DESIGN AND MANUFACTURING OF A DOG-LOBSTER HYBRID ROBOT AS IMPLEMENTATION OF THE "BIO- INSPIRED DESIGN METHODOLOGY" FOR INSECT / ANIMAL LOCOMOTION

A MASTER'S THESIS

In

Mechatronics Engineering

Atılım University

By

EMRE GÜNER

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DESIGN AND MANUFACTURING OF A DOG-LOBSTER HYBRID ROBOT AS IMPLEMENTATION OF THE "BIO- INSPIRED DESIGN METHODOLOGY" FOR INSECT / ANIMAL LOCOMOTION

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IN

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OCTOBER 2014

Approval of the Graduate School of Natural and Applied Sciences, Atılım University.

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Prof. Dr. K. İbrahim AKMAN

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I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

____

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This is to certify that we have read the thesis “Design and Manufacturing of a Dog-Lobster Hybrid Robot as Implementation Of the “Bio- Inspired Design Methodology” For Insect / Animal Locomotion” submitted by “Emre Güner” and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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ABSTRACT

DESIGN AND MANUFACTURING OF A DOG-LOBSTER HYBRID ROBOT AS IMPLEMENTATION OF THE "BIO- INSPIRED DESIGN METHODOLOGY" FOR INSECT / ANIMAL LOCOMOTION

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M.S., Mechatronics Engineering Department

Supervisor: Prof.Dr. Abdulkadir Erden

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This thesis includes the design and manufacturing of the hybrid robot via bio – inspired design methodology. In this thesis all the design steps of the hybrid robot are discussed. Design process of the hybrid robot separated into three parts; conceptual design, preliminary design, and detailed design. In these parts all details of the design and manufacturing phases will be discussed. In this thesis also locomotion of the dog and lobster are performed in hybrid robot. At last test procedures and test results of the hybrid robot are discussed. During this thesis study, test of the hybrid robot is performed on carrier platform, dynamic forces and other disturbances effects are ignored. As a conclusion comparison of hybrid robot with other robot and performance of the hybrid robot are discussed.

Keywords: Bio-inspired design, animal locomotion.

ÖZ

BÖCEK / HAYVAN HAREKETLERİ İÇİN "BİYO-ESİNLENİLMİŞ TASARIM METODOLOJİSİNİN" BİR KÖPEK – ISTAKOZ MELEZ ROBOTUN TASARIMI VE ÜRETİMİNE UYGULANMASI

Emre Güner

Yüksek Lisans, Mekatronik Mühendisliği Bölümü

Tez Yöneticisi: Prof.Dr. Abdulkadir Erden

EKİM 2014, 104 sayfa

Bu tez çalışmasında melez robotun biyo – esinlenilmis dizayn metodolojisine dayanan tasarımı ve üretimi incelenmiştir. Bu tez Melez robot tasarım ve üretim aşamalarının tamamını içermektedir. Melez robotun tasarım süreci 3 parçaya ayrılmıştır. Bu parçalar konsept dizayn, ön dizayn ve detaylı dizayn diye adlandırılmıştır. Bu parçalarda hibrit robotun bütün üretim aşamaları detaylıca anlatılacaktır. Aynı zamanda bu tezde köpek ve istakoz yürüyüş hareketi çalışılmıstır. Son olarak test prosedürleri ve sonuçları tartışılmıştır. Bu tez çalışması boyunca dinamik kuvvetler ve diğer dış etkiler göz ardı edilmiştir ve robotun testleri bir taşıyıcı platform üzerinde yapılmıştır. Sonuç kısmında ise melez robotun diğer robotlarla karşılaştırılması ve performansı tartışılmıştır.

Anahtar Kelimeler: Biyo-esinlenilmiş tasarım, Hayvan Hareketleri.

To My Family and Friends

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I express sincere appreciation to my supervisor Prof. Dr. Abdulkadir Erden for his guidance and insight throughout the research and also Dr. Aylin Konez Eroğlu for her guidance. The technical and mental assistance of Alp Kaçar, Aslı Çakır, Ayça Göçmen, Ayşe Kuyrukçu, Azime Çetiner, Barış Karabay, Canan Pekel, Cahit Gürel, Fırat Tansu, Seda Kibar, Simge Söğütlü, Meral Aday and Handan Kara are gratefully acknowledged. I offer sincere thanks to my parents, Erkan and Cavidan Güner and my friends Ahmet Okur, Işıl Okur, Sinan Göçer, Bahadır Gülcüler and, Özgü Aybayar, for their continuous support and patience during this period.

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LIST OF ABREVIATIONS

DIB: Bio inspired Design

DOD: Depends on Design

DOF: Degree of Freedom

CHAPTER 1

INTRODUCTION

Mechatronic is the synergistic combination of the mechanical, electronics, and control systems engineering. Mechatronic unites the principles of mechanics, electronics, and computing to generate a simpler, more economical and reliable system. The birth of the mechatronics engineering, is dated in the middle of the 20th century. First examples of the mechatronic systems were the industrial robot arms, used in the manufacturing. [1]

Mechatronic design is the integrated design of the mechanical systems and control systems. Mechatronic systems have their own autonomy and intelligence, they can perceive the environment and then act according to environmental conditions. This is achieved via instrumentation of mechanical, electrical and, control systems in an integrated system. The general trend is such that people desire more complex and automatic systems. They demand complex machines which can perform several functions in one unit. For example cleaning robots, intelligent houses, and intelligent cars are typical applications. Mechatronic design aims, mainly, to satisfy human needs. Mechatronic design implements some engineering design methodologies; one of these methodologies is “Bio –Inspired design”. Bio inspired design is the design which is inspired from the nature or biological systems. Bio – inspired design is also named as “Biomimetic Design”. Biomimetic is an ancient word that comes from the combination of the Greeks words “bios” which refers to life, and “mimesis” meaning to imitate. Early examples of the biomimetic design are started with the studies of Leonardo da Vinci. He worked on birds’ anatomy to enable human flight. Later Wright brothers created flying machines for this aim. In the middle of the of the 20th century American biophysicist Otto Schmitt studied on nerves in the squids, then the evolution of the biomimetic is accelerated. Today most famous examples of the biomimetic can be listed as robot arms inspired from the elephant's nose, jet fighters that inspired from hawks, car body also inspired from animals, carrier robots that inspired from the dogs. Biomimetic technology is used in different areas from of engineering to medicine and environment. This thesis incudes the design and manufacturing of the hybrid robot, in further chapters design and manufacturing steps of the hybrid robot, are given detail. [1]

1.2 Aim and Scope:

The aim of the thesis is to design and manufacture of a hybrid robot via Bio – inspired design methodology. In this thesis design and manufacturing steps of hybrid robot are given detail. After than some performance tests are performed on the hybrid robot. In these tests performance of the hybrid robot is measured. The aim of these tests are catching the walking pattern of the hybrid robot and compare them with real biological system. During these tests only locomotion of the hybrid robot is studied. Sensor feedback, dynamic effects such reaction forces, underwater effects are ignored during the tests.

CHAPTER 2

LITERATURE SURVEY & PREVIOUS WORK

2.1 Bio Inspired Design Applications:

The aim of the bio – inspired design is to provide solutions which initiate from the nature, for satisfying human needs. The usage area of the bio-inspired design (BID) is very common in today's world, these areas can be described as biology (molecular cell biology, genetic engineering, organismal biology, clinical medicine), Engineering (Biomedical engineering, chemical engineering, mechanical engineering, electrical engineering, robotics), and physical sciences (chemistry, physics, material science, and nanotechnology) [2]. These are the most common application areas of the BD. Robotic applications of the BD is the main subject in this thesis. Today, all of the developed countries work on biologically inspired machines (animal like robots, human like robots, planes, surgery robots, military robots etc.). Why is BD so important? The answer of this question is very simple; engineering studies do not satisfy human needs anymore and nature has a perfect structure, and everything is working flawlessly like a perfect machine. Nature provides many ideas and solutions for living on it. So what is the most popular examples of the BD? One of the most popular examples of BD is developed by Boston Dynamics [4], working on animal like robots. Big dog is a most challenging project of the company.

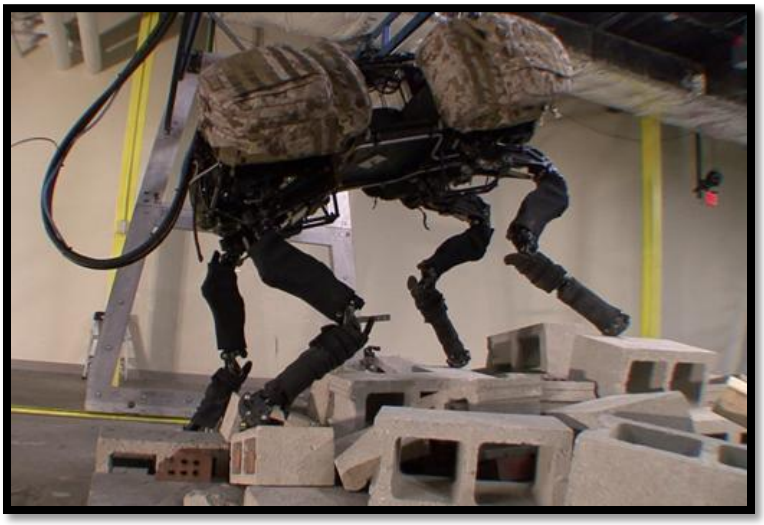


Figure 1 Big Dog [4]

Big dog is a robot is inspired from dog and its aim is to carry load on rough terrains, it is designed for military applications, Figure 1 represents the side view of the Big Dog. Another popular study of the Boston Dynamics is Cheetah like robot (Fig. 2).

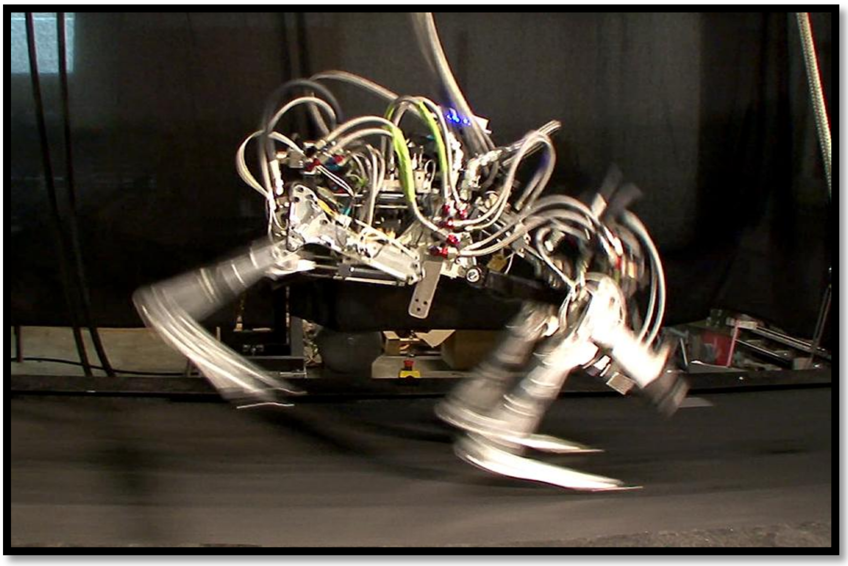


Figure 2 Cheetah Robot [4]

Another company studying on BD is FESTO [5], they are working on pneumatic, hydraulic and servo systems with BD concepts. They have 3 important flying robots which are called smart bird, aqua jelly, and dragonfly, which are completely inspired from nature.

Figure 3 Smart Bird of FESTO Company [5]

Smart bird is the one of the robots of the FESTO Company (Fig. 3). It uses electrical motor for flapping its wings and has a carbon fiber body to decrease its weight and energy consumption. Also Dragonfly robot has similar features (Fig. 4).

Figure 4 Dragonfly Robot [5]

So far, these are the most famous example of the BD, in Robotics.

Another example in literature is design, modeling and characterization of a miniature robotic fish [6]. In the design and manufacture of this robot researchers used waterproof servos, and chassis, manufactured in rapid prototyping machine. Another example was developed in MIT [7]. In this work researchers studied three types of locomotion control which are called Wilson, Cruse, and Pearson. They worked on small autonomous platform which is called Hannibal. It is 35 cm. long, 15 cm. high and 2.8 kg. weight, it has six legs and each of them has 3 degree of freedom (DOF). It has 19 actuators and over 60 sensors, they are leg mounted force sensor, joint angle sensors, joint velocity sensors, ground contact sensors and inclinometers. Another example about the BD is “Design and Simulation of a Cockroach – like Hexapod Robot.” [8]. in this study researchers studied on a 6 legged cockroach robot which is called R-III. This is the third generation of their cockroach robot. It has 24 DOF based upon a uniform length scale, and 17 times bigger than the real animal. Like a real cockroach each leg is composed of three moveable segments, proximal to distal: coxa, femur, and tibia with a flexible tarsus. Front legs of the robot have five, middle legs four, and rear legs have 3 DOF, and chassis of the robot is made from aluminum alloy. Robot locomotion is provided by pneumatic actuators. Another case study is rapidly running arthropods like cockroach study [9]. In this study, researchers inspired from the cockroaches running at high speed, robot has six legs and each leg connected to other with a four bar mechanism, motion of the robot provided by brushed DC motor. Also in literature some imaginary BD design examples are available. In one study six legged robot is designed in 3D matlab environment and locomotion of this robot is studied. Another case is defined in the articles is locomotion. In this thesis locomotion of the designed robots, are studied mainly, this methodology will be discussed in further chapters, but there is another technique for locomotion that exists in the literature, which is called central pattern generator (CPG). Implementation of the CPG is given detail in [11]. CPG is the locomotion control system, that behaving like a neural circuit, it produces rhythmic motor pattern without any sensor data.

2.2 Bio Inspired Conceptual Design Examples:

Another examples are given in literature [12], bio dog, and cockroach - like robot, in these case studies researchers study on locomotion of dog and cockroach. During these case studies researcher follows, bio inspired conceptual design methodology. This methodology includes 6 steps. These steps can be listed as follows.

- Task clarification
- Biological system selection
- Biological system analysis
- Bio inspired transformation
- Engineering structures generalization
- Engineering structures selection.

First step of the bio inspired conceptual design (BICD) is task clarification. This step includes costumer need analysis, problem definition, and design requirement list of the given project. Second step of the BICD is Biological system selection, in this step selection of the proper biological system according to the costumer need analysis is done. After than this biological system is analyzed according to given task. Fourth step of the BICD is Bio inspired transformation, in this step biological system transferred to the engineering domain, during this step links, joint types and another biological structures of the biological system matched with engineering structure. In fifth step which is called engineering structures generalization, design alternatives for bio robot are generated, and last step most suitable design alternative is chosen for the manufacturing of the bio robot. In the light of these information, two different case studies are achieved [12].

2.2.1 Cockroach – like Bio Robot:

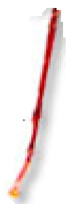
In the first case study cockroach - like robot will be discussed. In the lights of BICD, firstly the task clarification of the cockroach robot is achieved. At the beginning of the task clarification costumer need is analyzed. Customer said that “I desire a bio robot which can climb an indoor and smooth surface like a cockroach. It looks like a giant cockroach. The bio - robot should be midweight and carry itself while climbing. I have some servo motors and an Arduino platform; we can use them in the preliminary prototype with the plexiglass body”. According to the costumer need a requirement list of the customer is prepared. Table 1 represents the requirement list of the cockroach robot.

Table 1 Requirement List for Cockroach-like Bio robot [12]

Main Headings		Requirement List
Name of the Biological System (if known)		Cockroach
Type of the Biological System (if mentioned)		Animal (Insect)
Morphology of the Final Product		Cockroach-like Max. 1 kg Max. 21 dm^3
Desired Function of the final product	**Motoric**	Climbing
	Sensory	-
	Cognitive	-
Flow of the final product	**Material**	Plexiglass
	Energy	Battery
	Information	-
Robot Expected Features		servo motors, Arduino, compact, light
Operational Environment		Vertical plexiglass surface (≈125 Ra)
Cost		-
Schedule		-

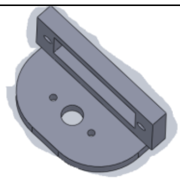
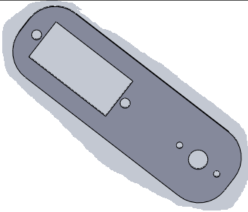
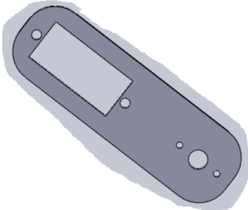
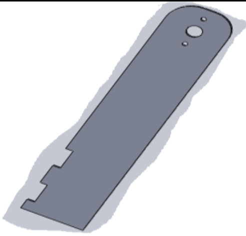
This table shows the brief summary of the costumer need. In this table, motoric actions weights, materials and actuators of the final product are clearly defined. After this step a biological system analysis is achieved. In this case study costumer defines, the biological system at the beginning. Customer desires a cockroach-like bio robot. The morphology of the cockroach should be examined because the geometrical property of robot should reflect the real cockroach. Therefore, leg length and form of cockroach are given in the Table 2.

Table 2 Forms of Limbs [12]

Limbs	Forms	Max. Dimensions for the selected cockroach (mm)
Coxa		**Front Leg:**1.4
		Middle Leg: 2
		Hind Leg: 2.3
Femur		**Front Leg:** 2.5
		Middle Leg: 3.4
		Hind Leg: 4.2
Tibia		**Front Leg:** 1.9
		Middle Leg: 3.1
		Hind Leg: 4.7
Tarsus		**Front Leg:** 2.3
		Middle Leg: 2.4
		Hind Leg: 4.1

As it shown in Table 2, dimensions of the cockroach are very small. For this reason the dimensions of the robot cockroach is resized, new sizes of the cockroach robot is 50 times bigger than the original cockroach. After the morphology, bio inspired transformation of the cockroach robot is done. Firstly the legs of the cockroach are transferred to the engineering domain. Cockroach legs have 4 links, these links are named as coxa, femur, tibia, and tarsus, and these are matched with engineering structures and are listed in Table 3.

Table 3 The Matched Forms and Structures [12]

Limbs	Forms	Matched Engineering Form/Structure	Max. Dimensions for the selected cockroach (mm)
Coxa			**Front Leg:** 74.6
			Middle Leg: 24 x 40
			Hind Leg: 24 x 40
Femur			**Front Leg:** 64.8
			Middle Leg: 102
			Hind Leg: 126
Tibia			**Front Leg:** 64.6
			Middle Leg: 93
			Hind Leg: 141
Tarsus			**Front Leg:** 69
			Middle Leg: 72
			Hind Leg: 123

After the matching of links, transformation of the link joints are completed. In front legs body – coxa, coxa – femur, femur – tibia and tibia – tarsus, links connect each other with hinge joints, in middle and hind legs body- coxa links connected each other with proximal joint and others connected with hinge joints. The matched joint structures are shown in Table 4.

Table 4 Matched Joints [12]

	Body- Coxa	Coxa-Femur	Femur-Tibia	Tibia - Tarsus
Prothoracic legs (Front legs)	“hinge joint” but coxa can move in sagital plane (y,z)	“hinge joint” with an axis parallel x axis	“hinge joint” with an axis parallel x axis	“hinge joint” with an axis parallel x axis
Mesothoracic legs (Middle legs)	“Proximal joint” with an axis parallel to x axis (1 DOF)	“hinge joint” with an axis parallel to z axis	“hinge joint” with an axis parallel z axis	“hinge joint” with an axis parallel x axis
Metathoracic legs (Hind legs)	“Proximal joint” with an axis parallel to x axis (1 DOF)	“hinge joint” with an axis parallel to z axis	“hinge joint” with an axis parallel to z axis	“hinge joint” with an axis parallel x axis

After bio inspired transformation of the cockroach robot is achieved. Design alternatives for cockroach - like robot are generated. These alternatives include different chassis materials, actuators, and microcontroller types. According the costumer need, most suitable alternative for cockroach robot is chosen and manufacturing of cockroach robot is achieved. After the mechanical design of the cockroach robot is completed, climbing locomotion of the insect should be examined. This is done by capturing the climbing of the insect on the plexiglass surface via high speed camera. By using the motion analysis software, 7 joints angles are calculated from the leg motion. From the analysis the joints angle vs. time graphics for 7 joints which are coxa front, femur front, tibia front, tarsus front, femur middle, tibia middle, and tarsus middle are gathered and plot in the Figure 11.

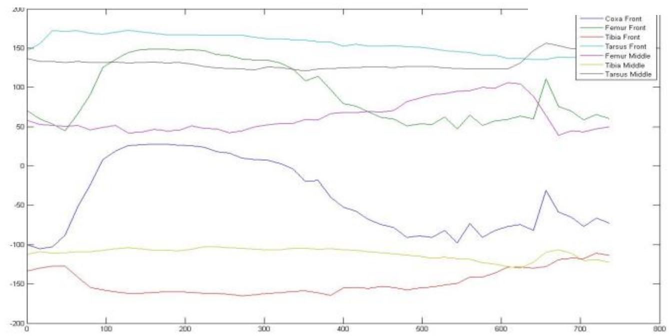


Figure 5 Graphs of The Angles Versus Time [12]

As it is seen in the Figure 5 data captured from the real cockroach is analyzed and transferred to the cockroach – like bio robot, via microcontroller, and climbing locomotion of the cockroach robot is achieved. Figure 6 represents the final view of the cockroach – like bio robot.

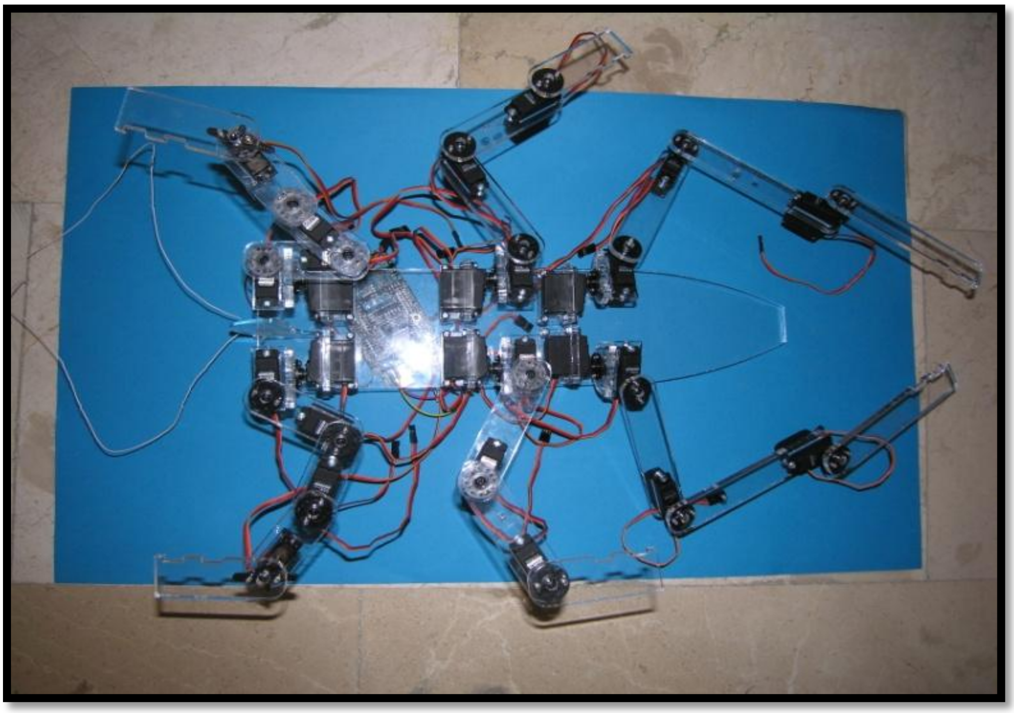


Figure 6 Cockroach – like Bio Robot [12]

2.2.2 Dog – Like Bio Robot:

In this case study, design and manufacturing of the dog – like bio robot is discussed. Again same with first case study. Design of the step of the dog – like bio robot is begins with the task clarification step. In this case study costumer need is analyzed, costumer desires a robot which can walk on floor like a dog. In the lights of the costumer need, requirement list of the dog – like bio robot is listed. Table 5 defines the requirement list of the dog – like bio robot.

Table 5 Requirement List for Dog-Like Bio – robot [12]

Main Headings	Requirement List
Name of the Biological System (if known)	Dog
Type of the Biological System (if mentioned)	Animal

Morphology of the Final Product		Dog-like Max. 1 kg Max. 20 dm^3
Desired Function of the final product	**Motoric**	Walking
	Sensory	-
	Cognitive	-
Flow of the final product	**Material**	Plexiglass
	Energy	Battery
	Information	-
Robot Expected Features		servo motors, Arduino, compact, light
Operational Environment		Smooth surface

In this table, sizes, weights motoric actions, materials, and actuator types of the dog – like bio robot are described by costumer. After this step biological system selecting and analyzing steps are achieved. Costumer defines, biological system at the beginning of the study, and he/she wants dog like robot, according to the costumer need analyzing of the real dog is achieved. Firstly the morphology of the real dog is studied, bio – robot should reflect all the features of real dog. Dogs have four legs, each leg includes three limb that connected each other with joints. These limbs can be described as Scapula, Humerus, Radius-Ulna and Metacarpus for front legs; Pelvis, Femur, Tibia- Fibula and Metatarsus for hind legs. Figure 7 represents the skeletal system of the real dog. As it is said before, each limb connected each other with joint, these joints are describe like, Shoulder, Elbow, Wrist for front legs; Hips, Knee, Ankle for hind legs. The morphology of the dog is studied in [12] detailed and lengths of limbs are given in Table 6.

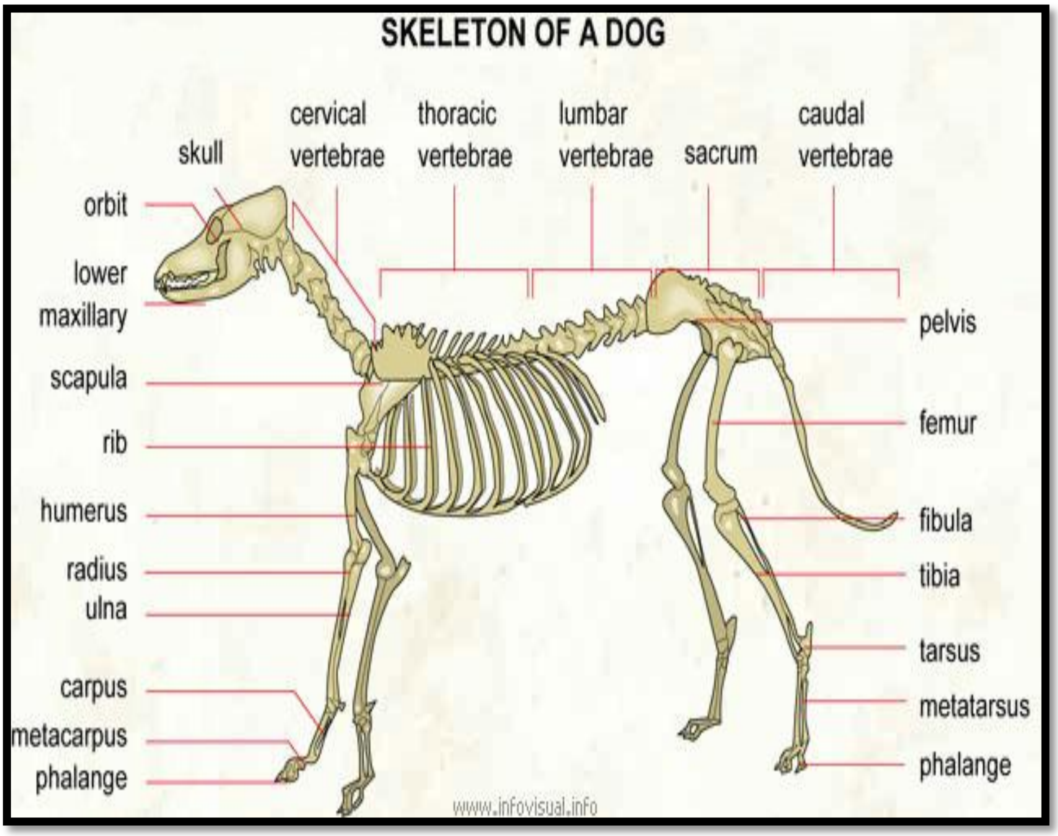


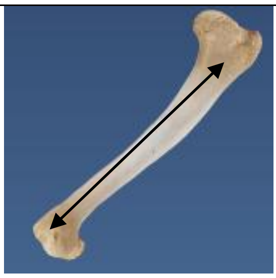
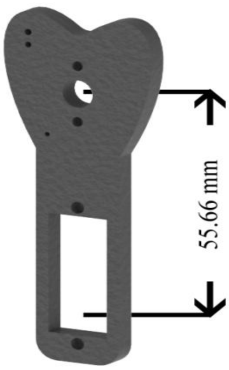
Figure 7 Skeletal System of The Dog [12]

Table 6 Leg Length of Dog [12]

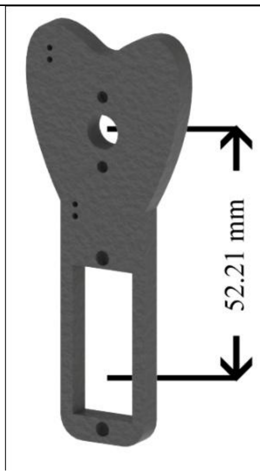
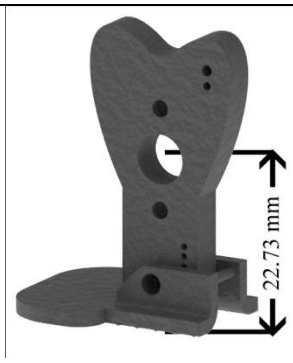
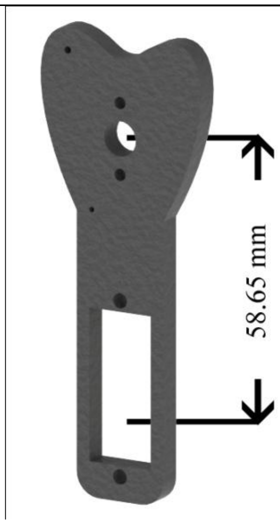
Legs	Bone name	Approximated lengths (mm)
Front Legs	Scapula	60
	Humerus	50
	Radius-Ulna and Metacarpus	130
Hind legs	Pelvis	80
	Femur	100
	Tibia-Fibula and Metatarsus	150

Dimensions of the bio-dog are arranged similar with the real dog, then the bio inspired transformation of the leg limbs is performed. Leg limbs of the real dog and matched engineering structures of the bio – dogs are shown in the Table 7.

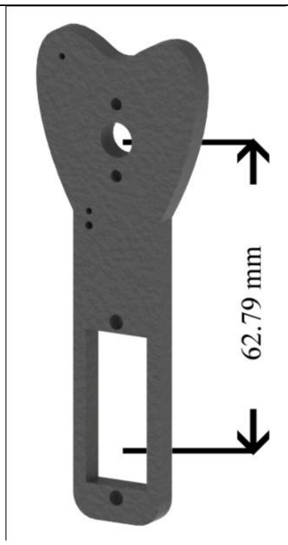
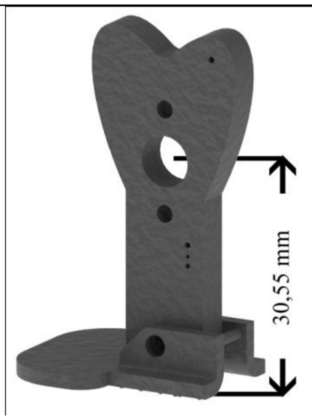
Table 7 the Matched Forms and Structures [12]

Limbs	**Forms**	**Matched Engineering Form/Structure**	**Max. Dimensions for the selected dog (Terrier)**
Humerus			Length = 50 mm

Continued

Radius and Ulna			Length = 130 mm
Forepaw			
Femur			Length = 100 mm

Continued

Tibia and Fibula			Length = 150 mm
Hindpaw			

After biological structures are matched with engineering structures, link connections are observed, and transformed into the engineering domains, matched joints are shown in the Table 8.

Table 8 the matched joints [12]

Legs	Joint Name	Joint Type	
		Biological	Engineering
Front Legs	Shoulder	Glenohumeral Joint	Ball and Socket
	Elbow	Ginglymus	Hinge Joint
	Wrist	Distal radioulnar	Hinge Joint
Hind Legs	Hips	Acetabulofemoral Joint	Ball and Socket
	Knee	Compound Joint	Hinge Joint
	Ankle	Talocrural Joint	Hinge Joint

After that the bio inspired transformation step, design alternatives for dog – like bio robot are generated. Table 9 represents the design alternatives for dog – like bio robot.

Table 9 Design Alternatives for Bio-Dog [12]

#	**Material**	**Joint**	**Actuator**	**Controller**
1	Plexiglass	Hinge Joint	Servo Motor	Arduino
2	Plexiglass	Hinge Joint	Pneumatic	Arduino
3	Plexiglass	Hinge Joint	Muscle Wire	Arduino
4	Aluminum	Hinge Joint	Servo Motor	Arduino
5	Aluminum	Hinge Joint	Pneumatic	Arduino
6	Aluminum	Hinge Joint	Mucle Wire	Arduino

From these alternatives the most suitable design alternative for dog – like bio robot is chosen and manufacturing of the robot is achieved. Figure 8 represents the final product.

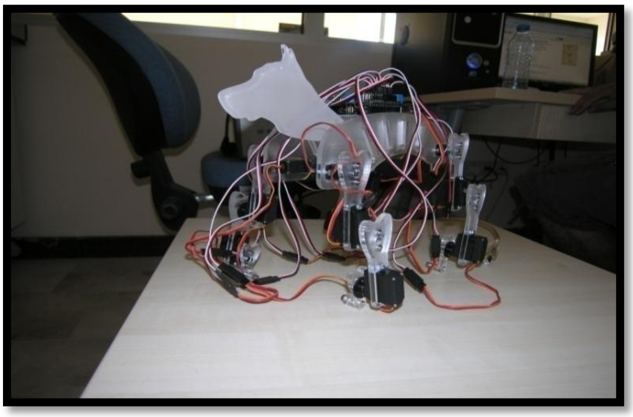


Figure 8 Dog Like Robot [12]

At last walking of the dog on smooth surface is observed via high speed camera. By using the motion analysis software, joint angles are calculated from the walking motion. In Figure 9, analysis of the joint angles is presented.

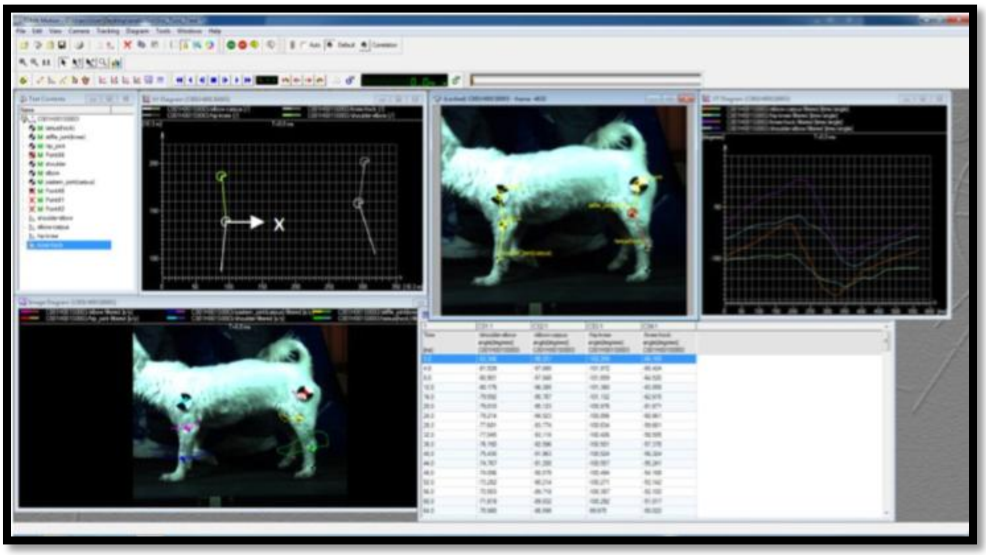


Figure 9 Analysis of The Joint Angle of Dog [12]

It is seen from the figure that, some markers are placed on dog body, these markers refers to the joints of the dog. In tema motion program, these markers are tracked and variation of angle vs time of the joints are presented in the graphs.

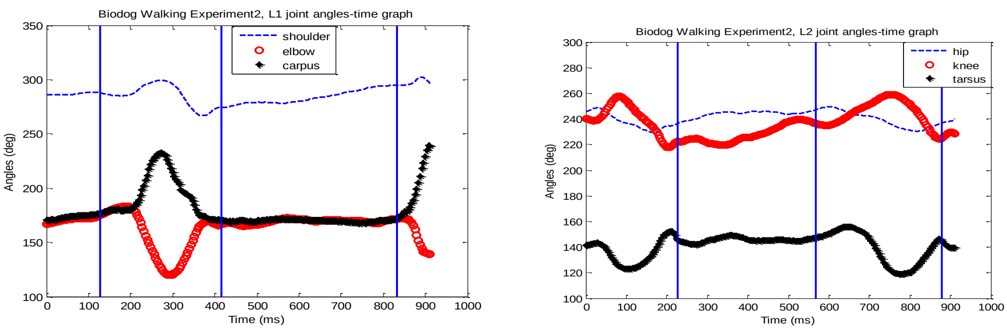


Figure 10 Angle vs Time Graphics of Dog Joints [12]

Then the walking cycle of the dog is observed, walking cycle includes the swing (no contact with ground) and stance (contact with ground) phases of the legs during the locomotion. Walking cycle is given in the Figure 11.

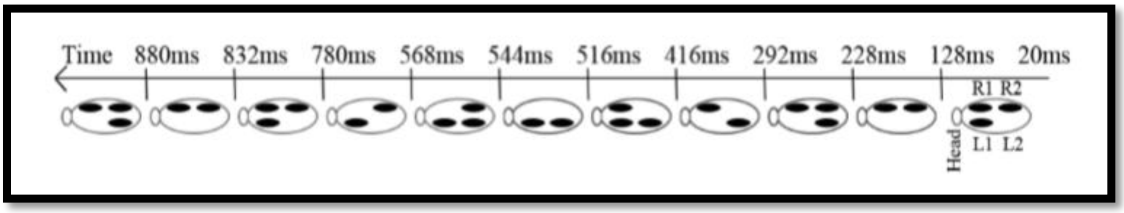


Figure 11 Walking Cycle of The Dog [12]

At last these angle data is transferred to robot platform by means of microcontroller and locomotion of the dog – like bio robot is achieved.

As a conclusion, in this chapter some of the bio inspired design examples in literature are discussed. In the lights of information bio inspired design applications are listed in Table 10. According to these examples design and manufacturing of the hybrid robot is discussed in further chapters.

Table 10 Bio Inspired Design Examples

Biological System	**Inspired Properties**	**Product**	**Referances**
Butterfly	Wing Structure	Waterproof Materials	Kesong Liu, 2011
Cat	Eye	Cat's eye reflectors	Losic, 2011
Gecko	Walking on Smooth Surface	Climbing robot	Mark R. Cutkosky, 2007
Dog	Walking	Bio dog	Boston Dynamics
Cheetah	Running	Cheetah Robot	Boston Dynamics
Bird	Flying	Smart bird	Festo
Dragonfly	Flying	Dragonfly Robot	Festo
Hawk	Wing Structure	Jet fighters	Lockheed Martin
Elephant	Nose	Robot Arm	Festo
Owl	Wing Structure	Silent and highly efficient fan	Ziehl-Abegg
Cockroach	Walking	Bio robot	Kingsley et al., 2003
Cockroach	Climbing	Bio robot	A.Eroğlu, 2013
Lobster	Walking	Bio robot	A.Eroğlu, 2013
Dog	Walking	Bio robot	A.Eroğlu, 2013
Bat	Navigation System	Submarine Sonar	USA Navy

CHAPTER 3

DESIGN OF THE HYBRID ROBOT

In this chapter design of the hybrid robot will be discussed. This chapter is separated into three parts. First part is conceptual design; where conceptual design of the hybrid robot will be discussed. In the second part, preliminary design of the hybrid robot will be discussed, in detail. In final part detailed design of the hybrid robot with all of design and test details of the hybrid robot will be discussed.

3.1 Conceptual Design

In this part of the thesis, conceptual design of the hybrid robot is described. Conceptual design outlines the solution to a design problem. A high - level overview of the design (in the form of a block diagram of interacting sub-systems) should be represented at this stage. Steps of the conceptual design can be described like this, problem definition, clear statement of the problem, design requirements, discussion of relevant alternative solutions, computer aided design of the final product, test plans and test procedures and conclusion.

3.1.1 Problem Definition:

In general, every engineering design study begins with the recognition of a need. Need can be defined as the expectations of the costumer, they define a need according to their problem, and engineering finds proper solutions to satisfy their needs. Recognition of the need can be achieved by several ways. Costumers define their needs directly or researchers can recognize need after research activity. Next step is problem definitions; this is the costumer need in the engineering domain. Engineers define the problem in engineering domain and then they try to solve the problem. The problem definitions of this thesis can be describe like this: “Design a legged bio-robot, which can walk on the indoor smooth surface and underwater rocky surface." This robot should prefer different types of walking according to the terrain status, on smooth surface it should walk like a land biological system, and underwater it walks like a sea biological system.

3.1.2 Design Requirements and Specifications:

A design specification provides explicit information about the requirements for a product and how the product is to be put together. Design requirements of the hybrid robot are described in Table 11.

Table 11 Design Requirement List for Hybrid Robot

Main Headings		**Requirement List**
Name of the Biological System (if known)		-
Type of the Biological System (if mentioned)		Animal
Desired Function of the final product	**Motoric**	Walking on smooth land surface and underwater rocky surface.
	Sensory	-
	Cognitive	-
Flow of the final product	**Material**	-DOD (Depends on Design)
	Energy	Battery
	Information	-
Robot Expected Features		-
Operational Environment		Smooth surface, Underwater rocky surface

As it is shown in the table, two different motoric tasks are described for hybrid robot. First task is that robot can move swiftly and clearly on smooth surface, and second task is that robot can overcome underwater terrains and conditions. These conditions can be described like rocks, water current, resistance and underwater pressures.

3.1.3 Design Alternatives and Evaluations of the Alternatives:

As it is described in Table 11 hybrid robot have two different type of motoric tasks. According to design needs, this robot must be able to walk on smooth land surface and underwater rocky surface. In this design costumer wants a legged robot, which can be walk like an animal. The main goal in this thesis, hybrid robot includes two different animals' morphologies in one base. In the light of this information, two different animals should be chosen. At first, as it is said before this robot should be able to walk on smooth surface, because of this the first biological system must be a land animal. There are many alternatives for land animals in literature, such as dog, cat, cheetah, horse, etc. As an underwater biological system lobster is selected, locomotion system of the lobster is suitable for hybrid robot design, lobster walks forward and backward directions while its motion like land creatures. Also there are some useful knowledge about the lobster in literature [13]. Design alternatives for hybrid robot can be described like this.

Table 12 Design Alternatives for Hybrid Robot

# of Alternative	Selected Land Animal	Selected Underwater Animal
1	Horse	Lobster
2	Cheetah	Lobster
3	Dog	Lobster
4	Cat	Lobster

As it is seen in Table 4 different design alternatives for hybrid robot are described. After that, these alternatives are evaluated. This evaluation is performed according to the accessible information in the literature. From the [12] the analyses of the dog are already known and analyses of the lobster are given detail in [13]. In the light of this information third alternative is selected as design of the hybrid robot. From the analysis, it is seen that main difference between these two biological systems is number of legs. Despite dogs have four legs, lobsters have eight legs, this difference makes problem in the structure of robot. Figure 12 is a picture of the lobster.

Figure 12 Top View of the Lobster

The robot should satisfy all leg conditions of the two biological systems. Structure of the dog leg is introduced in the literature part of the thesis. When the morphology of the lobster is analyzed, it is seen that number of the links in lobster leg is more than dog's. A schematic picture of the lobster leg is shown in Figure 13.

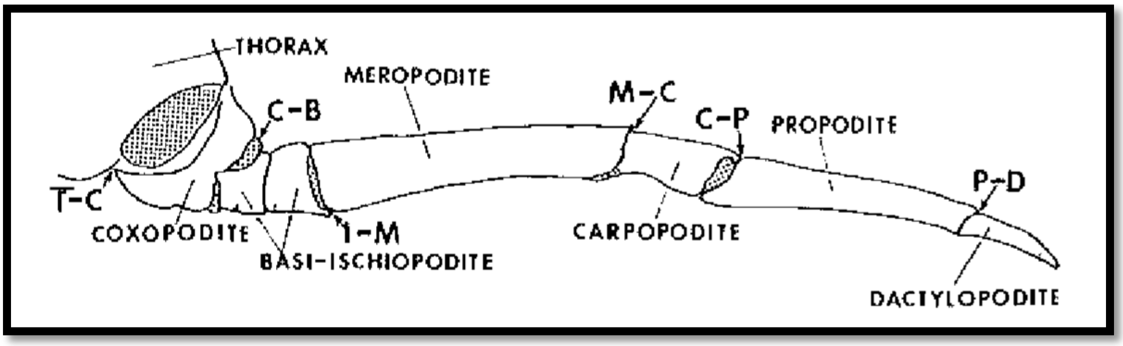


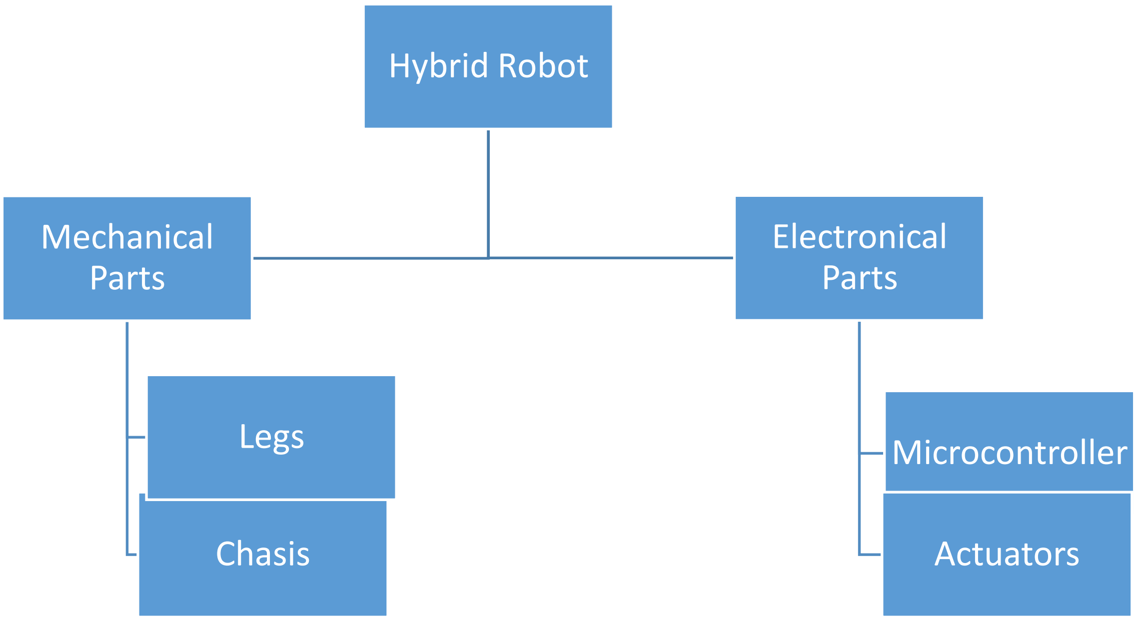
Figure 13 Schematic Picture of the Lobster leg [13,14]

As it is seen in the figure lobster leg has 6 joints 3 of them provides the locomotion of the lobster. According to these information leg design of the hybrid robot is achieved.

3.1.4 Design of the Hybrid Robot:

Hybrid robot contains some mechanical and electrical components. These parts can be described in table 13.

Table 13 Parts of the Hybrid robot



3.1.4.1 Electronical Parts:

As an electronical part, hybrid robot includes, microcontrollers and actuators. These electronical parts are discussed in this part of the thesis.

3.1.4.1.1 Microprocessor:

Controller unit is one of the most important parts of the intelligent systems. Control unit behaves like human brain, and control all of the actions of the hybrid–robot. In our case studies, Arduino Uno, and Arduino mega are used as micro controller units. Arduino is an embedded microcontroller card that includes Atmega type microprocessor [31]. The aim of the control unit in our systems is to control the angle positions of the servo motors, and drive them into right positions that received from analyze program. According to these processing operations motion of the hybrid– robot is provided. Figure 14 represents the 2 different models of Arduino.

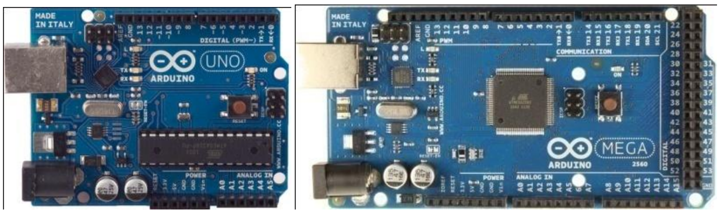


Figure 14 Arduino Uno and Arduino Mega [31]

Also another controller unit which is called servomatrix [30] (Fig. 15), can be used for control of our hybrid– robot. Servomatrix is a control card which able to drive sixty four servo motors simultaneously. This card cannot be used in our systems due to some disadvantages. Servomatrix is a huge card, it is two times larger than the Arduino mega, and it takes a lot of space on our systems. Another disadvantage of servomatrix is that it requires another microprocessor card like Arduino, displayduino, for programming. These disadvantages make the servomatrix disadvantageous for our hybrid– robot.

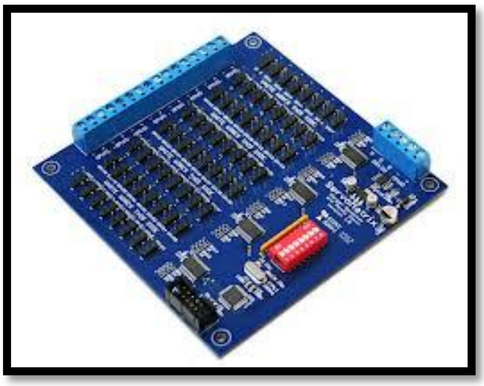


Figure 15 ServoMatrix [30]

3.1.4.1.2 Actuators:

Actuators are described as a motor for moving or controlling a mechanism or system. They operated by source of energy, and controlled by means of micro control unit. There are several types of actuators that exist in literature, like hydraulic, pneumatic, electric, and mechanical actuators. First alternative is hydraulic actuators, hydraulic actuators uses oil pressure for motion, they are very powerful actuators, and specifications of the hydraulic actuators are given in [29]. Hydraulic actuators have some disadvantageous, these can be listed like this. They are very powerful but control of the hydraulic actuators harder than the others, another disadvantage is hydraulic actuators requires some extra tools for working such valves regulators. These extra tools gives extra weight to robot. Also hydraulic actuators as not clean as the other actuators such pneumatic actuators, dc motors, and muscle wires, they use oil for motions, for these reason working and maintain of the hydraulic actuators is too hard. Another actuator example is pneumatic actuators [5 29], pneumatic actuators uses air pressure for motion, they also uses extra tools for working. Pneumatic actuators can be used in hybrid robot but, price and control of these actuators much more than the others. Third actuator example is muscle wire [30]. Muscle wire can be described as artificial muscle. When electric current apply to the muscle, it behaves like a human muscle, but power of the muscle wire is lower than the other actuators. Also control of them is too hard. Last actuator example is dc servo motor [28]. Servo motors have its own close loop controller mechanism. Usage of the servo motor is easier than the other actuators, they are also cheap and require low energy for working [28]. According to these information evaluation criteria of the actuators are listed in Table 14.

Table 14 Evaluation of the Actuators

Actuator Type	**Power Consumption**	**Torque**	**Clean**	**Control**	**Cost**
Servo Motor	X	XX	X	X	X
Hydraulic	XXX	XXX	XXX	XXX	XXX
Pneumatic	XXX	XXX	X	XXX	XXX
Muscle Wire	X	X	X	XX	X

(X Low, XX Moderate, XXX High)

As a result of this evaluation table, servo motor is chosen for manufacturing of hybrid-robot. They can produce more power with less consumption of energy. They are also clean, cheap and controlled easily by means of a microprocessor. Side view of the servo motor is shown in Figure 16.

Figure 16 Servo Motor [28]

3.1.4.2 Mechanical Parts:

Body of the hybrid consists two parts. First part of the body is chassis, this can be named as main body of the hybrid robot. Other parts are named as legs of the robot. In this part of the thesis detail design of the mechanical parts of the hybrid robot are discussed. The main criteria in manufacturing of hybrid robot is material selection.

Material selection is important for hybrid robot design. Materials that are used in the hybrid robot should be in reasonable weight and strength. Previous studies show that, there are many alternative materials for the manufacturing of the hybrid robot. These are aluminum, plexiglass, ABS, plastic, etc. If these alternatives are compared, each has advantages and disadvantages. The main criteria in our case studies, hybrid robot should be having reasonable weights. In some studies researchers used aluminum as a main material of their hybrid robot. Material properties of the aluminum is given in [24 26]. Aluminum is a metal based material; its strength is reasonably high, but it has 2.70 g/cm^3 density, this means the usage of aluminum makes the hybrid robot heavier than the other materials. For these reasons, aluminum is not proper material for our case study. Another alternative which shown in the literature is injected plastic. This is a good choice for our case studies, its lighter and tough material. But also it has some disadvantages, plastic injection is an expensive operation, also it takes long time. In plastic injection, manufacturer must produce a mold for all of the parts of the robot. Injection and cooling of the material takes long times. For these reasons usage of injected plastic is not proper for our case studies. ABS is another suitable material for our case studies in literature material properties of the ABS are given [25, 27], it has 1.04 g/cm^3 density it means that it is too lighter than the aluminum and the other materials. Injection of the ABS is done via Rapid prototyping machine, this machine can be described as a 3D printing machine, injection operation of the ABS takes long time and its price is more expensive than the other materials[27] for these reason ABS is not suitable for the our case study. And the last material that can be chosen is plexiglass [22, 23]. Plexiglass is a polymer material, often used as a lightweight or shatter-resistant alternative to glass. As it is mentioned, plexiglass is a light material it has 1.18 g/cm3 density, this is an important advantage for hybrid robot, it is also shatter – resistant. Processing of plexiglass is done via using laser cutting. It is also easier than other materials, these advantages makes the plexiglass the most suitable choice for our hybrid– robot. Table 15 gives the brief summary of evaluation criteria of the materials detailed. Figure 17 refers to selected material (plexiglass) for manufacturing of case studies.

Table 15 Evaluation of the Materials

	Strength	**Density**	**Cost**
Plexiglass	**XX**	**XX**	**X**
Aluminum	**XXX**	**XXX**	**XX**
ABS	**XX**	**X**	**XXX**

(X Low, XX Moderate, XXX High)

Figure 17 Plexiglass[23]

3.1.4.2.1 Chassis:

Chassis of the hybrid robot is made from plexiglass material, sizes of the chassis is arranged to the dog designed in the cad program, Figure 18 represents to the computer aided design of the dog chassis.

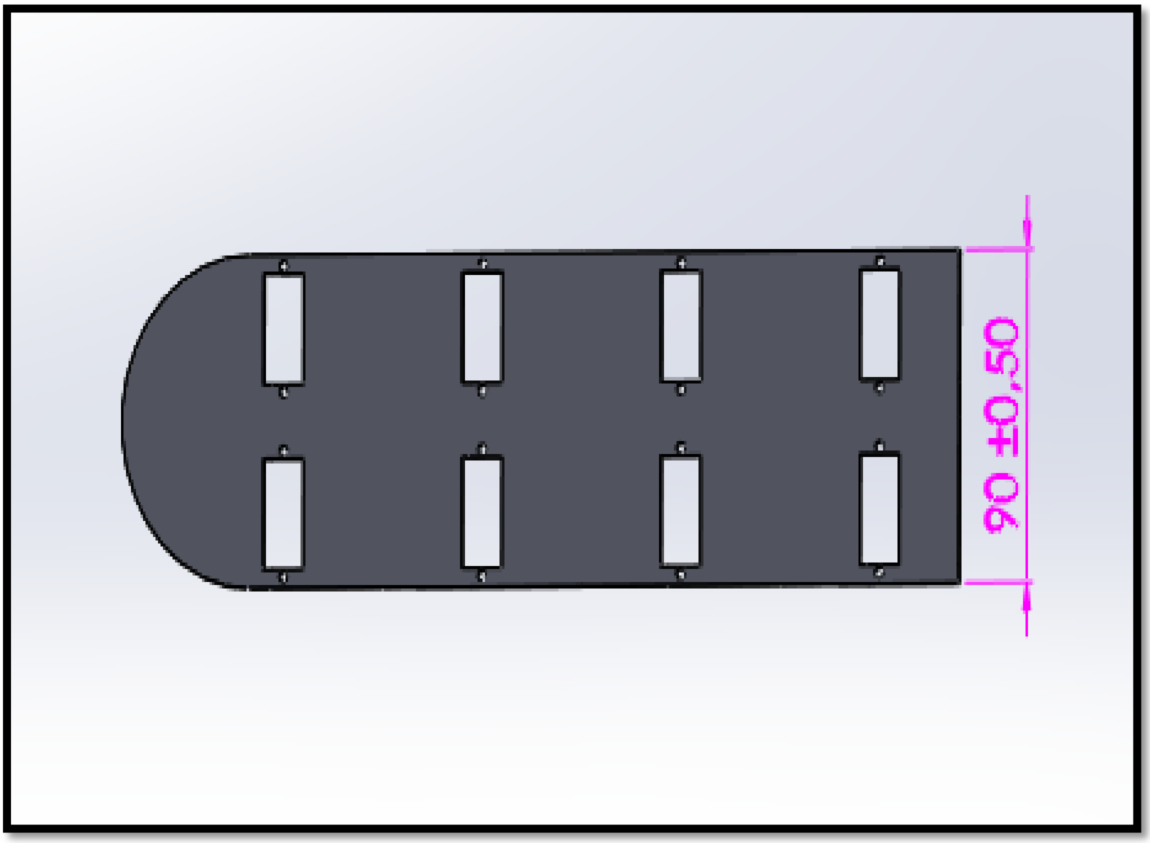


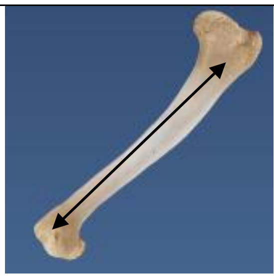
Figure 18 CAD design of the Hybrid Robot Chassis

Engineering drawing of the chassis is given in the appendix part of the thesis. As it is shown in the figure, there are 8 hole exist on the chassis. These holes are located on chassis for servo motors that provide the walking motion of the hybrid robot.

3.1.4.2.2 Legs:

Legs of the hybrid robot are sized according to the dog robot sizes that mentioned in [3]. Fore and hind legs of the hybrid robot are designed similar with dog robot, but middle legs are manufactured from one part. Sizes of the legs are described in Table 16.

Table 16 Sizes of the Legs

Limbs	**Forms**	**Max. Dimensions for the selected dog (Terrier)**
Humerus		Length = 50 mm
Radius and Ulna		Length = 130 mm
Forepaw		
Femur		Length = 100 mm Continued

Tibia and Fibula		Length = 150 mm
Hindpaw		

In the light of these information different design alternatives for the hybrid robot are generated. These alternatives can be described in Table 17.

Table 17 Design Alternatives for Hybrid Robot

#	**Material**	**Joint**	**Actuator**	**Controller**
1	Plexiglass	Hinge Joint	Servo Motor	Arduino
2	Plexiglass	Hinge Joint	Pneumatic	Arduino
3	Plexiglass	Hinge Joint	Muscle Wire	Arduino
4	Aluminum	Hinge Joint	Servo Motor	Arduino
5	Aluminum	Hinge Joint	Pneumatic	Arduino
6	Aluminum	Hinge Joint	Mucle Wire	Arduino

From this table, it is clear that 6 design alternatives are generated. According to evaluation of the materials, first alternative is selected as a most suitable design for hybrid robot. After that, computer aided drawing (CAD) of the hybrid robot is achieved.

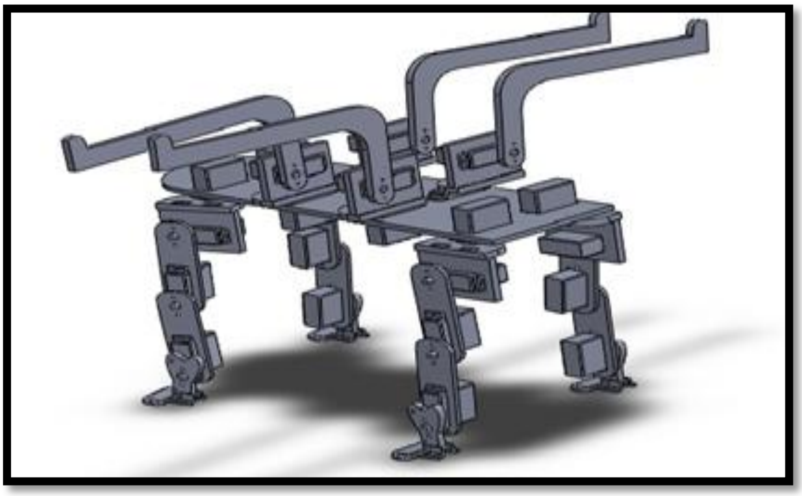


Figure 19 Design of the Hybrid Robot via CAD Program (Dog Form)

As it is shown in the figure, this is the art design of the hybrid robot and this sketch does not includes the dimensions and constraints of the hybrid robot. From the figure it is seen that, hybrid robot have 8 legs front and hind legs have different morphologies from the middle legs. These four legs provide the dog locomotion of the hybrid robot. When the robot takes this position, middle legs wait parallel position to the ground. Figure 20 shows the second initial position of the hybrid robot.

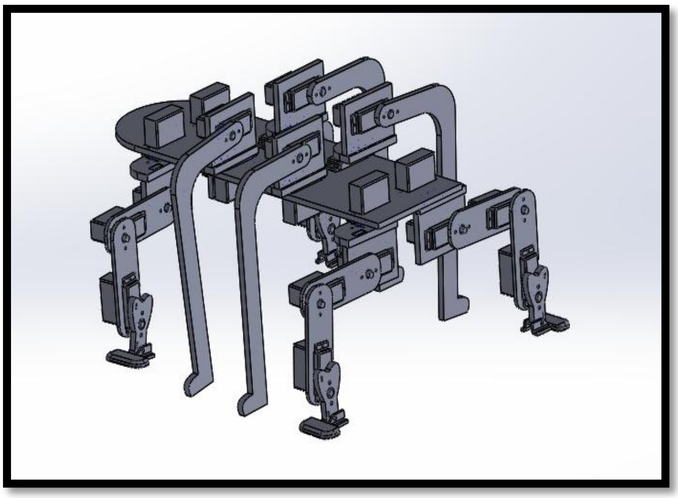


Figure 20 Second Position of the Hybrid Robot (Lobster Form)

When robot takes this position, middle legs touchdown to the ground and robot walks like a lobster.

This locomotion action is controlled by 24 mini servo motors. These servos perform angular motion in one axis and provide motoric tasks of the robot. These servo motors are controlled by microcontroller. This control unit provides PWM (Pulse width modulation) signals for control the motions of the servo motors. Details of the design are discussed in the preliminary and detailed design parts of the thesis.

3.1.5 Test Plans and Test Procedures:

After design and manufacturing of the hybrid robot are finished, tests are performed. After the locomotion of the hybrid robot is provided, motion of the robot is recorded via high speed camera. After that these videos are analyzed in tema motion program and output data of the hybrid robot are matched with the data taken from the literature.

As a conclusion in this part conceptual design of the hybrid robot is performed. Detail of the problem definition, design alternatives and test procedure of hybrid robot are discussed. Further detail of the system, is discussed in the further part of the thesis.

3.2 PRELIMINARY DESIGN:

Preliminary design means the embodiment design, transition phase between conceptual and detailed design parts. In previous chapter, conceptual design of the hybrid robot is discussed. As it is said before conceptual design is the artistic design of the system. In preliminary design phase detail of the desired system are decided. In the conceptual design part one alternative is chosen as a main design for hybrid robot. In this alternative servo motors, plexiglass, and Arduino microcontroller are chosen as a design materials. During this part of the thesis details of these materials are discussed.

3.2.1 Servo Motor:

As it is said before servo motor is decided as an actuators. Servo motors are dc motors that, allows precise control of angular position, velocity and acceleration. There are many alternatives for servo motors exist in literature [28], these motors can be separated according to its dimensions, torque, and gear types.

Table 18 Servo Motor Alternatives

Name	Gear Type	Torque	Speed	Price
ES08MA	Metal	2,0 kg/cm	0,10 sn/60º	56,64 TL
HD-2216MG	Metal	3,90 kg/cm	0,13 sn/60º	129,80 TL
ES08MD	Metal	2,0 kg/cm	0,10 sn/60º	42,48 TL
Dgservo	Metal	3.2kg/cm	0,18 sn/60º	41,54 TL

Expected weight of the hybrid robot is 2.5kg. accoridng to this information suitable servo motors are listed. Most important property of the servo motor is torque. When torque of servo motor is high, robot can carry itself more easily. According to its torque values HD-2216MG and Dgservo are suitable for the hybrid robot. When their price are compared Dgservo is selected as the most suitable servo for hybrid robot.

3.2.2 Plexiglass:

In conceptual design part, plexiglass is selected as a main material of chasis and legs. As it is said before plexiglass is a polymer material it has 1.18 g/cm^3 density. In hybrid robot 4500 cm^2 plexiglass is used. Its weight changes according to the its thickness. From the basic density formula Equation 3.1, weights of the plexiglasses are calculated.

$$d = \frac{m}{V} \quad (3.1)$$

For 5mm thickness:

$$1.18 = \frac{m}{4500*0,5} \quad (3.2)$$

$$m = 2655g$$

For 3mm thickness:

$$1.18 = \frac{m}{4500*0,3} \tag{3.3}$$

$$m = 1593g$$

These are the total weights of the plexiglasses according to their thickness. İn addition to these values, weights of the servo motors are added to the total weight, 24 servo motors are used in the design of the hybrid robot. Weight of the one servo motos is 20g total weight of the servo motors can be calculated like this.

$$TotalServoMass = 24*20 = 480g \tag{3.4}$$

İn the lights of these informations total weight of the hybrid robot is equal to 3135g for 5mm thichkness, 2083g for 3mm thichkness. Dgservo motors generate 3.2 kg/cm torque so that 5mm thickness can be used for design of the hybrid robot.

3.2.3 Microcontroller:

İn this section detail of the selected microcontroller is discussed. İn conceptual design part arduino is selected as a microcontroller unit of the hybrid robot. The aim of the microcontroller is, controlling the servo motors in hybrid robot, microcontroller behaves like human brain and sends the angle data to the servro motors. As it is said before arduino is selected as a microcontroller unit, in literature several models of arduino are exist [31]. Arduino uno, and arduino mega are the most famous microcontroller cards of this microcontroller family. Arduino microcontroller cards use Atmega thpe microcontrol chips, and generally they operate with 5V. Coding of arduino is easier than the other microcontroller cards, it can be coded easily via arduino coding language or MATLAB/Simulink tool box. Two type of arduino controllers are compared in Table 19.

Table 19 Compare of the Arduino Microcontrollers[31]

	Arduino Uno	Arduino Mega
Microcontroller	ATmega328	ATmega2560
Operating Voltage	5V	5V
Input Voltage (recommended)	7-12V	7-12V
Input Voltage (limits)	6-20V	6-20V
Digital I/O Pins	14 (of which 6 provide PWM output)	54 (of which 15 provide PWM output)
Analog Input Pins	6	16
DC Current per I/O Pin	40 mA	40 mA
DC Current for 3.3V Pin	50 mA	50 mA
Flash Memory	32KB (ATmega328) of which 0.5 KB used by boot loader	256 KB of which 8 KB used by boot loader
SRAM	2KB (ATmega328)	8 KB
EEPROM	1KB (ATmega328)	4 KB
Clock Speed	16 MHz	16 MHz

When they are compared, arduino uno has 14 digital I/O pins, it drives up to 14 servo motors, on the other hand arduino mega drives 54 servo motos in the same time. Another comparison criteria is the microcontroller type, arduino mega has Atmega2560 mircontroller, this controller is better than Atmega328 type microcontroller.

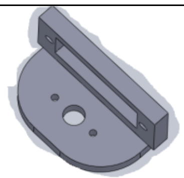
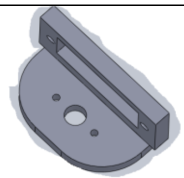
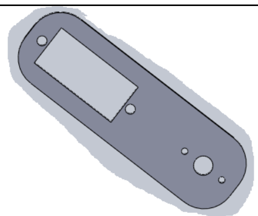
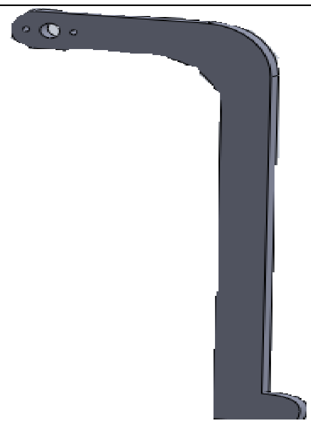
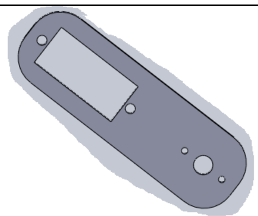
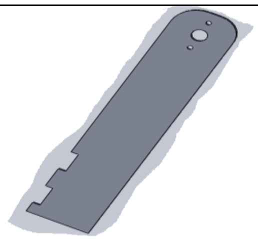
3.3 DETAILED DESIGN:

Detailed design last part of the design project. In detailed design all detail of the project are revealed. Final product, control, and locomotion of the hybrid robot are discussed.

3.3.1 Final Product:

As a final product CAD design of the hybrid robot is performed and shown in previous sections of the thesis. In final design sizes of the hybrid robot are arranged and final design of the robot is complete. At first body of the hybrid robot is designed, CAD model of the body is shown in the previous parts, after then matching of the leg structures of real biological systems and engineering structures is performed. Table 20 is represented the matched engineering and biological structures of the hybrid robot.

Table 20 Matched Forms and Structures of Lobster

Limbs	**Matched Engineering Form/Structure**	
	Fore / Hind Legs	**Middle Legs**
Thorax-Coxopodite		
Meropodite (Femur)		
Carpopodite + Propodite (Tibia)		
Daciylopodite		

As it is seen from the table legs of the hybrid robot are designed like this form. After then material selection is performed, compare of the materials is performed in the previous section of the thesis. As a result plexiglass chosen as a material of the legs.

3.3.1.1 Manufacturing:

Manufacturing process begins with the engineering drawings, all drawings of the hybrid robot are created in CAD program. Figure 21 represents the example of the one of the engineering drawing.

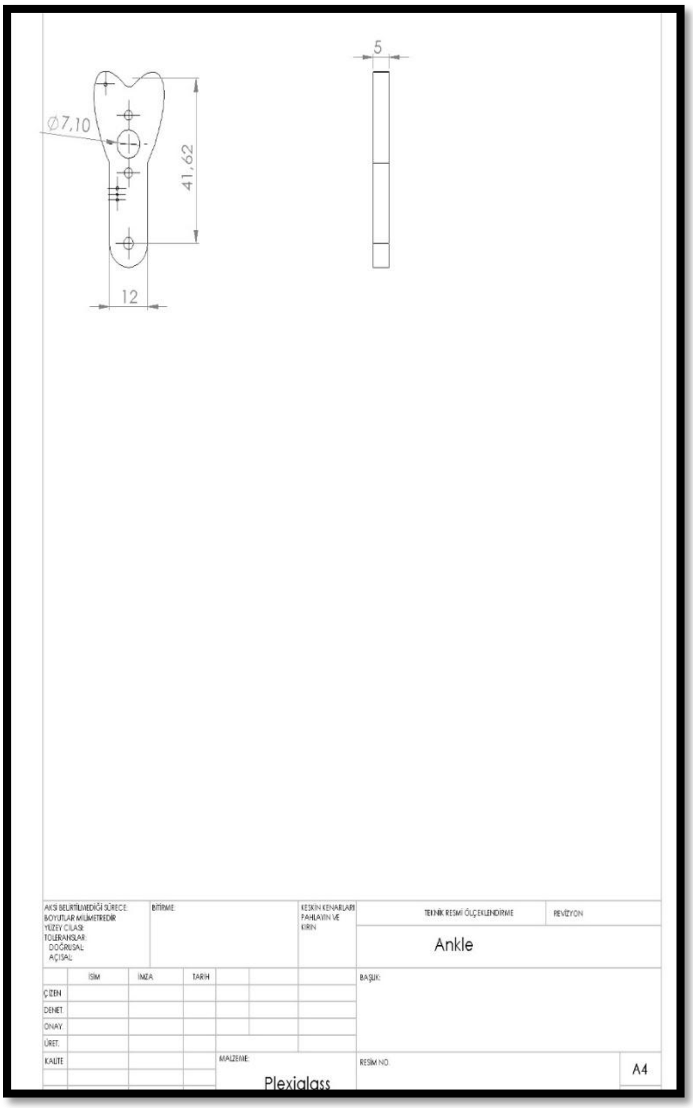


Figure 21 Engineering Drawing Example

These engineering drawings are collected in one drawing page and transferred to the laser cutting machine, this machine cuts polymer materials by means of laser beam. Figure 22 represents the laser cutting machine.

Figure 22 Laser Cutting Machine

After manufacturing of the mechanical parts are completed, connection between the parts are designed. Joints of the dog legs is already given in [12], in addition to the these joints walking legs joints of the lobster is added all legs of hybrid robot. These joints can be described as, T-C (thorax – coxopodite), C-B (coxopodite- basi), I-M (basi-meropodite), M-C (meropodite-carpopodite), C-P (carpopodite-propodite) and P-D(propodite-daciylopodite). Ayers (2004) [14] described T-C, C-B and M-C joints of the lobster as a three major leg joints of the lobster, these joints provide the locomotion of the lobster. Joint matching of the hybrid robot is shown in the Table 21.

Table 21 Matched Joints of Hybrid Robot

T-C (thorax – coxopodite)	C-B (coxopodite- basi)	M-C(meropodite- carpopodite),
hinge joint	hinge joint	hinge joint

Servo motor are used as a joint, for connecting two different parts of the hybrid robot. In fore and hind legs four servo motors are used for locomotion, but in middle legs two servo motors are used.

As a final product manufacturing of the hybrid robot is completed. Figure 23 represents the final product.

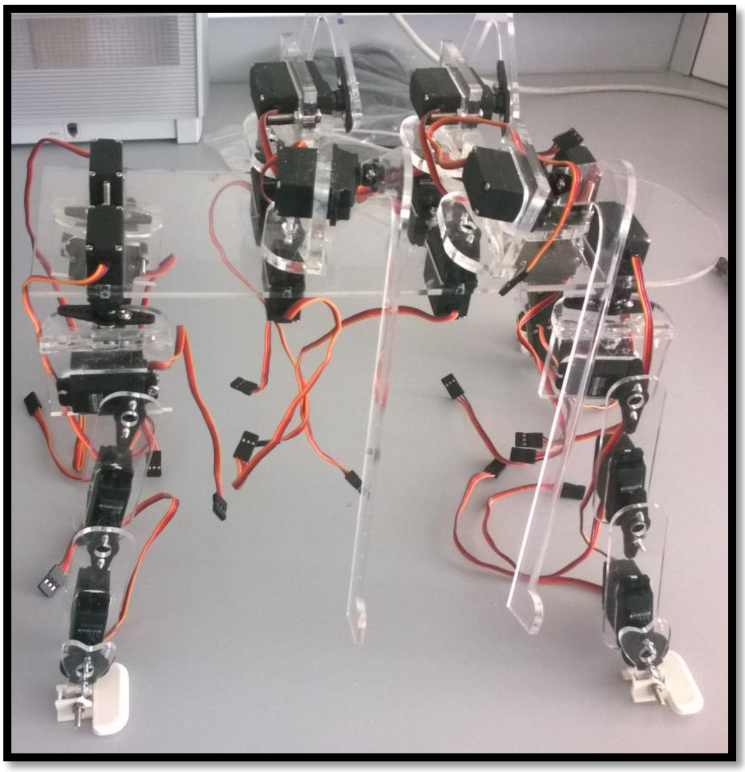


Figure 23 Final product

3.3.1.2 Control:

After manufacturing, next step is control of the hybrid robot. As it is mentioned before Arduino mega is used as a microcontroller unit of the hybrid robot. Control of Arduino is easier than the other microcontrollers. MATLAB is used for control software of the Arduino, angle data of the dog and lobster are transferred to the Arduino by means of simple block diagrams. Figure 24 represents the control model by means of block diagrams of one motor.

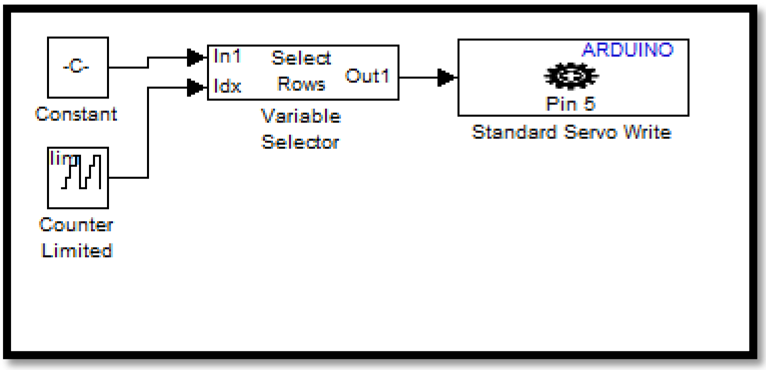


Figure 24 Sample control model by means of block diagrams

From this figure, constant data generator sends, angle data that taken from the video records to the variable selector, variable selector sends angle data one by one to servo motor. This control algorithm is just only one motor. In Figure 25 overall control algorithm of the hybrid robot is presented.

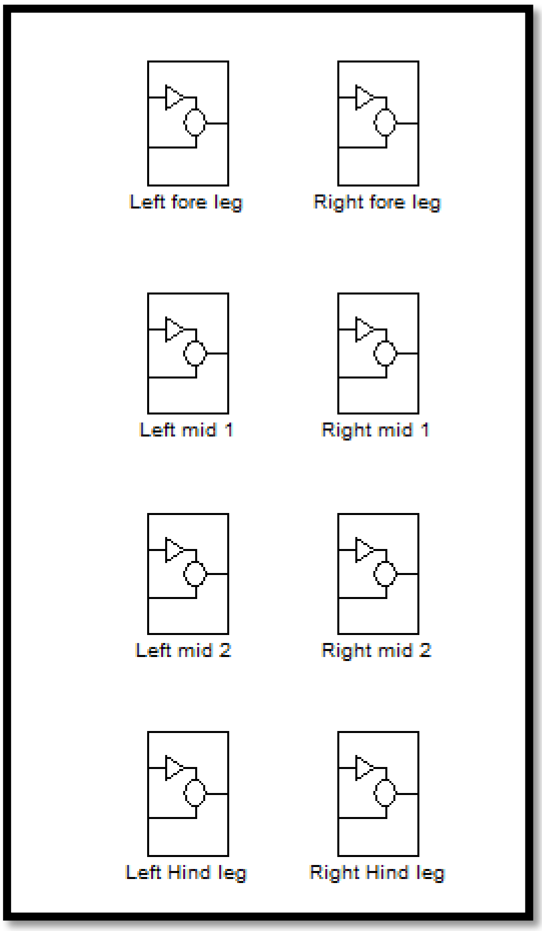


Figure 25 Overall control model of hybrid robot

This is the complete control algorithm of the hybrid robot, each leg of the robot defined as a subsystem and each subsystems includes four basic servo motor control algorithm. Figure 26 represents the inside of the one subsystem.

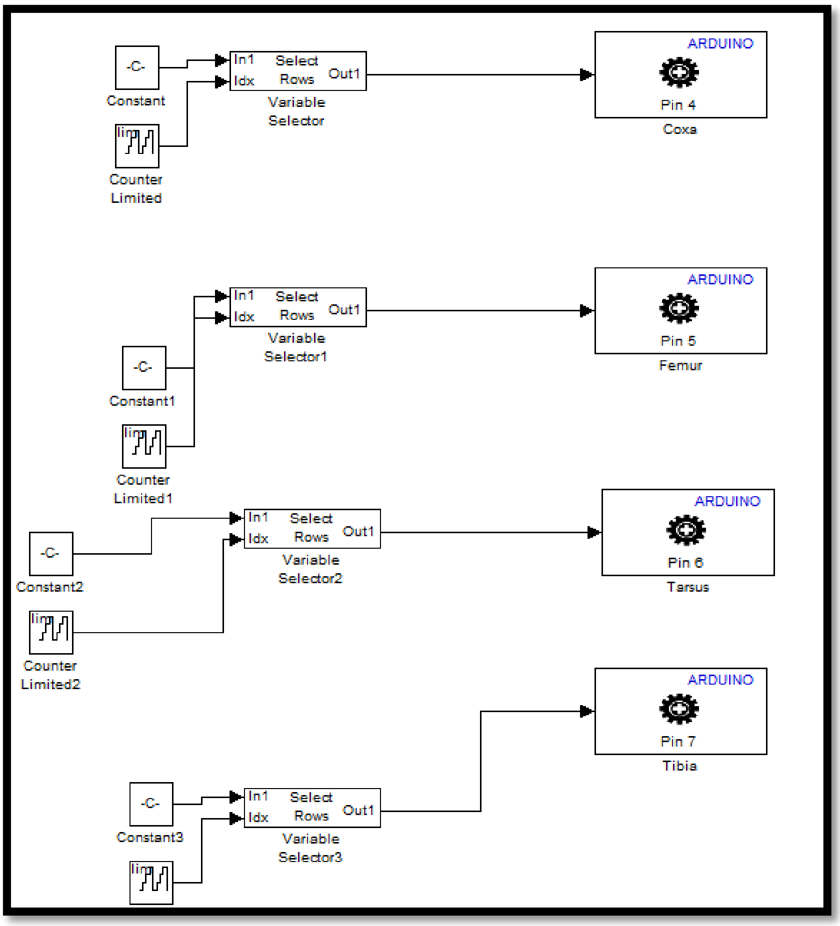


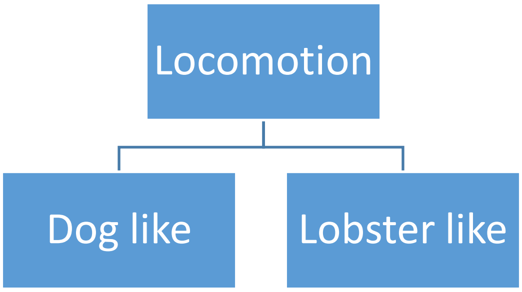
Figure 26 Inside of the one subsystem

Angle data that applied to the system will be given in the appendix part of the hybrid robot.

3.3.1.3 Locomotion:

In this part locomotion system of the hybrid robot is discussed. Locomotion is the main task of the hybrid robot, this robot has two different locomotion types, and these locomotion types are defined in Table 22.

Table 22 Locomotion types of the hybrid robot



3.3.1.3.1 Dog like Locomotion:

As it was mentioned before, hybrid robot should walk like a real dog. In dog form robot takes first initial position and then it begins its locomotion. Fist position of the robot is described in Figure 27.

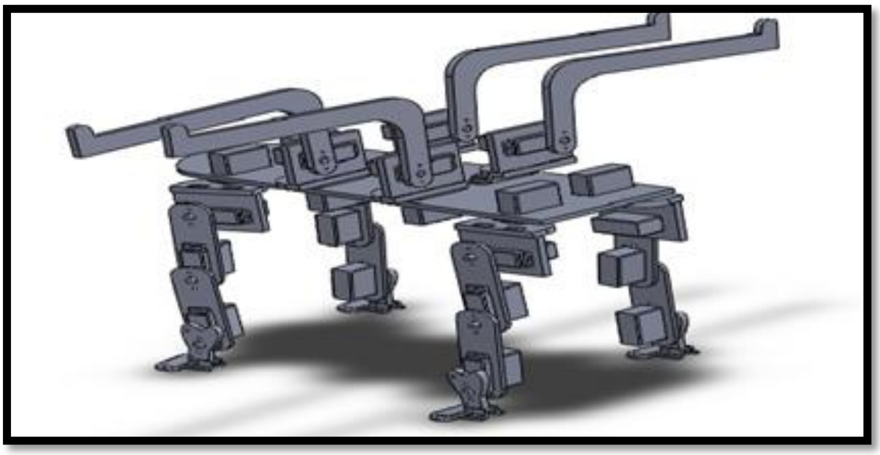


Figure 27 Fist Position of the Hybrid robot

As it is shown in the figure, fore and hind legs of the robot touchdown to ground and other legs are parallel to the surface. In this position robot is waiting for angle data that are supplied from the microcontroller unit. Angle data gathered from the video records that are mentioned in [3]. These data are represented in Figure 28.

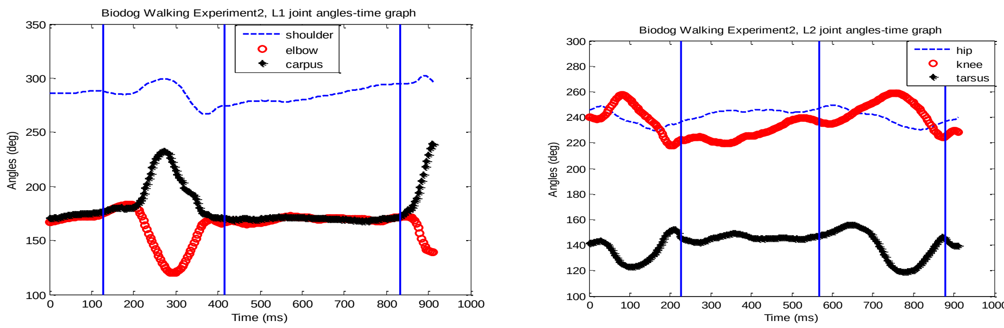


Figure 28 Recorded Video Data From Real Dog

These data are loaded to the microcontroller platform via MATLAB computer program. Detail of the MATLAB models are given in the control chapter of thesis.

3.3.1.3.2 Lobster like Locomotion:

Lobster walking is the second task of the hybrid robot. As it is said before this robot mimics the lobster locomotion on rough surface. When robot takes second position, its middle legs touchdown to ground surface and robot begins to walk like lobster. Lobster locomotion data are taken from the Ayers [13, 14] studies, Figure 29 represents the locomotion data of the lobster.

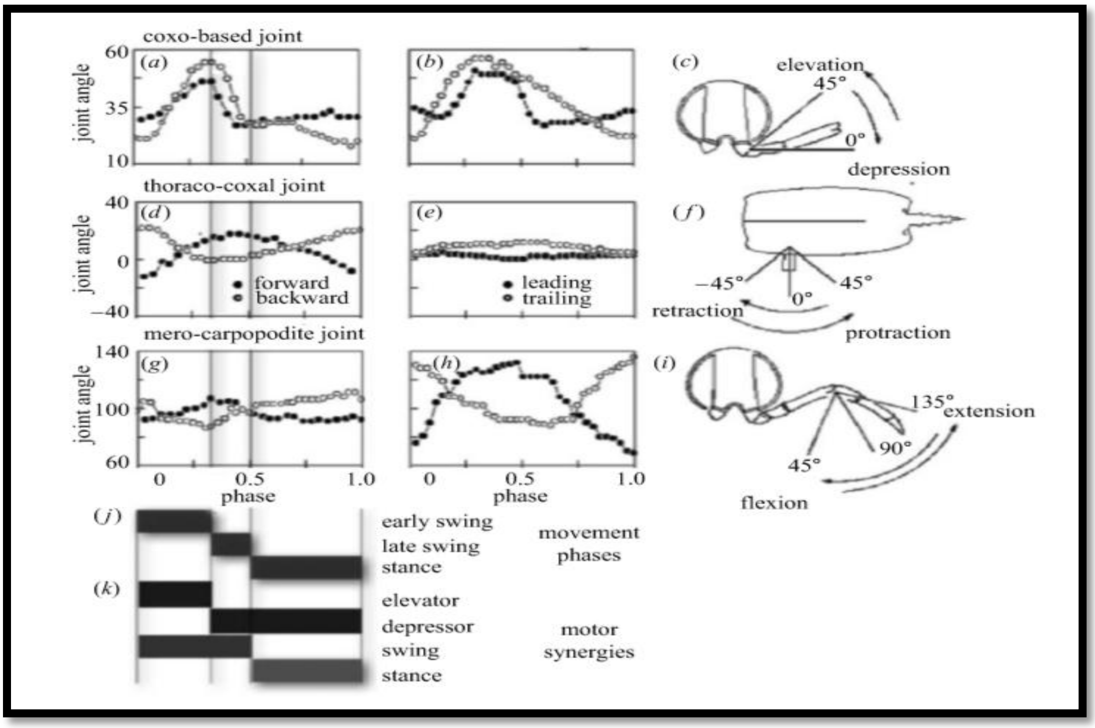


Figure 29 Locomotion data of the Lobster[13, 14]

Joint angles of the lobster are not seen clearly in these graphics, because of this reason graphics are transferred to the MATLAB image acquisition tool box and angle data are gathered via MATLAB code. Following figures represent the gathered data of the lobster from the graphics.

Coxabased joint:

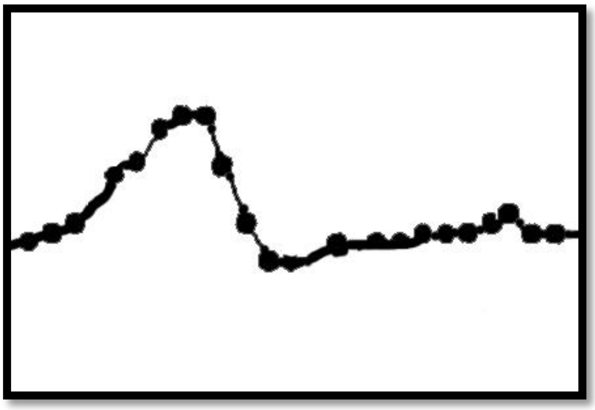


Figure 30 Cleared Table Data

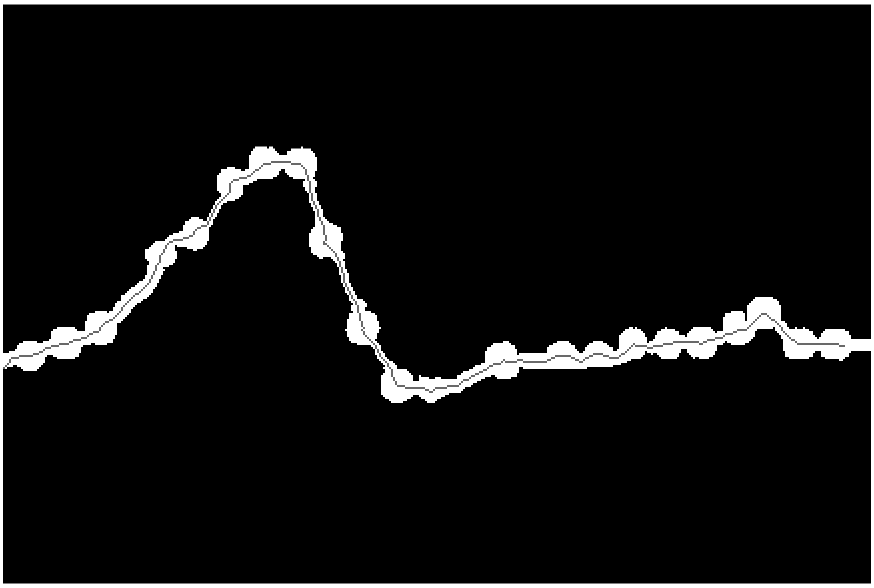


Figure 31 Middle Line of the Data

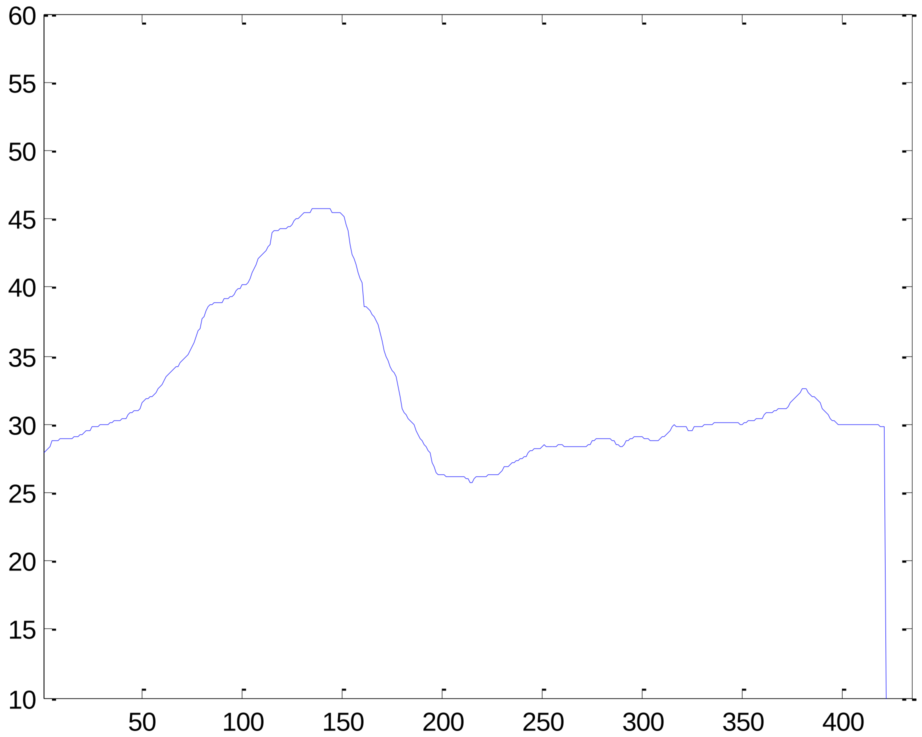


Figure 32 Gathered Angle Data

Output data of the graphics are given in the discussion part of the thesis. As a conclusion in this part preliminary design of the hybrid robot is performed. In the next chapter detailed design of the hybrid robot will be discussed.

3.3.2 Performance Test:

In this section performance tests of the hybrid robot will be discussed. After manufacturing of hybrid robot is completed, some performance tests are performed on robot. Aim of these test is check the performance of hybrid robot, whether its performance enough or not. Performance criteria of the hybrid robot can be described like this; Hybrid robot should catch the walking pattern of the real creatures. Test setup is shown in Figure 33. This setup includes 2 bars for hang the robot on, and blue background.

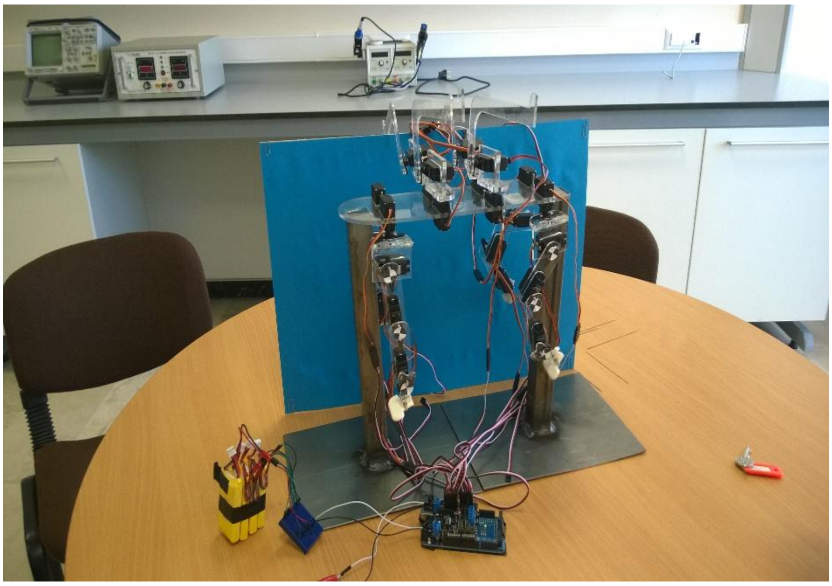


Figure 33 Test Setup

Performance test can be describe like this, hybrid robot is hanged on a carrier platform, and initialized for first position. In first test dog locomotion of the robot is controlled. Robot begins to locomotion on carrier platform and, while it is moving, video records of the robot is captured by means of high speed video camera. Figure 34 represents the high speed camera.

Figure 34 Photron MC2 Fast Cam

These recorded data are transferred to the tema motion program, for locomotion analysis. Figure 35 represents the motion analysis program. Result of the analysis are given in the results and discussion chapter.

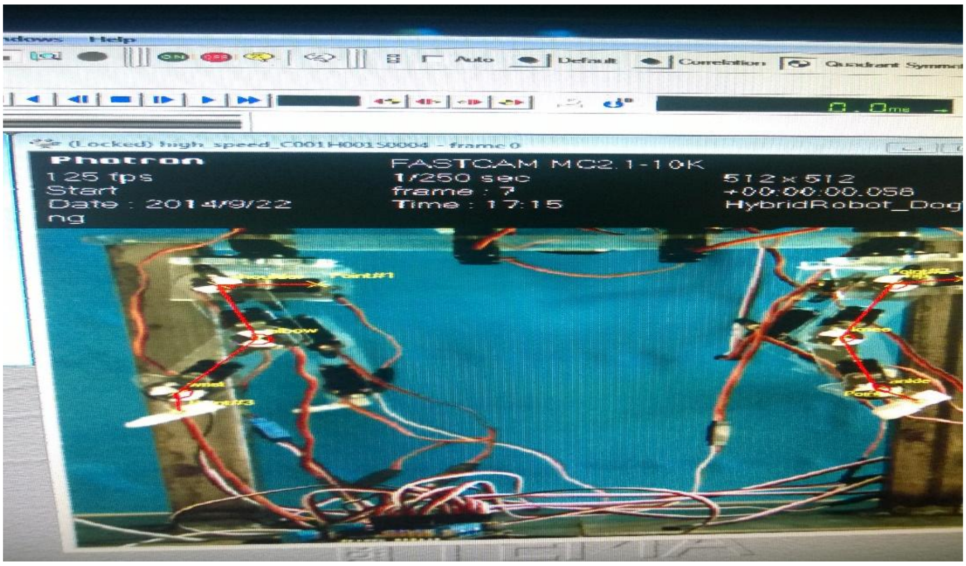


Figure 35 Motion Analysis Program

CHAPTER 4

RESULTS, DISCUSSION AND CONCLUSION

4.1 RESULTS AND DISCUSSION:

In the first part of this chapter test results are discussed. Test setup is shown in previous part, in this test dog locomotion of the hybrid robot is analyzed. Tema motion program is used as a motion analyze program. This program gathers data from the captured motion via fast cam. In this test some specific markers are placed on legs of the robot. These points can be described as shoulder, elbow, wrist for fore legs, hip, knee, ankle for rear legs. These points are observed by high speed camera during the locomotion and angle data are gathered according to its motions. Figure 36 shows the markers are placed on the legs.

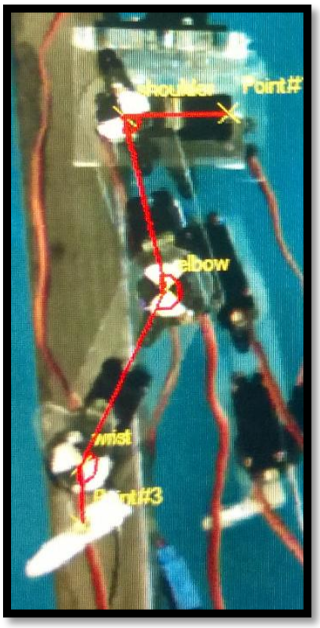


Figure 36 Markers

As it is seen from the figure three points are placed on leg, for analyze, extra two points are chosen as reference points, point 1 is referred to base reference of the robot. According to this point angles that performed by shoulder joint, is calculated. Figure 37 refers to the shoulder angle data that are gathered from the video record and real dog data.

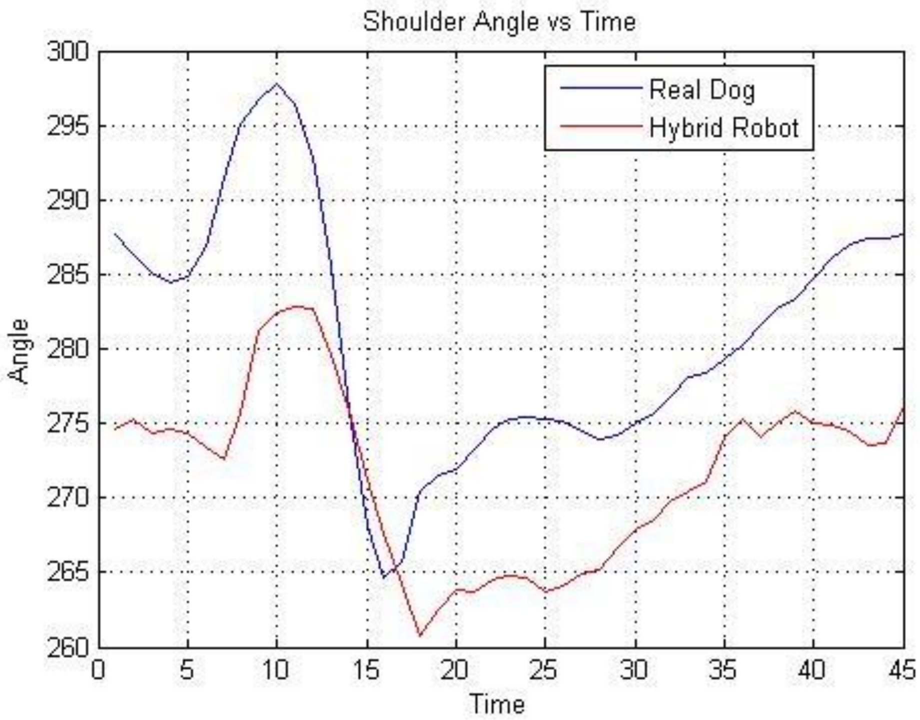


Figure 37 Shoulder Angle Data

As it is seen from the figure, blue line refers to the real dogs shoulder data, red line is refers to angle data that taken from the video capture. It is clear that walking pattern of the real dog and hybrid robot are matched. There is a small difference exists between the angles, which is caused by mechanical factors, such as the response time of the servo motors, when the response time of the servo motor is decreased, time difference between two graphics is reduced. Next figure represents the angle data of elbow joint with respect to the shoulder.

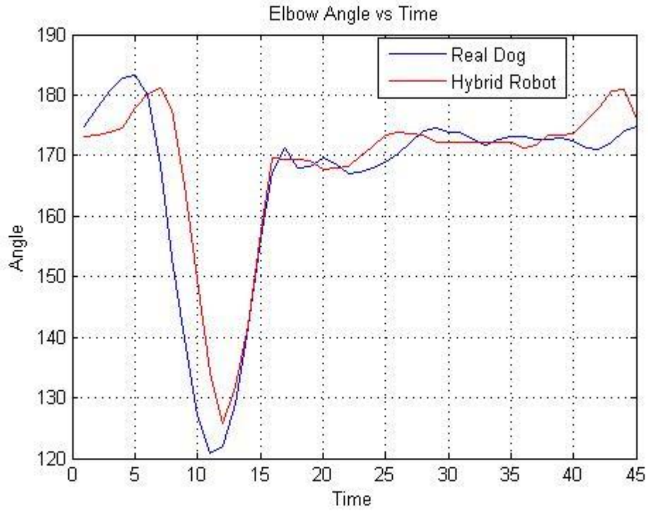


Figure 38 Elbow Angle Data

In this figure real dog data are matched with hybrid robot data, but again a difference exists between the two data again caused by the mechanical factors. Next figure represents the wrist angle data with respect to elbow and ground.

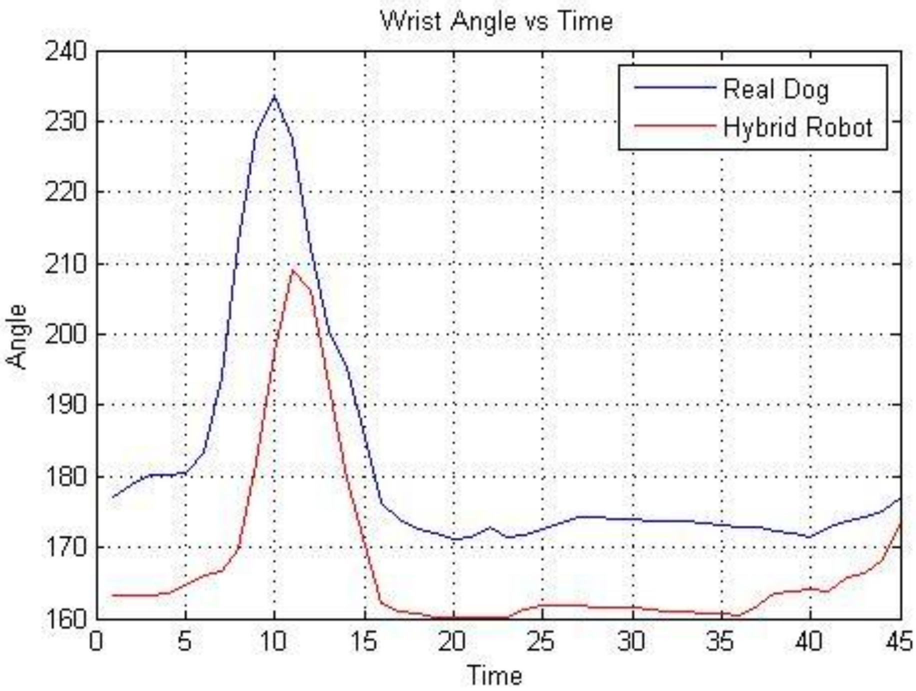


Figure 39 Wrist Angle Data

These figures represent the angle data that are gathered from the video captures for hind legs of the robot. Next three figures represent the angle data of the rear leg of the hybrid robot.

Figure 40 Hip Angle Data

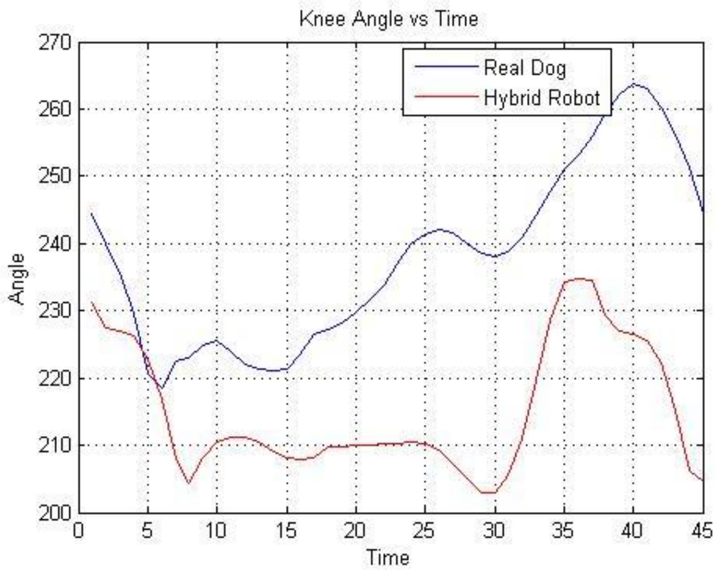


Figure 41 Knee Angle Data

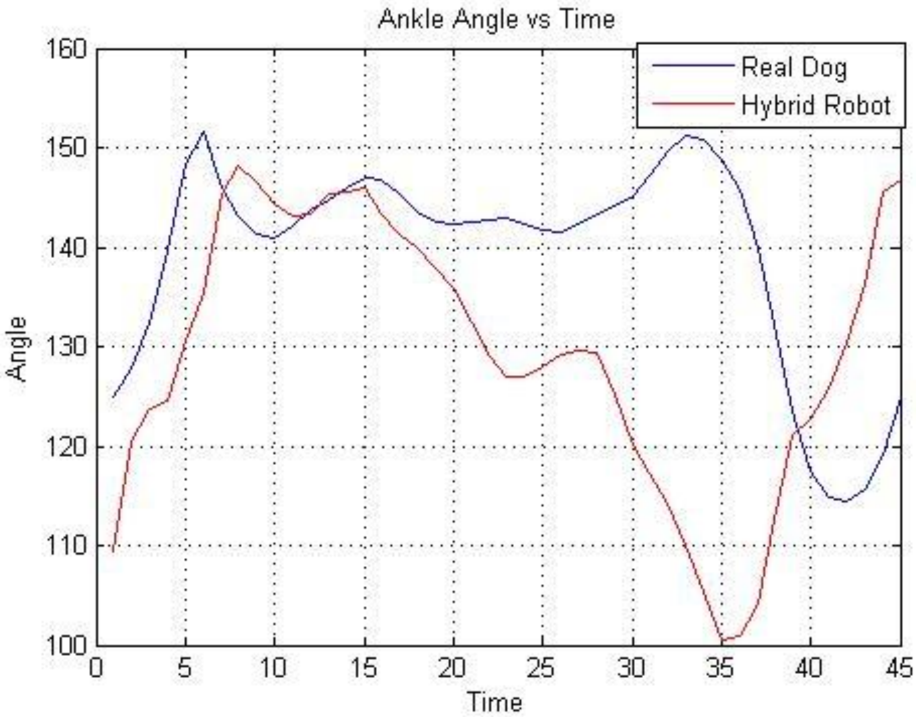


Figure 42 Ankle Angle Data

In these figures, it is clear that walking pattern of the rear of the hybrid robot and real dog are matched, but in ankle joint walking pattern of the hybrid robot is different from the real dog, this difference caused by difference of the reference points of real dog and hybrid robot.

When the lobster locomotion of the hybrid robot is observed, robot also catches the walking pattern of the lobster, but the due to lack of experimental setups, analysis of the lobster locomotion cannot performed in this thesis. Analysis of the lobster locomotion requires 3 – D motion analysis setups, because of this lobster locomotion of the hybrid robot is observed experimentally.

4.2 CONCLUSION:

As a conclusion, in this thesis design and manufacturing of the hybrid robot is achieved. When the hybrid robot is compared with the existing systems, hybrid robot includes the general features of the two different creatures. This robot performs the locomotion of the lobster and the dog in one chassis. When it is compared with the other octopod robots, hybrid robot performs two different animal's locomotion. The number of the locomotion types can be increased in future studies, and the hybrid robot design given in this study allows different locomotion types. This robot can be used for other locomotion studies in the future. Also in this thesis locomotion analysis of the hybrid robot is performed. At the beginning of the thesis, it was said that reaction forces on the legs are ignored. Hybrid robot walks on a carrier platform, and this test setup ignored the forces caused by the ground reaction, and frictions. The aim of these tests was to observe the walking pattern of the hybrid robot. From these tests it is seen that hybrid robot mimics the dog locomotion, with some deviation for actual results in the graphics. These differences are caused by mechanical the restrictions, and reference point errors. In the previous sections comparison of the servo motors were discussed. Servo motors have different response times, and this results in errors in the time axis of the graphics. When the response time of the servo motor is decreased also the error in the time axis is decreased. Difference of the reference points also cause errors on graphics. These differences causes difference in angles. When they are compared errors exist between the real dogs and hybrid robots locomotion angles. These errors are directly caused by the differences of the reference points of the real dog and the hybrid robot. On the other hand, these graphics are unique for the servo motors. When the actuators are changed, errors in the graphics will also change. Also when the dynamic forces (reaction forces, friction, and vibrations) act on hybrid robot these graphics show differences. In further studies reasons, of the errors can be analyzed in more detail and mathematical modeling of the errors can be created.

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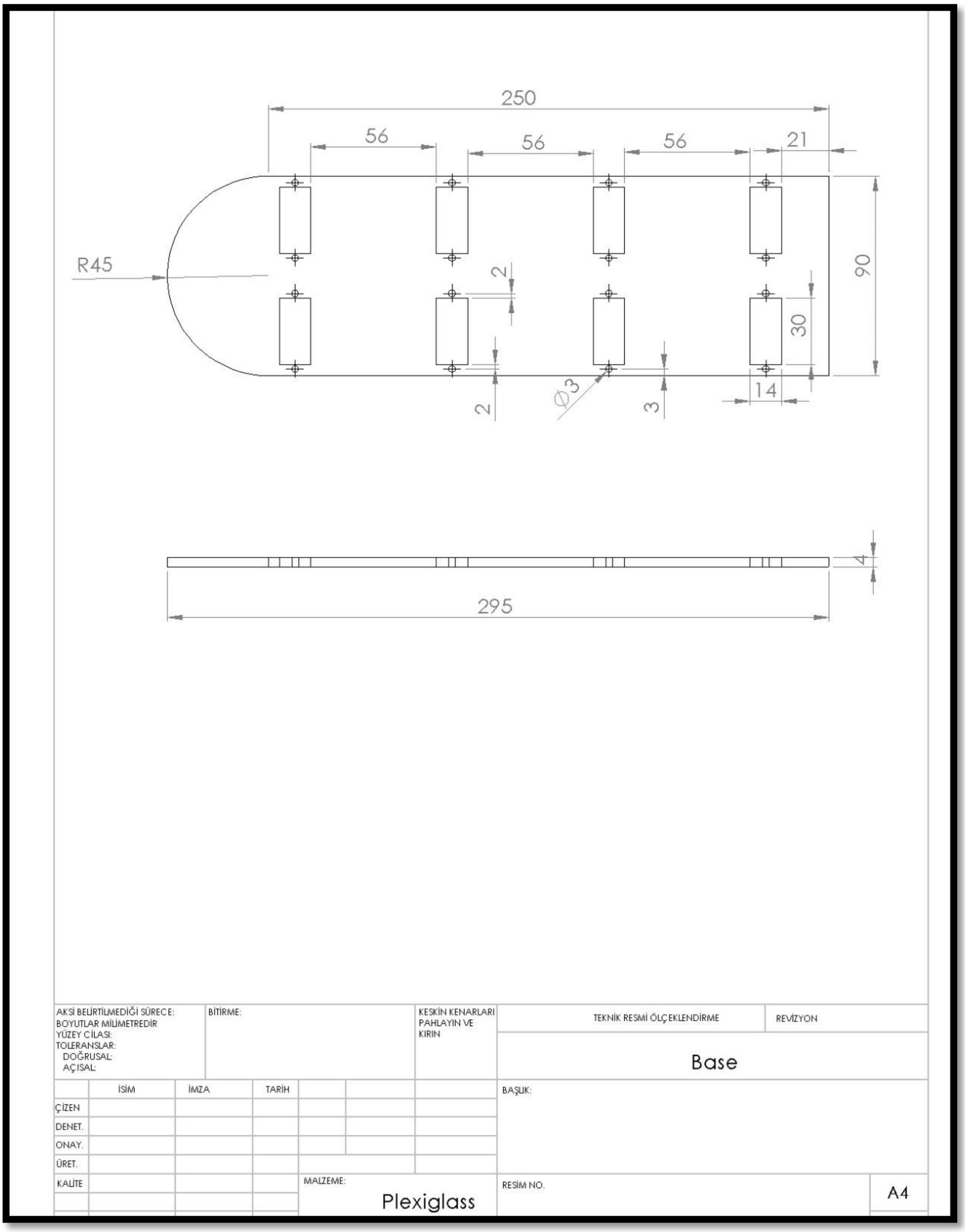
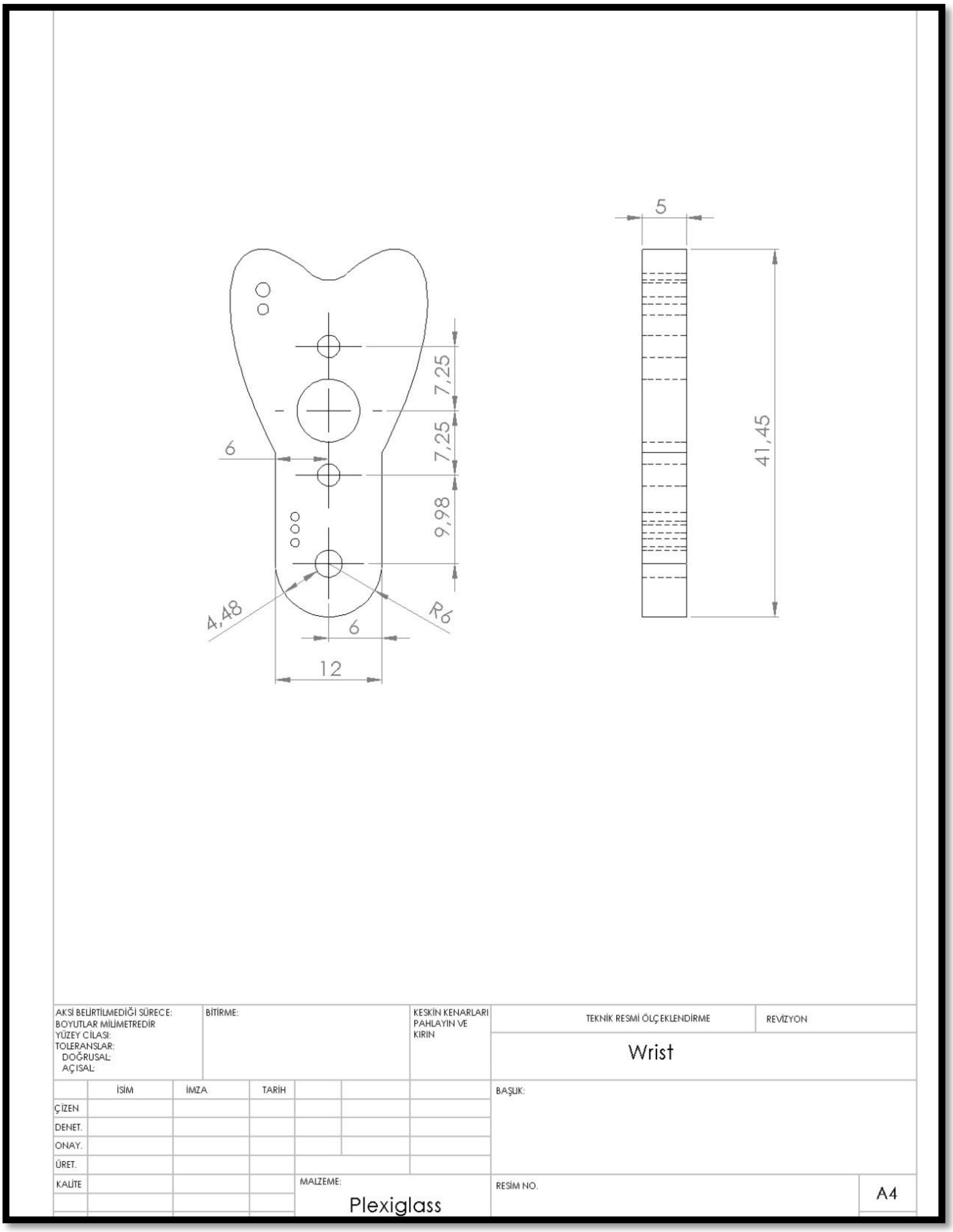
APPENDICES

A.ENGINEERING DRAWINGS

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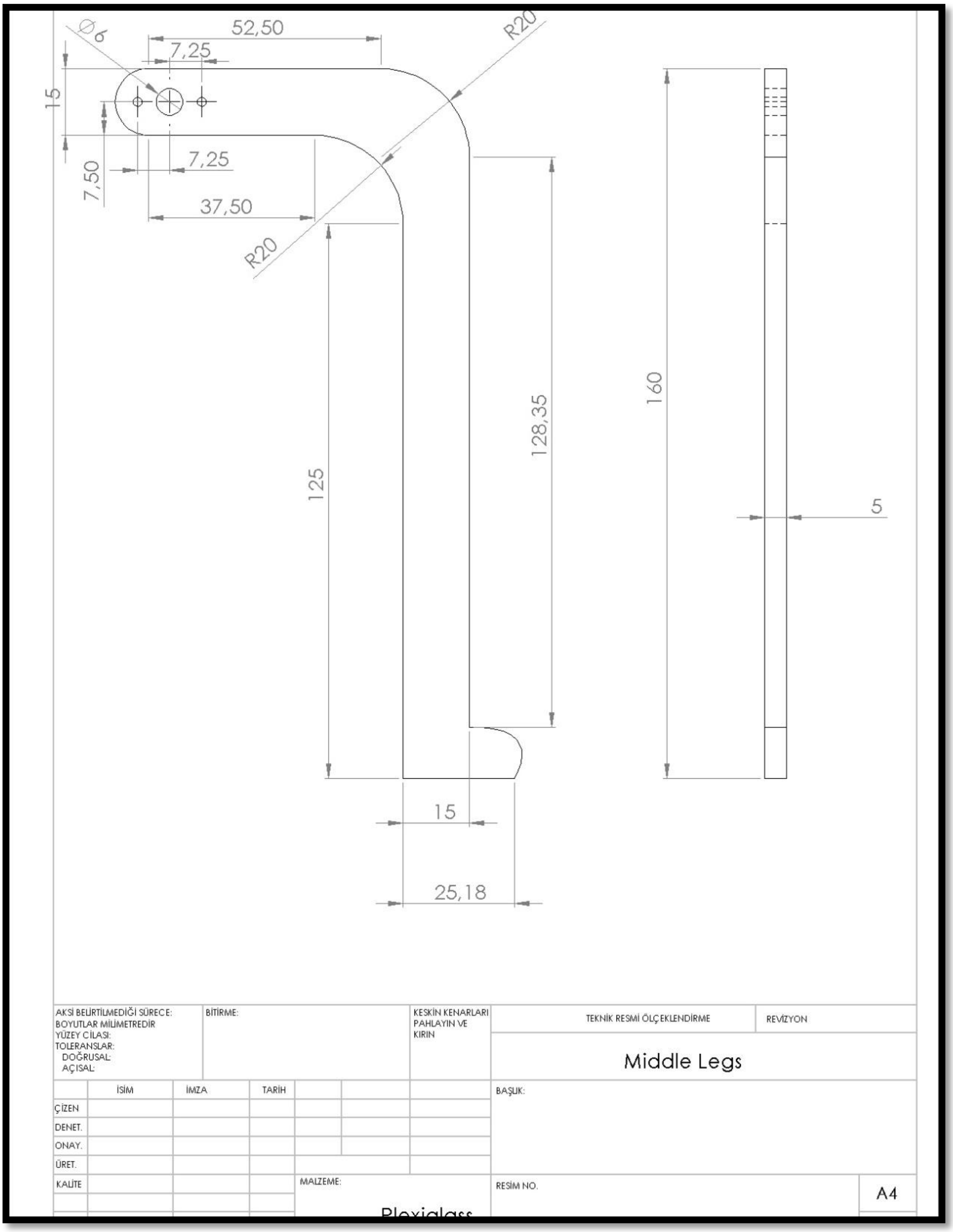

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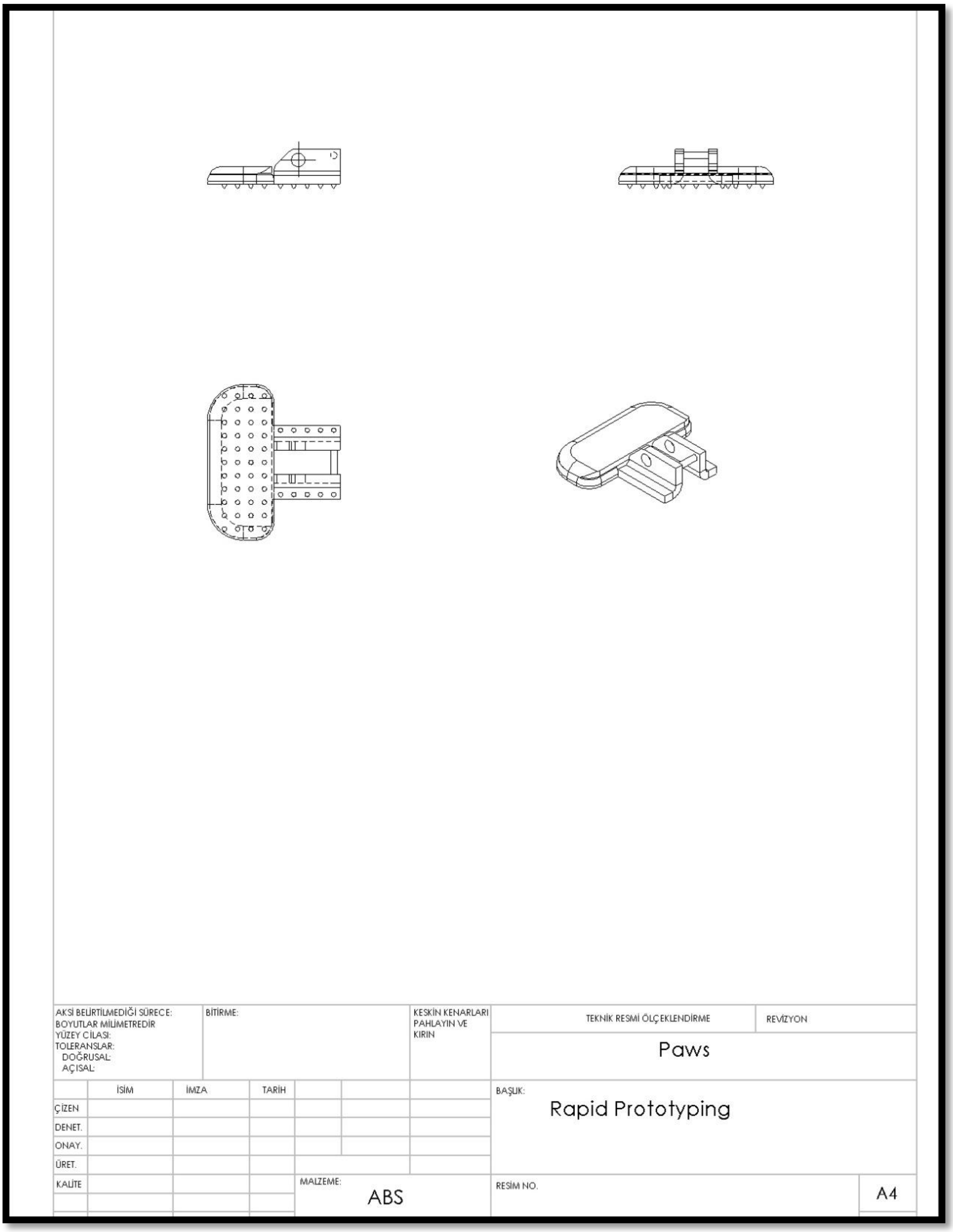
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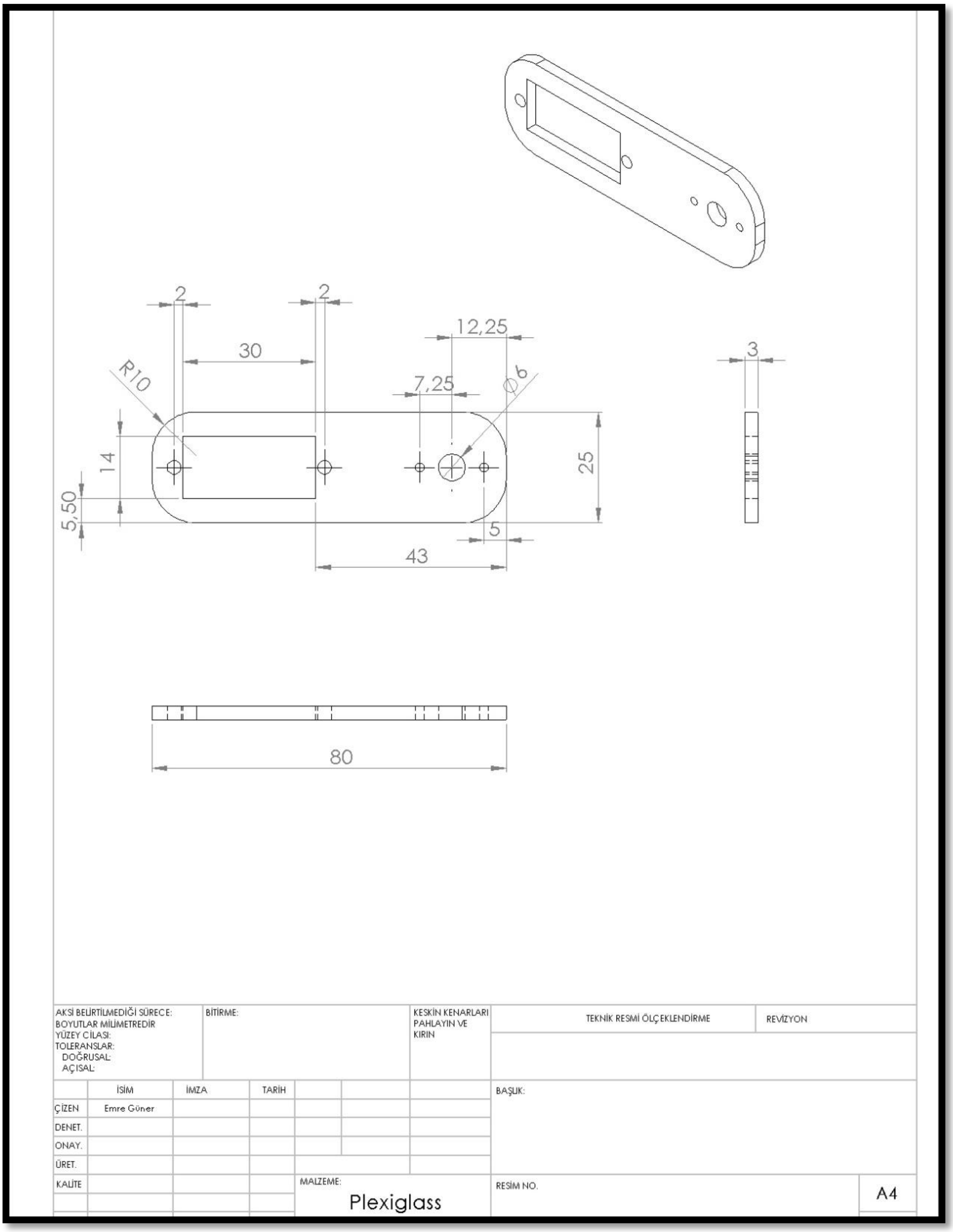
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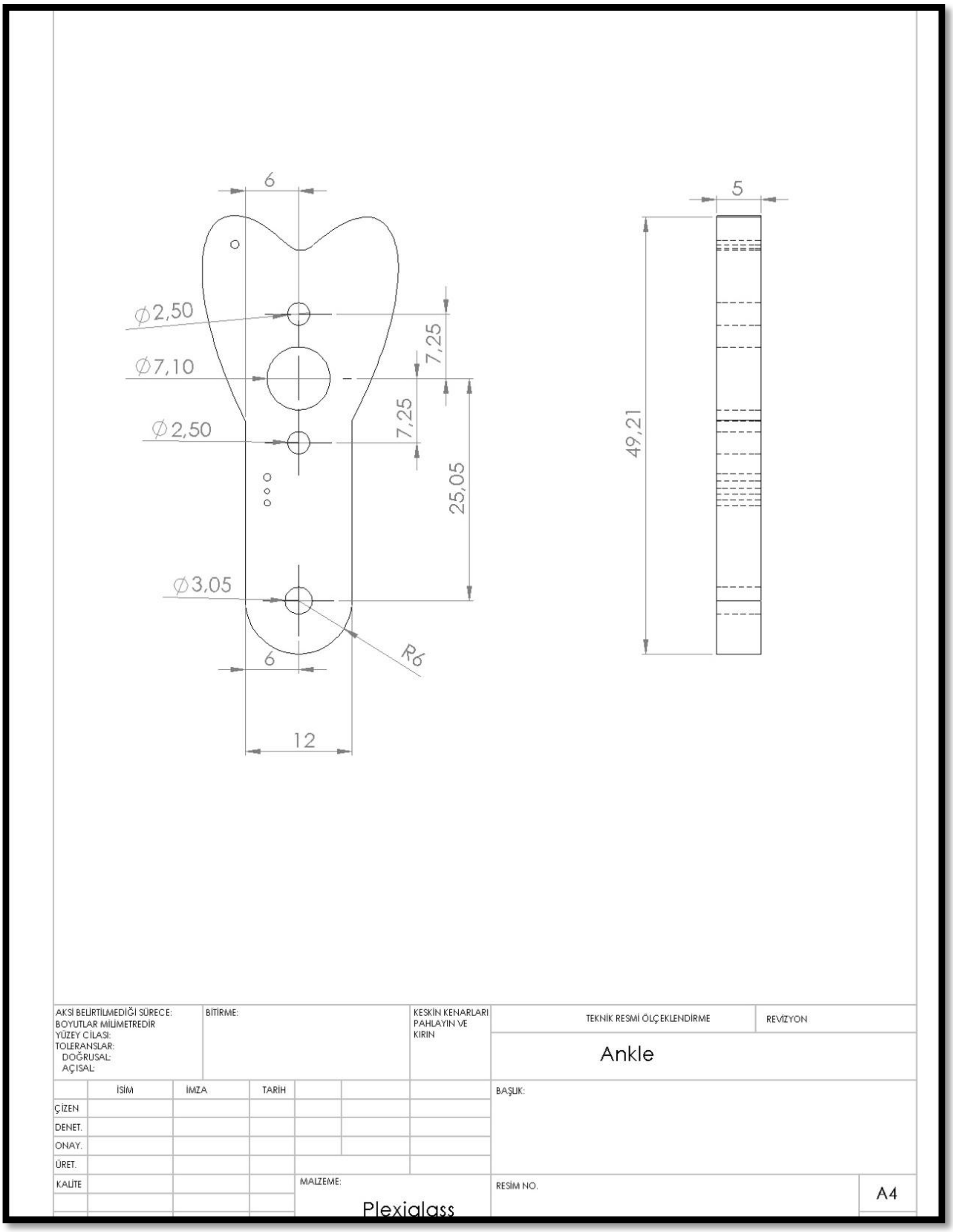
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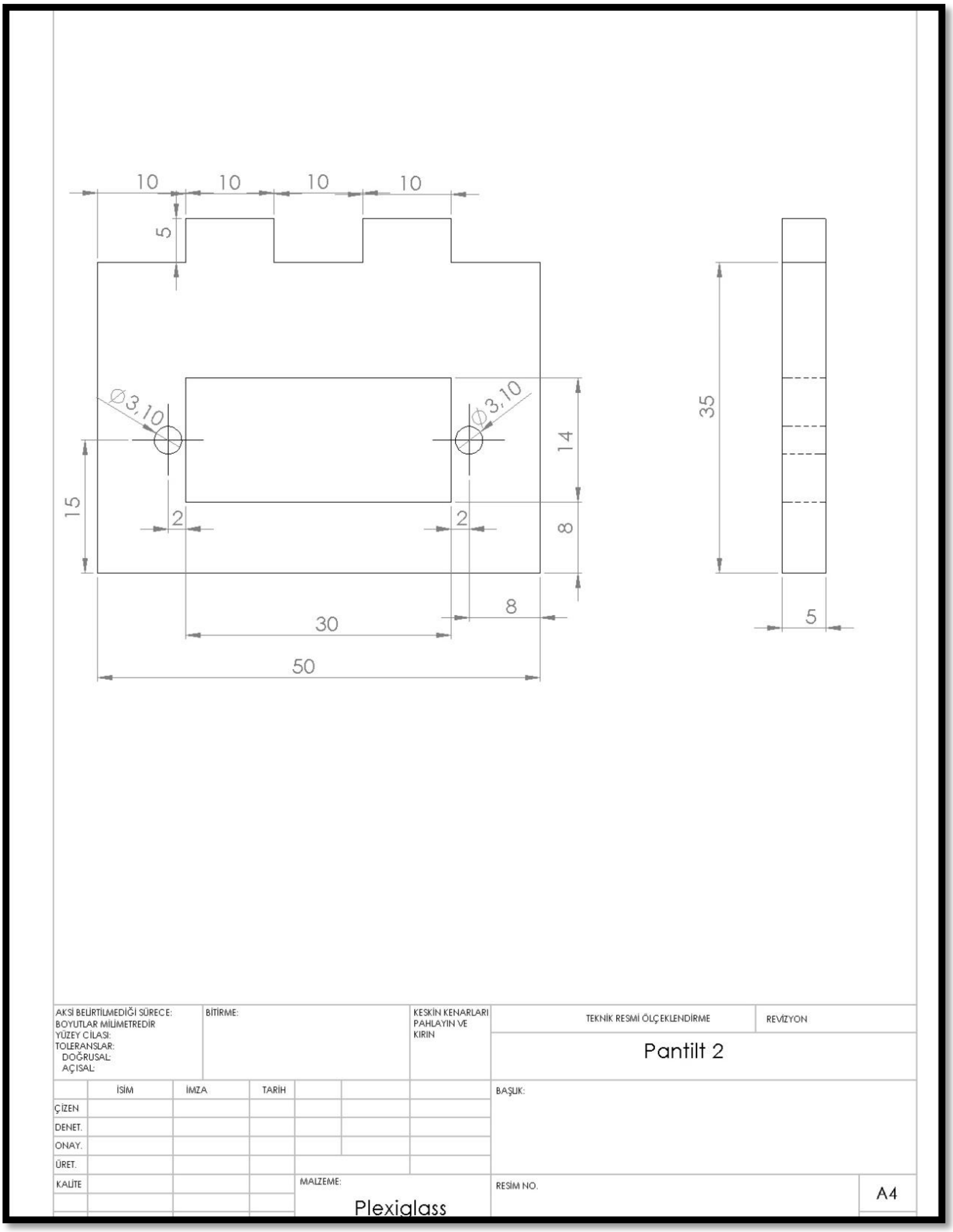
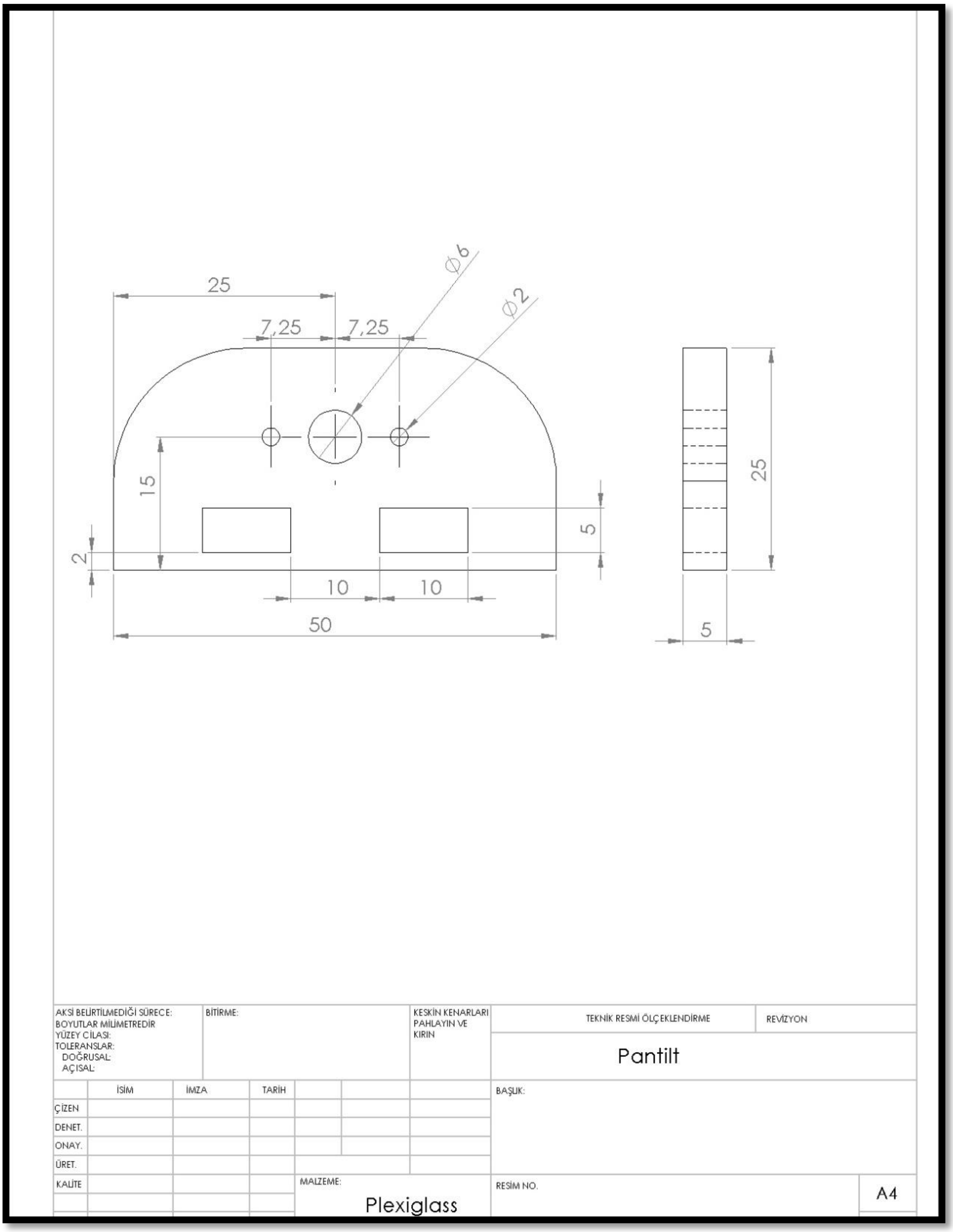
RESİM NO.
A4


10
10
10
10
5
Ø3,10
Ø3,10
14
15
2
2
8
35
8
30
50
5
AKSİ BELİRTİLMEDİĞİ SÜRECE:
BOYUTLAR MİLİMETREDİR
YÜZEY CİLASI:
TOLERANSLAR:
DOĞRUSAL:
AÇISAL:
BİTİRME:
KESKİN KENARLARI PAHLAYIN VE KIRIN
TEKNİK RESMİ ÖLÇEKLENDİRME
REVİZYON
Pantilt 2
İSİM
İMZA
TARİH
ÇİZEN
DENET.
ONAY.
ÜRET.
KALİTE
BAŞLIK:
MALZEME:
Plexiglass
RESİM NO.
A4


25
7,25
7,25
Ø6
Ø2
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2
5
10
10
50
25
5
AKSİ BELİRTİLMEDİĞİ SÜRECE:
BOYUTLAR MİLİMETREDİR
YÜZEY CİLASI:
TOLERANSLAR:
DOĞRUSAL:
AÇISAL:
BİTİRME:
KESKİN KENARLARI PAHLAYIN VE KIRIN
TEKNİK RESMİ ÖLÇEKLENDİRME
REVİZYON
Pantilt
İSİM
İMZA
TARİH
BAŞLIK:
ÇİZEN
DENET.
ONAY.
ÜRET.
KALİTE
MALZEME:
Plexiglass
RESİM NO.
A4

B. JOINT ANGLES

Real dog Lomotion Data:

Time	Shoulder	Elbow	Wrist	Hip	Knee	Ankle
0	287,74	174,84	177,09	233,96	244,33	125,01
16	286,30	177,94	178,87	231,54	239,91	127,83
32	285,12	180,71	180,26	229,85	235,74	132,35
48	284,42	182,85	180,10	230,37	229,64	139,69
64	284,83	183,27	180,46	233,67	220,61	148,46
80	286,82	180,08	183,24	234,87	218,57	151,60
96	291,49	168,45	193,95	236,24	222,52	145,96
112	295,11	153,07	212,70	238,42	223,00	143,08
128	296,64	139,66	228,66	239,25	224,90	141,40
144	297,74	127,14	233,66	240,65	225,50	140,87
160	296,42	120,80	227,52	242,59	224,01	142,06
176	292,85	122,01	212,13	244,44	221,93	143,83
192	285,59	129,12	200,45	245,33	221,34	144,78
208	275,85	141,84	195,33	245,96	221,17	145,96
224	268,17	156,36	185,65	246,57	221,31	146,92
240	264,63	167,21	176,13	245,95	223,54	146,81
256	265,66	171,25	173,93	245,31	226,44	145,45
272	270,45	167,86	172,68	246,45	227,30	143,62
288	271,49	168,15	172,09	247,14	228,17	142,62
304	271,87	169,59	171,26	247,00	229,91	142,38
320	273,23	168,64	171,42	247,16	231,63	142,53
336	274,57	166,91	172,84	246,99	233,87	142,66
352	275,27	167,14	171,47	246,21	236,81	142,88
368	275,40	167,97	171,68	245,45	239,84	142,24
384	275,29	169,02	172,50	245,73	241,42	141,62
400	275,11	170,24	173,53	246,20	242,16	141,42
416	274,43	172,32	174,16	247,07	241,61	142,27
432	273,98	174,10	174,23	248,51	239,98	143,26
448	274,26	174,51	173,90	250,03	238,64	144,07
464	275,04	173,86	173,96	251,27	238,09	145,17
480	275,51	173,80	173,75	251,56	238,71	147,26
496	276,82	172,75	173,72	250,28	240,89	149,68
512	278,09	171,76	173,58	248,19	244,19	151,29
528	278,44	172,74	173,37	246,50	247,71	150,76
544	279,37	173,03	173,08	245,53	250,92	148,72
560	280,29	173,26	172,91	245,12	253,24	145,86
576	281,65	172,69	172,93	244,63	256,06	139,88
592	282,73	172,61	172,29	243,47	259,25	132,15
608	283,40	172,96	172,04	241,39	262,02	123,50
624	284,66	172,52	171,54	238,67	263,67	117,44
640	286,04	171,23	172,77	236,43	263,04	114,89
656	286,95	170,98	173,75	235,06	260,16	114,49
672	287,36	172,13	174,28	234,05	256,27	115,60
688	287,35	174,08	175,08	233,41	251,16	119,12
704	287,74	174,86	177,01	233,95	244,34	125,00

Hybrid Robot Dog Locomotion Data:

Time	Shoulder	Elbow	Wrist	Hip	Knee	Ankle
51900	274,61	-173,207	196,804	123,416	128,856	109,394
52700	275,296	-173,4	196,764	123,745	132,552	120,569
53500	274,362	-173,859	196,629	123,619	133,085	123,678
54300	274,561	-174,568	196,55	123,947	133,627	124,472
55100	274,378	-177,927	195,435	126,334	137,167	130,528
55900	273,456	-180,224	193,938	127,094	143,141	135,541
56700	272,534	-181,107	193,24	123,181	152,169	145,276
57500	275,727	-177,525	190,369	121,724	155,619	148,243
58300	281,255	-165,139	178,196	119,606	151,906	146,489
59100	282,374	-149,463	162,595	117,586	149,531	144,298
59900	282,783	-134,146	150,898	117,049	148,783	143,082
60700	282,746	-125,881	153,695	115,005	148,858	143,327
61500	279,632	-131,79	167,196	111,995	149,61	145,376
62300	275,867	-142,136	180,278	112,02	150,885	145,539
63100	271,187	-157,374	189,55	112,381	151,804	146,033
63900	267,641	-169,714	197,954	112,058	152,02	143,315
64700	264,245	-169,398	198,897	112,045	151,931	141,371
65500	260,702	-169,291	199,152	111,455	150,26	139,899
66300	262,426	-169,073	199,829	110,742	150,104	137,888
67100	263,786	-167,839	199,797	111,077	149,949	135,931
67900	263,687	-167,987	199,929	111,674	149,958	132,427
68700	264,506	-168,173	199,778	112,711	149,851	129,042
69500	264,797	-169,783	199,834	112,551	149,64	127,044
70300	264,659	-171,59	198,636	111,876	149,554	127,003
71100	263,711	-173,496	198,227	110,119	149,745	127,991
71900	264,041	-173,804	198,039	107,366	150,672	129,102
72700	264,949	-173,701	198,126	106,95	152,853	129,636
73500	265,141	-173,406	198,304	108,29	155,049	129,374
74300	266,65	-172,121	198,432	110,517	157,125	125,058
75100	267,932	-172,107	198,448	112,926	157,008	120,137
75900	268,48	-172,24	198,821	112,978	154,471	117,3
76700	269,753	-172,143	199,057	113,632	148,939	114,219
77500	270,501	-172,13	199,069	115,921	140,364	109,968
78300	271,07	-172,173	199,237	118,319	131,477	105,325
79100	274,045	-172,147	199,323	121,119	125,8	100,497
79900	275,243	-171,23	199,516	122,541	125,138	100,985
80700	274,017	-171,729	198,08	122,952	125,442	104,094
81500	274,988	-173,286	196,344	123,633	130,751	112,714
82300	275,768	-173,385	196,17	123,845	132,988	121,21
83100	274,958	-173,69	196,031	123,559	133,39	122,819

Time	Shoulder	Elbow	Wrist	Hip	Knee	Ankle
83900	274,827	-175,647	196,28	124,629	134,498	125,768
84700	274,537	-177,956	194,089	126,434	137,71	130,33
85500	273,574	-180,709	193,622	126,421	144,844	136,286
86300	273,668	-180,861	191,68	122,594	153,784	145,518
87100	276,177	-176,094	186,251	121,612	155,36	146,797

Lobster Locomotion Data:

Coxabased	Thoracoxal	Merocarpopodite
28	-41	59
29	-41	59
29	-12	59
30	-11	92
30	-9	93
30	-6	94
31	-2	94
32	-3	95
34	-3	95
35	1	95
38	3	96
39	5	98
40	7	99
41	8	99
43	9	100
44	10	101
45	12	102
46	14	104
46	15	105
44	15	104
39	15	104
37	16	104
33	17	104
30	17	104
28	17	102
26	17	100
26	16	98
26	16	96
26	15	96
27	15	94
28	14	94
28	13	93
28	14	92

Coxabased	Thoracoxal	Merocarpopodite
28	14	93
29	12	93
29	10	93
28	8	95
29	7	94
29	6	93
29	6	91
30	6	91
30	6	90
30	5	91
30	4	92
30	3	92
31	2	91
31	1	91
32	-2	91
32	-3	92
31	-4	92
30	-6	92
30	-8	93
30	-9	94
9	-41	93
9	-41	59