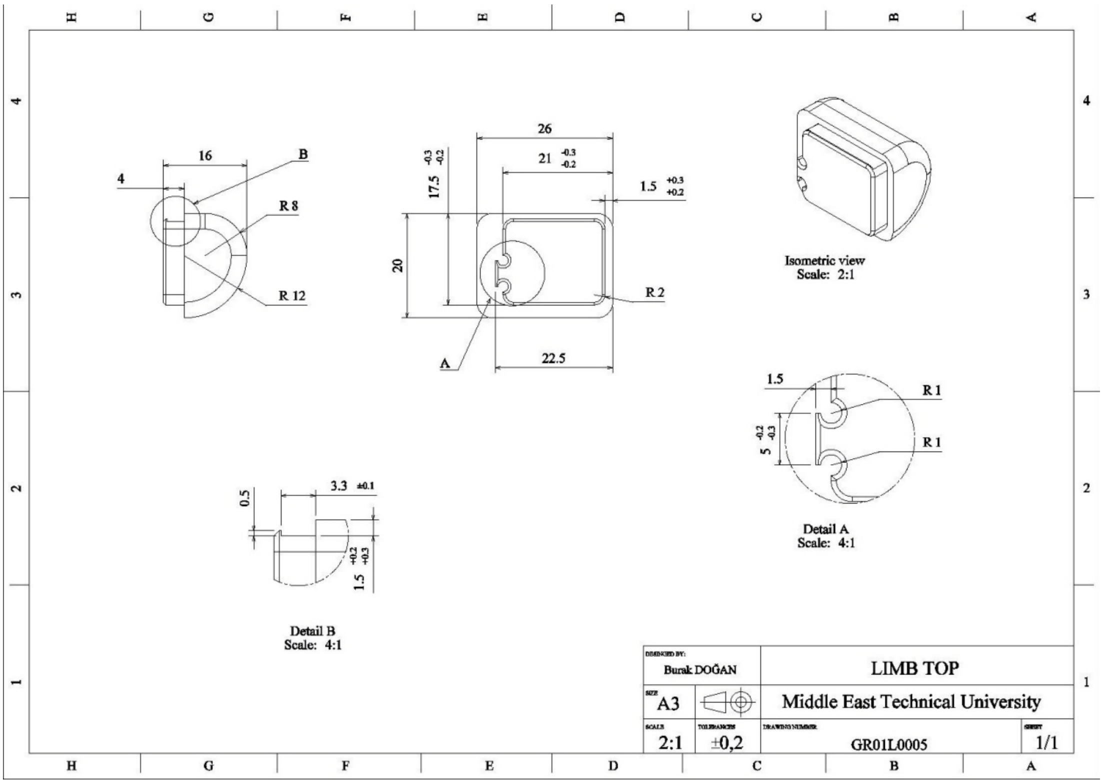


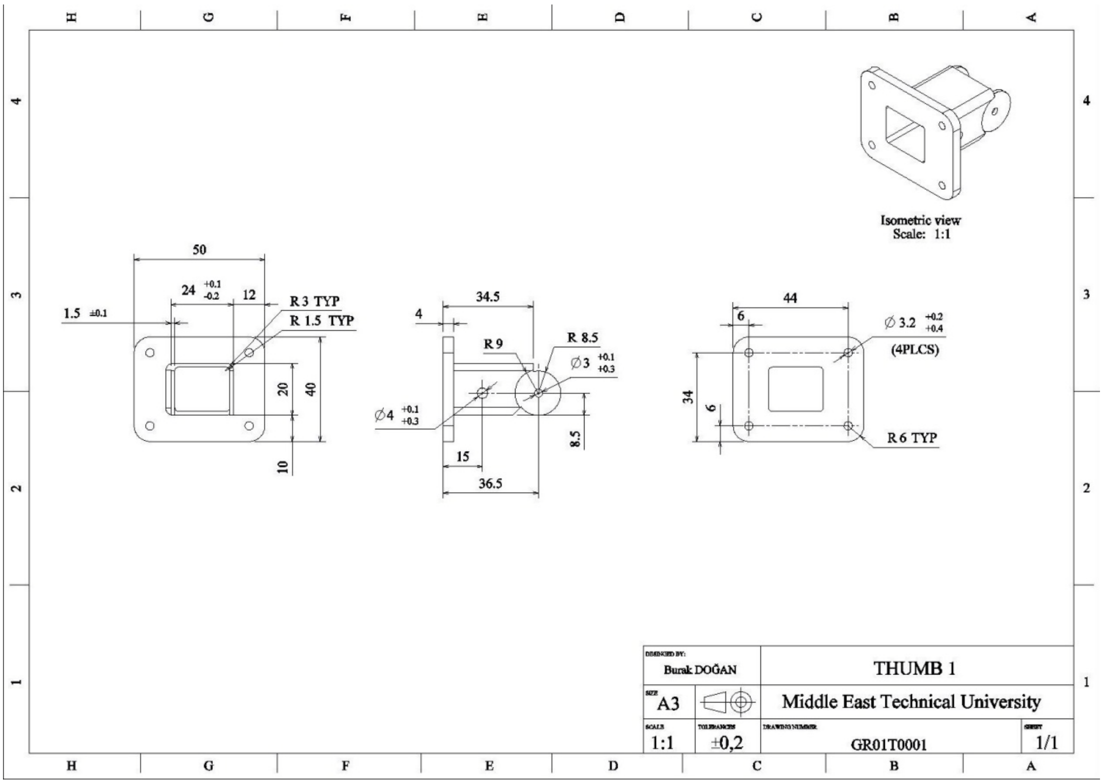
28.5
10
∅ 3.4 ±0.2
(2 PLCS)
13
Isometric view
Scale: 1:1
R 1.5 TYP
R 3 TYP
1.5 ±0.1
24 +0.1 -0.2
49.5
R 5
22
R 9
∅ 3 +0.3 +0.1
R 8.5
135°
20
10
41.5
51.5
8.5 ±0.1
26
1.5 ±0.1 TYP
3.5 +0.3 0
DESIGNED BY:
Burak DOĞAN
LIMB 1
A3
Middle East Technical University
1:1
±0,2
GR01L0001
1/1

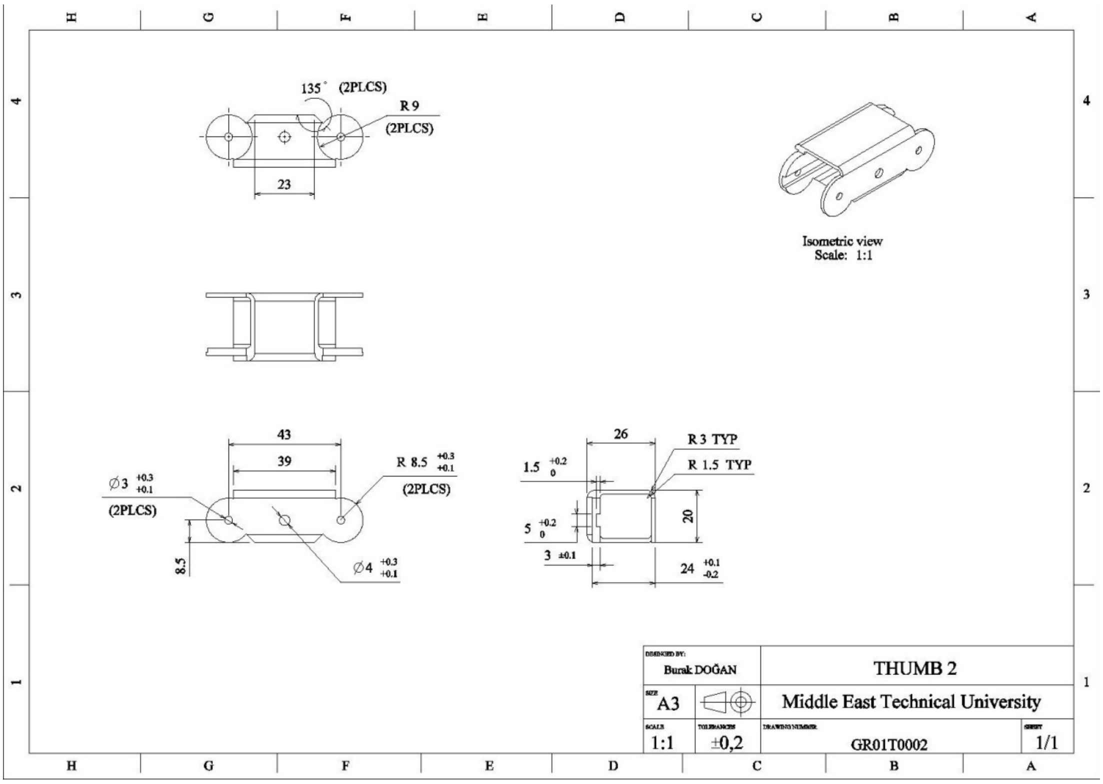

135° (2PLCS)
R 9
(2PLCS)
35
Isometric view
Scale: 1:1
55
51
R 8.5
(2PLCS)
∅3 +0.3 +0.1
(2PLCS)
8.5
∅4 +0.3 +0.1
26
R 3 TYP
R 1.5 TYP
1.5 +0.2 0
20
5 +0.2 0
3 ±0.1
24 +0.1 -0.2
Left view
Scale: 1:1
Burak DOĞAN
LIMB 2
A3
Middle East Technical University
1:1
±0,2
GR01L0002
1/1

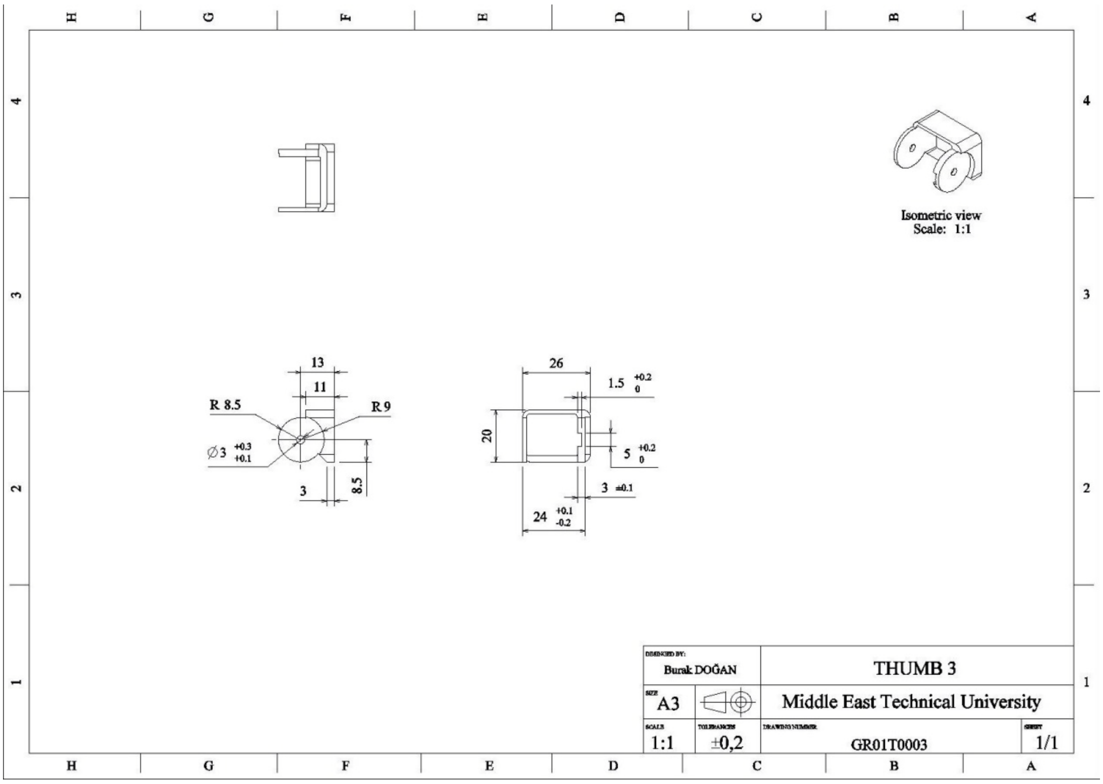

Isometric view
Scale: 1:1
R 1.5 TYP
R 3 TYP
35
31
∅3 +0.3 +0.1
R 8.5
R 9
∅4 +0.3 +0.1
8.5
26
1.5 +0.2 0
20
5 +0.2 0
3 ±0.1
24 +0.1 -0.2
Burak DOĞAN
LIMB 3
A3
Middle East Technical University
1:1
±0,2
GR01L0003
1/1

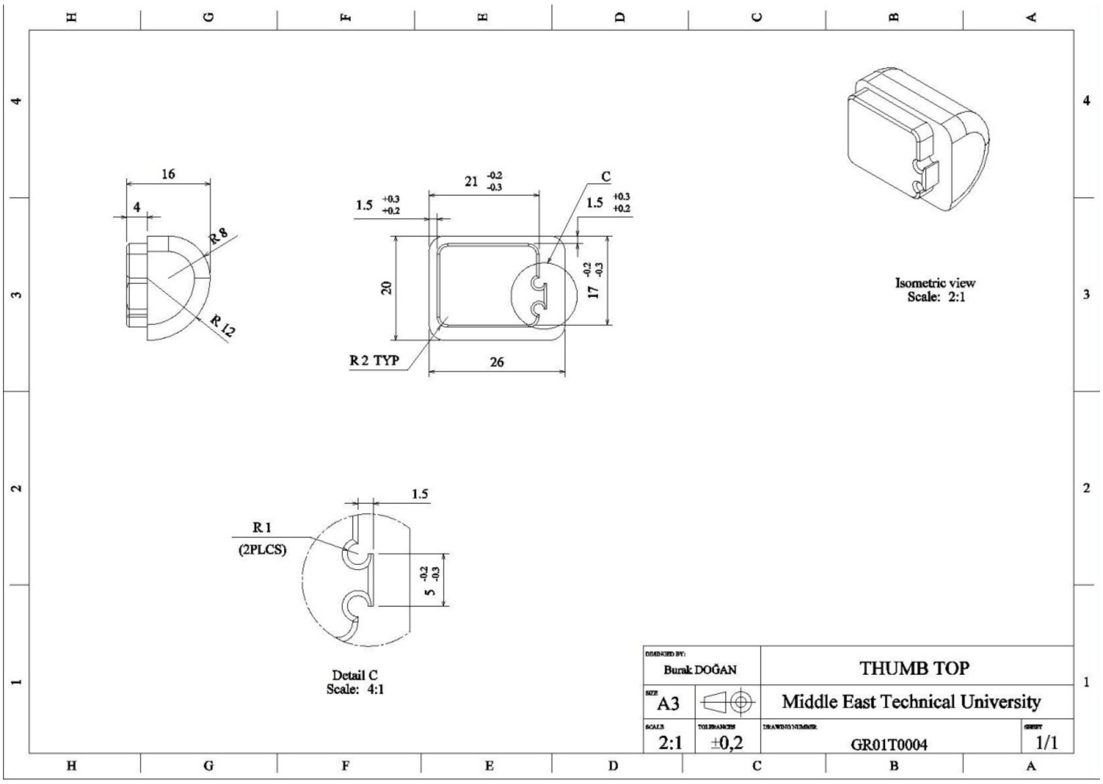

Isometric view
Scale: 1:1
Burak DOĞAN
LIMB 4
A3
Middle East Technical University
1:1
±0,2
GR01L0004
1/1

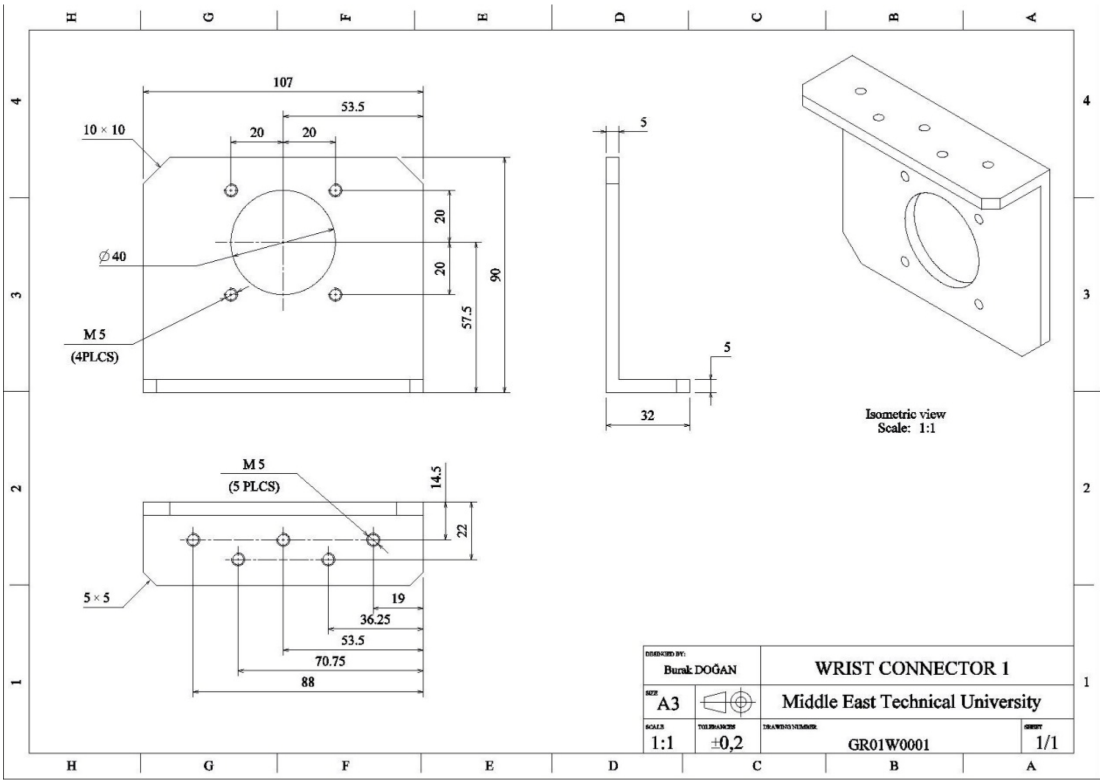

Isometric view
Scale: 2:1
Detail A
Scale: 4:1
Detail B
Scale: 4:1
Burak DOĞAN
LIMB TOP
A3
Middle East Technical University
2:1
±0,2
GR01L0005
1/1

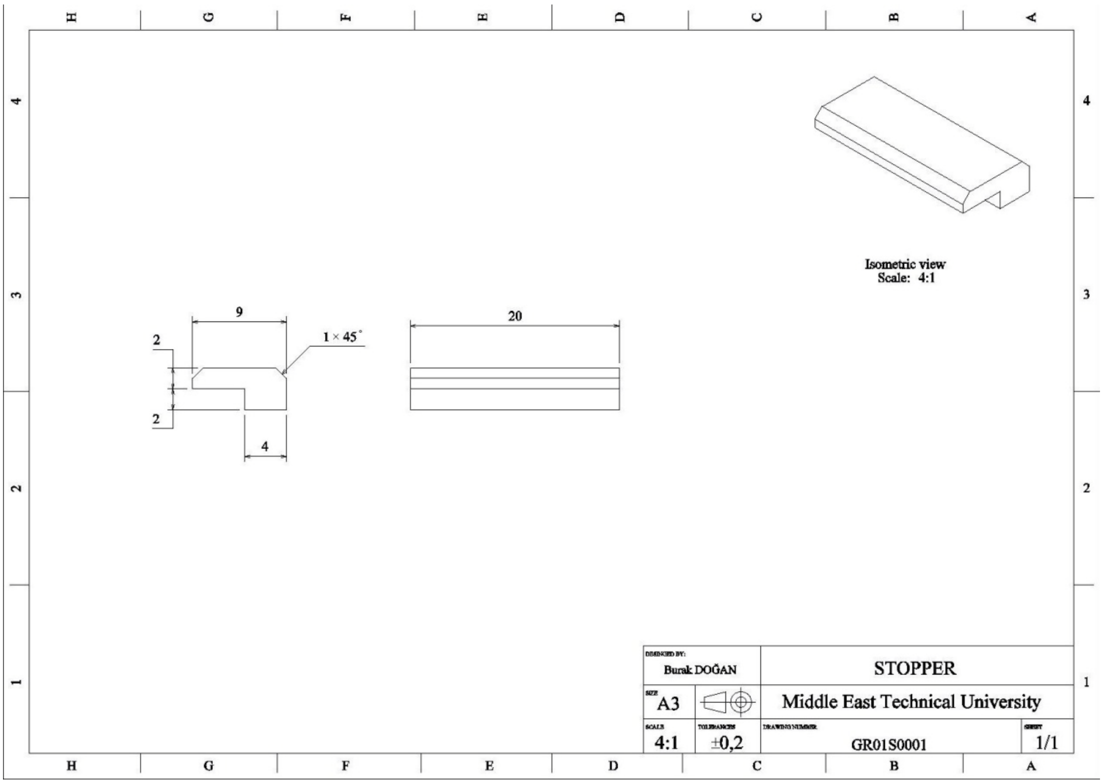

Isometric view
Scale: 1:1
Burak DOĞAN
THUMB 1
A3
Middle East Technical University
1:1
±0,2
GR01T0001
1/1

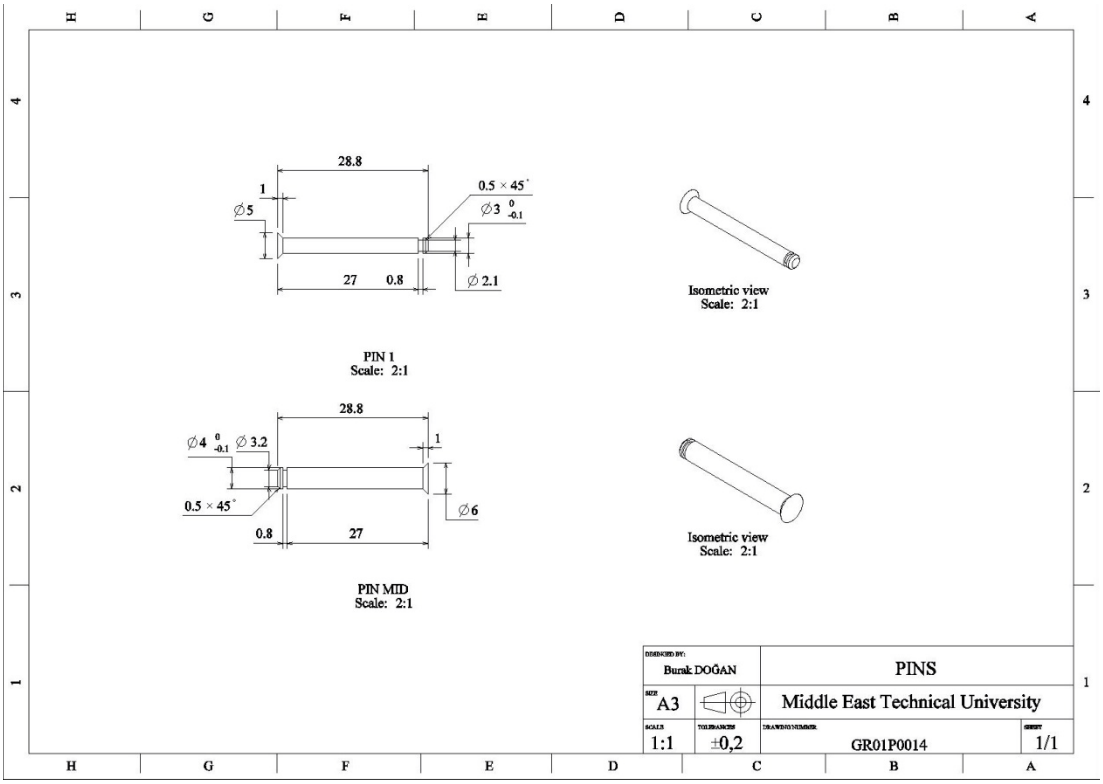

Isometric view
Scale: 1:1
Burak DOĞAN
THUMB 2
A3
Middle East Technical University
1:1
±0,2
GR01T0002
1/1

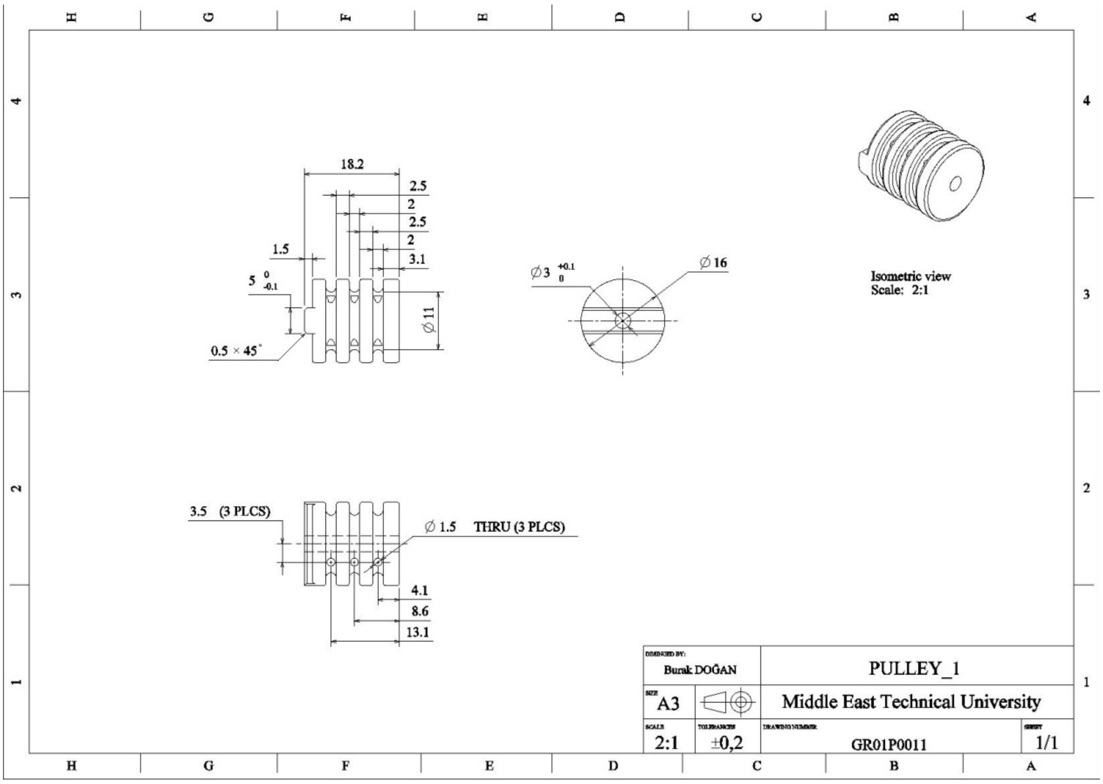

Isometric view
Scale: 1:1
13
11
R 8.5
R 9
∅3 +0.3 +0.1
3
8.5
26
1.5 +0.2 0
20
5 +0.2 0
3 ±0.1
24 +0.1 -0.2
Burak DOĞAN
THUMB 3
A3
Middle East Technical University
1:1
±0,2
GR01T0003
1/1

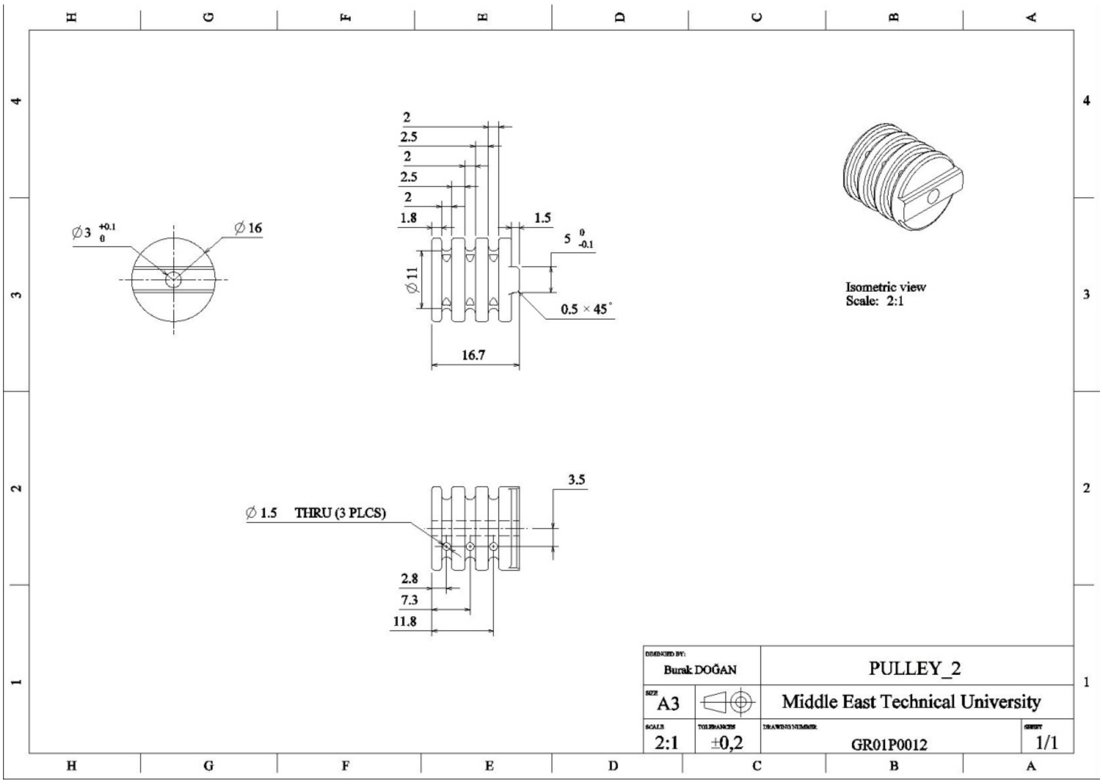

16
4
R 8
R 12
21 -0.2 -0.3
C
1.5 +0.3 +0.2
1.5 +0.3 +0.2
20
17 -0.2 -0.3
R 2 TYP
26
Isometric view
Scale: 2:1
1.5
R 1
(2PLCS)
5 -0.2 -0.3
Detail C
Scale: 4:1
Burak DOĞAN
THUMB TOP
A3
Middle East Technical University
2:1
±0,2
GR01T0004
1/1


107
53.5
10 × 10
20
20
⌀40
M 5
(4PLCS)
57.5
90
5
5
32
M 5
(5 PLCS)
14.5
22
5 × 5
19
36.25
53.5
70.75
88
Isometric view
Scale: 1:1
Burak DOĞAN
WRIST CONNECTOR 1
A3
Middle East Technical University
1:1
±0,2
GR01W0001
1/1

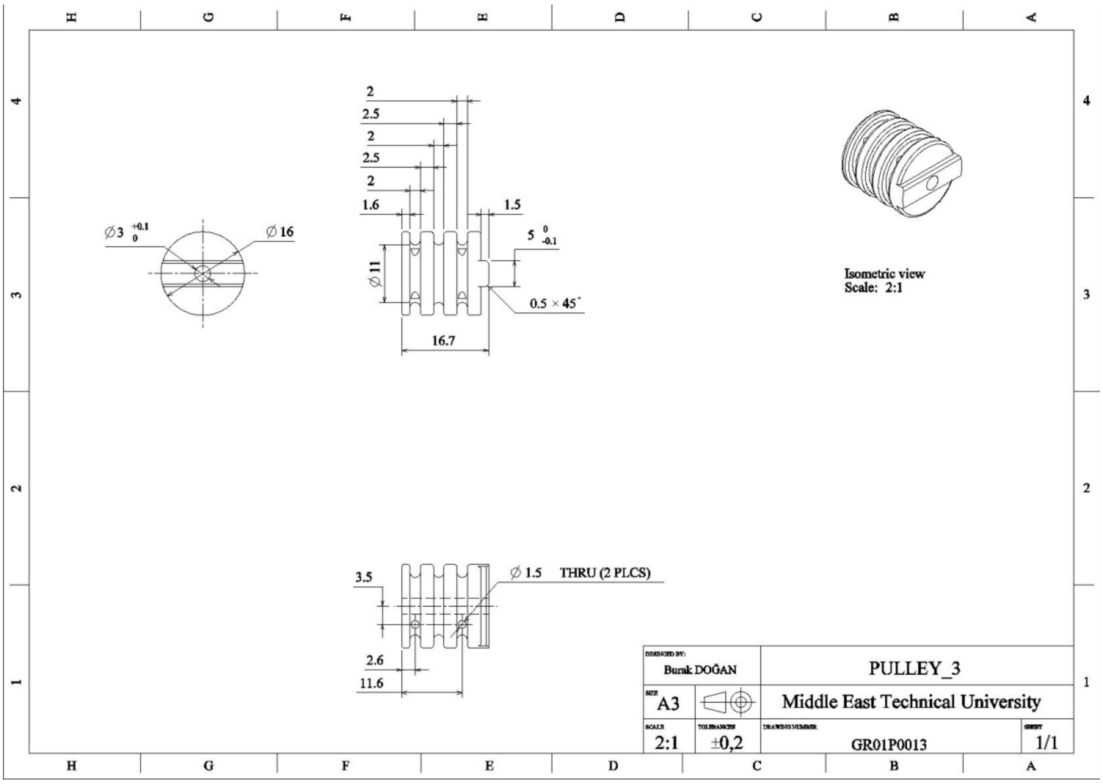

9
2
1 × 45°
2
4
20
Isometric view
Scale: 4:1
Burak DOĞAN
STOPPER
A3
Middle East Technical University
4:1
±0,2
GR01S0001
1/1


28.8
1
0.5 × 45°
∅5
∅3 0 -0.1
27
0.8
∅2.1
Isometric view
Scale: 2:1
PIN 1
Scale: 2:1
28.8
∅4 0 -0.1
∅3.2
1
0.5 × 45°
∅6
0.8
27
Isometric view
Scale: 2:1
PIN MID
Scale: 2:1
DESIGNED BY:
Burak DOĞAN
PINS
SIZE
A3
Middle East Technical University
SCALE
1:1
TOLERANCES
±0,2
DRAWING NUMBER
GR01P0014
SHEET
1/1

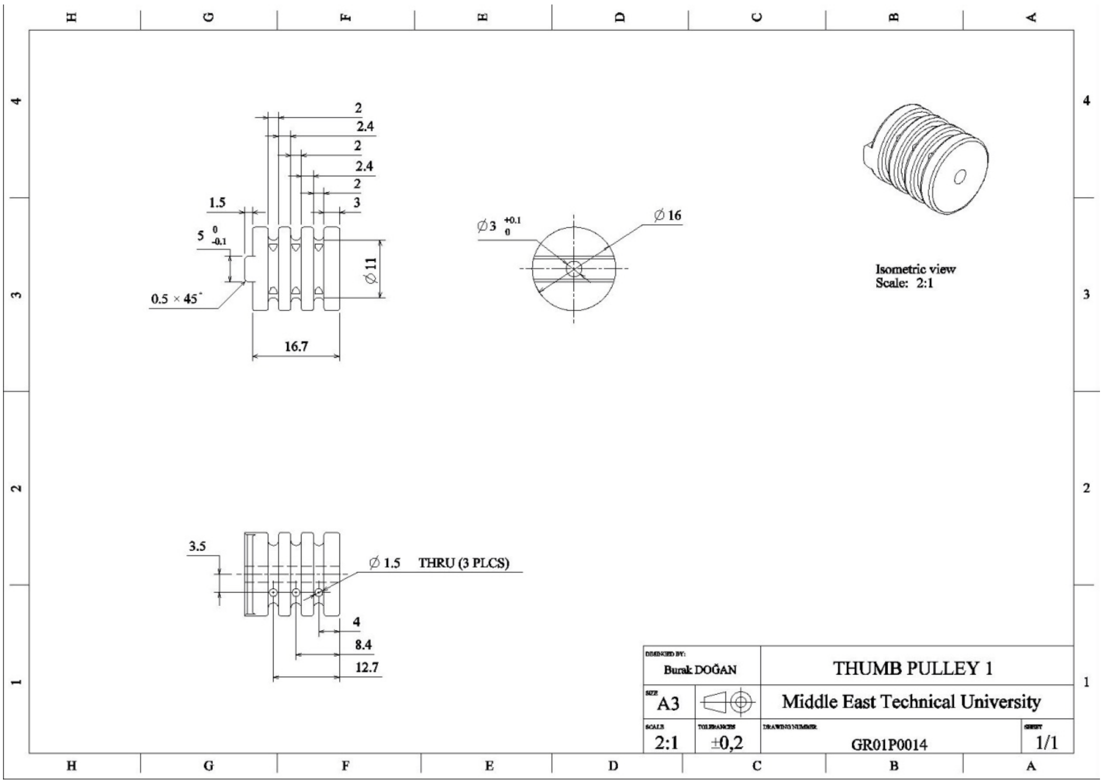

18.2
2.5
2
2.5
2
3.1
1.5
5 0 -0.1
∅11
0.5 × 45°
∅3 +0.1 0
∅16
Isometric view
Scale: 2:1
3.5 (3 PLCS)
∅1.5 THRU (3 PLCS)
4.1
8.6
13.1
DESIGNED BY:
Burak DOĞAN
PULLEY_1
SIZE
A3
Middle East Technical University
SCALE
2:1
TOLERANCES
±0,2
DRAWING NUMBER
GR01P0011
SHEET
1/1



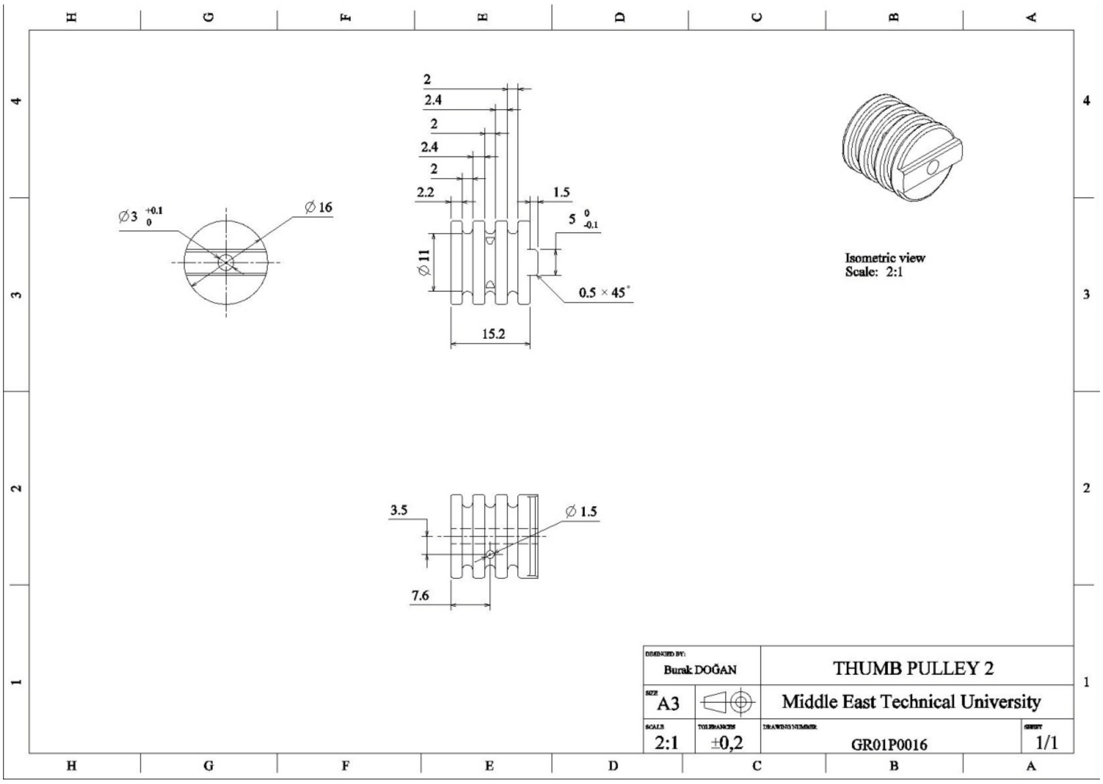
Isometric view
Scale: 2:1
Ø 1.5 THRU (3 PLCS)
Burak DOĞAN
PULLEY_2
A3
Middle East Technical University
2:1
±0,2
GR01P0012
1/1



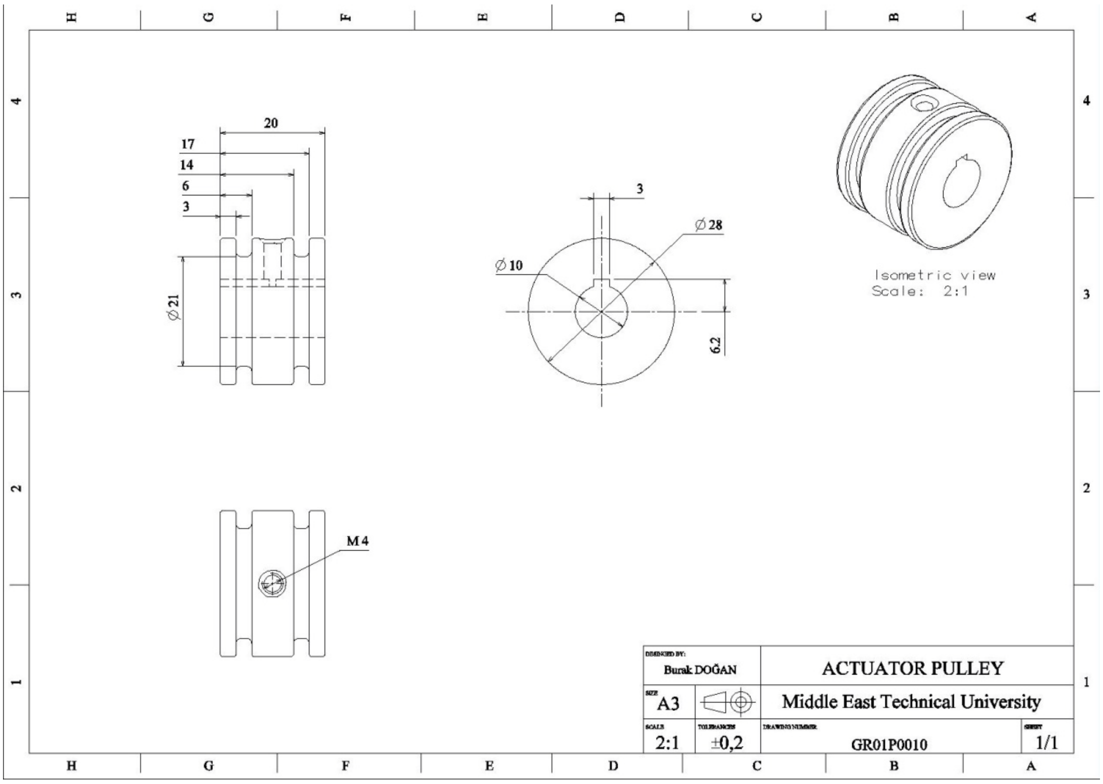
Isometric view
Scale: 2:1
Ø 1.5 THRU (2 PLCS)
Burak DOĞAN
PULLEY_3
A3
Middle East Technical University
2:1
±0,2
GR01P0013
1/1



2
2.4
2
2.4
2
3
1.5
5 0 -0.1
0.5 × 45°
Ø11
16.7
Ø3 +0.1 0
Ø16
Isometric view
Scale: 2:1
3.5
Ø 1.5 THRU (3 PLCS)
4
8.4
12.7
DESIGNED BY:
Burak DOĞAN
THUMB PULLEY 1
SIZE
A3
Middle East Technical University
SCALE
2:1
TOLERANCES
±0,2
DRAWING NUMBER
GR01P0014
SHEET
1/1



Ø3 +0.1 0
Ø16
2
2.4
2
2.4
2
2.2
1.5
5 0 -0.1
Ø11
0.5 × 45°
15.2
Isometric view
Scale: 2:1
3.5
Ø1.5
7.6
DESIGNED BY:
Burak DOĞAN
THUMB PULLEY 2
SIZE
A3
Middle East Technical University
SCALE
2:1
TOLERANCES
±0,2
DRAWING NUMBER
GR01P0016
SHEET
1/1



20
17
14
6
3
Ø21
3
Ø28
Ø10
6,2
Isometric view
Scale: 2:1
M4
DESIGNED BY:
Burak DOĞAN
ACTUATOR PULLEY
SIZE
A3
Middle East Technical University
SCALE
2:1
TOLERANCES
±0,2
DRAWING NUMBER
GR01P0010
SHEET
1/1

APPENDIX G

VELOCITY ANALYSIS FOR THE FOUR-FINGERED GRIPPER

G.1. Velocity Analysis for Fingers.

The position vector $\overrightarrow{r_f}$ of the finger tip point derived in section 5.6.3 is;

$$\overrightarrow{r_f} = [L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2) + L_3 \cos(\theta_1 + \theta_2 + \theta_3)]\vec{\imath} + [L_1 \sin\theta_1 + L_2 \sin(\theta_1 + \theta_2) + L_3 \sin(\theta_1 + \theta_2 + \theta_3)]\vec{\jmath} \quad (G.1)$$

If the derivative of the position vector is taken, the velocity components in x and y direction of the tip point is obtained as;

$$V_x = -L_1 \sin\theta_1\, \dot{\theta}_1 - L_2 \sin(\theta_1+\theta_2)\,(\dot{\theta}_1 + \dot{\theta}_2) - L_3 \sin(\theta_1+\theta_2+\theta_3)\,(\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3) \quad (G.2)$$

$$V_y = L_1 \cos\theta_1\, \dot{\theta}_1 + L_2 \cos(\theta_1+\theta_2)\,(\dot{\theta}_1 + \dot{\theta}_2) + L_3 \cos(\theta_1+\theta_2+\theta_3)\,(\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3) \quad (G.3)$$

For equations G.2 and G.3 following definitions are done for simplicity;

$$s_1 = \sin(\theta_1), \quad s_{12} = \sin(\theta_1+\theta_2), \quad s_{123} = \sin(\theta_1+\theta_2+\theta_3) \quad (G.4a)$$

$$c_1 = \cos(\theta_1), \quad c_{12} = \cos(\theta_1+\theta_2), \quad c_{123} = \cos(\theta_1+\theta_2+\theta_3) \quad (G.4b)$$

Using equations G.4, velocity vector for finger is written in matrix form as;

$$\begin{bmatrix} V_x \\ V_y \end{bmatrix} = \begin{bmatrix} -L_1 s_1 - L_2 s_{12} - L_3 s_{123} & -L_2 s_{12} - L_3 s_{123} & -L_3 s_{123} \\ L_1 c_1 + L_2 c_{12} + L_3 c_{123} & L_2 c_{12} + L_3 c_{123} & L_3 c_{123} \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \end{bmatrix} \quad (G.5)$$

After obtaining the velocity vector in matrix form, definitions for $\dot{\theta}_1$, $\dot{\theta}_2$ and $\dot{\theta}_3$ can be given as;

$$\dot{\theta}_1 = r_p v \quad (G.6a)$$

$$\dot{\theta}_2 = f(\dot{\theta}_1) \quad (G.6b)$$

$\dot{\theta}_3 = f(\dot{\theta}_2)$ (G.6c)

Here; r_p is the radius of pulley and v is the velocity of the rope connection the pulley at joint 1.

The equations obtained until now were general equations and applies for 3 degree of freedom finger. But, the developed gripper has one degree of freedom for each finger. This means all joints rotate together according to the rotation of first joint. As a result $\theta_1 = \theta_2 = \theta_3 = \theta$.

$$\begin{bmatrix} V_x \\ V_y \end{bmatrix} = r_p \begin{bmatrix} -L_1 \sin\theta - L_2 \sin 2\theta - L_3 \sin 3\theta - L_2 \sin 2\theta - L_3 \sin 3\theta - L_3 \sin 3\theta \\ L_1 \cos\theta + L_2 \cos 2\theta + L_3 \cos 3\theta + L_2 \cos 2\theta + L_3 \cos 3\theta - L_3 \cos 3\theta \end{bmatrix} v \quad \text{(G.7)}$$

$$\begin{bmatrix} V_x \\ V_y \end{bmatrix} = r_p \begin{bmatrix} -L_1 \sin\theta - 2L_2 \sin 2\theta - 3L_3 \sin 3\theta \\ L_1 \cos\theta + 2L_2 \cos 2\theta + 3L_3 \cos 3\theta \end{bmatrix} v \quad \text{(G.8)}$$

Using the numerical values of L_1 = 55mm, L_2=35mm, L_3=25 and r_p=6mm. Jacobian matrix for fingers is obtained as;

$$\begin{bmatrix} V_x \\ V_y \end{bmatrix} = 6 \begin{bmatrix} -55 \sin\theta - 70 \sin 2\theta - 75 \sin 3\theta \\ 55 \cos\theta + 70 \cos 2\theta + 75 \cos 3\theta \end{bmatrix} v \quad \text{(G.9)}$$

G.2. Velocity Analysis for Thumb.

The position vector for thumb obtainer in section 5.6.4 is;

$$\vec{r_t} = [L_1 \sin\theta_1 + L_2 \sin(\theta_1 + \theta_2)]\vec{\imath} - [L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2)]\vec{\jmath} \quad \text{(G.10)}$$

from the derivative of the position vector, the velocity components in x and y direction of the tip point are obtained as;

$$V_{tx} = L_1 \cos\theta_1 \dot{\theta}_1 + L_2 \cos(\theta_1+\theta_2)(\dot{\theta}_1 + \dot{\theta}_2) \quad \text{(G.11)}$$

$$V_{ty} = -L_1 \sin\theta_1 \dot{\theta}_1 - L_2 \sin(\theta_1+\theta_2)(\dot{\theta}_1 + \dot{\theta}_2) \quad \text{(G.12)}$$

Using definitions from equations G.4a and G.4b, velocity vector for thumb is written in matrix form as;

$$\begin{bmatrix} V_{tx} \\ V_{tz} \end{bmatrix} = \begin{bmatrix} L_1 c_1 + L_2 c_{12} & L_2 c_{12} \\ -L_1 s_1 - L_2 s_{12} & -L_2 s_{12} \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} \tag{G.13}$$

After obtaining the velocity vector in matrix form, definitions for $\dot{\theta}_1$ and $\dot{\theta}_2$ can be given as;

$$\dot{\theta}_1 = r_t v_t \tag{G.14a}$$

$$\dot{\theta}_2 = f(\dot{\theta}_1) \tag{G.14b}$$

Where r_t is the radius of thumb pulley and v_t is the velocity of rope connecting actuator of thumb to the first joint. Like for fingers rotation of all joints are equal coming from transmission system. $\theta_1 = \theta_2 = \theta$, then;

$$\begin{bmatrix} V_x \\ V_y \end{bmatrix} = r_t \begin{bmatrix} L_1 \cos\theta + 2L_2 \cos 2\theta \\ -L_1 \sin\theta - 2L_2 \sin 2\theta \end{bmatrix} v_t \tag{G.15}$$

From geometry, L_1=43mm, L_2=25mm and r_t=6mm. Then Jacobian matrix becomes;

$$\begin{bmatrix} V_x \\ V_y \end{bmatrix} = 6 \begin{bmatrix} 43 \cos\theta + 50 \cos 2\theta \\ -43 \sin\theta - 50 \sin 2\theta \end{bmatrix} v_t \tag{G.16}$$

APPENDIX H

ELECTRONIC CIRCUIT DIAGRAMS AND SOFTWARE CODES

H.1. Electronic Circuit Diagrams.

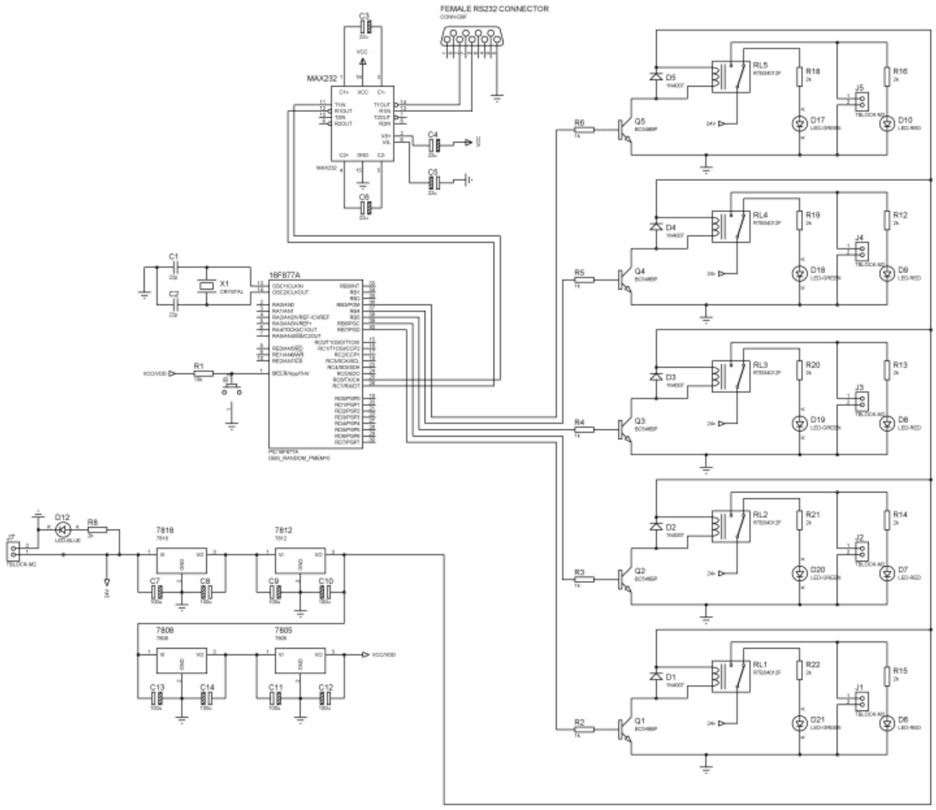


Figure H.1: General View of the Circuit Diagram for the Motion Control Card.

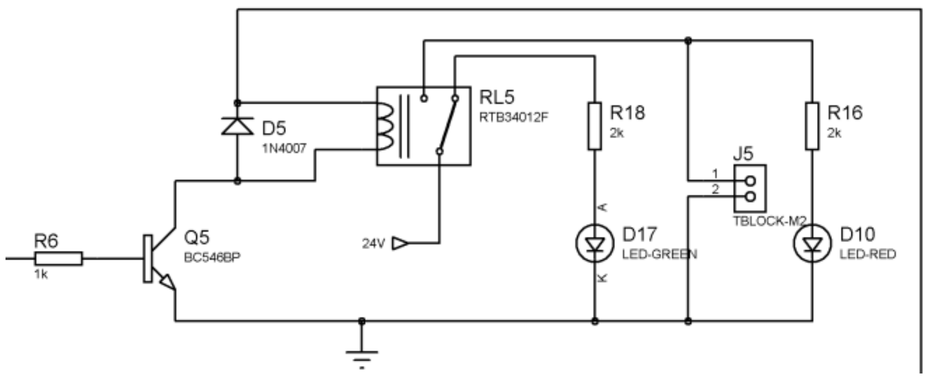


Figure H.2: Relay Circuit.

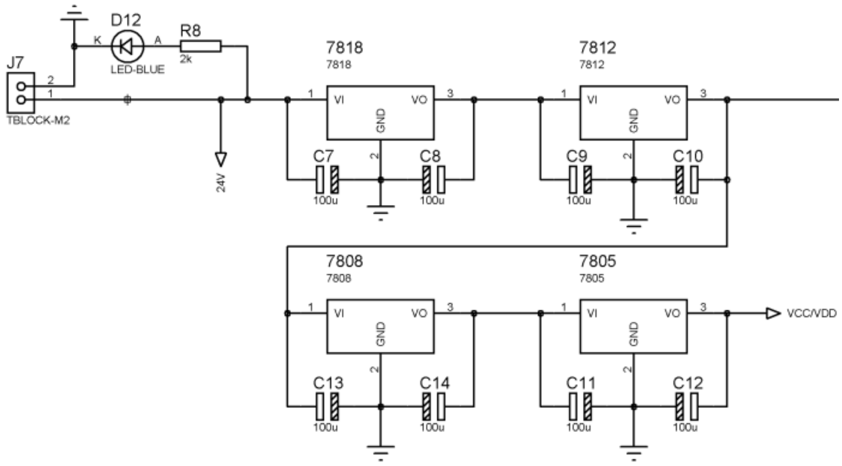


Figure H.3: Power Supply Circuit

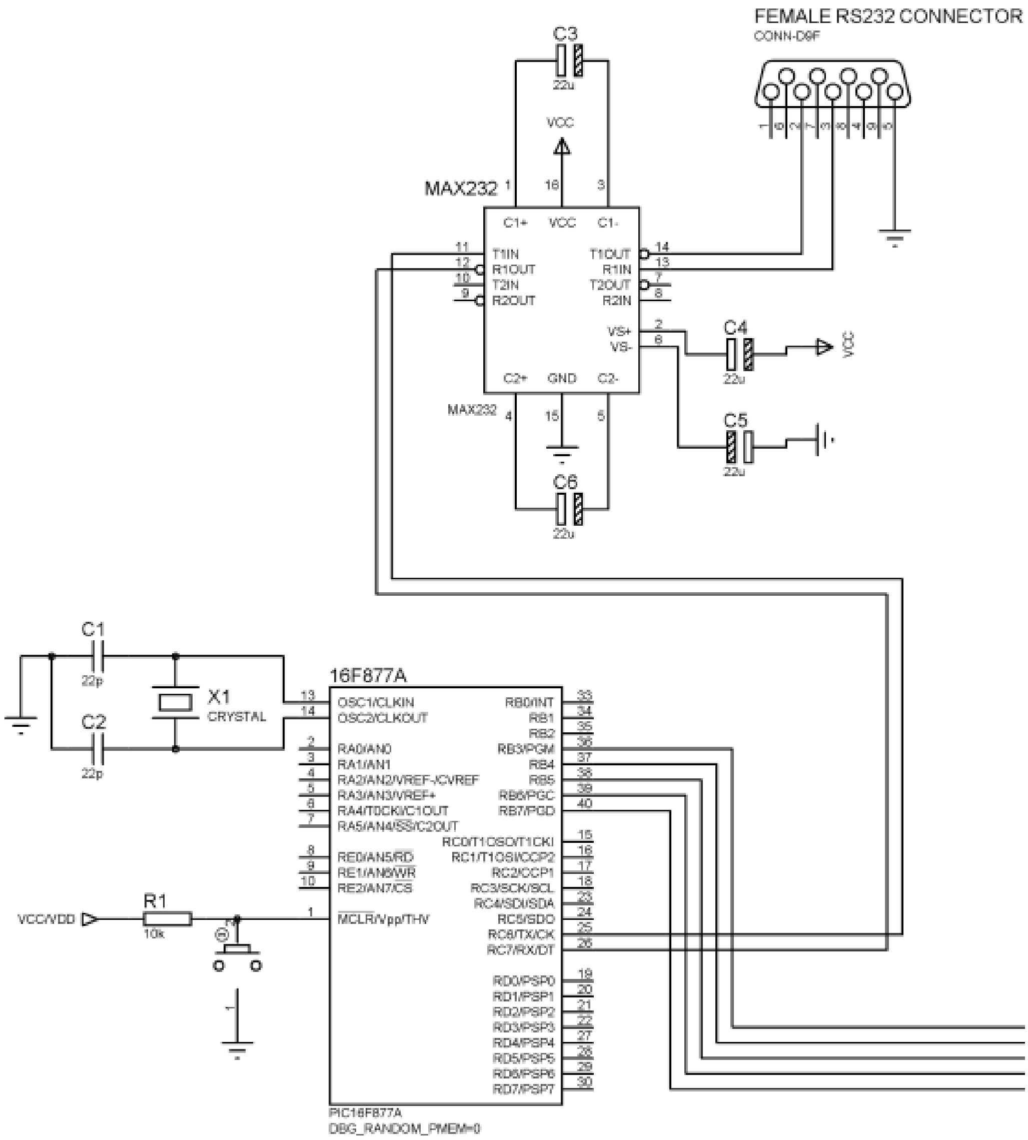


Figure H.4: Microcontroller and Serial Interface Circuit.

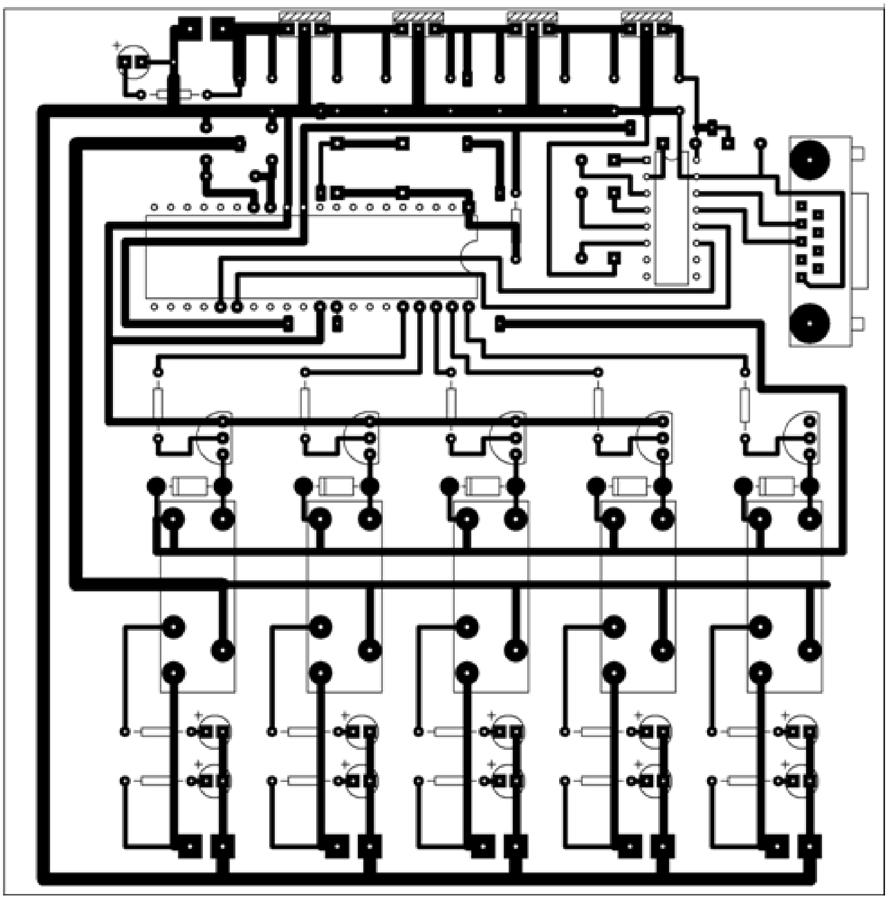


Figure H.5: PCB Layout for the Motion Control Card.

H.2. Codes for PIC Microcontroller.

Codes for PIC microcontroller are developed by using C programming language and compiled as a hex file.

```
#include <16f877A.h>
#include <stdlib.h>
#fuses
XT,NOWDT,NOPROTECT,NOBROWNOUT,NOLVP,NOPUT,NOWRT,NODEB
UG,NOCPD
#use delay (clock=4000000)
#use rs232 (baud=9600, xmit=pin_C6, rcv=pin_C7, parity=N, stop=1)
void main ( )
{
  setup_psp(PSP_DISABLED);              // PSP port disabled
  setup_spi(SPI_SS_DISABLED);           // SPI port disabled
  setup_timer_1(T1_DISABLED);           // T1 timer disabled
  setup_timer_2(T2_DISABLED,0,1);       // T2 timer disabled
  setup_adc_ports(NO_ANALOGS);          // No ANALOG inputs
  setup_adc(ADC_OFF);                   // ADC port disabled
```

```
setup_CCP1(CCP_OFF);                    // CCP1 port disabled
setup_CCP2(CCP_OFF);                    // CCP2 port disabled
while (1) {
  if (getchar()== '1')                  // Finger 1 Control
  {
    output_high(pin_b7);                // Activate Finger 1
  }
  else if (getchar()== '2')             // Finger 2 Control
  {
    output_high(pin_b6);                // Activate Finger 2
  }
  else if (getchar() == '3')            // Finger 3 Control
  {
    output_high(pin_b5);                // Activate Finger 3
  }
  else if (getchar() == '4')            // Finger 4 Control
  {
    output_high(pin_b4);                // Activate Finger 4
  }
  else if (getchar() == '5')            // Full Gripping
  {
    output_high(pin_b7);                // Activate Finger 1,2,3
    output_high(pin_b6);
    output_high(pin_b5);
  }
  else if (getchar() == '6')            // Precision Gripping
  {
   output_B(0b01000000);                // Activate Finger 2
    delay_ms(1000);
    output_B(0b01010000);               // Activate Finger 2,4
  }
  else if (getchar()== '7')             // Deactivation
  {
    output_low(pin_b7);                 // Deactivate Finger 1,2,3 and Thumb
    output_low(pin_b6);
    output_low(pin_b5);
    output_low(pin_b4);
  }
  else if (getchar()== '8')             // Two Fingered Gripper Control
  {
    output_high(pin_b3);                // Activate Gripper
  }
  else if (getchar()== '9')             // Serial Port connection Control
  {
    printf("ok");                       // Transfer Text from RS232.
    output_B(0b00000000);               // Deactivate all outputs
  }
  else if (getchar()== 'a')             // Finger 1 Control
```

```
    {
      output_low(pin_b7);                    // Deactivate Finger 1
    }
    else if (getchar()== 'b')                // Finger 2 Control
    {
      output_low(pin_b6);                    // Deactivate Finger 2
    }
    else if (getchar()== 'c')                // Finger 3 Control
    {
      output_low(pin_b5);                    // Deactivate Finger 3
    }
    else if (getchar()== 'd')                // Finger 4 Control
    {
      output_low(pin_b4);                    // Deactivate Finger 4
    }
    else if (getchar()== 'e')                // 2 Fingered Gripper Control
    {
      output_low(pin_b3);                    // Deactivate Gripper
    }
  }
  }
```

H.3. Software Codes for the Two Fingered Gripper.

For the computer control of the two fingered gripper, software is developed using Microsoft Visual Basic 6.0.

Main Program:

```
Private Sub Command1_Click()

   Dim j As String
   Dim message As String
   If Option1.Value = False And Option2.Value = False And Option3.Value = False
And Option4.Value = False Then
      message = MsgBox("Please Select Communication Port", vbOKOnly +
vbExclamation + vbDefaultButton1, "Serial Port Selection")
      GoTo 10
   End If
   If MSComm1.PortOpen = False Then MSComm1.PortOpen = True
   j = 8
   For i = 1 To j
      MSComm1.Output = j
   Next
   Text1.Text = "Gripper is Active"
   MSComm1.PortOpen = False
```

```
10 End Sub

Private Sub Command2_Click()

   Dim j As String
   Dim message As String
   If Option1.Value = False And Option2.Value = False And Option3.Value = False
And Option4.Value = False Then
      message = MsgBox("Please Select Communication Port", vbOKOnly +
vbExclamation + vbDefaultButton1, "Serial Port Selection")
      GoTo 20
   End If
   If MSComm1.PortOpen = False Then MSComm1.PortOpen = True
   j = "e"
   For i = 1 To 14
      MSComm1.Output = j
   Next
   Text1.Text = "Gripper is Released"
   MSComm1.PortOpen = False
20 End Sub

Private Sub Command3_Click()

   Dim j As String
   Dim question
   question = MsgBox("Gripping will be Cancelled", vbOKCancel + vbCritical +
vbDefaultButton2, "Exit Program")
   If question = vbOK Then
   If Option1.Value = False And Option2.Value = False And Option3.Value = False
And Option4.Value = False Then
      GoTo 30
   End If
   If MSComm1.PortOpen = False Then MSComm1.PortOpen = True
      j = "e"
      For i = 1 To 14
         MSComm1.Output = j
      Next
      Sleep (500)
30 End
   Else
      Cancel = True
   End If
End Sub

Private Sub Form_Load()

   Dim X As String
   If MSComm1.PortOpen = True Then MSComm1.PortOpen = False
```

```
MSComm1.Settings = "9600,N,8,1"
MSComm1.RThreshold = 1
MSComm1.OutBufferSize = 1
Timer1.Interval = 1
Timer1.Enabled = False
Label2.Caption = "Please Select Communication Port"
Text1.BackColor = QBColor(4)
Text1.ForeColor = QBColor(15)
Text1.Text = "Device Not Ready"

Dim i As Integer
   cboComm.Clear
   For i = 1 To 16
      If COMAvailable(i) Then
      cboComm.AddItem i
      List1.AddItem ("COM " + Str(i))
      End If
   Next

cboComm.ListIndex = 0
   On Error Resume Next
   If cboComm.Text = "1" Then
      Option1.Enabled = True
   ElseIf cboComm.Text = "2" Then
      Option2.Enabled = True
   ElseIf cboComm.Text = "3" Then
     Option3.Enabled = True
   ElseIf cboComm.Text = "4" Then
      Option4.Enabled = True
   End If

cboComm.ListIndex = 1
   On Error Resume Next
   If cboComm.Text = "1" Then
      Option1.Enabled = True
   ElseIf cboComm.Text = "2" Then
      Option2.Enabled = True
   ElseIf cboComm.Text = "3" Then
      Option3.Enabled = True
   ElseIf cboComm.Text = "4" Then
      Option4.Enabled = True
   End If

cboComm.ListIndex = 2
   On Error Resume Next
   If cboComm.Text = "1" Then
      Option1.Enabled = True
   ElseIf cboComm.Text = "2" Then
```

```
      Option2.Enabled = True
    ElseIf cboComm.Text = "3" Then
      Option3.Enabled = True
    ElseIf cboComm.Text = "4" Then
      Option4.Enabled = True
    End If

  cboComm.ListIndex = 3
    On Error Resume Next
    If cboComm.Text = "1" Then
      Option1.Enabled = True
    ElseIf cboComm.Text = "2" Then
      Option2.Enabled = True
    ElseIf cboComm.Text = "3" Then
      Option3.Enabled = True
    ElseIf cboComm.Text = "4" Then
      Option4.Enabled = True
    End If
End Sub

Private Sub Option1_MouseDown(Button As Integer, Shift As Integer, X As Single,
Y As Single)

  Dim j As String
  If MSComm1.PortOpen = True Then MSComm1.PortOpen = False
  MSComm1.CommPort = 1
  MSComm1.PortOpen = True
  j = 9
  For i = 1 To j
    MSComm1.Output = j
  Next
  Text3.Text = ""
  Timer1.Enabled = True
End Sub

Private Sub Option1_Click()

  Dim Control As String
  Control = Text3.Text
  If Control = "ok" Then
    Label2.ForeColor = QBColor(2)
    Label2.Caption = "Motion Control Card is Connected"
    Text1.BackColor = QBColor(2)
    Text1.ForeColor = QBColor(15)
    Text1.Text = "Gripper is Ready"
    Option1.Value = True
    Timer1.Enabled = False
    MSComm1.PortOpen = False
```

```
   Else
      Label2.ForeColor = QBColor(4)
      Label2.Caption = "Motion Control Card is not Connected. Connect the Control
Card to Serial Port 1"
      Text1.BackColor = QBColor(4)
      Text1.ForeColor = QBColor(15)
      Text1.Text = "Device Not Ready"
      Option1.Value = False
      Timer1.Enabled = False
      MSComm1.PortOpen = False
   End If
End Sub

Private Sub Option2_MouseDown(Button As Integer, Shift As Integer, X As Single,
Y As Single)

   Dim j As String
   If MSComm1.PortOpen = True Then MSComm1.PortOpen = False
   MSComm1.CommPort = 2
   MSComm1.PortOpen = True
   j = 9
   For i = 1 To j
      MSComm1.Output = j
   Next
   Text3.Text = ""
   Timer1.Enabled = True
End Sub

Private Sub Option2_Click()

   Dim Control As String
   Control = Text3.Text
   If Control = "ok" Then
      Label2.ForeColor = QBColor(2)
      Label2.Caption = "Motion Control Card is Connected"
      Text1.BackColor = QBColor(2)
      Text1.ForeColor = QBColor(15)
      Text1.Text = "Gripper is Ready"
      Option2.Value = True
      Timer1.Enabled = False
      MSComm1.PortOpen = False
   Else
      Label2.ForeColor = QBColor(4)
      Label2.Caption = "Motion Control Card is not Connected. Connect the Control
Card to Serial Port 2"
      Text1.BackColor = QBColor(4)
      Text1.ForeColor = QBColor(15)
      Text1.Text = "Device Not Ready"
```

```
      Option2.Value = False
      Timer1.Enabled = False
      MSComm1.PortOpen = False
   End If
End Sub

Private Sub Option3_MouseDown(Button As Integer, Shift As Integer, X As Single,
Y As Single)

   Dim j As String
   If MSComm1.PortOpen = True Then MSComm1.PortOpen = False
   MSComm1.CommPort = 3
   MSComm1.PortOpen = True
   j = 9
   For i = 1 To j
      MSComm1.Output = j
   Next
   Text3.Text = ""
   Timer1.Enabled = True
End Sub

Private Sub Option3_Click()

   Dim Control As String
   Control = Text3.Text
   If Control = "ok" Then
      Label2.ForeColor = QBColor(2)
      Label2.Caption = "Motion Control Card is Connected"
      Text1.BackColor = QBColor(2)
      Text1.ForeColor = QBColor(15)
      Text1.Text = "Gripper is Ready"
      Option3.Value = True
      Timer1.Enabled = False
      MSComm1.PortOpen = False
   Else
      Label2.ForeColor = QBColor(4)
      Label2.Caption = "Motion Control Card is not Connected. Connect the Control
Card to Serial Port 3"
      Text1.BackColor = QBColor(4)
      Text1.ForeColor = QBColor(15)
      Text1.Text = "Device Not Ready"
      Option3.Value = False
      Timer1.Enabled = False
      MSComm1.PortOpen = False
   End If
End Sub
```

```
Private Sub Option4_MouseDown(Button As Integer, Shift As Integer, X As Single,
Y As Single)

   Dim j As String
   If MSComm1.PortOpen = True Then MSComm1.PortOpen = False
   MSComm1.CommPort = 4
   MSComm1.PortOpen = True
   j = 9
   For i = 1 To j
      MSComm1.Output = j
   Next
   Text3.Text = ""
   Timer1.Enabled = True
End Sub

Private Sub Option4_Click()
   Dim Control As String
   Control = Text3.Text
   If Control = "ok" Then
      Label2.ForeColor = QBColor(2)
      Label2.Caption = "Motion Control Card is Connected"
      Text1.BackColor = QBColor(2)
      Text1.ForeColor = QBColor(15)
      Text1.Text = "Gripper is Ready"
      Option4.Value = True
      Timer1.Enabled = False
      MSComm1.PortOpen = False
   Else
      Label2.ForeColor = QBColor(4)
      Label2.Caption = "Motion Control Card is not Connected. Connect the Control
Card to Serial Port 4"
      Text1.BackColor = QBColor(4)
      Text1.ForeColor = QBColor(15)
      Text1.Text = "Device Not Ready"
      Option4.Value = False
      Timer1.Enabled = False
      MSComm1.PortOpen = False
   End If
End Sub

Private Sub ListComPorts()

   Dim i As Integer
   cboComm.Clear
   For i = 1 To 16
      If COMAvailable(i) Then
         cboComm.AddItem i
      End If
```

```
    Next
    cboComm.ListIndex = 0
End Sub

Private Sub Timer1_Timer()
    Text3 = Text3 & MSComm1.Input
End Sub
```

"Sleep" Subfunction:

```
Public Declare Sub Sleep Lib "kernel32" (ByVal dwMilliseconds As Long)
```

"COMAvailable" Subfunction:

```
'// API Declarations
Public Declare Function CreateFile Lib "kernel32" Alias "CreateFileA" (ByVal
lpFileName As String, ByVal dwDesiredAccess As Long, ByVal dwShareMode As
Long, lpSecurityAttributes As SECURITY_ATTRIBUTES, ByVal
dwCreationDisposition As Long, ByVal dwFlagsAndAttributes As Long, ByVal
hTemplateFile As Long) As Long
Public Declare Function CloseHandle Lib "kernel32" (ByVal hObject As Long) As
Long

'// API Structures
Public Type SECURITY_ATTRIBUTES
    nLength As Long
    lpSecurityDescriptor As Long
    bInheritHandle As Long
End Type

'// API constants
Public Const FILE_SHARE_READ = &H1
Public Const FILE_SHARE_WRITE = &H2
Public Const OPEN_EXISTING = 3
Public Const FILE_ATTRIBUTE_NORMAL = &H80

'// Return TRUE if the COM exists, FALSE if the COM does not exist
Public Function COMAvailable(COMNum As Integer) As Boolean
    Dim hCOM As Long
    Dim ret As Long
    Dim sec As SECURITY_ATTRIBUTES

    '// try to open the COM port
    hCOM = CreateFile("\\.\COM" & COMNum & "", 0, FILE_SHARE_READ + _
        FILE_SHARE_WRITE, sec, OPEN_EXISTING,
FILE_ATTRIBUTE_NORMAL, 0)
    If hCOM = -1 Then
```

```
      COMAvailable = False
   Else
      COMAvailable = True
      '// close the COM port
      ret = CloseHandle(hCOM)
   End If
End Function
```

H.4. Software Codes for the Four Fingered Gripper.

For the computer control of the Four fingered gripper, software is developed using Microsoft Visual Basic 6.0.

Main Program:

```
Private Sub Command1_Click()

   Dim j As String
   Dim message As String
   If Option1.Value = False And Option2.Value = False And Option3.Value = False
And Option4.Value = False Then
      message = MsgBox("Please Select Communication Port", vbOKOnly +
vbExclamation + vbDefaultButton1, "Serial Port Selection")
      GoTo 10
   End If
   If MSComm1.PortOpen = False Then MSComm1.PortOpen = True
   j = 1
   For i = 1 To j
      MSComm1.Output = j
   Next
   Text1.Text = "Finger 1 is Active"
   MSComm1.PortOpen = False
10 End Sub

Private Sub Command2_Click()

   Dim j As String
   Dim message As String
   If Option1.Value = False And Option2.Value = False And Option3.Value = False
And Option4.Value = False Then
      message = MsgBox("Please Select Communication Port", vbOKOnly +
vbExclamation + vbDefaultButton1, "Serial Port Selection")
      GoTo 20
   End If
   If MSComm1.PortOpen = False Then MSComm1.PortOpen = True
   j = 2
```

```
   For i = 1 To j
      MSComm1.Output = j
   Next
   Text1.Text = "Finger 2 is Active"
   MSComm1.PortOpen = False
20 End Sub

Private Sub Command3_Click()

   Dim j As String
   Dim message As String
   If Option1.Value = False And Option2.Value = False And Option3.Value = False
And Option4.Value = False Then
      message = MsgBox("Please Select Communication Port", vbOKOnly +
vbExclamation + vbDefaultButton1, "Serial Port Selection")
      GoTo 30
   End If
   If MSComm1.PortOpen = False Then MSComm1.PortOpen = True
   j = 3
   For i = 1 To j
      MSComm1.Output = j
   Next
   Text1.Text = "Finger 3 is Active"
   MSComm1.PortOpen = False
30 End Sub

Private Sub Command4_Click()

   Dim j As String
   Dim message As String
   If Option1.Value = False And Option2.Value = False And Option3.Value = False
And Option4.Value = False Then
      message = MsgBox("Please Select Communication Port", vbOKOnly +
vbExclamation + vbDefaultButton1, "Serial Port Selection")
      GoTo 40
   End If
   If MSComm1.PortOpen = False Then MSComm1.PortOpen = True
   j = 4
   For i = 1 To j
      MSComm1.Output = j
   Next
   Text1.Text = "Thumb is Active"
   MSComm1.PortOpen = False
40 End Sub

Private Sub Command5_Click()

   Dim j As String
```

```
    Dim message As String
    Dim a As String
    If Option1.Value = False And Option2.Value = False And Option3.Value = False
And Option4.Value = False Then
        message = MsgBox("Please Select Communication Port", vbOKOnly +
vbExclamation + vbDefaultButton1, "Serial Port Selection")
        GoTo 50
    End If
    If MSComm1.PortOpen = False Then MSComm1.PortOpen = True
    j = "a"
    For i = 1 To 10
        MSComm1.Output = j
    Next
    Text1.Text = "Finger 1 Released"
    MSComm1.PortOpen = False
50 End Sub



Private Sub Command6_Click()

    Dim j As String
    Dim message As String
    If Option1.Value = False And Option2.Value = False And Option3.Value = False
And Option4.Value = False Then
        message = MsgBox("Please Select Communication Port", vbOKOnly +
vbExclamation + vbDefaultButton1, "Serial Port Selection")
        GoTo 60
    End If
    If MSComm1.PortOpen = False Then MSComm1.PortOpen = True
    j = "b"
    For i = 1 To 11
        MSComm1.Output = j
    Next
    Text1.Text = "Finger 2 Released"
    MSComm1.PortOpen = False
60 End Sub

Private Sub Command7_Click()

    Dim j As String
    Dim message As String
    If Option1.Value = False And Option2.Value = False And Option3.Value = False
And Option4.Value = False Then
        message = MsgBox("Please Select Communication Port", vbOKOnly +
vbExclamation + vbDefaultButton1, "Serial Port Selection")
        GoTo 70
    End If
```

```
    If MSComm1.PortOpen = False Then MSComm1.PortOpen = True
    j = "c"
    For i = 1 To 12
        MSComm1.Output = j
    Next
    Text1.Text = "Finger 3 Released"
    MSComm1.PortOpen = False
70 End Sub

Private Sub Command8_Click()

    Dim j As String
    Dim message As String
    If Option1.Value = False And Option2.Value = False And Option3.Value = False
And Option4.Value = False Then
        message = MsgBox("Please Select Communication Port", vbOKOnly +
vbExclamation + vbDefaultButton1, "Serial Port Selection")
        GoTo 80
    End If
    If MSComm1.PortOpen = False Then MSComm1.PortOpen = True
    j = "d"
    For i = 1 To 13
        MSComm1.Output = j
    Next
    Text1.Text = "Thumb Released"
    MSComm1.PortOpen = False
80 End Sub

Private Sub Command9_Click()

    Dim j As String
    Dim message As String
    If Option1.Value = False And Option2.Value = False And Option3.Value = False
And Option4.Value = False Then
        message = MsgBox("Please Select Communication Port", vbOKOnly +
vbExclamation + vbDefaultButton1, "Serial Port Selection")
        GoTo 90
    End If
    If MSComm1.PortOpen = False Then MSComm1.PortOpen = True
    Text1.Text = "All Fingers are Active"
    j = 5
    For i = 1 To j
        MSComm1.Output = j
    Next
    Sleep (1000)
    j = 4
    For i = 1 To j
        MSComm1.Output = j
```

```
   Next
   MSComm1.PortOpen = False
90 End Sub

Private Sub Command10_Click()

   Dim j As String
   Dim message As String
   If Option1.Value = False And Option2.Value = False And Option3.Value = False
And Option4.Value = False Then
      message = MsgBox("Please Select Communication Port", vbOKOnly +
vbExclamation + vbDefaultButton1, "Serial Port Selection")
      GoTo 100
   End If
   If MSComm1.PortOpen = False Then MSComm1.PortOpen = True
   j = 7
   For i = 1 To j
      MSComm1.Output = j
   Next
   Text1.Text = "All Fingers are Released"
   MSComm1.PortOpen = False
100 End Sub

Private Sub Command11_Click()

   Dim j As String
   Dim message As String
   If Option1.Value = False And Option2.Value = False And Option3.Value = False
And Option4.Value = False Then
      message = MsgBox("Please Select Communication Port", vbOKOnly +
vbExclamation + vbDefaultButton1, "Serial Port Selection")
      GoTo 110
   End If
   If MSComm1.PortOpen = False Then MSComm1.PortOpen = True
   Text1.Text = "Finger 2 and Thumb is Active"
   j = 2
   For i = 1 To j
      MSComm1.Output = j
   Next
   Sleep (1000)
   j = 4
   For i = 1 To j
      MSComm1.Output = j
   Next
   MSComm1.PortOpen = False
110 End Sub

Private Sub Command12_Click()
```

```
    Dim j As String
    Dim message As String
    If Option1.Value = False And Option2.Value = False And Option3.Value = False
And Option4.Value = False Then
        message = MsgBox("Please Select Communication Port", vbOKOnly +
vbExclamation + vbDefaultButton1, "Serial Port Selection")
        GoTo 120
    End If
    If MSComm1.PortOpen = False Then MSComm1.PortOpen = True
    j = 7
    For i = 1 To j
        MSComm1.Output = j
    Next
    Text1.Text = "Precision Gripping Cancelled"
    MSComm1.PortOpen = False
120 End Sub

Private Sub Command13_Click()
    Dim j As String
    Dim message As String
    Dim question
    If Option1.Value = False And Option2.Value = False And Option3.Value = False
And Option4.Value = False Then
        message = MsgBox("Please Select Communication Port", vbOKOnly +
vbExclamation + vbDefaultButton1, "Serial Port Selection")
        GoTo 130
    End If
    question = MsgBox("Gripper is Entering Demo Mode. Please Remove All Work
Objects.", vbOKCancel + vbInformation + vbDefaultButton2, "Demo Mode")
    If question = vbOK Then
        If MSComm1.PortOpen = False Then MSComm1.PortOpen = True
        Text1.Text = "Gripper in Demo Mode"
        j = 1   'Activate Finger 1
        For i = 1 To j
            MSComm1.Output = j
        Next
        Sleep (3000)
        j = "a" 'Deactivate Finger 1
        For i = 1 To 10
            MSComm1.Output = j
        Next
        j = 2   'Activate Finger 2
        For i = 1 To j
            MSComm1.Output = j
        Next
        Sleep (3000)
        j = "b" 'Deactivate Finger 2
```

```
For i = 1 To 11
   MSComm1.Output = j
Next
j = 3   'Activate Finger 3
For i = 1 To j
   MSComm1.Output = j
Next
Sleep (3000)
j = "c" 'Deactivate Finger 3
For i = 1 To 12
   MSComm1.Output = j
Next
j = 4   'Activate Finger 4
For i = 1 To j
   MSComm1.Output = j
Next
Sleep (3000)
j = "d" 'Deactivate Finger 4
For i = 1 To 13
   MSComm1.Output = j
Next
Sleep (3000)
j = 5   'Activate Fingers 1, 2 & 3
For i = 1 To j
   MSComm1.Output = j
Next
Sleep (3000)
j = 7   'Deactivate All Fingers
For i = 1 To j
   MSComm1.Output = j
Next
Sleep (3000)
j = 1   'Activate Finger 1
For i = 1 To j
   MSComm1.Output = j
Next
Sleep (1000)
j = 2   'Activate Finger 2
For i = 1 To j
   MSComm1.Output = j
Next
Sleep (1000)
j = 3   'Activate Finger 3
For i = 1 To j
   MSComm1.Output = j
Next
Sleep (3000)
j = "c" 'Deactivate Finger 1
```

```
        For i = 1 To 12
            MSComm1.Output = j
        Next
        Sleep (1000)
        j = "b" 'Deactivate Finger 2
        For i = 1 To 11
            MSComm1.Output = j
        Next
        Sleep (1000)
        j = "a" 'Deactivate Finger 3
        For i = 1 To 10
            MSComm1.Output = j
        Next
        Sleep (1000)
        Text1.Text = "End of Demo Mode"
        question = MsgBox("End of Demo Mode.", vbOKOnly + vbInformation +
vbDefaultButton1, "Demo Mode")

    Else
        Cancel = True
    End If
'       MSComm1.PortOpen = False
130 End Sub

Private Sub Command14_Click()

    Dim j As String
    Dim question
    question = MsgBox("All Active Fingers will be Released", vbOKCancel +
vbCritical + vbDefaultButton2, "Exit Program")
    If question = vbOK Then
    If Option1.Value = False And Option2.Value = False And Option3.Value = False
And Option4.Value = False Then
        GoTo 140
    End If
    If MSComm1.PortOpen = False Then MSComm1.PortOpen = True
        j = 7
        For i = 1 To j
            MSComm1.Output = j
        Next
140 End
    Else
        Cancel = True
    End If

End Sub

Private Sub Form_Load()
```

```
Dim X As String
If MSComm1.PortOpen = True Then MSComm1.PortOpen = False
MSComm1.Settings = "9600,N,8,1"
MSComm1.RThreshold = 1
MSComm1.OutBufferSize = 1
Timer1.Interval = 1
Timer1.Enabled = False
Label2.Caption = "Please Select Communication Port"
Text1.BackColor = QBColor(4)
Text1.ForeColor = QBColor(15)
Text1.Text = "Device Not Ready"

Dim i As Integer
   cboComm.Clear
   For i = 1 To 16
      If COMAvailable(i) Then
      cboComm.AddItem i
      List1.AddItem ("COM " + Str(i))
      End If
   Next

cboComm.ListIndex = 0
   On Error Resume Next
   If cboComm.Text = "1" Then
      Option1.Enabled = True
   ElseIf cboComm.Text = "2" Then
      Option2.Enabled = True
   ElseIf cboComm.Text = "3" Then
     Option3.Enabled = True
   ElseIf cboComm.Text = "4" Then
      Option4.Enabled = True
   End If
cboComm.ListIndex = 1
   On Error Resume Next
   If cboComm.Text = "1" Then
      Option1.Enabled = True
   ElseIf cboComm.Text = "2" Then
      Option2.Enabled = True
   ElseIf cboComm.Text = "3" Then
      Option3.Enabled = True
   ElseIf cboComm.Text = "4" Then
      Option4.Enabled = True
   End If

cboComm.ListIndex = 2
   On Error Resume Next
   If cboComm.Text = "1" Then
```

```
            Option1.Enabled = True
        ElseIf cboComm.Text = "2" Then
            Option2.Enabled = True
        ElseIf cboComm.Text = "3" Then
            Option3.Enabled = True
        ElseIf cboComm.Text = "4" Then
            Option4.Enabled = True
        End If

    cboComm.ListIndex = 3
        On Error Resume Next
        If cboComm.Text = "1" Then
            Option1.Enabled = True
        ElseIf cboComm.Text = "2" Then
            Option2.Enabled = True
        ElseIf cboComm.Text = "3" Then
            Option3.Enabled = True
        ElseIf cboComm.Text = "4" Then
            Option4.Enabled = True
        End If
End Sub

Private Sub Option1_MouseDown(Button As Integer, Shift As Integer, X As Single,
Y As Single)

    Dim j As String
    If MSComm1.PortOpen = True Then MSComm1.PortOpen = False
    MSComm1.CommPort = 1
    MSComm1.PortOpen = True
    j = 9
    For i = 1 To j
        MSComm1.Output = j
    Next
    Text3.Text = ""
    Timer1.Enabled = True
End Sub

Private Sub Option1_Click()

    Dim Control As String
    Control = Text3.Text
    If Control = "ok" Then
        Label2.ForeColor = QBColor(2)
        Label2.Caption = "Motion Control Card is Connected"
        Text1.BackColor = QBColor(2)
        Text1.ForeColor = QBColor(15)
        Text1.Text = "Gripper is Ready"
        Option1.Value = True
```

```
        Timer1.Enabled = False
        MSComm1.PortOpen = False
    Else
        Label2.ForeColor = QBColor(4)
        Label2.Caption = "Motion Control Card is not Connected. Connect the Control
Card to Serial Port 1"
        Text1.BackColor = QBColor(4)
        Text1.ForeColor = QBColor(15)
        Text1.Text = "Device Not Ready"
        Option1.Value = False
        Timer1.Enabled = False
        MSComm1.PortOpen = False
    End If
End Sub

Private Sub Option2_MouseDown(Button As Integer, Shift As Integer, X As Single,
Y As Single)

    Dim j As String
    If MSComm1.PortOpen = True Then MSComm1.PortOpen = False
    MSComm1.CommPort = 2
    MSComm1.PortOpen = True
    j = 9
    For i = 1 To j
        MSComm1.Output = j
    Next
    Text3.Text = ""
    Timer1.Enabled = True
End Sub

Private Sub Option2_Click()

    Dim Control As String
    Control = Text3.Text
    If Control = "ok" Then
        Label2.ForeColor = QBColor(2)
        Label2.Caption = "Motion Control Card is Connected"
        Text1.BackColor = QBColor(2)
        Text1.ForeColor = QBColor(15)
        Text1.Text = "Gripper is Ready"
        Option2.Value = True
        Timer1.Enabled = False
        MSComm1.PortOpen = False
    Else
        Label2.ForeColor = QBColor(4)
        Label2.Caption = "Motion Control Card is not Connected. Connect the Control
Card to Serial Port 2"
        Text1.BackColor = QBColor(4)
```

```
        Text1.ForeColor = QBColor(15)
        Text1.Text = "Device Not Ready"
        Option2.Value = False
        Timer1.Enabled = False
        MSComm1.PortOpen = False
    End If
End Sub

Private Sub Option3_MouseDown(Button As Integer, Shift As Integer, X As Single,
Y As Single)

    Dim j As String
    If MSComm1.PortOpen = True Then MSComm1.PortOpen = False
    MSComm1.CommPort = 3
    MSComm1.PortOpen = True
    j = 9
    For i = 1 To j
        MSComm1.Output = j
    Next
    Text3.Text = ""
    Timer1.Enabled = True
End Sub

Private Sub Option3_Click()

    Dim Control As String
    Control = Text3.Text
    If Control = "ok" Then
        Label2.ForeColor = QBColor(2)
        Label2.Caption = "Motion Control Card is Connected"
        Text1.BackColor = QBColor(2)
        Text1.ForeColor = QBColor(15)
        Text1.Text = "Gripper is Ready"
        Option3.Value = True
        Timer1.Enabled = False
        MSComm1.PortOpen = False
    Else
        Label2.ForeColor = QBColor(4)
        Label2.Caption = "Motion Control Card is not Connected. Connect the Control
Card to Serial Port 3"
        Text1.BackColor = QBColor(4)
        Text1.ForeColor = QBColor(15)
        Text1.Text = "Device Not Ready"
        Option3.Value = False
        Timer1.Enabled = False
        MSComm1.PortOpen = False
    End If
End Sub
```

```
Private Sub Option4_MouseDown(Button As Integer, Shift As Integer, X As Single,
Y As Single)

   Dim j As String
   If MSComm1.PortOpen = True Then MSComm1.PortOpen = False
   MSComm1.CommPort = 4
   MSComm1.PortOpen = True
   j = 9
   For i = 1 To j
      MSComm1.Output = j
   Next
   Text3.Text = ""
   Timer1.Enabled = True
End Sub

Private Sub Option4_Click()

   Dim Control As String
   Control = Text3.Text
   If Control = "ok" Then
      Label2.ForeColor = QBColor(2)
      Label2.Caption = "Motion Control Card is Connected"
      Text1.BackColor = QBColor(2)
      Text1.ForeColor = QBColor(15)
      Text1.Text = "Gripper is Ready"
      Option4.Value = True
      Timer1.Enabled = False
      MSComm1.PortOpen = False
   Else
      Label2.ForeColor = QBColor(4)
      Label2.Caption = "Motion Control Card is not Connected. Connect the Control
Card to Serial Port 4"
      Text1.BackColor = QBColor(4)
      Text1.ForeColor = QBColor(15)
      Text1.Text = "Device Not Ready"
      Option4.Value = False
      Timer1.Enabled = False
      MSComm1.PortOpen = False
   End If
End Sub

Private Sub ListComPorts()

   Dim i As Integer
   cboComm.Clear
   For i = 1 To 16
      If COMAvailable(i) Then
```

```
            cboComm.AddItem i
        End If
    Next
    cboComm.ListIndex = 0
End Sub

Private Sub Timer1_Timer()
    Text3 = Text3 & MSComm1.Input
End Sub
```

Sleep Subfunction:

```
Public Declare Sub Sleep Lib "kernel32" (ByVal dwMilliseconds As Long)
```

COMAvaliable Subfunction:

```
'// API Declarations
Public Declare Function CreateFile Lib "kernel32" Alias "CreateFileA" (ByVal lpFileName As String, ByVal dwDesiredAccess As Long, ByVal dwShareMode As Long, lpSecurityAttributes As SECURITY_ATTRIBUTES, ByVal dwCreationDisposition As Long, ByVal dwFlagsAndAttributes As Long, ByVal hTemplateFile As Long) As Long
Public Declare Function CloseHandle Lib "kernel32" (ByVal hObject As Long) As Long

'// API Structures
Public Type SECURITY_ATTRIBUTES
    nLength As Long
    lpSecurityDescriptor As Long
    bInheritHandle As Long
End Type

'// API constants
Public Const FILE_SHARE_READ = &H1
Public Const FILE_SHARE_WRITE = &H2
Public Const OPEN_EXISTING = 3
Public Const FILE_ATTRIBUTE_NORMAL = &H80


'// Return TRUE if the COM exists, FALSE if the COM does not exist
Public Function COMAvailable(COMNum As Integer) As Boolean
    Dim hCOM As Long
    Dim ret As Long
    Dim sec As SECURITY_ATTRIBUTES

    '// try to open the COM port
    hCOM = CreateFile("\.\COM" & COMNum & "", 0, FILE_SHARE_READ + _
```

```
    FILE_SHARE_WRITE, sec, OPEN_EXISTING,
FILE_ATTRIBUTE_NORMAL, 0)
  If hCOM = -1 Then
    COMAvailable = False
  Else
    COMAvailable = True
    '// close the COM port
    ret = CloseHandle(hCOM)
  End If
End Function
```