DESIGN, PROTOTYPING AND TESTING OF AN AUTONOMOUS HEXAPOD ROBOT WITH C SHAPED COMPLIANT LEGS: AbhisHex

By

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THESIS

Presented To The Graduate Faculty Of

The University Of Texas At San Antonio

In Partial Fulfillment Of The Requirements

For The Degree Of

MASTER OF SCIENCE IN ADVANCED MANUFACTURING AND ENTERPRISE ENGINEERING

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DEPARTMENT OF MECHANICAL ENGINEERING

DECEMBER 2016

ACKNOLEDGEMENTS

This thesis project bears imprints of many individuals. I would like to take this opportunity to express my heartfelt gratitude to all of them without whom my project wouldn't have been successful.

The creation of my robot “AbhisHex” is definitely one of my biggest achievements and is a turning point of my life. I would like to extend my deep gratitude to Dr. Pranav Bhounsule whose expertise in legged robots helped me achieve AbhisHex. I am extremely thankful for his valuable suggestions, constructive criticism and constant encouragement which helped me push my limits to prove this concept. He not only supported me through smallest of the issues I wished to address but also introduced me to a completely different approach in handling and achieving things I desired.

The project would not have been completed without the support of Dr. Frank Chen, Dr. Hung-Da Wan, Paul Krueger (Machine shop) and all RAM lab members Ali, Christian, Christopher, Eric, Robert and Jeoffrey who were a strong source of help, support and inspiration during all these hectic days.

It was a great pleasure working with Maxon Motors USA. who virtually guided me at every minute instant while addressing all sorts of problems to get their products working. Lastly, I would like to thank the UTSA and The Department of Mechanical Engineering staff for their help extended during this project.

ABSTRACT

DESIGN, PROTOTYPING AND TESTING OF AN AUTONOMOUS HEXAPOD ROBOT WITH C SHAPED COMPLIANT LEGS: AbhisHex

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The University Of Texas At San Antonio, 2016

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Animals have always inspired our intuition that legs are essential for performing gaits and actions over highly rough landscapes. In this view, legged robots can be used to maneuver over different terrains where wheeled robots cannot approach. AbhisHex was inspired from a cockroach running and walking style which helped it to overcome locomotion over any terrains. Cockroach legs are arranged in sprawled posture and are moved in a stereotypical “clock” signal pattern giving it extreme stability over all the terrains. Although the robot leg design is not similar to the cockroach but their co-ordination from stance to swing state is adjusted so as to match that of cockroach gaits. Each of the six legs is actuated by individual motors and has one degree of freedom. AbhisHex is designed in order to achieve speeds covering up to one body length per second over different terrains. The main purpose of building AbhisHex was to use it in exploration of remote locations and hostile environments like space, planets, nuclear power plants, bomb disposal, fire fighting, search and rescue where humans have life risks.

In this thesis, a design procedure is outlined in order to systematically design an autonomous hexapod. The main features considered are mechanical structure and analysis of the body, C shaped leg design, material selection, actuating and driving mechanisms, walking gaits and speeds, payload, control architecture and cost. The hexapod was tested to stand and walk on flat grounds, slopes and uneven terrains.

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CHAPTER ONE: HISTORY

A) Concept and Inspiration:

Morphology of arthropods suggests that most of creatures had more number of legs than six. The evolution process stopped at six legs, as those are the minimum number of legs for a small creature especially with a rigid hexa-skeleton. This option for the creature to move forward as well as backward freely without losing the balance is based on what was named as tripod gait.

Over and above the benefits of six legs and tripod gait the unique shape (S type) and location (center of body) offer many important benefits. S shaped legs help in negotiating even the most odd ups and downs either manmade (stairs) or natural ones (rocks or wooden logs). The location of the legs provide continuity in locomotion even when the robot gets toppled upside down on account of center of gravity when approaching extremely rough terrains. [38]

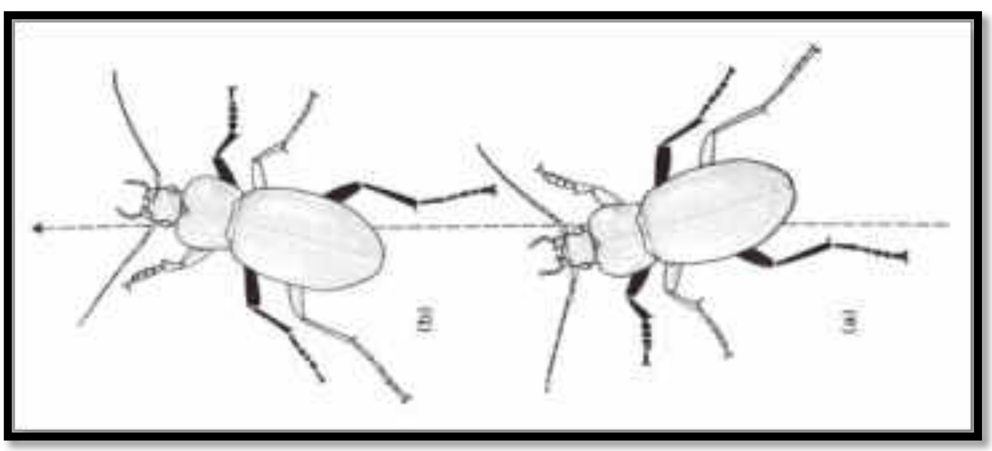


Figure 1: Arthropods Morphology [38]

B) What are Legged Robots ?

Legged robots are the types of mobile robot, which use legs for their locomotion instead of wheels. ***Mobility*** and ***ability to walk on rough terrain*** are the main reasons why legs are preferred over wheels. This covers classic human tasks like walking, climbing stairs and running. The classification of legged robots is discussed below.

C) Types, Comparison and Development of Legged Robots:

- **One-legged robots:** These are generally hopping robots. These robots remain stable by changing their center of gravity and applying reactive forces to prevent them from falling. These offer a specific advantage of movement over any uneven surfaces as they only hop from one position to other. These robots are also more efficient compared to robots with more legs. However, controlling these robots is one of the major challenges [1].

Figure 2: Toyota's One-legged robot [1]

- **Bipedal Robots (2 Legs):** Bipedal robots are the most famous robots, which resemble humans to the closest. These robots imitate human actions and behaviors like walking, running, climbing. These robots are dynamically stable but require complex algorithms for them to balance and carry out all the actions [1].

Figure 3: Cornell Ranger: A 4 legged Robot [1]

- **<u>Three Legged Robots (Triped):</u>** With the benefit of having three contacts with the ground at any given point of time, this category offers more stability compared to the earlier one. However, tripod gait is not commonly seen in nature and hence is not very commonly researched [1].

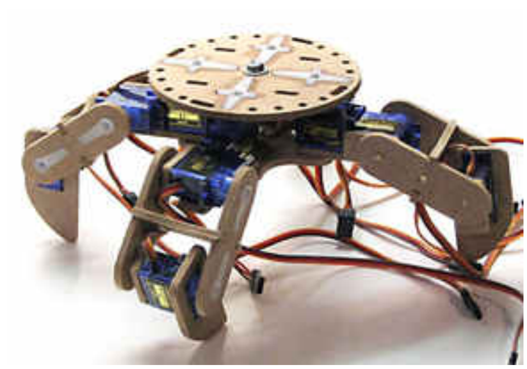


Figure 4: A three-legged robot [1]

- **<u>Four Legged Robots (Quadruped):</u>** These robots use all four legs to balance themselves while moving. As they offer large number of contact points with the ground, these quadrupeds are preferred for activities requiring higher stability. The motion of these robots is very similar to four legged animals. Controlling these robots is difficult and requires complex algorithms and analysis [1].

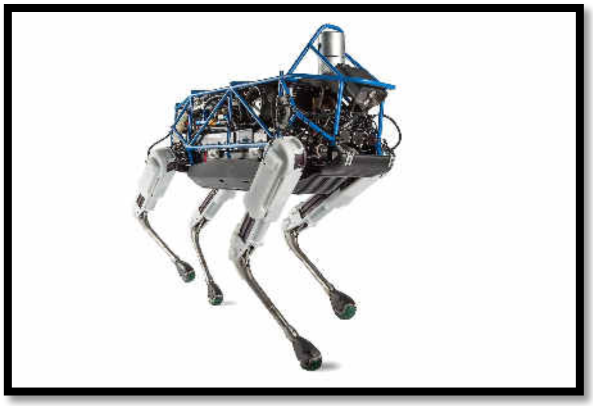


Figure 5: Boston Dynamics Big Dog: A 4-legged robot [1]

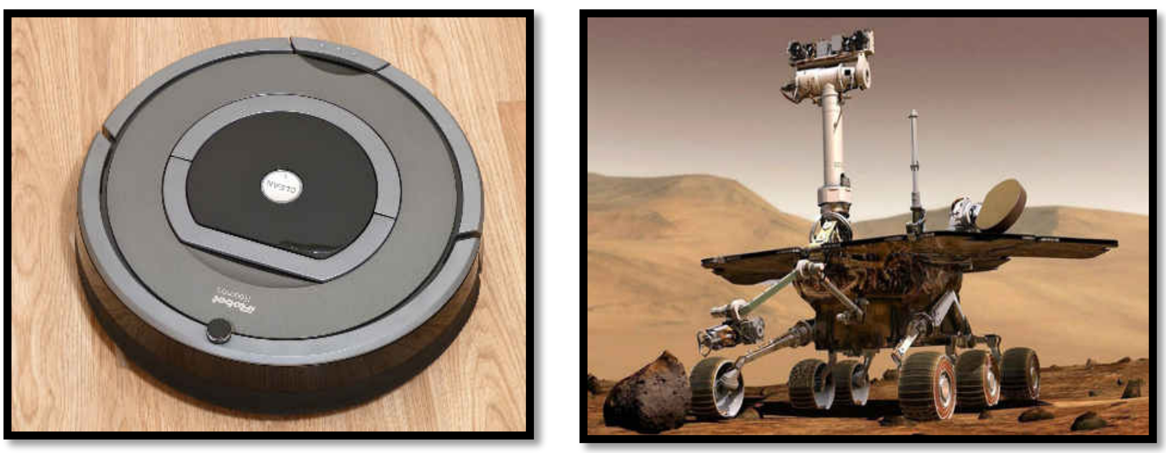
- **<u>Six Legged Robots (Hexapods):</u>** Most of the hexapods are biologically inspired from insects like spiders and cockroaches. These are six legged robots, which offer greater stability in comparison to other legged varieties. Here, at any given point of time at least three legs create a stable contact with the ground, which makes them statically and dynamically stable for almost all types of movements like running, standing, pronking etc. Hexapods usually perform two types of gaits ***a) Wave gait*** and ***b) Tripod Gait*** which are discussed later in the report [1].

Figure 6: Rhex: A six legged robot [1]

D) Wheeled Robots vs Legged Robots:

D.1) What are Wheeled robotss ?:

All the robots using wheels for their locomotion come under the category of wheeled robots. In terms of energy efficiency on flat surfaces wheeled robots are seen to be the most efficient. In case of wheels once the robot is set into motion brakes can be used to stop it apart from any other external forces. One of the major concerns in case of motion planning of wheeled robots are non-holonomic constraints that are subjected to the robots. These constraints are decided based on the types of wheels used, number of wheels used and direction of axis of motion. Some of the common wheeled robots are shown in figure 6 (a) and (b) [24].



(a) (b)

Figure 7: (a) Roomba i-robot and (b) Mars Rover [24]

C.2) Why are Legged Robots preferred over Wheeled Robots ?:

Adding legs to robots is always a complex task. People are researching for years to get robot walk, run and perform functions like humans. However, there are many advantages of legs over wheels and that is the reason why most of the living organisms in the world have legs, so that they can adapt to all the environmental changes and terrains. Here are a few advantages of legs over wheels:

- Legged robots can navigate on any surfaces, which cannot be achieved in case of wheeled robots. The wheels need to be designed as per the required surface in order to make the robot function on respective terrains like smooth surfaces, roads, rails, rocks etc.
- Legged robots can jump or take a long step to cross obstacles in the path whereas wheeled robots either take long time to cross or need to plan a different route to cross the obstacle.
- A legged robot also helps in exploring human and animal locomotion's, which is not possible in wheeled robots.

Although legs have various advantages over wheels there are a few things why wheels are still preferred by humans.

- Wheel based robots or vehicles are easy to design and maintain compared to legged robots, which need complex mechanics, computations and equilibrium.
- Cost of wheels is very economical than that of legs.
- Wheel based robots travel faster and are more efficient in normal terrains than legged robots.

CHAPTER TWO: OVERVIEW

A) What is RHEX ?

RHEX is a six-legged autonomous robot inspired by the cockroach gait. The design is such that it can travel on uneven and flat surfaces or terrains even under challenging environmental conditions. The robot consists of 6 C-Shaped passive compliant legs, each of which is controlled individually by an actuator. This not only gives the robot the ability to perform all the motions as per the requirements but also provides more power and stability [2]. RHEX climbs in rock fields, mud, sand, vegetation, railroad tracks, horizontal telephone poles and stairways. The RHEX is designed in such a way that it can operate even if it is turned upside down. The body of some RHex is sealed fully to make it weather proof. The RHEX consists of a central computer controller, which stores and sends all the required signals to the actuators based on the feedback. This helps it to decide how the legs should move in a particular situation. The RHEX can be easily controlled wirelessly up to a nominal distance of 700 meters. The onboard cameras help the user to see through and record the activities. [3]

B) Purpose of Building RHEX:

RHex was basically designed for working in dangerous, missions such as fire fighting, search and rescue, bomb disposal, planetary exploration, military action and law enforcement [6]. Powerful independent legs used in the RHex can perform a wide range of behaviors. Passive compliance in the legs overcome the limitations of under actuations and helps simplify mechanical design and increase robustness. [7]

C) Different types of RHEX:

- **Research-RHex:** This was the first project by Defense Advanced Research Projects Agency, Defense Sciences Office (DARPA DSO) on the hexapods under the 1998

CBS/CBBS program called Computational Neuromechanics. The main goal of this project was to develop a highly mobile hexapedal robot that could easily navigate over artificial as well highly broken and unstable natural terrains with animal like locomotion's. Hence the robot was named "***RHex - Robotic Hexapod***". [4]

Figure 8: Research – Rhex [4]

- **EduBot:** The goal of this project was to develop a modular form of RHex that would be cost effective and can be used as a research and education tool. The project started in 2005 as a part of NSF-FIBR program. EduBot v1.0 and EduBot v2.0 were later built with a few modifications in terms of mechanics, stronger sensory capabilities, more robust, modular electronics and programing infrastructure for research purpose. [4]

Figure 9: EduBot v2.0 [4]

- **SandBot:** SandBot was developed as a collaboration between the CRAB Lab, Georgia Institute of Technology and Kod*Lab, The University of Pennsylvania with the aim of studying the behavior in places such as sandy beaches or snow covered mountains. The UPenn group aims in 1) building a concrete understanding of the dynamics of granular materials 2) design and built a legged robotic system to demonstrate the performance on granular media. [4]

Figure 10: SandBot v1.0 [4]

- **<u>Desert RHex:</u>** In June 2009, Kod*Lab members developed the Research RHex to the next platform by taking it to the Mojave Desert for the purpose of evaluating the performance of legged robots in desert sand and mountain conditions. More sophisticated position, proximity sensors and electronic signaling devices were used to precisely collect the data from the robot directly. It was made robust for severe environmental conditions that it might confront in the deserts, which included strong wind currents, higher temperature levels, contaminated ambiance etc. In the year 2010, after successful modifications and tests, a completely autonomous version was taken back to the desert for further trails. [4]

Figure 11: Desert RHex: A modified Research RHex [4]

- **X-RHEX Lite (XRL):** XRL is a lighter version of X-RHex designed to be more agile with same leg spacing and features of the earlier RHex models. In XRL, the main focus was on the legs, which were re-structured for easy fabrication and lightweight without affecting the strength and payload capacity of the model. XRL was designed by interlocking flat aluminum pieces machined using a water jet cutter rather than CNC milling for more accuracy. The XRL has very similar structure to that of Research – RHex except the space is more effectively managed for battery, on board computers and communication devices. [4]

Figure 12: The XRL Robot [4]

- **X-RHex:** X-RHex is the latest version of the highly mobile RHex family designed for greater strength, longer runtime, more mobility and higher modular payload support. Like the earlier models X-RHex consists of six individual motors to control each compliant leg allowing it to travel on wide variety of terrains. Unlike previous models, X-RHex can walk, run and pronk on almost all surfaces including asphalt, sand, mud and rocks. This model also has parallel processing sensors along with powerful CPU for detailed analysis of each smallest activity. Rail mounted handles are introduced in this model for ease of handling. [4]

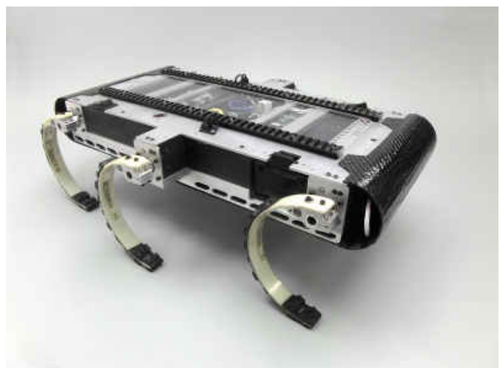


Figure 13: X-RHex Robot [4]

D) Abhishex VS RHex:

ABHISHEX is designed with an idea to perform exactly similar functions as that of the RHex. However there are few things, which are different in ABHISHEX as compared to the RHex. The following table describes the differences in the two hexapods:

	RHEX	AbhisHex
L x B x H	52 x 39 x 13 cm	56 x 38 x 10 cm
Leg to Leg Spacing	20 cm	22 cm
Ground Clearance	11.5 cm	11.5 cm
Leg Diameter	17.5 cm	18 cm
Total Weight (without batteries)	9 kg (19.85 lbs)	9.2 kg (20.3 lbs)

Chassis Material	Al 7075 T6 & Carbon Fiber	Al 6061 T6, Al 7075 T6 & Polycarbonate
Battery	NiMH (24V, 1 set of 3)	LiPo (37V and 22V)
Motors	Brushed DC	Brushed DC
Gear-head	33:1 (Planetary)	33:1 (Planetary)
Encoders	Magnetic	Optical
Controller	Advanced Motion Controls (AMC) DZRLATE-20L080	EPOS 2P and EPOS 36/2 modules
Operating System	QNX (UNIX)	Windows
Software	MATLAB, ROS, C	MATLAB, SOLIDWORKS, EPOS STUDIO, SimMechanics
Max Speed	5 bodylengths /sec	1 bodylength /sec
Gaits	Tripod and Wave	Wave

Table 1: Comparison of AbhisHex and RHEX

CHAPTER THREE: MECHANICAL DESIGN AND MODELLING

A) <u>Design of Chassis</u>:

The main aim in designing the body was to make it durable, lightweight and robust to all environmental conditions. The target was to try and achieve performance similar to the earlier RHex robots. The dimensions of the body are selected from the Research RHex models and then modified as per our requirements. The overall dimensions are 22 x 15 x 0.30 inch, to accommodate the batteries, controllers and electronics compartment. The length is adjusted in such a way that there is enough space between two legs while rotating. The entire frame is machined out of Aluminum alloy (Al-6061 T6). This includes the runners, cross members and motor mountings. The alloy Al-6061 T6 is selected for its high yield strength, lightweight and easy machinability [5].

The cross members are attached to the runner at three positions as shown in the figure.

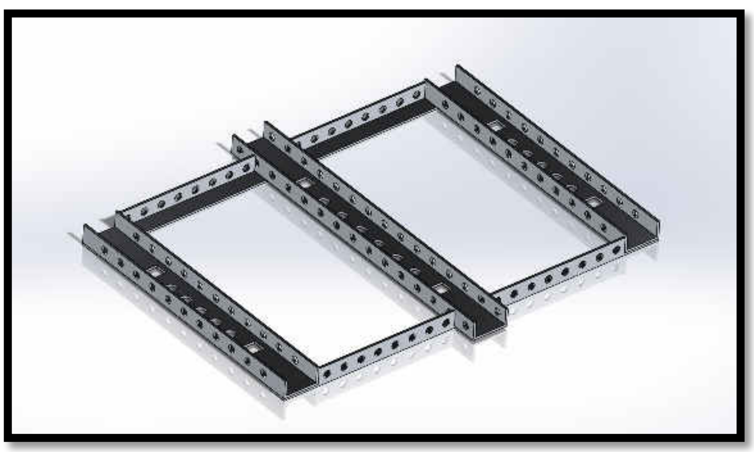


Figure 14: Cross member frame

It can be seen from the figure 13, that the center cross member is longer compared to end cross members. This makes the robot stable by offering it stability against toppling. This also decreases the overall length of the chassis as the central two legs rotate in a different plane. The chassis is perforated, which reduces the body weight and dimensions and provides cooling passages in case of over heating. The sides, top and bottom of the chassis is covered by Polycarbonate sheets (2-3mm thick) to seal it from external environmental attacks due to dirt, dust, and water. The transparent variety offers scope for inspecting the internals during operation of AbhisHex. The motor mounting is designed in such a way that the shaft is at the center of the overall robot height which helps in quick stabilization even during its roll over in an upside down way. This makes AbhisHex an invertible robot. [5]

B) Design of C Shaped Leg and Gait Patterns:

AbhisHex is designed with the motive to have a cockroach like walking style. The past studies have shown that cockroaches can walk on any terrains at considerable speeds and complete stability without requiring high-level neural control systems. It has also been observed that cockroaches used two groups of legs for walking to form a pair of tripods. In any position one set of three legs is always in stance position to support the body and keeps it stable. This gait is called as tripod gait. The tripod gait can be better explained from the figure given below. In this case legs L1, L3 and R2 work in sync whereas legs R1, R3 and L2 work in same sequence.

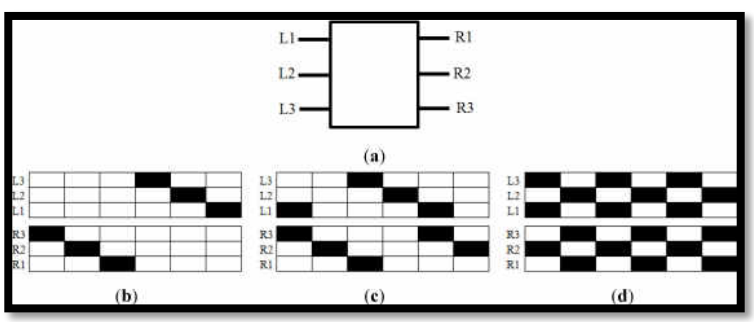


Figure 15: Tripod gait patterns

Based on the previous research, a C shaped leg was designed as per the specifications. The height (diameter) was calculated to provide sufficient clearance to the body on all terrains including flat ground, rocks and stairs.

After some initial study, analysis and trials the actual dimensions of the legs were finalized. Delrin, a synthetic resinous plastic is finalized as it provides passive compliance. Passive compliance is ability to absorb some component of applied forces. These absorbed forces are then released to push the leg off ground during locomotion. Passive compliance is different as compared to active compliance where motors or actuators are used to achieve actuation.

C) Selection of Materials:

The material selection was dependent on three major factors strength, weight and cost of the material. Aluminum alloy 6061 T6 was selected as the final material for making the robot chassis components as this material complies with the above requirements. The properties of Al 6061 T6 can be seen in the table 1.

ALUMINIUM 6061 T6

Physical Properties	**Metric**	**English**
Density	2.7 g/cc	0.0975 lb/in³
Mechanical Properties		
Hardness, Brinell	95	95
Hardness, Rockwell A	40	40
Hardness, Rockwell B	60	60
Ultimate Tensile Strength	310 MPa	45000 psi
Tensile Yield Strength	276 MPa	40000 psi
Modulus of Elasticity	68.9 GPa	10000 ksi
Ultimate Bearing Strength	607 MPa	88000 psi
Bearing Yield Strength	386 MPa	56000 psi
Poisson's Ratio	0.33	0.33
Fatigue Strength	96.5 MPa	14000 psi
Fracture Toughness	29 MPa-m½	26.4 ksi-in½
Machinability	50%	50%
Shear Modulus	26 GPa	3770 ksi
Shear Strength	207 MPa	30000 psi
Electrical Properties		
Electrical Resistivity	3.99e-006 ohm-cm	3.99e-006 ohm-cm
Thermal Properties		
Thermal Conductivity	167 W/m-K	1160 BTU-in/hr-ft²-°F
Melting Point	582 - 652 °C	1080 - 1205 °F

Table 2: Properties of Al 6061-T6

For more detailed understanding of the material and its strength, the Specific Strength (C) of Al 6061 T6 is calculated using the following equation [7]:

$$C = \frac{\sigma}{\rho}$$

Where σ is the tensile strength of the material and ρ is the density of the material. Considering the values from the above chart we get the following answers.

$\sigma = 40000\ psi$

Therefore, σ = 40000 psi * (6894.76 pa / 1 psi)

= 2.7579e+8 pa

= 275.8 Mpa

ρ = 2.7 g/cm^3

= 2.7 g/cm^3 * (1 cm^3 / 1.0E – 6 m^3) * (1 Mg / 1.0E6 g)

= 2.7 Mg/m^3

Thus, C = (275.8 Mpa / 2.7 Mg/m^3)

C = 102.148 kN.m/kg

Thus, it can be seen that the Specific strength of Al 6061-T6 is high enough to sustain in all conditions. Apart from strength, cost and weight were also the deciding factors in the selection. The following table explains a short summary of the factors considered for finalizing the material.

	Al 6061	Al 7075	Carbon Fiber
Strength to Weight Ratio (Specific Strengths) (kNm/kg)	115	204	2457
Hardness	40	53.5	120
Price (1' thick, 10" long rod)	4.21	9.9	~28
Composition	Magnesium, silicon, iron, copper, zinc, titanium, manganese, chromium	Magnesium, silicon, iron, copper, zinc, titanium, manganese, chromium (in diff proportion)	Magnesium, silicon, iron, copper, zinc, titanium, manganese, chromium (in diff proportion)

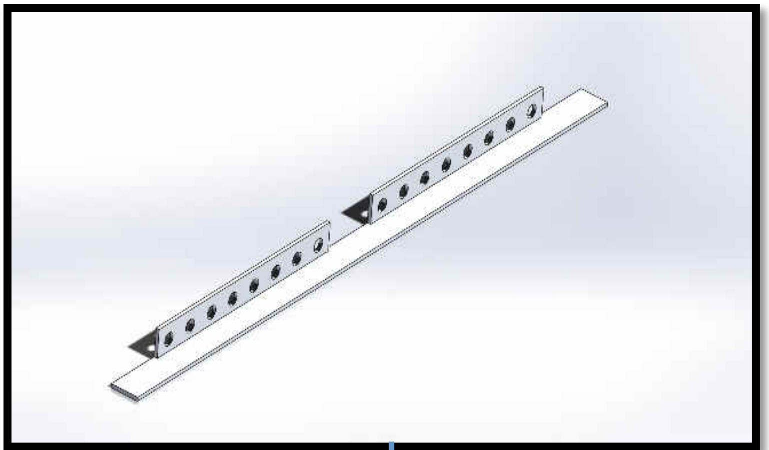
Table 3: Comparison of different materials properties

It can be seen from the above table that the strength to weight ratio and hardness of Al 7075 and Carbon Fiber are much higher than Al 6061. However, the cost of these materials is almost twice or thrice compared to that of Al 6061, which finally emerged out as the best option.

D) 3D Part and Assembly Drawings of the Components:

The figures below show the part drawing in the sequence of their assembly.

CROSS MEMBERS

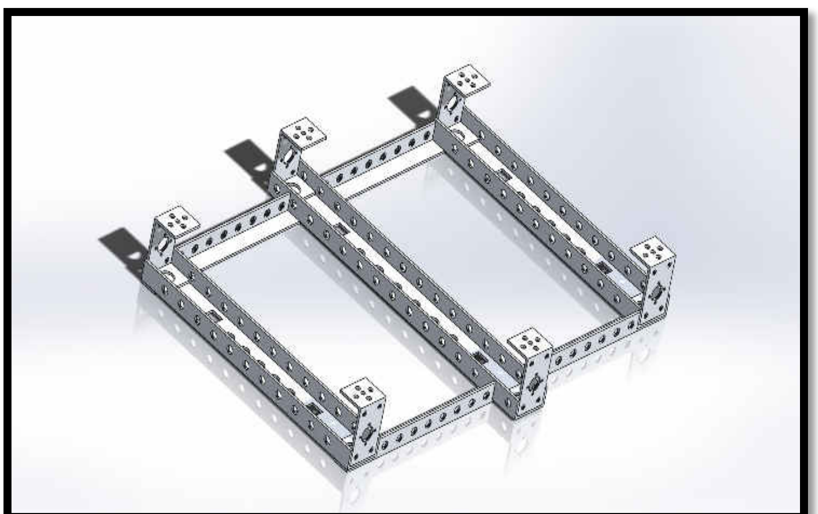


RUNNERS

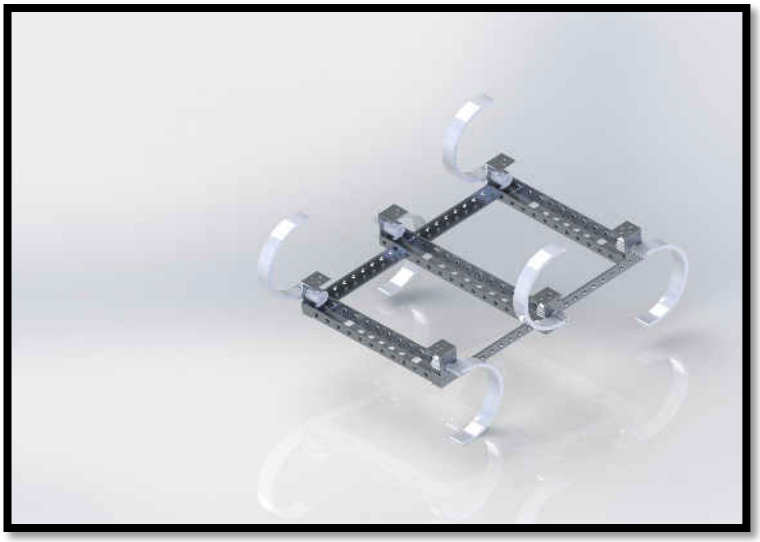
MOTOR MOUNTINGS

LEG ATTACHMENT

C-SHAPED LEG



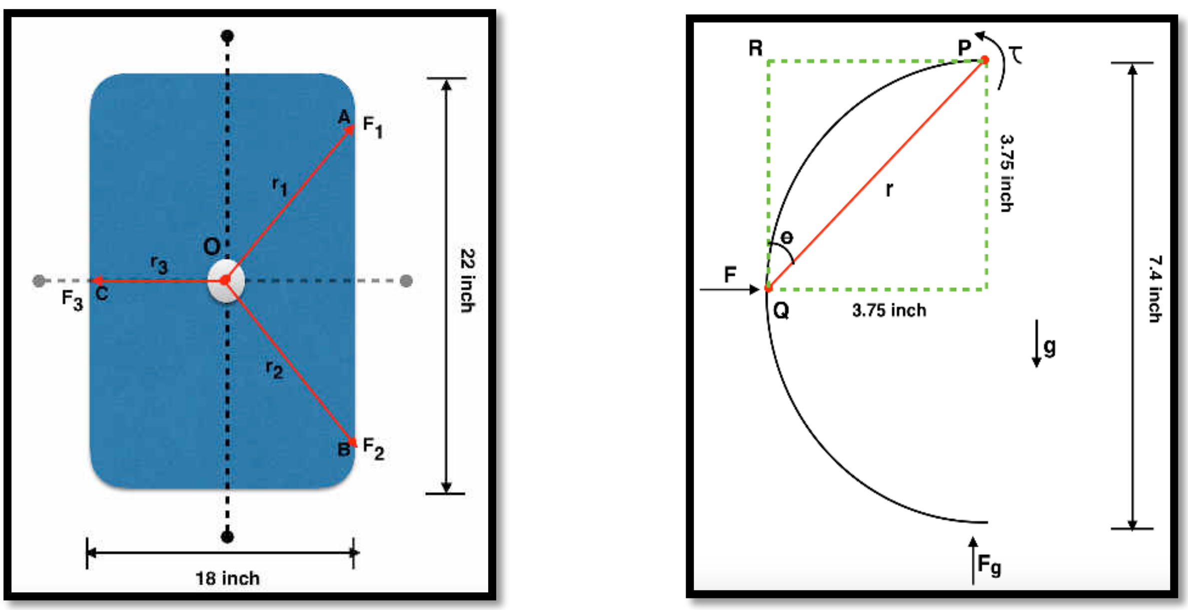
BASE FRAME ASSEMBLY



AbhisHex FINAL ASSEMBLY

Figure 16: AbhisHex component list

E) Free Body Diagrams (Body + Leg):



(a) (b)

Figure 17: (a) FBD of Body and (b) FBD of Leg

In figure 1(a), the overall dimensions of the body are 22 x 18 inch.

Let $\mathbf{F_1}$, $\mathbf{F_2}$ and $\mathbf{F_3}$ be the forces acting on the legs A, B and C respectively, **W** be the weight of the entire assembly, **r** be the radius of the legs, $\boldsymbol{\tau}$ be the torque acting on the leg and **g** is the gravity.

W = 8.5kg = 85N

r = 3.75 inch = 0.0953 m

Now,

$F_1 + F_2 + F_3 = W$ and $\Sigma\boldsymbol{\tau} = 0$

$F_1{*}r_1 + F_2{*}r_2 + F_3{*}r_3 = 0$ ……………………………….(1)

$F_1 * [1\ 1\ 0]^{-1} + F_2{*}[1\ 1\ 0]^{-1} + F_3{*}[-1\ 0\ 0]^{-1}$ ...…………………………….(2)

From equation (2), we can see that,

$F_1 = F_2$ ……………………………….(3)

Therefore, $F_3 = F_1 + F_2$

$$\begin{bmatrix} 1 & -1 & 0 \\ -1 & -1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 85 \end{bmatrix} = \begin{bmatrix} F1 \\ F2 \\ F3 \end{bmatrix}$$ ……………………………….(4)

Solving equation (4) using gauss-elimination method we get,

$F_1 = F_2 = 85/4 = 21.25$ N

$F_3 = 85/2 = 42.5$ N

The above values show that $F_3 = F_1 + F_2$. It can be seen from the figure that legs A and B have a force of 21.25 N acting on each of them, while leg C has a force of 42.5N acting on it. Hence, it can be concluded that the forces are equally divided on all the three legs when they are touching the ground.

F) <u>Building / Construction of the Chassis:</u>

The entire chassis as seen earlier is made form Al 6061 T6. All the members of the main frame including the cross members, runners and motor mountings were machined using the

VMC (Vertical Milling Machine). Initially the C channels and L channels shown in Figure 15. were cut to plus 1/8th ‘’ of the actual size. These pieces were then milled to exact size using the vertical milling machine keeping a tolerance of $\pm$ 0.0005’’. The holes on the chassis were marked from the center of the channels and were drilled on a drill machine. These holes were then finished using a countersunk tool to make the surfaces smooth and clean. The rectangular slots on the runners were cut on an end-milling machine, followed by countersunk tool to make final surface finishing and smoothening. All the mainframe channels were bolted using 18-8, 5/8’’ length Stainless Steel Flanged Button Head Socket screws having a thread size of 10-32. These screws had a built-in spring washer which helped it give more strength and tightening.

One of the problems faced during this process was designing the leg attachment piece on which the motor shaft and legs will be mounted. The leg attachment piece is going to be subjected to continuous wear and tear and stress conditions because of continuous high-speed rotation of motor shaft and sudden impact on the surface when the leg hits the ground or gets stuck. After multiple experiments and design alterations, Al 7075 T6 was selected for this part. Al 7075 T6 being an aerospace grade material is even stronger and lighter than Al 6061 T6. The attachment was constructed in two separate sections. These two sections are then fixed on the motor shaft and bolted to each other to make it hold firmly on the shaft. The leg is then bolted on this attachment using small screws. The detailed assembly drawings of these parts are shown in the sections D.

The aim was to try making the robot transparent in order to see and analyze the entire internal electronics. Hence, the top, bottom and side regions of the robot were covered using Transparent Polycarbonate material. A ¼’’ thick Polycarbonate sheet was used as outer body cover. This provided a mounting base for all the electronic components along with an impact resistant outer shield to the chassis.

To summarize the chassis was designed in such a way that the motors and controllers can be easily replaced or removed with minimal disassembly. This provides ease of serviceability for all the internal components. [1]

CHAPTER FOUR: ELECTRICAL COMPONENTS AND NETWORK COMMUNICATIONS

A) List of all Electrical Components:

A wide range of electronics was used in the AbhisHex for controlling, analyzing, data management, storage and processing. The majority of the electronic components were procured from a company named Maxon Motors, USA.

The EPOS2 P 24/5 is the main Controller in AbhisHex. It stores the program and controls the motors connected to it. All the data analysis, power management and signal processing is done from this EPOS controller.

Figure 18: EPOS2 P 24/5 Controller [5]

To control the overall size and weight of the robot, only one EPOS2 P 24/5 controller was used and all rest five were EPOS2 Motherboard and 36/2 Modules, which are compact, lightweight and can perform exactly the same function as that of the main controller except for data storage.

Figure 19: EPOS2 Motherboard & 36/2 Module [5]

The Maxon DC motors (118752) are extremely powerful, high quality motors fitted with powerful permanent magnets. These motors have ironless rotors which makes them extremely compact and have low inertia drives. These motors are selected on the basis of the calculations shown in the next section. There compact size helps in better management of the on-board space.

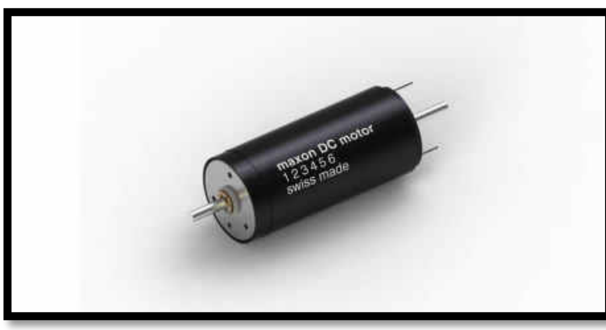


Figure 20: Maxon EC Motor [5]

Maxon Planetary gearhead (166163) is used for its high accuracy and precision. The gearhead is selected based on the reduction ratio and motor calculations discussed in the next section. Here the motor pinion is the input gearwheel for the first stage and is rigidly fixed to the motor shaft. This makes the assembly of gearhead and motor very compact and lightweight.

Figure 21: Maxon Planetary Gearhead [5]

The encoder senses and calculates the position of the motors which can be later used to plot the required graphs and compute results. Maxon HEDL Encoders (110512) are Optical encoders fitted at the extreme ends of the assembly. These are high precision encoders (500 counts per turn) with high signal resolution mounted on the motor shaft for resonance reasons. The overall dimensions of these encoders helped the assembly to be compact.

Figure 22: Maxon HEDL Encoder [5]

The entire internal electrical circuit in ABHISHEX is powered by two Lithium Polymer (LiPo) batteries. LiPo batteries are preferred on account of their high energy-to- weight and energy-to-cost ratios. Based on the design, the battery was selected which could be sufficient to handle all the power requirements of the controller, motors and other onboard sensors. Two "10 cell, 37V" batteries were selected for powering motherboards and One "3 cell, 11.1 V" battery for powering the main EPOS controller. The calculations for the above selected batteries are discussed in the next section. [5]

Figure 23: Batteries

B) <u>Calculation and Selection of Electrical Components:</u>

<u>MOTOR AND GEARHEAD</u>

The motor and gearhead were selected on the basis of the following assumptions:

1. Total Weight = 8.5kg (legs + body)
2. Max Speed of robot = 8kmph = 2.23m/s = 87.8 inch/sec
3. Leg Diameter = 19cm = 7.4 inch = 0.19m   ::   Radius = 9.50cm = 3.75 inch = 0.095m
4. Dimensions of the body = 22 x 18 x 3.75 inch = 55.9 x 45.70 x 9.50 cm

Thus, for selecting any motor we need three factors: Torque, Speed and Power of the motor.

a) Speed: 8kmph ……………………………………………………(assumed)

   Thus the RPM can be calculated as,

   RPM = (60 * Speed) / (Diameter * π)…………..(speed in inch/sec & diameter in inch)

   = (60 * 87.8 / 7.4 * π)

   = 226.7 rpm

   ~ 227 rpm

DC motors of this range have a nominal speed of 6000-9000 rpm. Assuming the nominal speed to be the mean value of 7500 rpm the gear ratio of a planetary gearbox is calculated as:

Gear Ratio(R) = 7500/227

$= 33.04$

Thus, the gearhead with a reduction ration of 33:1 is selected from the above calculations.

b) Stall Torque:

Max weight = Stall torque / (radius * g)

Therefore, Stall Torque = Max weight * radius * g

Here, Stall torque is in Nm, radius is in mts, g is in m/s^2 and weight is in kgs.

$t_{\_stall} = 8.5 * 0.095 * 9.81$

$= 7.921$ Nm

$= 7921$ mNm ……………………………………(torque required for the entire robot)

$t_{\_stall} = 5.85$ ft-lb

This stall torque can be raised by 3 out of 6 motors, which would be working at any given point of time. Theoretically, the max stall torque required from each motor should be $1/3^{rd}$ of this value. This will happen only on flat or smooth terrains. However, AbhisHex is designed to be an all terrain robot and hence there might be situations when only 1 or 2 legs out of the 3 will be active and would need sufficient traction to get the robot moving. Assuming this condition, the stall torque near to the above value should be expected from the each motor.

c) Power:

Power(HP) = $(N * t_{\_nominal} / 5252)$

Where, N is the speed in rpm, $t_{\_nominal}$ is the nominal torque in ft-lb

The ratio of $t_{\_nominal}$ to $t_{\_stall}$ is normally considered between 5 to 10. Assuming the ratio to be 10,

$t_{\_nominal} = t_{\_stall} / 10$

$= 7921 / 10$

= 792.1 mNm

= 0.585 ft-lb

Therefore,

Power (HP) = (227 * 0.585) / 5252

= 0.0252 HP

= 18.8 Watts

Power (W) ~ 20 Watts

Based on the above calculations, a 20W (24V) motor was selected from the Maxon data sheet. The nominal speed of the motor (Part Number: 118752) is 8330 rpm (instead of 7500 assumed above) and the gearhead (Part Number: 166163) having a gear ratio of 33:1.

Therefore,

a) Actual Speed = 8330/33

= 252.4 rpm

This change of speed from 227 rpm to 252 rpm will increase the speed of AbhisHex than assumed earlier.

Based on the above calculations, the Maxon selection software was used to select the suitable encoder, which would perfectly match the combination of selected motors and gearheads. Here, Maxon HEDL 5540 Encoder (110512) was a preferred choice and hence was selected.

BATTERIES

The batteries were selected based on the controller and motherboard voltage and current requirements. The main aim was to select the batteries that would provide adequate power to the controllers to offer required speed and torque without over heating. LiPo batteries are selected on basis of their C ratings. C rating is an indicator for the maximum continues discharge rate of the LiPo (Lithium Polymer) battery.

Continuous current drawn = (mah x 0.001) x (C rating)……………………………………(A)

EPOS Motherboard Batteries:

Continuous current drawn = (3900 x 0.001) x (25)

= 97.5 A

This is the max current the can offer when it is full charged.

This battery will be used to control three motherboards along with the set of motors and encoders connected to it.

Controller Battery:

Continuous current drawn = (2200 x 0.001) x (20)

= 44 A

A fully charged battery would offer a max current 44A, though the controller would normally require only 24A of current at any point during its operation. This offers enhanced working hours of the robot.

C) <u>Design of Internal Communication Diagram</u>

The communication in the AbhisHex is divided into three different sections. A summary of the internal communications along with the structured physical layout is shown in figure 23. The desktop computer is connected to the main computer. The required code is uploaded on the main computer. The main computer (EPOS2 P 24/5) is then connected to one set of gearhead, motor and encoder assembly. A separate 11.1 V battery powers this main computer. The EPOS 36/2 modules are mounted on the motherboard, which are then connected to individual set of gearheads, motors and encoders. Two separate batteries of 37V each power these five modules. Finally, the motor assembly consists of a brushless motor connected to the gearhead in the front and an optical encoder at the end.

The figure shows a representation of one set of connections in AbhisHex. Similarly, the AbhisHex will have five EPOS modules connected as shown in the figure.

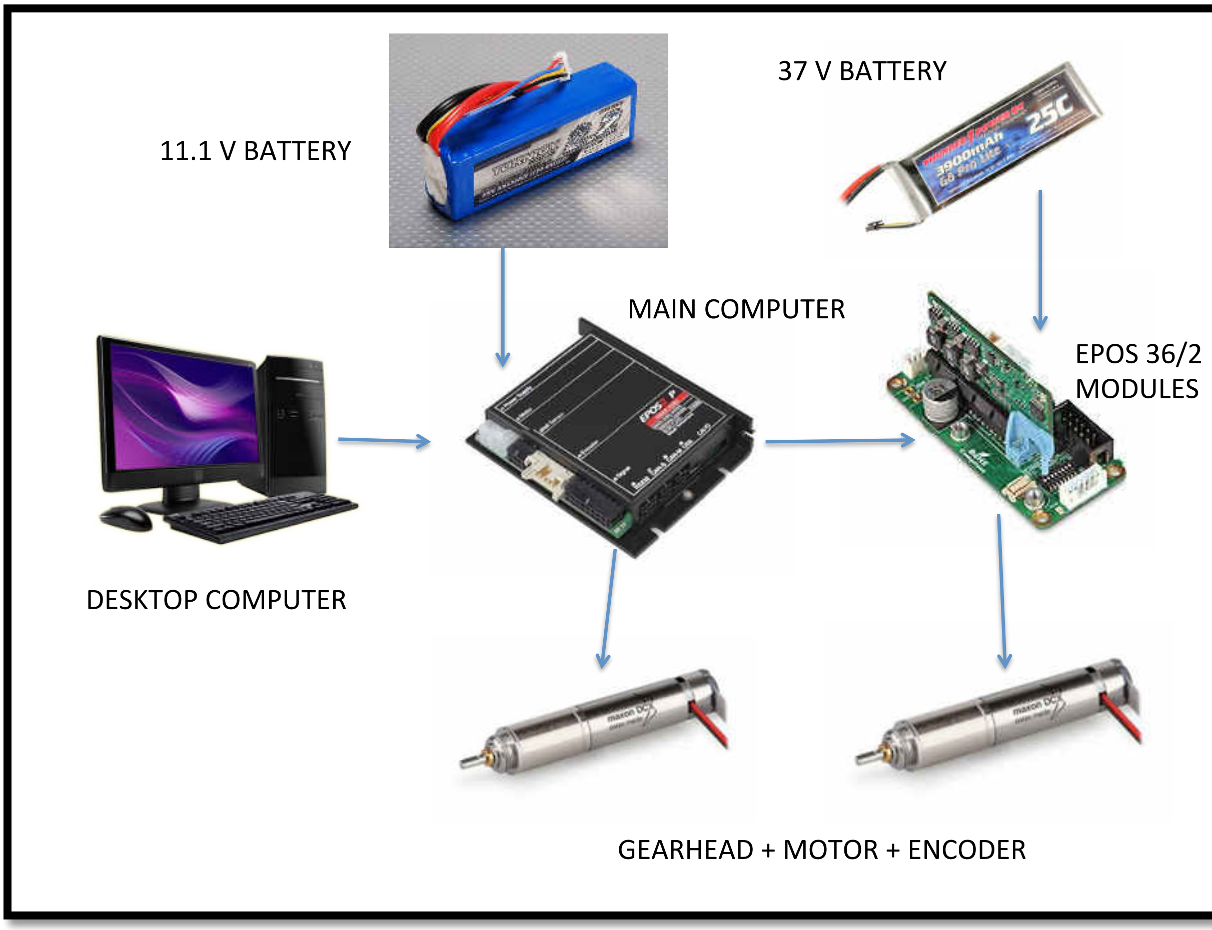


Figure 24: A Physical Layout of Internal Communication in AbhisHex

CHAPTER FIVE: SOFTWARE DESIGN

A) <u>PI Control Algorithm:</u>

Proportional–Integral (PI Controller) is a closed look feedback mechanism used in industrial systems. A PI Controller continuously calculates the error value and the difference between the desired set point and process variable. The controller attempts to minimize the error by adjusting the values of control variables such as position control, damper or the power supply. The standard equation of PI control is given below-

$$u(t) = K\mathrm{p}\, e(t) + Ki \int_0^t e(t)dt$$

Where K_p and K_i are the coefficients for Proportional and Integral terms respectively, e(t) is the error between actual and reference value of the controller. [8]

In this study, a PI controller is designed based on motor speed and position. These values are then used in the simulations to check if the robot is moving with required stability.

The transfer functions of DC motor for Speed and Position are given below. [8,9]

G(s) = $\frac{k}{(Js+b)*(Ls+R)+K^2}$ ………………….(speed in rad/sec)

G(s) = $\frac{k}{s*(Js+b)*(Ls+R)+K^2}$ ………………….(position in radians)

Where,

K = Torque Constant

J = Moment of Inertia of the rotor

b = Motor friction constant

R = Electrical resistance

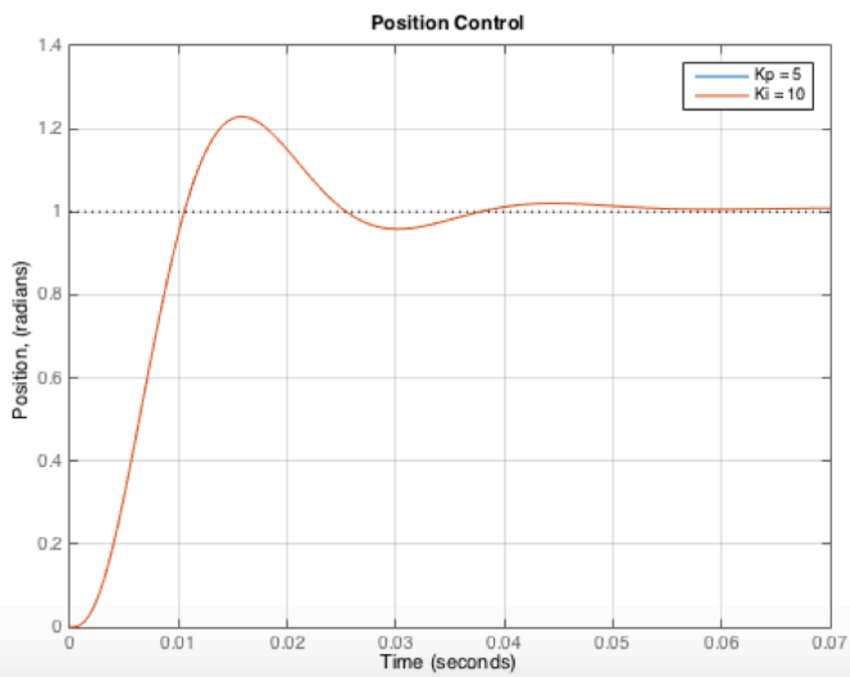
L = Inductance of the motor

s = Laplace Transformation variable

Based on the data sheet provided by Maxon motors, the above values were taken and a PI controller was designed suitable for this particular operation. The plots of the PI controller MATLAB code for speed and position is shown below:

```
ans =

        RiseTime: 0.0066
    SettlingTime: 0.0459
     SettlingMin: 0.9408
     SettlingMax: 1.2293
       Overshoot: 22.9311
      Undershoot: 0
            Peak: 1.2293
        PeakTime: 0.0158
```



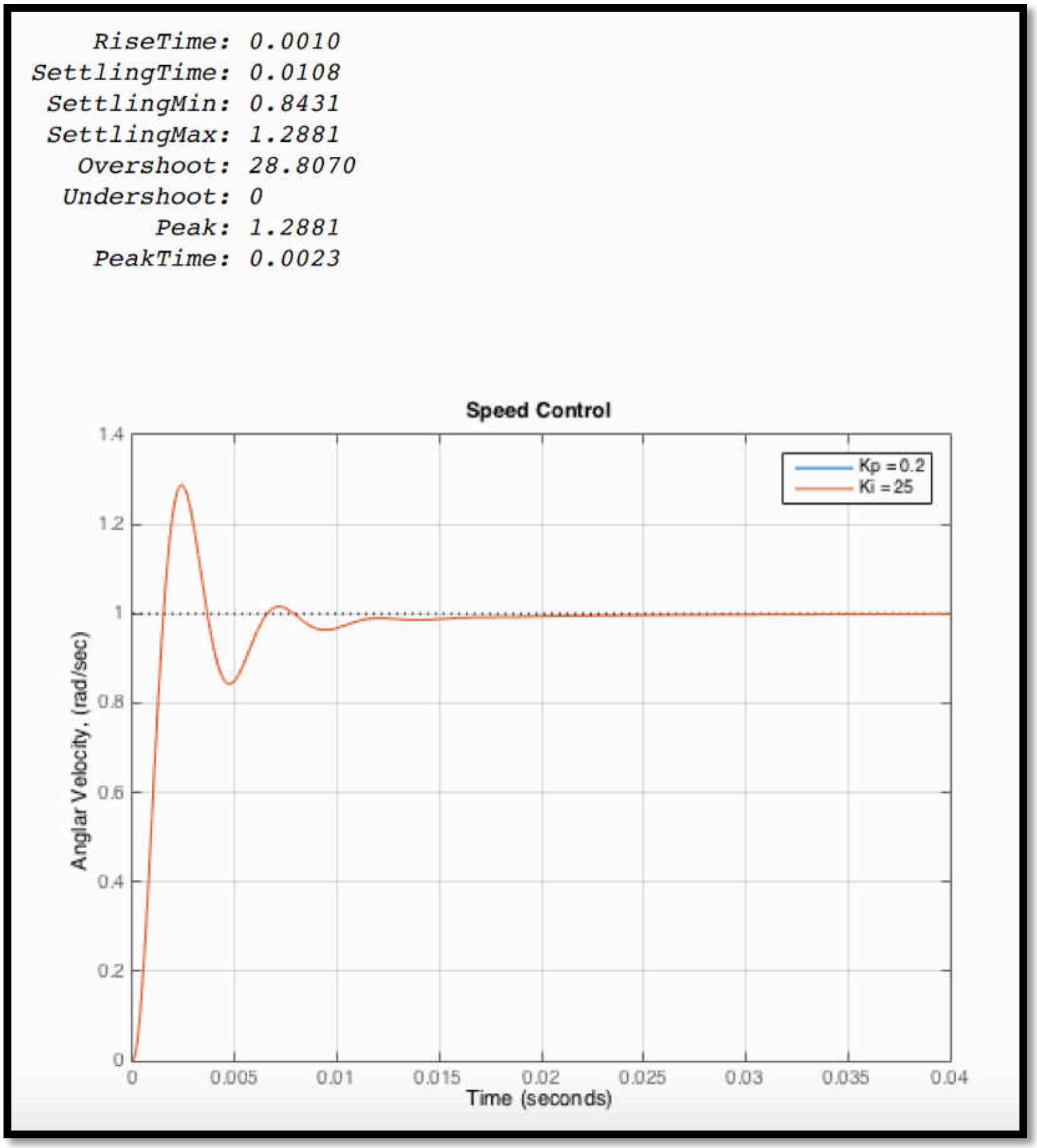


Figure 25: MATLAB code for PI Control Algorithm

The following table shows the effects of gains on changing the values of K_p, K_i and K_d.

Rise time: Rise time refers to the time required for a signal to change from a specified low value to a high value.

Overshoot: Overshoot is when a signal or function exceeds its target. It is defined as the maximum positive deviation of the response from its desired value

Setting time: This time is represented by t_s. The time required by the response to reach and settle within the specified range of its final value for the first time is known as settling time.

Steady State Error: It can be defined as the difference between the actual output and the desired output as time tends to infinity

	Rise Time	Overshoot	Settling Time	Steady-State Error
K_p	Decrease	Increase	Minor change	Decrease
K_i	Decrease	Increase	Increase	Eliminate
K_d	Minor change	Decrease	Decrease	No influence

Table 4: Effect of gains for Kp,Ki,Kd

B) Structured Functional Chart (SFC) Code (Maxon EPOS Studio):

B.1) Introduction:

The SFC editor is hosted by the OpenPCS framework in EPOS Studio software. A Structured Functional Chart is an editor in EPOS Studio where the Maxon motors are coded. It is separated in three different parts. The top part consists of the declarations, the central part consists of the charts and last part consists of the required code. The reference code has been added to the appendix. [35]

B.2) Elements of a sequential functional chart:

The SFC offers with the following language elements:

- Steps and Initial Steps: If the steps are in the active state the code is executed in a cyclic manner. Initial steps are always active at the time of starting the program and hence no preceding transition is needed. Every step can be converted into an initial step by activating the control box in the properties window. Steps have a maximum length of 31 characters.

- Transitions: transitions are responsible for the change of active state of previous step to the next step. The changes are in the form of a true, Boolean statement. The code is written in such a way that the current result at the end of code is of type BOOL. The transition is done only if the variable is TRUE. [35]

CHAPTER SIX: SIMULATIONS AND ANALYSIS

A) FEA Analysis of Body (Frame):

In this chapter a Static stress analysis is done on the body frame of the AbhisHex as shown in the figure 26. The frame is designed in order to withstand all the forces and stresses acting on the body. The cross members and motor mountings serve to connect the two ends of the frame as well as give enough rigidity to it thereby increasing the overall stiffness of the frame in lateral and longitudinal direction. The holes provided in the frame not only makes it light weight but also provides sufficient heat sinks for motor and controllers. Note that it can be seen from the figure below, with the current design and material used, the stress concentrations experienced in the frame is very low. [10]

The entire frame is made up of Al 6061-T6 and weighs 3.6lbs (approx. 1.7kgs). The static analysis on the frame was done using two software's Solidworks and ANSYS. The following conditions were imposed for the analysis:-

a) Load of 3.5 N acting on the motor mountings
b) Load of 0.5 N acting on the cross members
c) Load of 1 N acting on the top of the body
d) The entire body is subjected to operate at an optimal temperature of 28^0C
e) The cross members will be bolted to the runners, motor mountings on the cross members and the polycarbonate sheet will be fixed at the top of motor mountings.
f) Gravity of 9.8 m/s^2 acting on the body

(* NOTE: All the forces considered are calculated based on the material specifications, speed of robot and conditions of operation.)

After adding the required conditions mentioned above, a solid mesh is generated for the entire body. A solid mesh having an element size of 0.5 inch and a tolerance of 0.02 inch was selected for the analysis. The meshing results generated can be seen in Figure 25. After the meshing is done the stress analysis is started based on the given conditions. Figure 26 shows the stresses acting on the body frame are very low and hence it can be concluded that the design and material chosen can for AbhisHex can work perfectly in the given conditions.

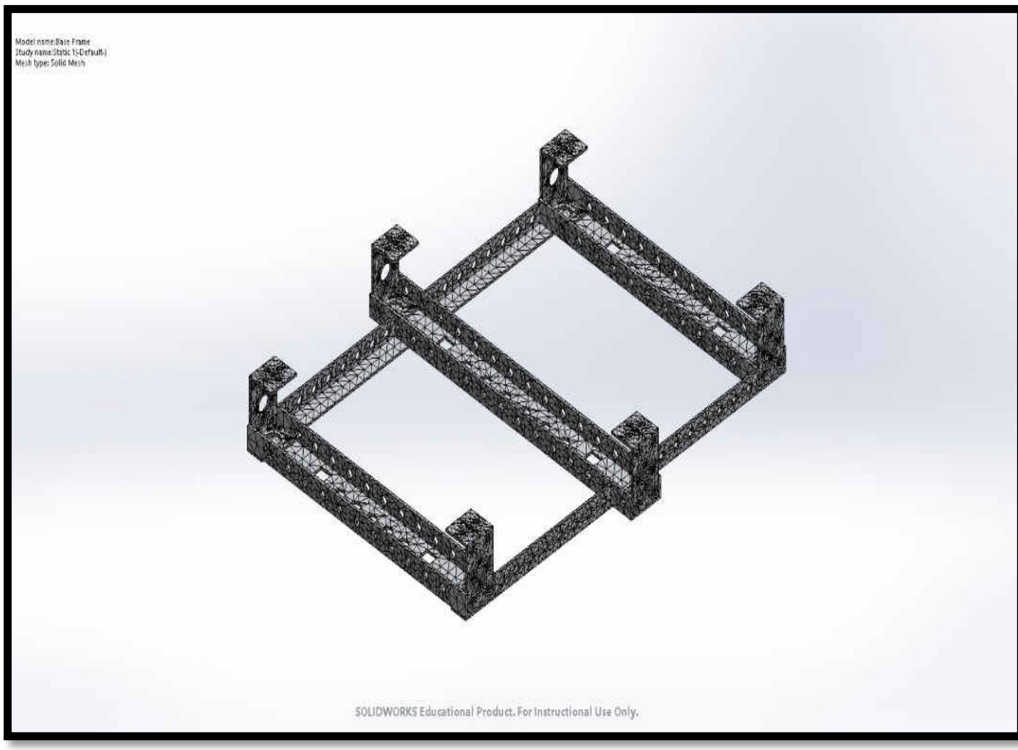


Figure 26: Meshing of AbhisHex body frame.

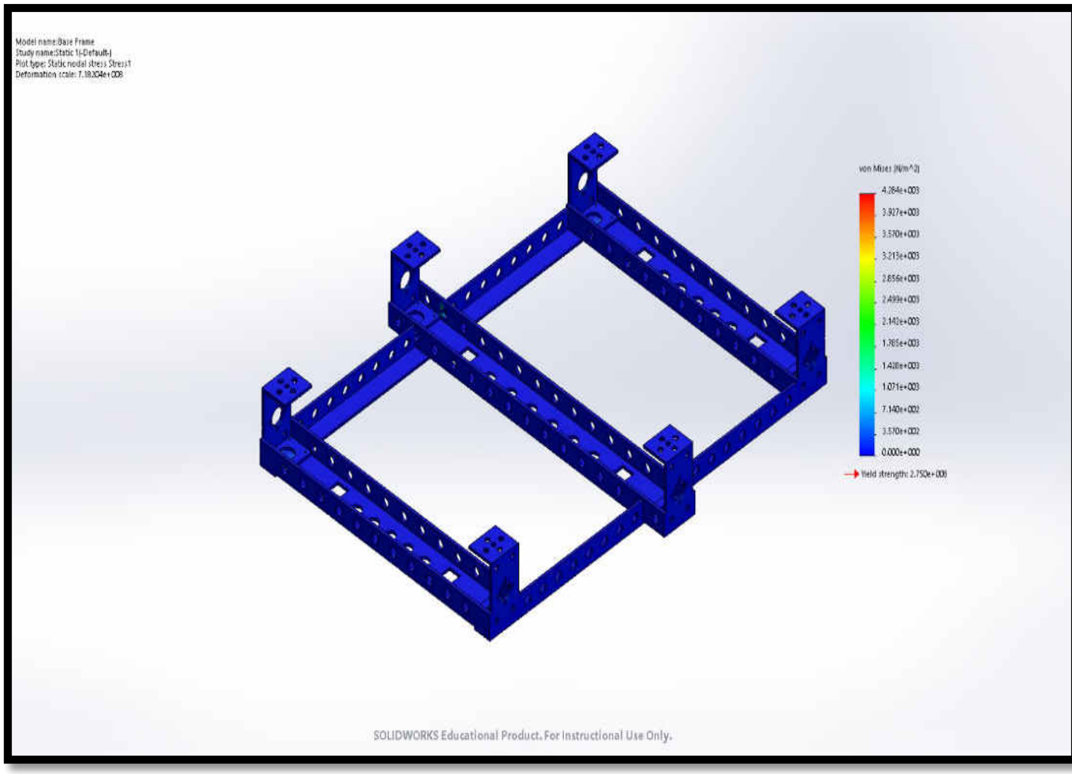


Figure 27: Static Stress Analysis of AbhisHex frame

B) <u>FEA Analysis on Leg:</u>

In this chapter a static stress analysis is done on the AbhisHex leg as shown in the figure 28. The leg is designed in order to withstand all the forces and stresses acting on the body along with the weight of the entire robot on any terrain. Similar to the base frame, a solid mesh having an element size of 0.123 inch and a tolerance of 0.06 inch was selected. It can be seen from the figure 28 and 29 that with the current design and material used the stress concentrations experienced in the leg are moderately high (region in red) at the lower end of the leg where the leg is expected to come in contact with the ground. The meshing results generated can be seen in figure 27.

The entire leg is made up of Delrin and weighs 0.6lbs (approx. 0.28kgs). The static analysis on the leg was done using two software's Solidworks and ANSYS. The initial conditions imposed on leg were based on the calculations done in Chapter 3 (Section E) as follows:-

a) Load of 42 N acting on the normal face of Leg

b) Max torque of 7.5Nm acting on Leg

c) Gravity of $9.8m/s^2$ acting on the leg

d) Angular acceleration of $27rad/s^2$

e) Top attachment fixed using bolts to the Leg

(* NOTE: All the forces, torques and acceleration values considered are approximately calculated based on the material specifications, speed of robot and conditions of operation.)

The same procedure as discussed in the previous chapter was followed to analyze the leg under the above conditions. As seen in figure 29 the portion of the leg which is in direct contact with the ground will comparatively high stresses acting as compared to other areas. Thus rubber pads or covers will be used in that are in order to damp the forces acting at bottom as well as provide sufficient friction on all terrains [13].

Figure 28: Meshing of AbhisHex Leg

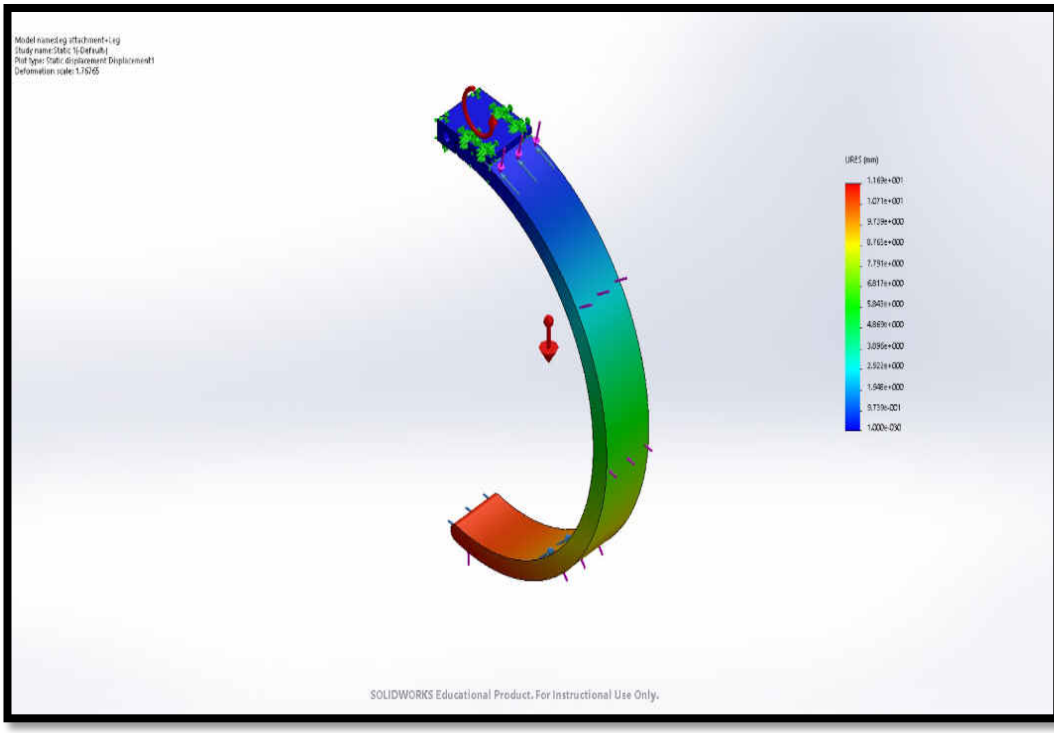


Figure 29: Static Stress Analysis of AbhisHex Leg

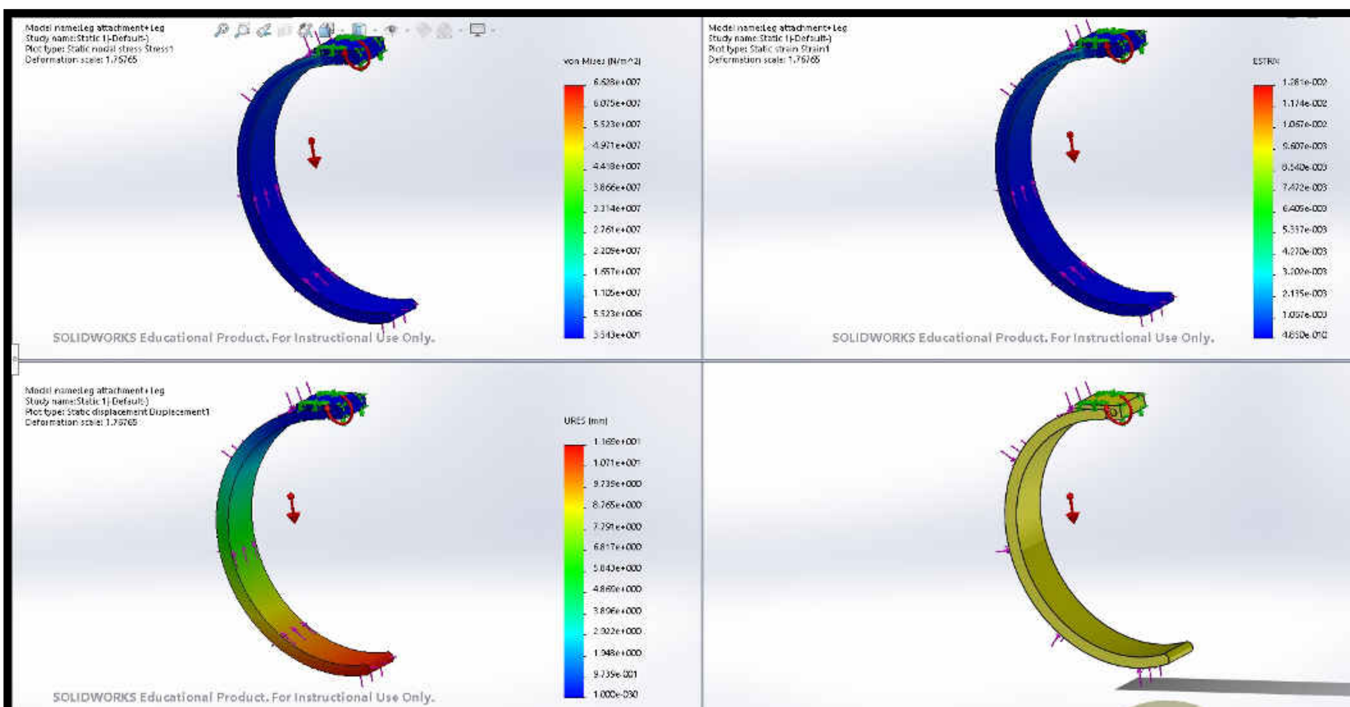


Figure 30: Strain, Displacement and Stress Analysis of AbhisHex Leg

C) Simulations and Plots in SolidWorks:

C.1) SolidWorks Software:

A mechanical system design needs some basic data like motor specifications, body specifications (rigid or flexible), forces acting on the bodies and external conditions before creating any design. SolidWorks is a solid modeling computer-aided design (CAD) and computer aided engineering (CAE) computer software. SolidWorks allows one to create, tests and analyze the prototypes before they can be actually built.

In SolidWorks, the required model is created as per the actual dimensions. This model is then subjected to various conditions such as forces, external factors, motions, constraints etc. Once these conditions are set, then SolidWorks offers a wide variety of simulation options like Animation, Basic Motion and Motion Analysis. Another property of this software is to interface easily with finite element software as well as high end programing software's like MATLAB/Simulink. The model built and simulated in SolidWorks can be easily exported to other software's for detailed analysis or programing them in new environments. [14]

C.2) Modeling AbhisHex using SolidWorks:

To start with modeling of AbhisHex, initially all the components were designed individually according to the actual dimensions. These components were then assembled to build the prototype. A flat ground was then added at the bottom on which the robot can rest during simulations.

This assembly was then subjected to all the simulation conditions in Motion Analysis environment. The entire geometry was assigned with required constraints, environmental conditions like gravity, ground surface, drag force etc. When the basic geometry was ready, motion conditions were added which included motors, speed (velocity/acceleration), forces, spring and damper conditions and ground contacts. After adding all the required conditions the simulation was started. The results from the simulation were then plotted to get the required plots. The graphs shown below were plotted on the basis of simulation results.

It can be seen from Angular displacement vs Time plots in figure 30 that the plots for Motors 1, 3 and 5 are similar and the plots for Motors 2,4,6 are same. Since the AbhisHex follows are tripod gait pattern the font and rear legs on one side and middle leg on the other side perform the same function. Thus it can be seen in the plots that motors associated with this set of legs have same graphs. As seen in case of Motors 1,3,5 the motors start at 90^0 while for Motors 2,4,6 they start at -90^0 which is exactly opposite as seen in the previous assembly figures.

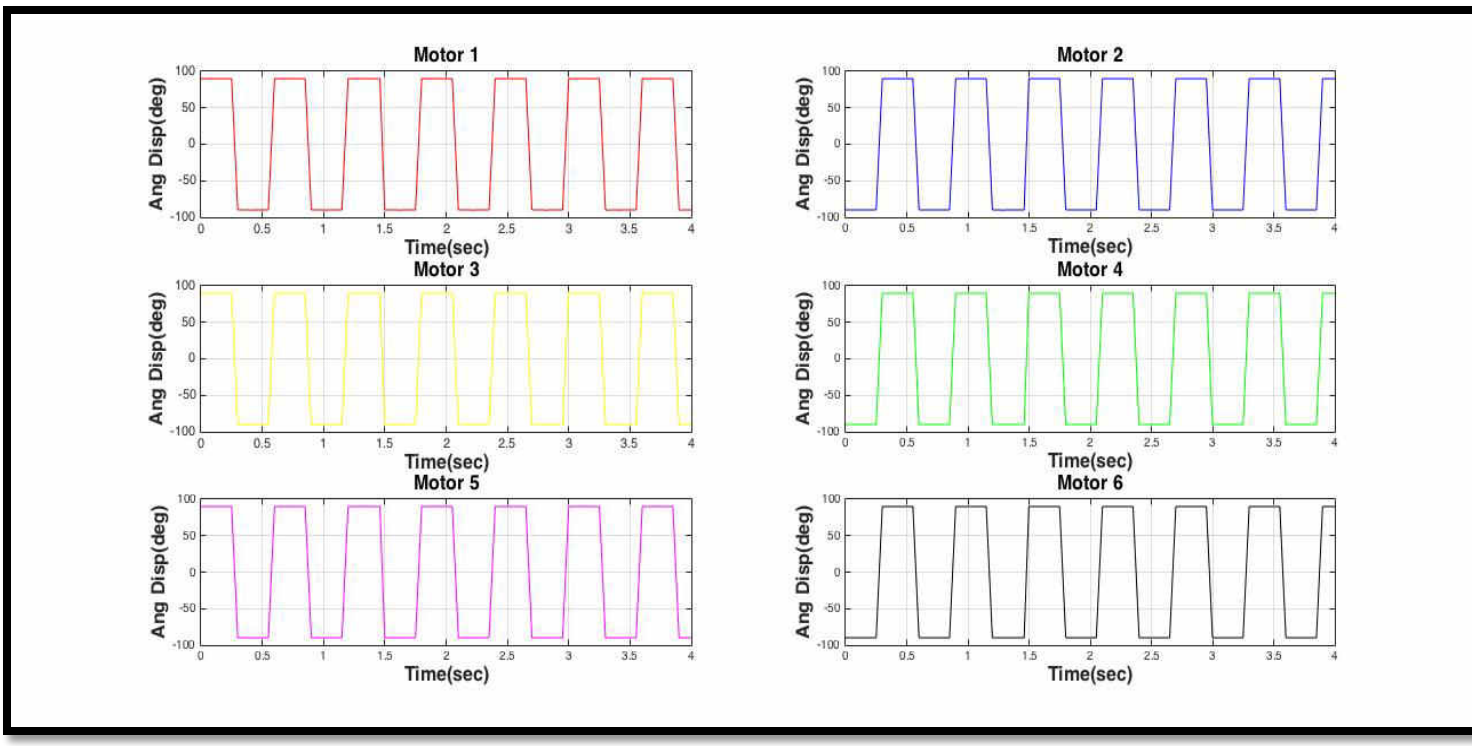


Figure 31: Angular displacements vs Time Plots

Similar to the previous plots it can seen from the Reaction Force versus Time plots in figure 31 that same forces are acting on the Legs 1,3,5 and Legs 2,4,6. In case of Legs 1,3,5 it can be seen that the average force acting on every leg ranges from 8N to 11N over a period of 10 seconds. Similarly in case of legs 2,4,6 an average force of 7N to 10N is acting on every leg over the same time period.

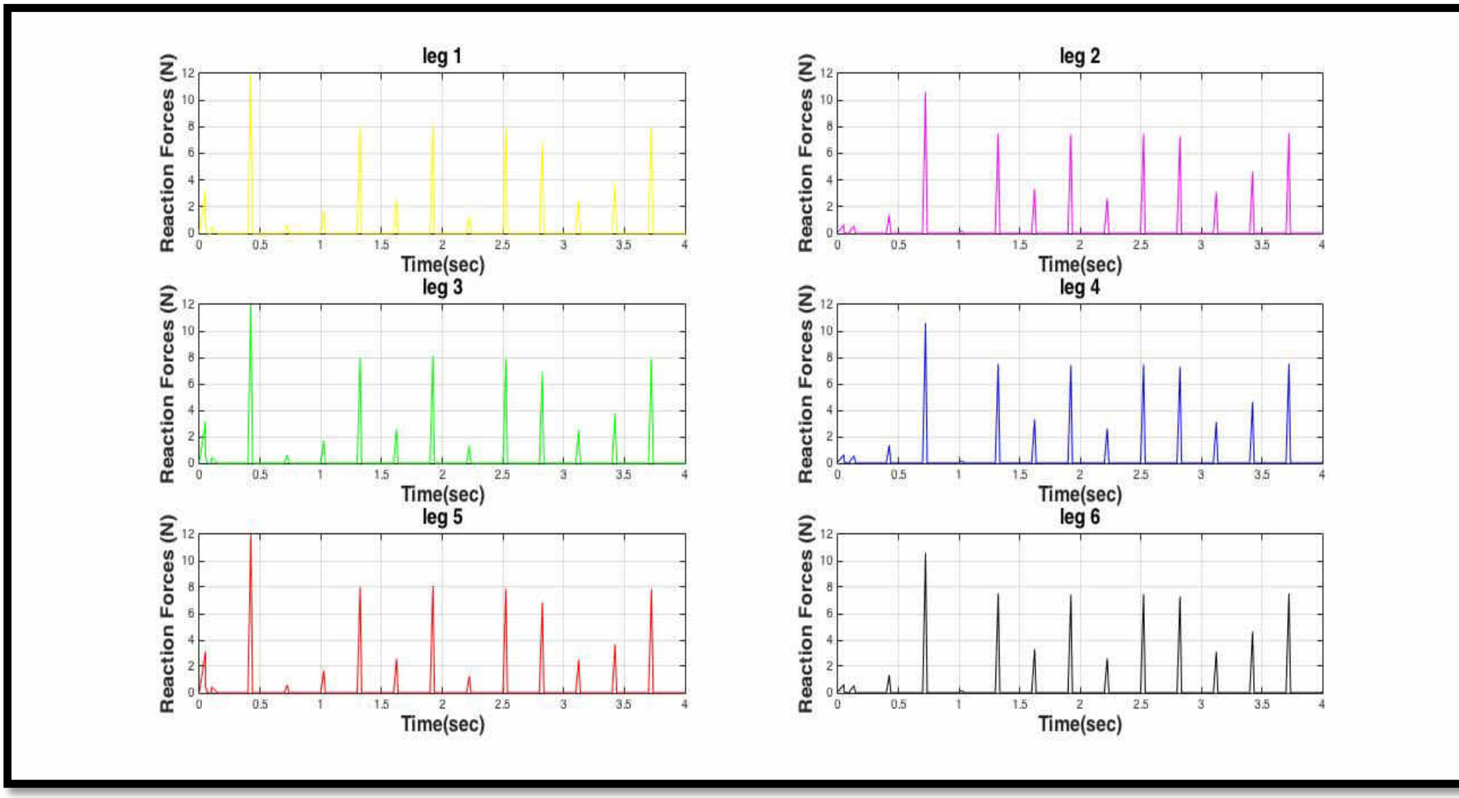


Figure 32: Reaction Forces vs Time Plots

A typical path traced by AbhisHex in the SolidWorks Simulations is shown below in figure 32. It can be seen from the figure that a hopping pattern can be observed where the body at one point is close to the ground and then is lifted when one of the tripod completely touches the ground.

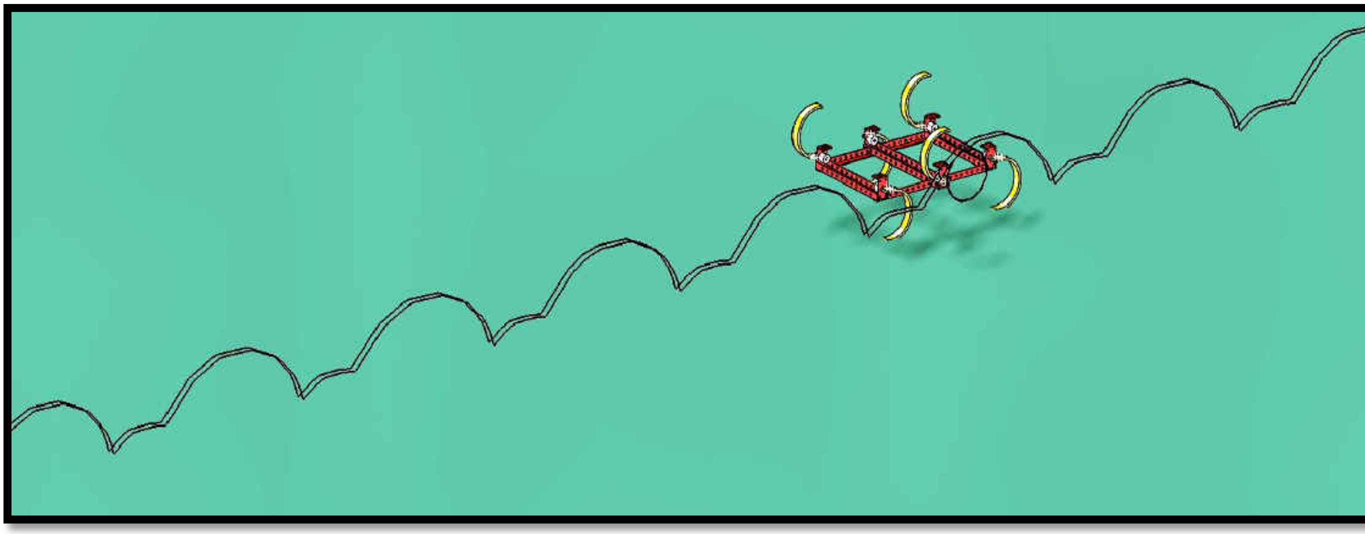


Figure 33: Path Traced by AbhisHex in Simulation

D) Simulations in SimMechanics (MATLAB):

Simscape Multibody also called as SimMechanics is a multibody simulation environment for 3D Mechanical systems. SimMechanics uses blocks representing bodies, joints, constraints, force elements and sensors to formulate the equations of motion and solve the problem. A CAD model can be directly imported in this including the assemblies, masses, joints, constraints and then modeled in SimMechanics. SimMechanics then automatically generates an animation, which helps to visualize the system dynamics. SimMechanics also offers generation of C code based on the simulation. [16]

In this case the ABHISHEX was first modeled in SolidWorks and then the assembly drawing was imported to SimMechanics. The required constraints, joints, masses were then added to these blocks for the entire assembly as shown in the figure below. At the end this block diagram code was simulated to obtain a similar simulation as in SolidWorks.

CHAPTER SEVEN: TESTING AND RESULTS

A) Test Setup and Prototype Testing:

EPOS 2P controller is the main controller on board, which is connected to the EPOS 36/2 modules via CAN cables. The EPOS 2P controller stores all the code, which is then transferred to the modules and then to the respective motors at the rate of 1000000 bits/sec. Once the connections are done EPOS Studio software is used to send signals to the controller. Before tuning all the motors are tested to check the connections and data transfer rate. Once this is done the EPOS 2P controller and EPOS 36/2 modules are tuned as per the requirements by adjusting the DIP (Dual In-line package) switches provided on board. The DIP switches are usually used to select the operating modes of any device to be controlled. An example of DIP switch settings is shown in figure 34. In case of AbhisHex the DIP switch settings were adjusted as follows. The combination indicates the DIP switches in ON mode.

EPOS 2P → 1,8

Module 2 → 2

Module 3 → 1,2

Module 4 → 3

Module 5 → 1,3

Module 6 → 2,3

JP 1 → 1

Use following table as a (non-concluding) guide:

CAN ID	CAN ID/Switch Valence DIP Setting	1 1	2 2	3 4	4 8	5 16	6 32	7 64	Calculation
1		1	0	0	0	0	0	0	1
2		0	1	0	0	0	0	0	2
32		0	0	0	0	0	1	0	32
35		1	1	0	0	0	1	0	1 + 2 + 32
127		1	1	1	1	1	1	1	1 + 2 + 4 + 8 + 16 + 32 + 64

Table 4-17 CAN ID – DIP Switch Settings (Example)

Figure 34: DIP Switch Settings

The AbhisHex prototype testing was carried out in two phases:- **a) Off ground testing (Air Walking)** and **b) On ground testing**.

In the Off ground-testing phase the entire robot was supported in air in such a way that none of the legs touched the ground. The main aim of this testing was to check the code for tripod gait and wave gait (discussed in CHAPTER FIVE), on board electronics placements and connections. Each actuator was first tuned in the MAXON software for its actual position, actual current drawn and actual rpm. Once the tuning was done for the above mentioned factors, the tripod gait was manually tuned for all the six actuators individually. Once tuned the real time graphs were obtained for all the six actuators based on their current and velocity actual values @ 1000rpm as shown below. [17]

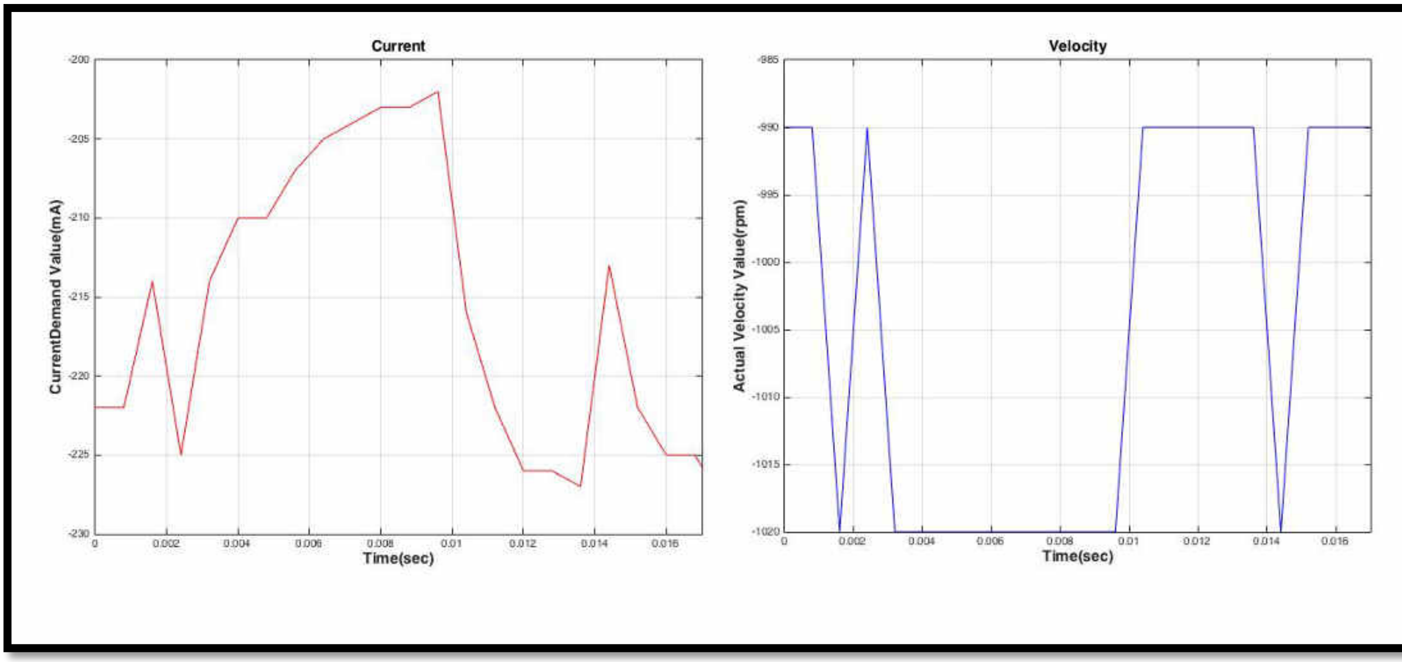


Figure 35: Actual Velocity, Current vs Time

Once the Off ground testing was done successfully the robot was then placed on the ground for actual walking and testing.

In the On ground testing phase the robot was tested for the following things:

1. Its ability to lift the entire body from ground.
2. The ability of all the legs to sustain the weight of the entire body without breaking or cracking.
3. Making it stand from ground, walk using the wave gait and tripod gait patterns.

In order to lift the entire robot from rest 3 actuators on one side were rotated in clockwise direction while the other 3 were rotated in anti-clockwise direction. Based on the weight it had to lift the current and voltage values were decided after multiple trials. It could be seen that a the actuators drew maximum current from the point the legs start touching the ground till the point the entire body is lifted on all the six legs. The maximum current and voltage drawn by the actuators were approx. 4 Amps and 32 Volts respectively. [17]

Wave gait is a gait where the robot is made to walk with all the six legs moving in the same direction and making the robot walk forward or backward. In this case the robot moves one body length during one gait cycle. [25]

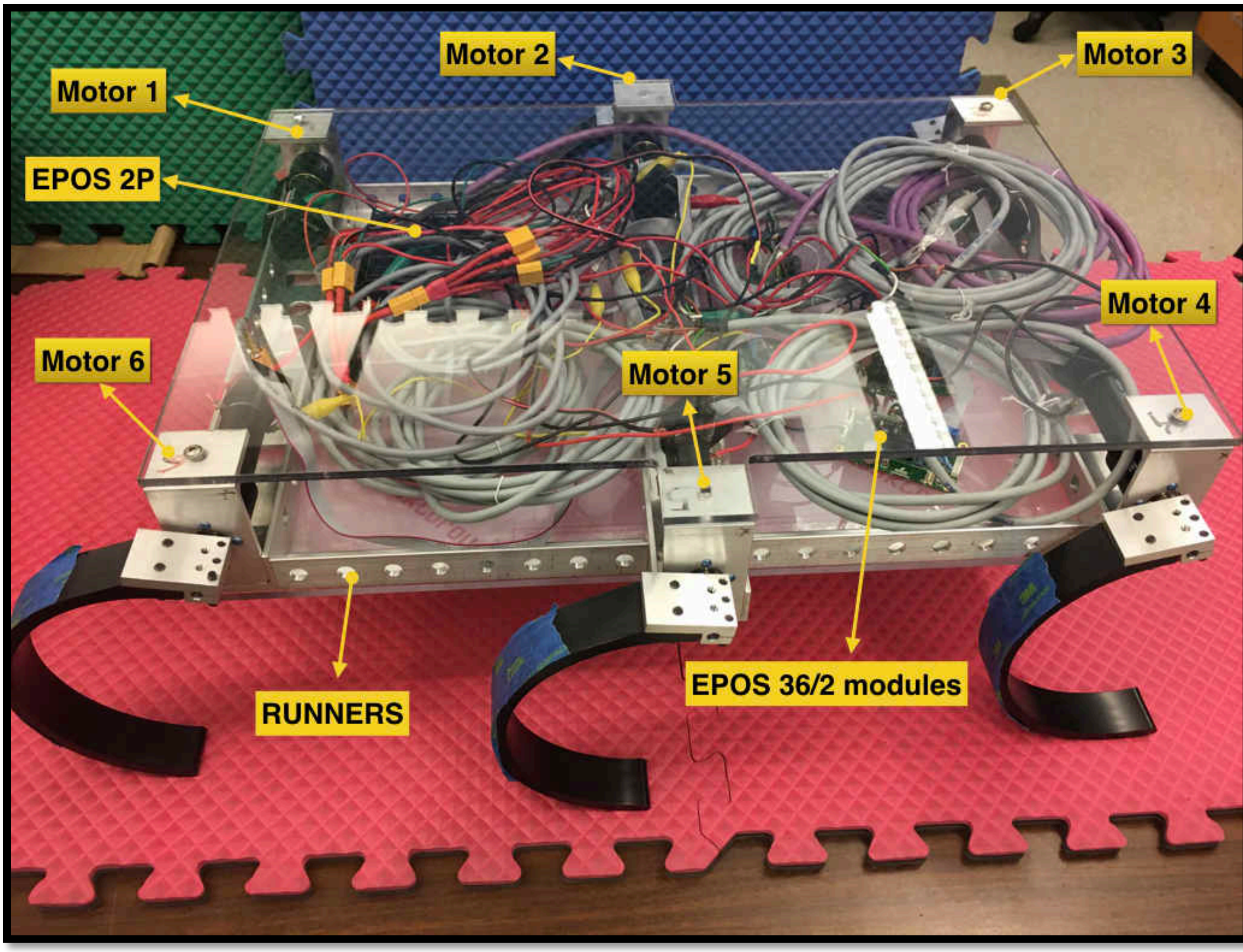


Figure 36: The AbhisHex Prototype (Part 1)

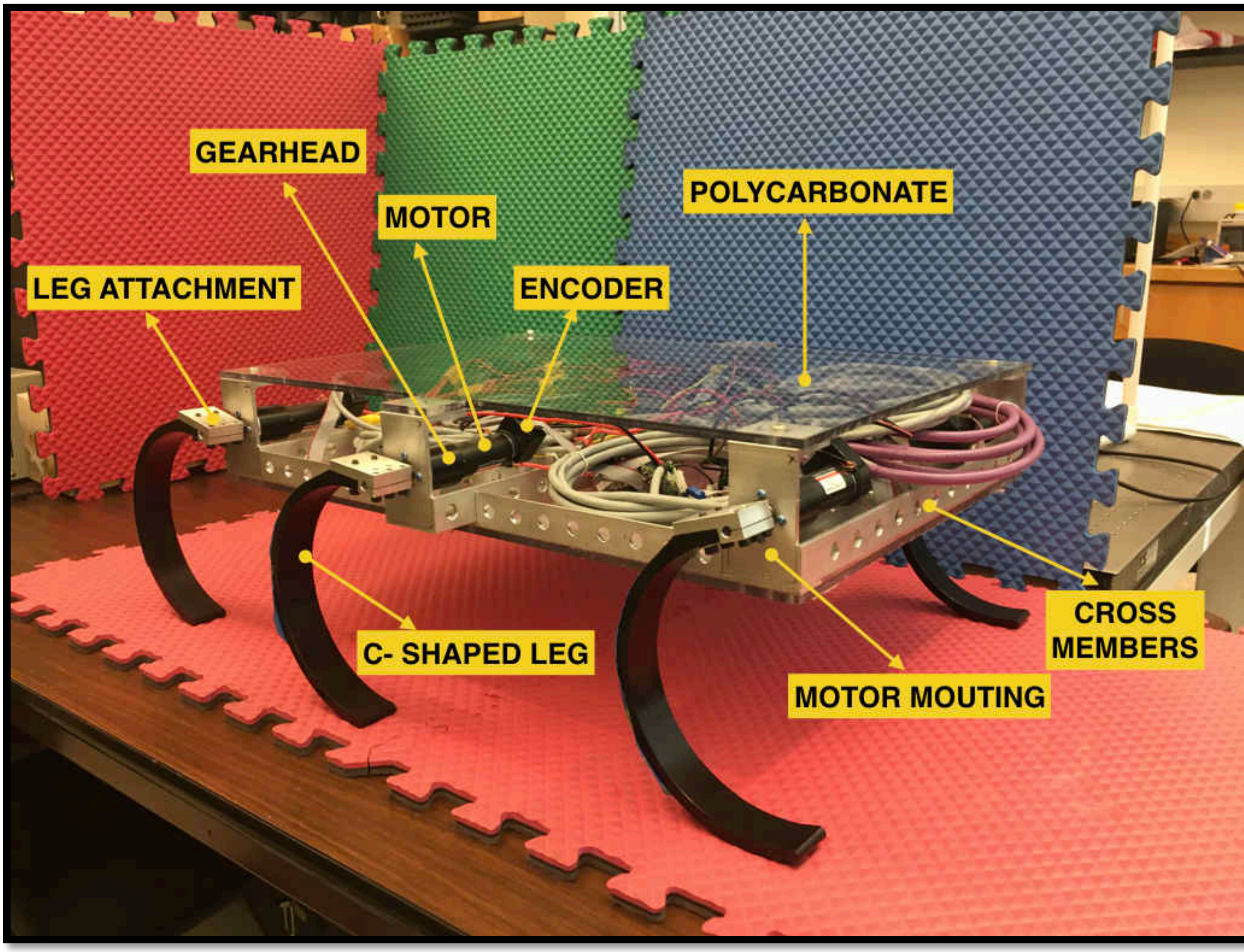


Figure 37: The AbhisHex Prototype (Part 2)

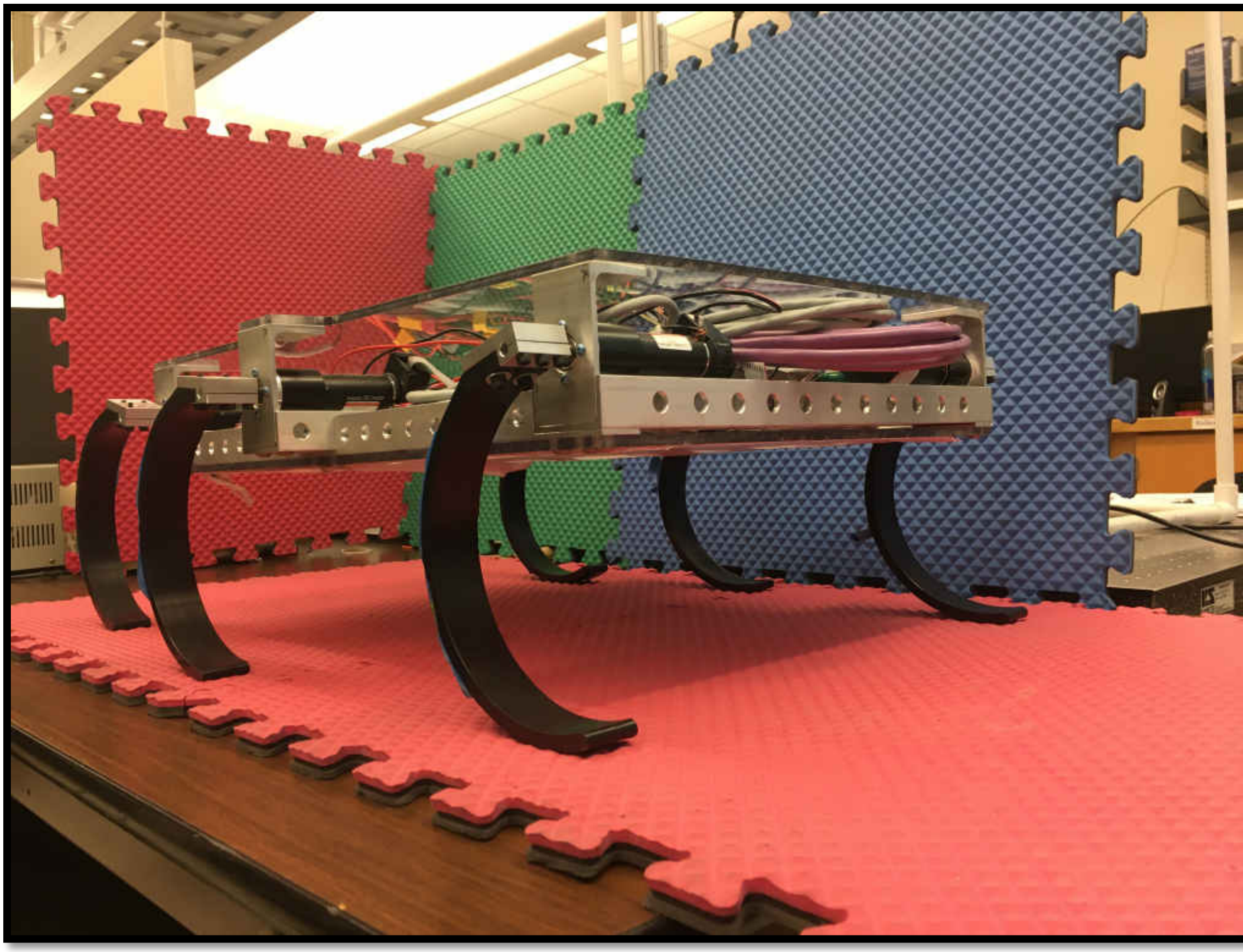


Figure 38: The AbhisHex standing on all six legs

B) <u>Computing the Results:</u>

a) <u>STANDING / LIFT OFF:</u> Initially the robot was made to stand on all the six legs from ground to test the current and voltage requirements along with the ability of legs to sustain its weight. The following observations were recorded.

- Required Current: 3.3-3.5 Amps
- Gait: Standing with all legs supported

It can be seen from figure 38. that the legs can sustain the weight of the entire robot at the given configurations.

b) **<u>WALKING (FLAT GROUND):</u>** Once the robot was able to stand on all the six legs it was tested for walking the wave gait. Wave gait is a pattern where all the six legs move in the same direction simultaneously. This makes the robot travel one-body length in one cycle. During this the robot stands on all the six legs and then again touches the ground completely before the next round and hence the body moves in a wave pattern. The plots for walking can be seen in figure 37. below. Since torque is directly proportional to current drawn, it can be seen that the motors draw a maximum current when the legs touch the ground and try to lift the body back to the original position to generate a maximum torque of approx. 6-7 Nm. The following observations were recorded.

- Required Current: 3.8-4 Amps
- Required Voltage: 36 V
- Gait: Wave gait (Flat Ground)
- Velocity: 800 rpm ……………….(EPOS Studio specifications)
- Acceleration: 6000 rpm/s ………..(EPOS Studio specifications)
- Deceleration: 6000 rpm/s ………..(EPOS Studio specifications)

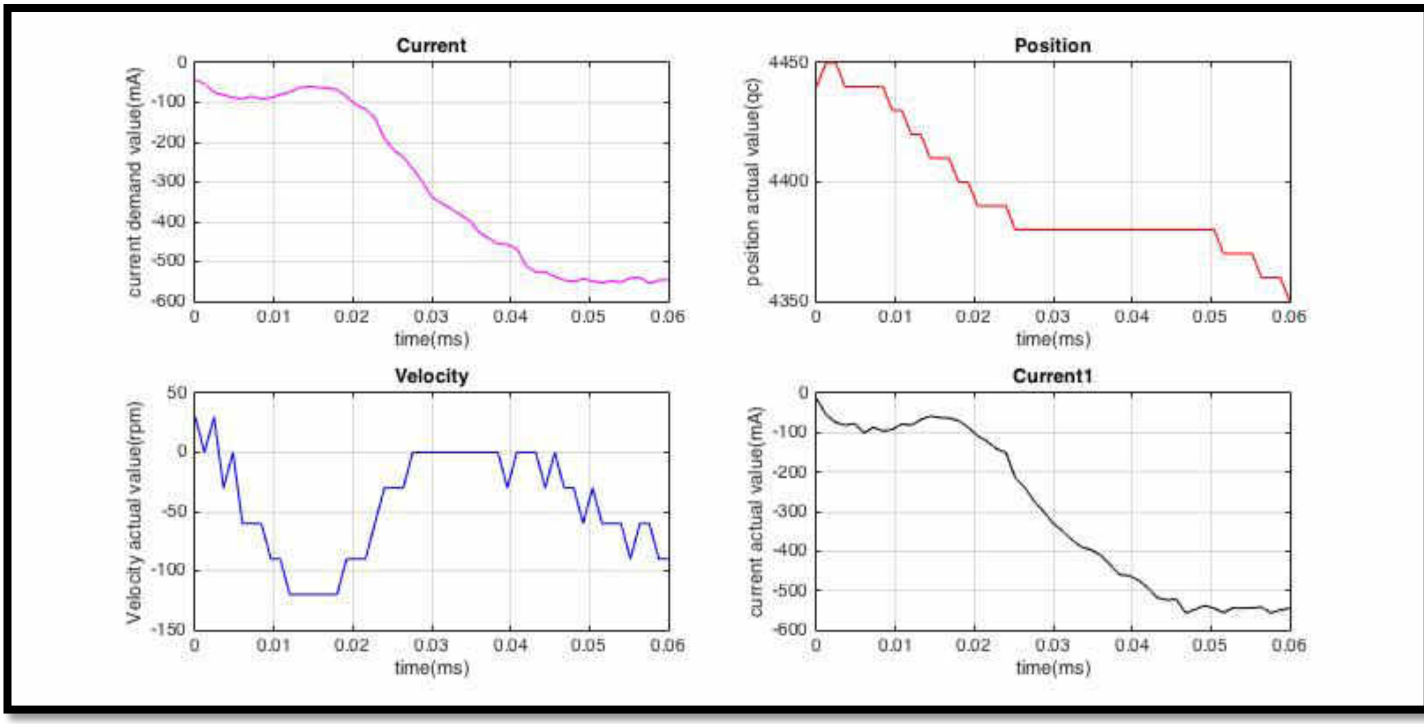


Figure 39: Velocity, Current, Position vs Time Plots for STANDING / LIFT OFF + WALKING (0 degrees)

c) **WALKING (INCLINED PLANE):** In these trials the robot was made to walk the wave gait on an inclined plane of 10 degrees. It was seen that the robot draws more current than any previous trials to achieve a torque suitable to climb the inclinations. The following observations were made during this walk.

- Required Current: 4-4.2 Amps
- Required Voltage: 36 V
- Gait: Wave gait (10 degrees)
- Velocity: 600 rpm
- Acceleration: 6000 rpm/s
- Deceleration: 6000 rpm/s

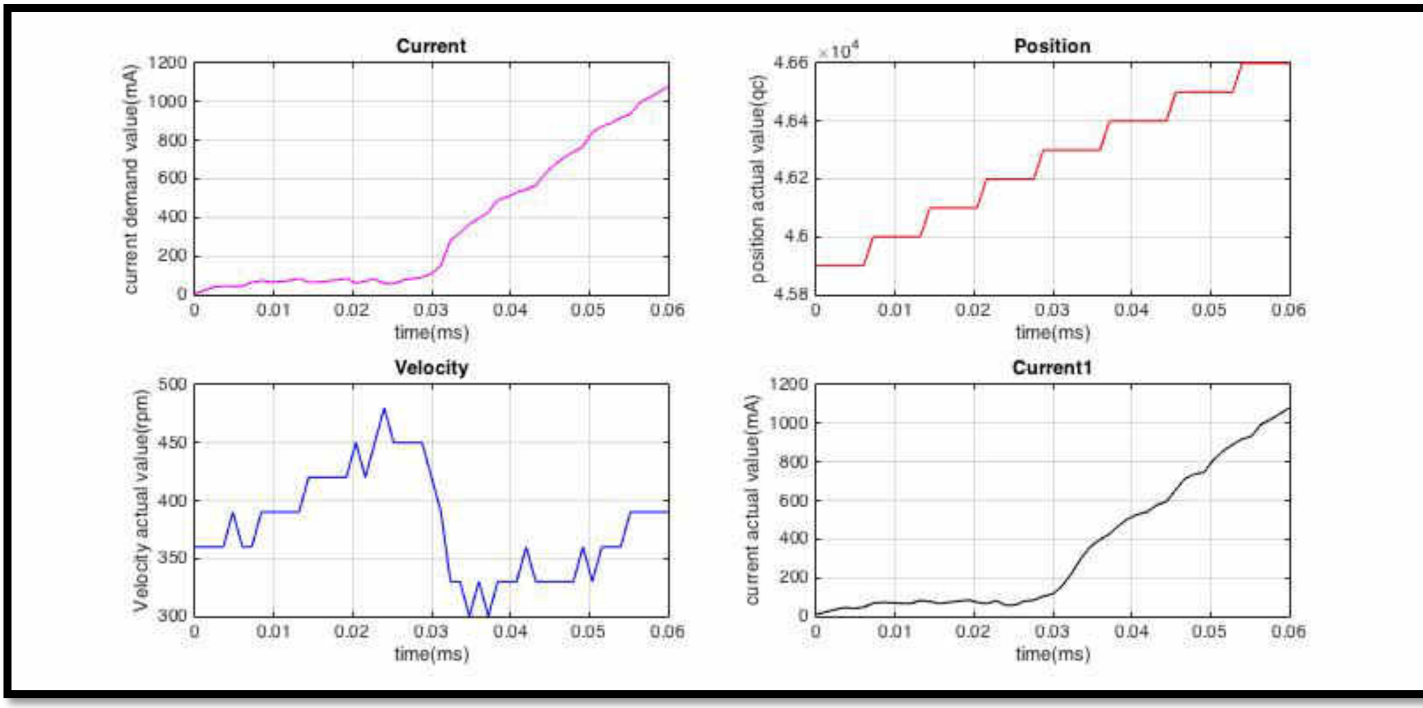


Figure 40: Velocity, Current, Position vs Time Plots for WALKING (10 degrees inclined)

C) Cost Analysis:

The table below shows the approximate cost estimation of the entire robot, which includes material costs, machining and manufacturing costs and running costs.

SR NO	PRODUCT	QUANTITY / SIZE	COST ($)
1	Maxon Brushed Motor	6	1674.78
2	Maxon Planetary Gearhead	6	813.78
3	Maxon Encoder	6	617.28
4	Maxon EPOS2 Module 36/2	5	1889.28
5	Maxon EPOS2 Motherboard	5	585.78
6	Maxon EPOS2 P 24/5 (CPU Controller)	1	884.25
7	Power Cable (3m,EPOS2 P 24/5)	1	15.25
8	EPOS2 Motherboard Power Cable (1m)	5	30
9	Motor Cable (3m)	6	192.78
10	CAN-CAN Cable (3m, EPOS2 P to modules)	1	28.88
11	USB Type A-mini B Cable (3m, EPOS2 P to computer)	1	28.13
12	Al 6061-T6 (RUNNERS)	1 (48 INCH LONG)	4.65
13	Al 6061-T6 (CROSS MEMBERS)	1 (36 INCH LONG)	9.58
14	Al 6061-T6 (CENTRE CROSS MEMBER)	1 (24 INCH LONG)	6.81

15	Al 6061-T6 (MOTOR MOUNTINGS)	1 (12 INCH LONG)	6.88
16	BLACK DELRIN (LEGS)	1 (12 " X 24 ")	235
17	BOLTS AND WASHERS	100	12
18	37 V LIPO BATTERY	1	289.99
19	22.2 V LIPO BATTERY	1	65
20	CONNECTORS + CABLES + OTHER EXPENSES	N/A	600
21	THUNDER POWER BATTERY CHARGER	1	200
	TOTAL		**8190.1**

Table 5: Cost Analysis of AbhisHex

CHAPTER EIGHT: CONCLUSION AND FUTURE WORK

Over the past few years RHex robots have been modified to perform more efficient and stable operation in any fields with new robots like X-RHex and XRL having more strengths and robustness. High performance behaviors are displayed to navigate over various difficult terrains and analyze these behaviors using advanced tools. Attempts have been made to replicate the functionality of AbhisHex similar to that of RHex.

Chapter three presented the design and modeling of AbhisHex. In this chapter the entire robot is divided into multiple sections and designed individually. The sections covers the design of robot body and legs, all the materials required to manufacture the robot and legs, component drawing and free body diagrams of the robot. [31]

Chapters four and five gave a brief description of AbhisHex electrical and communication network along with the software design and algorithm. The chapter includes list and calculations of various electrical components along with internal communication diagrams required in building AbhisHex. The software design demonstrates controller design and design of algorithm to test the robot under different conditions for smooth gait.

Chapter six explored the stress–strain analysis on the robot frame and legs. The frame and legs were subjected to different loads, impact forces, temperatures, acceleration and torque values to check its design and operations durability under extreme conditions. Based on the stress, strain results the body and leg design was modifying the thickness, length and number of heat sinks.

Chapter seven extends this entire thing by testing the actual prototype, computing the results for different gait patterns and analyzing the cost of the project. The robot was made to perform standing and wave gaits over different terrains at different angles. These results were computed to analyze its behavior at different acceleration, velocity and current values. [33]

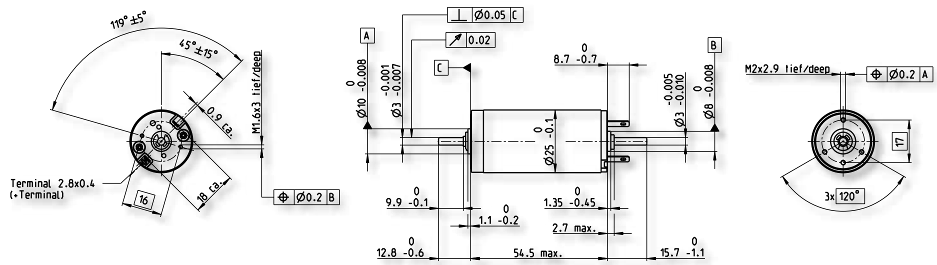
Future works includes building a legged robot that is fully autonomous and capable of surviving all the outdoor conditions over a period of time. This may consist of designing a more robust AbhisHex to walk a stable tripod gait over multiple terrains, run at multiple speeds, climb stairs and take leaps over surfaces, controlling it wirelessly and using camera to monitor the robot in areas where humans do not have access. [35]

APPENDIX

A) Specification sheet of the Motor:

RE 25 ∅25 mm, Graphite Brushes, 20 Watt

maxon DC motor



M 1:2

Stock program
Standard program
Special program (on request)

Part Numbers

		1	2	3	4	5	6	7	8	9
according to dimensional drawing		118749	118750	118751	118752	118753	118754	118755	118756	118757
shaft length 15.7 shortened to 4 mm		302002	302003	302004	302005	302006	302007	302001	302008	302009
Motor Data										
Values at nominal voltage										
1 Nominal voltage	V	9	15	18	24	30	42	48	48	48
2 No load speed	rpm	10000	9660	10200	9560	9860	11100	10300	8240	5050
3 No load current	mA	110	60.8	53.9	36.9	30.5	25.2	20.1	15.2	8.52
4 Nominal speed	rpm	8970	8430	8850	8330	8640	9920	9160	7040	3830
5 Nominal torque (max. continuous torque)	mNm	11.1	20.5	22.9	26.3	26.7	27.1	27.7	28.7	30
6 Nominal current (max. continuous current)	A	1.5	1.5	1.46	1.16	0.968	0.784	0.653	0.536	0.343
7 Stall torque	mNm	232	225	220	243	249	283	264	209	129
8 Stall current	A	29.1	15.8	13.5	10.4	8.72	7.94	6.03	3.81	1.44
9 Max. efficiency	%	76	82	83	85	86	87	87	86	84
Characteristics										
10 Terminal resistance	Ω	0.309	0.952	1.33	2.32	3.44	5.29	7.96	12.6	33.4
11 Terminal inductance	mH	0.028	0.088	0.115	0.238	0.353	0.551	0.832	1.31	3.48
12 Torque constant	mNm/A	7.96	14.3	16.3	23.4	28.5	35.6	43.8	55	89.6
13 Speed constant	rpm/V	1200	670	586	408	335	268	218	174	107
14 Speed / torque gradient	rpm/mNm	46.5	44.7	48	40.3	40.4	39.8	39.6	39.8	39.7
15 Mechanical time constant	ms	5.68	4.87	4.77	4.55	4.47	4.4	4.37	4.37	4.35
16 Rotor inertia	gcm^2	11.7	10.4	9.49	10.8	10.6	10.6	10.5	10.5	10.5

Specifications

Thermal data

17 Thermal resistance housing-ambient	14 K/W
18 Thermal resistance winding-housing	3.1 K/W
19 Thermal time constant winding	12.5 s
20 Thermal time constant motor	612 s
21 Ambient temperature	-30…+100°C
22 Max. winding temperature	+125°C

Mechanical data (ball bearings)

23 Max. speed	14000 rpm
24 Axial play	0.05 - 0.15 mm
25 Radial play	0.025 mm
26 Max. axial load (dynamic)	3.2 N
27 Max. force for press fits (static)	64 N
(static, shaft supported)	800 N
28 Max. radial load, 5 mm from flange	16 N

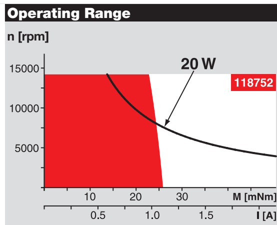
Other specifications

29 Number of pole pairs	1
30 Number of commutator segments	11
31 Weight of motor	130 g

Values listed in the table are nominal.
Explanation of the figures on page 151.

Option
Preloaded ball bearings

Operating Range



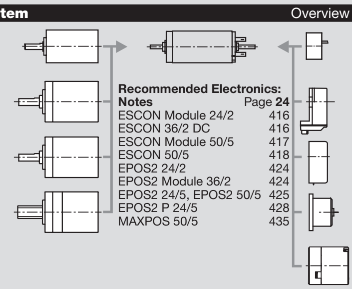
Comments

Continuous operation
In observation of above listed thermal resistance (lines 17 and 18) the maximum permissible winding temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit.

Short term operation
The motor may be briefly overloaded (recurring).

Assigned power rating

maxon Modular System Overview on page 20–27



Planetary Gearhead
∅26 mm
0.75 - 4.5 Nm
Page 336

Planetary Gearhead
∅32 mm
0.75 - 6.0 Nm
Page 338/339/342

Koaxdrive
∅32 mm
1.0 - 4.5 Nm
Page 347

Spindle Drive
∅32 mm
Page 370–372

Recommended Electronics:

Notes	Page **24**
ESCON Module 24/2	416
ESCON 36/2 DC	416
ESCON Module 50/5	417
ESCON 50/5	418
EPOS2 24/2	424
EPOS2 Module 36/2	424
EPOS2 24/5, EPOS2 50/5	425
EPOS2 P 24/5	428
MAXPOS 50/5	435

Encoder MR
128 - 1000 CPT,
3 channels
Page 392

Encoder Enc
22 mm
100 CPT, 2 channels
Page 398

Encoder HED_ 5540
500 CPT,
3 channels
Page 399/401

DC-Tacho DCT
∅22 mm
0.52 V
Page 411

Brake AB 28
24 VDC
0.4 Nm
Page 446

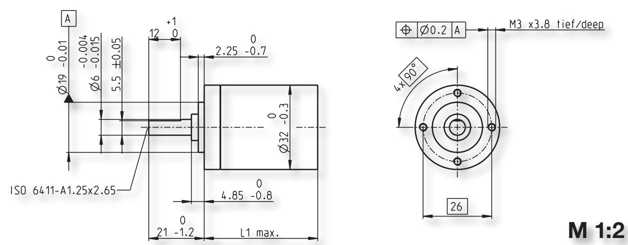
April 2016 edition / subject to change

maxon DC motor 181

B) Specification Sheet of Gear head:

Planetary Gearhead GP 32 A ∅32 mm, 0.75–4.5 Nm

maxon gear



M 1:2

Technical Data

Planetary Gearhead	straight teeth
Output shaft	stainless steel
Shaft diameter as option	8 mm
Bearing at output	ball bearing
Radial play, 5 mm from flange	max. 0.14 mm
Axial play	max. 0.4 mm
Max. axial load (dynamic)	120 N
Max. force for press fits	120 N
Direction of rotation, drive to output	=
Max. continuous input speed	6000 rpm
Recommended temperature range	-40…+100°C

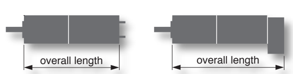
Number of stages	1	2	3	4	5
Max. radial load, 10 mm from flange	90 N	140 N	200 N	220 N	220 N

Option: Low-noise version

Stock program
Standard program
Special program (on request)

Part Numbers

Gearhead Data													
Part Numbers		166155	166158	166163	166164	166169	166174	166179	166184	166187	166192	166197	166202
1 Reduction		3.7 : 1	14 : 1	33 : 1	51 : 1	111 : 1	246 : 1	492 : 1	762 : 1	1181 : 1	1972 : 1	2829 : 1	4380 : 1
2 Absolute reduction		26/7	676/49	529/16	17576/343	13824/125	421824/1715	86112/175	19044/25	10123776/8575	8626176/4375	495144/175	109503/25
3 Max. motor shaft diameter	mm	6	6	3	6	4	4	3	3	4	4	3	3
Part Numbers		166156	166159		166165	166170	166175	166180	166185	166188	166193	166198	166203
1 Reduction		4.8 : 1	18 : 1		66 : 1	123 : 1	295 : 1	531 : 1	913 : 1	1414 : 1	2189 : 1	3052 : 1	5247 : 1
2 Absolute reduction		24/5	624/35		16224/245	6877/56	101062/343	331776/625	36501/40	2425488/1715	536406/245	1907712/625	839523/160
3 Max. motor shaft diameter	mm	4	4		4	3	3	4	3	3	3	3	3
Part Numbers		166157	166160		166166	166171	166176	166181	166186	166189	166194	166199	166204
1 Reduction		5.8 : 1	21 : 1		79 : 1	132 : 1	318 : 1	589 : 1	1093 : 1	1526 : 1	2362 : 1	3389 : 1	6285 : 1
2 Absolute reduction		23/4	299/14		3887/49	3312/25	389376/1225	20631/35	279841/256	9345024/6125	2066688/875	474513/140	6436343/1024
3 Max. motor shaft diameter	mm	3	3		3	3	4	3	3	4	3	3	3
Part Numbers			166161		166167	166172	166177	166182		166190	166195	166200	
1 Reduction			23 : 1		86 : 1	159 : 1	411 : 1	636 : 1		1694 : 1	2548 : 1	3656 : 1	
2 Absolute reduction			576/25		14976/175	1587/10	359424/875	79488/125		1162213/686	7962624/3125	457056/125	
3 Max. motor shaft diameter	mm		4		4	3	4	3		3	4	3	
Part Numbers			166162		166168	166173	166178	166183		166191	166196	166201	
1 Reduction			28 : 1		103 : 1	190 : 1	456 : 1	706 : 1		1828 : 1	2623 : 1	4060 : 1	
2 Absolute reduction			138/5		3588/35	12167/64	89401/196	158171/224		2238912/1225	2056223/784	3637933/896	
3 Max. motor shaft diameter	mm		3		3	3	3	3		3	3	3	
4 Number of stages		1	2	2	3	3	4	4	4	5	5	5	5
5 Max. continuous torque	Nm	0.75	2.25	2.25	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50
6 Max. intermittent torque at gear output	Nm	1.1	3.4	3.4	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
7 Max. efficiency	%	80	75	75	70	70	60	60	60	50	50	50	50
8 Weight	g	118	162	162	194	194	226	226	226	258	258	258	258
9 Average backlash no load	°	0.7	0.8	0.8	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
10 Mass inertia	gcm^2	1.5	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
11 Gearhead length L1	mm	26.5	36.4	36.4	43.1	43.1	49.8	49.8	49.8	56.5	56.5	56.5	56.5



maxon Modular System

+ Motor	Page	+ Sensor/Brake	Page	Overall length [mm] = Motor length + gearhead length + (sensor/brake) + assembly parts											
RE 25	179/181			81.1	91.0	91.0	97.7	97.7	104.4	104.4	104.4	111.1	111.1	111.1	111.1
RE 25	179/181	MR	392	92.1	102.0	102.0	108.7	108.7	115.4	115.4	115.4	122.1	122.1	122.1	122.1
RE 25	179/181	Enc 22	398	95.2	105.1	105.1	111.8	111.8	118.5	118.5	118.5	125.2	125.2	125.2	125.2
RE 25	179/181	HED_ 5540	399/401	101.9	111.8	111.8	118.5	118.5	125.2	125.2	125.2	131.9	131.9	131.9	131.9
RE 25	179/181	DCT 22	411	103.4	113.3	113.3	120.0	120.0	126.7	126.7	126.7	133.4	133.4	133.4	133.4
RE 25, 20 W	180			69.6	79.5	79.5	86.2	86.2	92.9	92.9	92.9	99.6	99.6	99.6	99.6
RE 25, 20 W	180	MR	392	80.6	90.5	90.5	97.2	97.2	103.9	103.9	103.9	110.6	110.6	110.6	110.6
RE 25, 20 W	180	HED_ 5540	400/403	90.4	100.3	100.3	107.0	107.0	113.7	113.7	113.7	120.4	120.4	120.4	120.4
RE 25, 20 W	180	DCT22	411	91.9	101.8	101.8	108.5	108.5	115.2	115.2	115.2	121.9	121.9	121.9	121.9
RE 25, 20 W	180	AB 28	446	103.7	113.6	113.6	120.3	120.3	127.0	127.0	127.0	133.7	133.7	133.7	133.7
RE 25, 20 W	180	HED_ 5540/AB 28	400/446	120.9	130.8	130.8	137.5	137.5	144.2	144.2	144.2	150.9	150.9	150.9	150.9
RE 25, 20 W	181	AB 28	446	115.2	125.1	125.1	131.8	131.8	138.5	138.5	138.5	145.2	145.2	145.2	145.2
RE 25, 20 W	181	HED_ 5540/AB 28	399/446	132.4	142.3	142.3	149.0	149.0	155.7	155.7	155.7	162.4	162.4	162.4	162.4
A-max 26	205-212			71.3	81.2	81.2	87.9	87.9	94.6	94.6	94.6	101.3	101.3	101.3	101.3
A-max 26	206-212	MEnc 13	410	78.4	88.3	88.3	95.0	95.0	101.7	101.7	101.7	108.4	108.4	108.4	108.4
A-max 26	206-212	MR	392	80.1	90.0	90.0	96.7	96.7	103.4	103.4	103.4	110.1	110.1	110.1	110.1
A-max 26	206-212	Enc 22	398	85.7	95.6	95.6	102.3	102.3	109.0	109.0	109.0	115.7	115.7	115.7	115.7
A-max 26	206-212	HED_ 5540	400/402	89.7	99.6	99.6	106.3	106.3	113.0	113.0	113.0	119.7	119.7	119.7	119.7
RE-max 29	227-230			71.3	81.2	81.2	87.9	87.9	94.6	94.6	94.6	101.3	101.3	101.3	101.3
RE-max 29	228/230	MR	392	80.1	90.0	90.0	96.7	96.7	103.4	103.4	103.4	110.1	110.1	110.1	110.1

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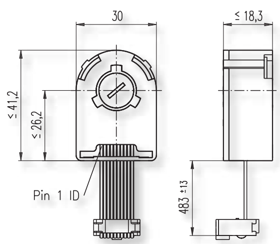
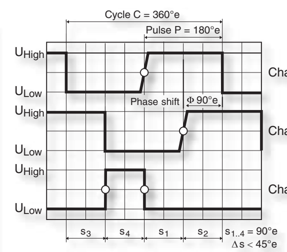
C) Specification Sheet of Encoder:

Encoder HEDL 5540 500 CPT, 3 Channels, with Line Driver RS 422

maxon sensor

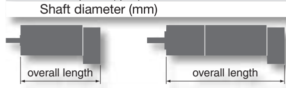




Direction of rotation cw (definition cw p. 150)

- Stock program
- Standard program
- Special program (on request)

Part Numbers	110512	110514	110516
Type			
Counts per turn	500	500	500
Number of channels	3	3	3
Max. operating frequency (kHz)	100	100	100
Max. speed (rpm)	12 000	12 000	12 000
Shaft diameter (mm)	3	4	6



maxon Modular System

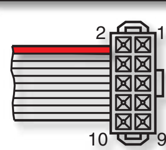
+ Motor	Page	+ Gearhead	Page	+ Brake	Page	Overall length [mm] / ● see Gearhead		
RE 25	179/181					75.3		
RE 25	179/181	GP 26/GP 32	336/338			●		
RE 25	179/181	KD 32, 1.0 - 4.5 Nm	347			●		
RE 25	179/181	GP 32, 0.75 - 6.0 Nm	339/342			●		
RE 25	179/181	GP 32 S	370-372			●		
RE 25, 20 W	180					63.8		
RE 25, 20 W	180	GP 26/GP 32	336/338			●		
RE 25, 20 W	180	KD 32, 1.0 - 4.5 Nm	347			●		
RE 25, 20 W	180	GP 32, 0.75 - 6.0 Nm	339/342			●		
RE 25, 20 W	180	GP 32 S	370-372			●		
RE 25, 20 W	180			AB 28	446	94.3		
RE 25, 20 W	180	GP 26/GP 32	336/338	AB 28	446	●		
RE 25, 20 W	180	KD 32, 1.0 - 4.5 Nm	347	AB 28	446	●		
RE 25, 20 W	180	GP 32, 0.75 - 6.0 Nm	339/342	AB 28	446	●		
RE 25, 20 W	180	GP 32 S	370-372	AB 28	446	●		
RE 25, 20 W	181			AB 28	446	105.8		
RE 25, 20 W	181	GP 26/GP 32	336/338	AB 28	446	●		
RE 25, 20 W	181	KD 32, 1.0 - 4.5 Nm	347	AB 28	446	●		
RE 25, 20 W	181	GP 32, 0.75 - 6.0 Nm	339/342	AB 28	446	●		
RE 25, 20 W	181	GP 32 S	370-372	AB 28	446	●		
RE 30, 15 W	182					88.8		
RE 30, 15 W	182	GP 32, 0.75 - 4.5 Nm	340			●		
RE 30, 60 W	183					88.8		
RE 30, 60 W	183	GP 32, 0.75 - 6.0 Nm	338-344			●		
RE 30, 60 W	183	KD 32, 1.0 - 4.5 Nm	347			●		
RE 30, 60 W	183	GP 32 S	370-372			●		
RE 35, 90 W	184						91.7	
RE 35, 90 W	184	GP 32, 0.75 - 8.0 Nm	338-345				●	
RE 35, 90 W	184	GP 42, 3.0 - 15 Nm	349				●	
RE 35, 90 W	184	GP 32 S	370-372				●	
RE 35, 90 W	184			AB 28	446	124.3		
RE 35, 90 W	184	GP 32, 0.75 - 8.0 Nm	338-345	AB 28	446	●		
RE 35, 90 W	184	GP 42, 3.0 - 15 Nm	349	AB 28	446	●		
RE 35, 90 W	184	GP 32 S	370-372	AB 28	446	●		

Technical Data

Supply voltage V_{CC}	5 V ± 10%
Output signal	EIA Standard RS 422
driver used:	DS26LS31
Phase shift Φ	90°e ± 45°e
Signal rise time (typically, at C_L = 25 pF, R_L = 2.7 kΩ, 25 °C)	180 ns
Signal fall time (typically, at C_L = 25 pF, R_L = 2.7 kΩ, 25 °C)	40 ns
Index pulse width	90°e
Operating temperature range	-40…+100 °C
Moment of inertia of code wheel	≤ 0.6 gcm²
Max. angular acceleration	250 000 rad s⁻²
Output current per channel	min. -20 mA, max. 20 mA
Option	1000 Counts per turn, 2 Channels

The index signal I is synchronized with channel A or B.

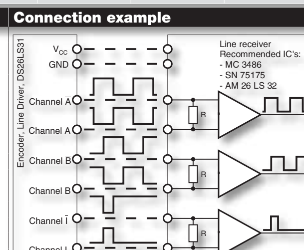
Pin Allocation



1 N.C.
2 V_{CC}
3 GND
4 N.C.
5 Channel $\bar{A}$
6 Channel A
7 Channel $\bar{B}$
8 Channel B
9 Channel $\bar{I}$ (Index)
10 Channel I (Index)

Pin type DIN 41651/
EN 60603-13
flat band cable AWG 28

Connection example



Terminal resistance R = typical 120 Ω

May 2016 edition / subject to change

maxon sensor 401

D) Specification sheet of EPOS2 P 24/5 Controller:

maxon motor control

EPOS2 P Programmable Positioning Controller Data

CANopen USB RS232 GUI

EPOS2 P 24/5
Matched with DC brush motors with encoder or brushless EC motors with Hall sensors and encoder, from 5 to 120 watts.

Controller versions	
	CANopen Master (programmable)
Electrical data	
Operating voltage V_{CC}	11 - 24 VDC
Logic supply voltage V_C (optional)	11 - 24 VDC
Max. output voltage	0.9 x V_{CC}
Max. output current I_{max} (<1 s)	10 A
Continuous output current I_{cont}	5 A
Switching frequency of power stage	50 kHz
Sample rate of PI - current controller	10 kHz
Sample rate of PI - speed controller	1 kHz
Sample rate of PID - positioning control	1 kHz
Max. speed (1 pole pair)	25 000 rpm (sinusoidal); 100000 rpm (block)
Built-in motor choke per phase	15 µH / 5 A
Input	
Hall sensor signals	H1, H2, H3
Encoder signals	A, A\, B, B\, I, I\ (max. 5 MHz)
Digital inputs	6 (TTL and PLC level)
Analog inputs	2 12-bit resolution, 0…+5 V
CAN-ID (CAN node identification)	Configurable with DIP switch 1…7
Output	
Digital outputs	4
Encoder voltage output	+5 VDC, max. 100 mA
Hall sensor voltage output	+5 VDC, max. 30 mA
Auxiliary voltage output	V_{CC}, max. 1300 mA
Interface	
RS232	RxD; TxD (max. 115 200 bit/s)
CAN	high; low (max. 1 Mbit/s)
USB 2.0/3.0	Data+; Data- (full speed)
Indicator	
Operating/Error/Program	green LED, red LED, blue LED
Environmental conditions	
Temperature – Operation	-10…+55°C
Temperature – Extended range	+55…+83°C; Derating: -0.179 A/°C
Temperature – Storage	-40…+85°C
Humidity (condensation not permitted)	5…90%
Mechanical data	
Weight	Approx. 180 g
Dimensions (L x W x H)	105 x 83 x 24 mm
Mounting	Flange for M3-screws
Part numbers	
	378308 EPOS2 P 24/5
Accessories	
	309687 DSR 50/5 Shunt regulator
	Order accessories separately, see page 437

Additional information

Operating modes
CANopen Profile Position, Profile Velocity- and Homing Mode
Position, Velocity and Current Mode
Path generating with trapezoidal or sinusoidal profiles
Feed forward for velocity and acceleration
Interpolated Position Mode (PVT)
Sinusoidal or block commutation for EC motors
Communication
Programming interface (Windows) via USB 2.0/3.0 or RS232
Communication via CANopen, RS232 or USB 2.0/3.0 maxon protocol
Inputs / Outputs
Free configurable digital inputs e.g. for limit switches and reference switches
Free configurable digital outputs e.g. for holding brakes
Free analog inputs
Available software
EPOS Studio programming according to IEC 61131-3
IEC 61131-3 standard libraries
motion control library
maxon utility function block library
CANopen function block library
maxon utility library
Application Examples
Best Practice Examples
Firmware
Available documentation
Getting Started
Cable Starting Set
Hardware Reference
Firmware Specification
Programming Reference
Application Notes
Cable
A comprehensive range of cables is available as an option. Details can be found on page 437.

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E) Specification Sheet of EPOS2 Motherboard and Position Controller:

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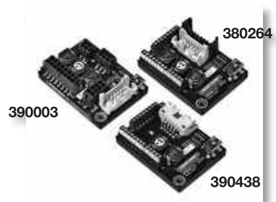
EPOS2 Positioning Controllers Data



EPOS2 24/2
Matched with DC brush motors with encoder or brushless EC motors with Hall sensors and encoder up to 48 watts.

EPOS2 Module 36/2
The EPOS2 is an OEM positioning controller plug-in module for brushed DC motors with encoder or brushless EC motors with Hall sensors and encoder up to 72 watts.

	EPOS2 24/2	EPOS2 Module 36/2
Controller versions		
	CANopen Slave	**CANopen Slave**
Electrical data		
Operating voltage V_{CC}	9 - 24 VDC	11 - 36 VDC (optional 0 - 36 VDC)
Logic supply voltage V_C (optional)		11 - 36 VDC (optional 5.0 VDC)
Max. output voltage	0.9 x V_{CC}	0.9 x V_{CC}
Max. output current I_{max} (<1 s)	4 A	4 A
Continuous output current I_{cont}	2 A	2 A
Switching frequency of power stage	100 kHz	50 kHz
Sample rate of PI - current controller	10 kHz	10 kHz
Sample rate of PI - speed controller	1 kHz	1 kHz
Sample rate of PID - positioning control	1 kHz	1 kHz
Max. speed (1 pole pair)	25 000 rpm (sinusoidal); 100 000 rpm (block)	25 000 rpm (sinusoidal); 100 000 rpm (block)
Built-in motor choke per phase	47 µH / 2 A	10 µH / 2 A
Input		
Hall sensor signals	H1, H2, H3	H1, H2, H3
Encoder signals	A, A\, B, B\, I, I\ (max. 5 MHz)	A, A\, B, B\, I, I\ (max. 5 MHz)
Digital inputs	6 (TTL level)	6 (TTL level)
Analog inputs	2 (12-bit resolution, 0…+5 V)	2 (11-bit resolution, 0…+5 V)
CAN-ID (CAN node identification)	configurable with DIP switch 1…4	set by external wiring
Output		
Digital outputs	2	3
Analog outputs		
Encoder voltage output	+5 VDC, max. 100 mA	+5 VDC, max. 100 mA
Hall sensor voltage output	+5 VDC, max. 30 mA	+5 VDC, max. 30 mA
Auxiliary voltage output	+5 VDC, max. 10 mA	
Interface		
RS232	RxD; TxD (max. 115 200 bit/s)	RxD; TxD (max. 115 200 bit/s)
CAN	high; low (max. 1 Mbit/s)	high; low (max. 1 Mbit/s)
USB 2.0/3.0	Data+; Data- (full speed)	external USB transceiver required
Indicator		
LED green = READY, red = ERROR	green LED, red LED	green LED, red LED
Environmental conditions		
Temperature – Operation	-10…+55°C	-10…+45°C
Temperature – Extended range	+55…+74°C; Derating: -0.105 A/°C	+45…+75°C; Derating: -0.067 A/°C
Temperature – Storage	-40…+85°C	-40…+85°C
Humidity (condensation not permitted)	5…90%	5…90%
Mechanical data		
Weight	Approx. 30 g	Approx. 10 g
Dimensions (L x W x H)	55 x 40 x 19.6 mm	54.5 x 28.2 x 9 mm
Mounting	Flange for M2.5-screws	PCB edge connector with locking mechanism
Part numbers		
	390438 EPOS2 24/2 for DC motors **380264** EPOS2 24/2 for EC motors **390003** EPOS2 24/2 for DC/EC motors	**360665** EPOS2 Module 36/2
Accessories		
	309687 DSR 50/5 Shunt regulator	**363407** EPOS2 Module Starter-Kit
	Order accessories separately, see page 437	Order accessories separately, see page 437

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F) MAXON Studio SFC Code:

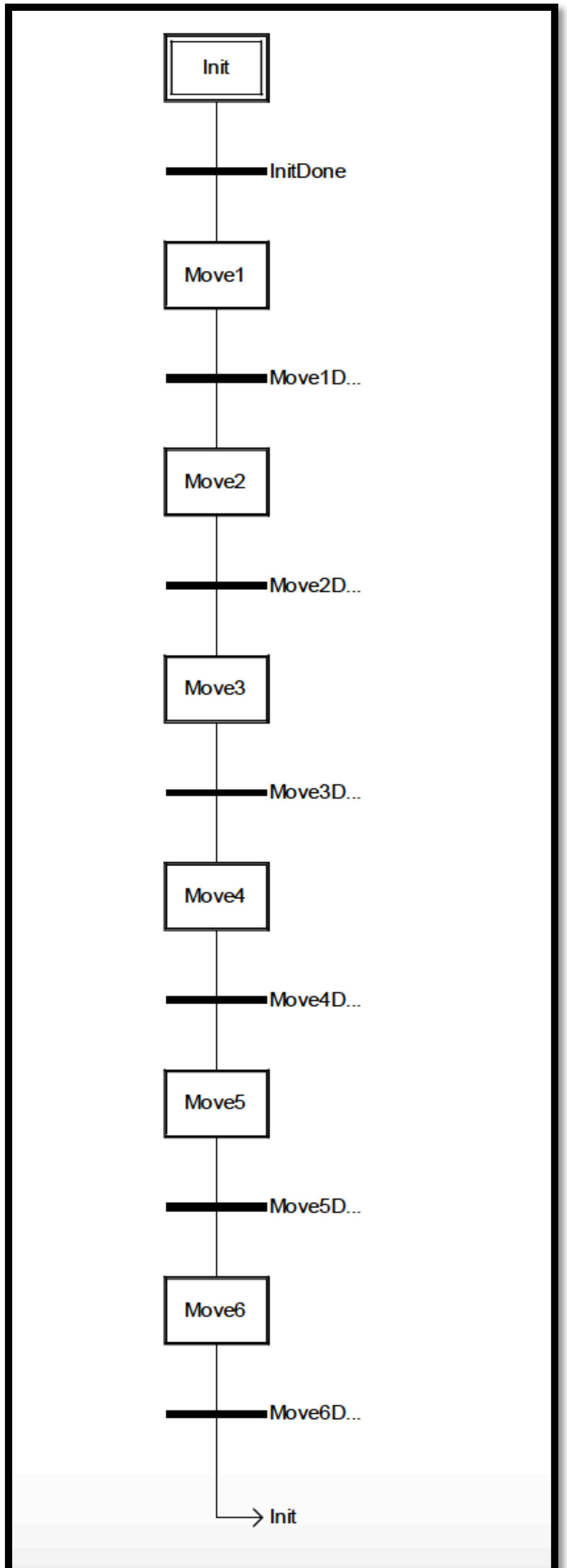
```
Variable declaration:

  VAR_EXTERNAL
      Axis1                                                    : AXIS_REF;
      Axis2                                                    : AXIS_REF;
      Axis3                                                    : AXIS_REF;
      Axis4                                                    : AXIS_REF;
      Axis5                                                    : AXIS_REF;
      Axis6                                                    : AXIS_REF;
  END_VAR

  VAR_GLOBAL

  END_VAR

  VAR

      fbReset                                                  :MC_Reset;
      fbPower                                                  :MC_Power;
      fbMove1, fbMove2, fbfbMove3, fbMove4, fbMove5, fbMove6   :MC_MoveRelative;
      fbSpeed1, fbSpeed2, fbSpeed3, fbSpeed4, fbSpeed5, fbSpeed6 :MC_MoveVelocity;
      fbWait1, fbWait2, fbWait3, fbWait4, fbWait5, fbWait6     :TON;

  END_VAR



Steps:

  INIT STEP Init:
    Action_Init(N);
  END_STEP


  STEP Move1:
    Action_Move1(N);
  END_STEP
```

```
VAR_EXTERNAL
    Axis1                                                    : AXIS_REF;
    Axis2                                                    : AXIS_REF;
    Axis3                                                    : AXIS_REF;
    Axis4                                                    : AXIS_REF;
    Axis5                                                    : AXIS_REF;
    Axis6                                                    : AXIS_REF;
END_VAR

VAR_GLOBAL

END_VAR

VAR

    fbReset                                                  :MC_Reset;
    fbPower                                                  :MC_Power;
    fbMove1, fbMove2, fbfbMove3, fbMove4, fbMove5, fbMove6   :MC_MoveRelative;
    fbSpeed1, fbSpeed2, fbSpeed3, fbSpeed4, fbSpeed5, fbSpeed6 :MC_MoveVelocity;
    fbWait1, fbWait2, fbWait3, fbWait4, fbWait5, fbWait6     :TON;

END_VAR


Steps:

  INIT_STEP Init:
    Action_Init(N);
  END_STEP


  STEP Move1:
    Action_Move1(N);
  END_STEP


  STEP Move2:
    Action_Move2(N);
  END_STEP


  STEP Move3:
    Action_Move3(N);
  END_STEP


  STEP Move4:
    Action_Move4(N);
  END_STEP


  STEP Move5:
    Action_Move5(N);
  END_STEP
```

```
Transitons:

   (* InitDone *)
   TRANSITION FROM (Init) TO (Move1) :
   END_TRANSITION


   (* Move1Done *)
   TRANSITION FROM (Move1) TO (Move2) :
   END_TRANSITION


   (* Move2Done *)
   TRANSITION FROM (Move2) TO (Move3) :
   END_TRANSITION


   (* Move3Done *)
   TRANSITION FROM (Move3) TO (Move4) :
   END_TRANSITION


   (* Move4Done *)
   TRANSITION FROM (Move4) TO (Move5) :
   END_TRANSITION


   (* Move5Done *)
   TRANSITION FROM (Move5) TO (Move6) :
   END_TRANSITION


   (* Move6Done *)
   TRANSITION FROM (Move6) TO (Init) :
   END_TRANSITION


Actions:

   ACTION Action_Init :
         fbReset(Axis := Axis1, Execute := true);
         if fbReset.done then
              fbPower(Axis := Axis1, Enable := true);
         end_if;

         fbReset(Axis := Axis2, Execute := true);
         if fbReset.done then
              fbPower(Axis := Axis2, Enable := true);
         end_if;

         fbReset(Axis := Axis3, Execute := true);
         if fbReset.done then
```

```
            fbPower(Axis := Axis3, Enable := true);
        end_if;

        fbReset(Axis := Axis4, Execute := true);
        if fbReset.done then
            fbPower(Axis := Axis4, Enable := true);
        end_if;

        fbReset(Axis := Axis5, Execute := true);
        if fbReset.done then
            fbPower(Axis := Axis5, Enable := true);
        end_if;

        fbReset(Axis := Axis6, Execute := true);
        if fbReset.done then
            fbPower(Axis := Axis6, Enable := true);
        end_if;

        if fbPower.status then
        end_if;
    END_ACTION

    ACTION Action_Move1 :
        (* Reset the fucntion blocks and transition flags *)
        fbReset(Axis := Axis1, Execute := true);
        (*Move and Dwell *)
        fbMove1(Execute := true, Axis := Axis1 , Velocity := 5000, Acceleration :=
        8000000, Deceleration := 1000);
        fbSpeed1(Execute := true, Axis := Axis1 , Direction := MCPositive,
        Velocity := 5000, Acceleration := 8000000, Deceleration := 1000);
        If fbMove1.done then
            fbWait1(IN := true, PT := t#1s);
        end_if;

        (* Set transition flag*)
    END_ACTION

    ACTION Action_Move2 :
        (* Reset the fucntion blocks and transition flags *)
        fbReset(Axis := Axis2, Execute := true);
        (*Move and Dwell *)
        fbMove2(Execute := true, Axis := Axis2 , Velocity := 5000, Acceleration :=
        8000000, Deceleration := 1000);
        fbSpeed2(Execute := true, Axis := Axis2 , Direction := MCPositive,
        Velocity := 5000, Acceleration := 8000000, Deceleration := 1000);
        If fbMove2.done then
            fbWait2(IN := true, PT := t#1s);
        end_if;

        (* Set transition flag*)
    END_ACTION

    ACTION Action_Move3 :
        (* Reset the fucntion blocks and transition flags *)
        fbReset(Axis := Axis3, Execute := true);
```

```
    fbSpeed3(Execute := true, Axis := Axis3 , Direction := MCPositive,
    Velocity := 5000, Acceleration := 8000000, Deceleration := 1000);
    If fbMove3.done then
        fbWait3(IN := true, PT := t#1s);
    end_if;

    (* Set transition flag*)
END_ACTION

ACTION Action_Move4 :
    (* Reset the fucntion blocks and transition flags *)
    fbReset(Axis := Axis4, Execute := true);
    (*Move and Dwell *)
    fbMove4(Execute := true, Axis := Axis4 , Velocity := 5000, Acceleration :=
    8000000, Deceleration := 1000);
    fbSpeed4(Execute := true, Axis := Axis4 , Direction := MCPositive,
    Velocity := 5000, Acceleration := 8000000, Deceleration := 1000);
    If fbMove4.done then
        fbWait4(IN := true, PT := t#1s);
    end_if;

    (* Set transition flag*)
END_ACTION

ACTION Action_Move5 :
    (* Reset the fucntion blocks and transition flags *)
    fbReset(Axis := Axis5, Execute := true);
    (*Move and Dwell *)
    fbMove5(Execute := true, Axis := Axis5 , Velocity := 5000, Acceleration :=
    8000000, Deceleration := 1000);
    fbSpeed5(Execute := true, Axis := Axis5 , Direction := MCPositive,
    Velocity := 5000, Acceleration := 8000000, Deceleration := 1000);
    If fbMove5.done then
        fbWait5(IN := true, PT := t#1s);
    end_if;

    (* Set transition flag*)
END_ACTION

ACTION Action_Move6 :
    (* Reset the fucntion blocks and transition flags *)
    fbReset(Axis := Axis6, Execute := true);
    (*Move and Dwell *)
    fbMove6(Execute := true, Axis := Axis6 , Velocity := 5000, Acceleration :=
    8000000, Deceleration := 1000);
    fbSpeed6(Execute := true, Axis := Axis6 , Direction := MCPositive,
    Velocity := 5000, Acceleration := 8000000, Deceleration := 1000);
    If fbMove6.done then
        fbWait6(IN := true, PT := t#1s);
    end_if;

    (* Set transition flag*)
END_ACTION
```



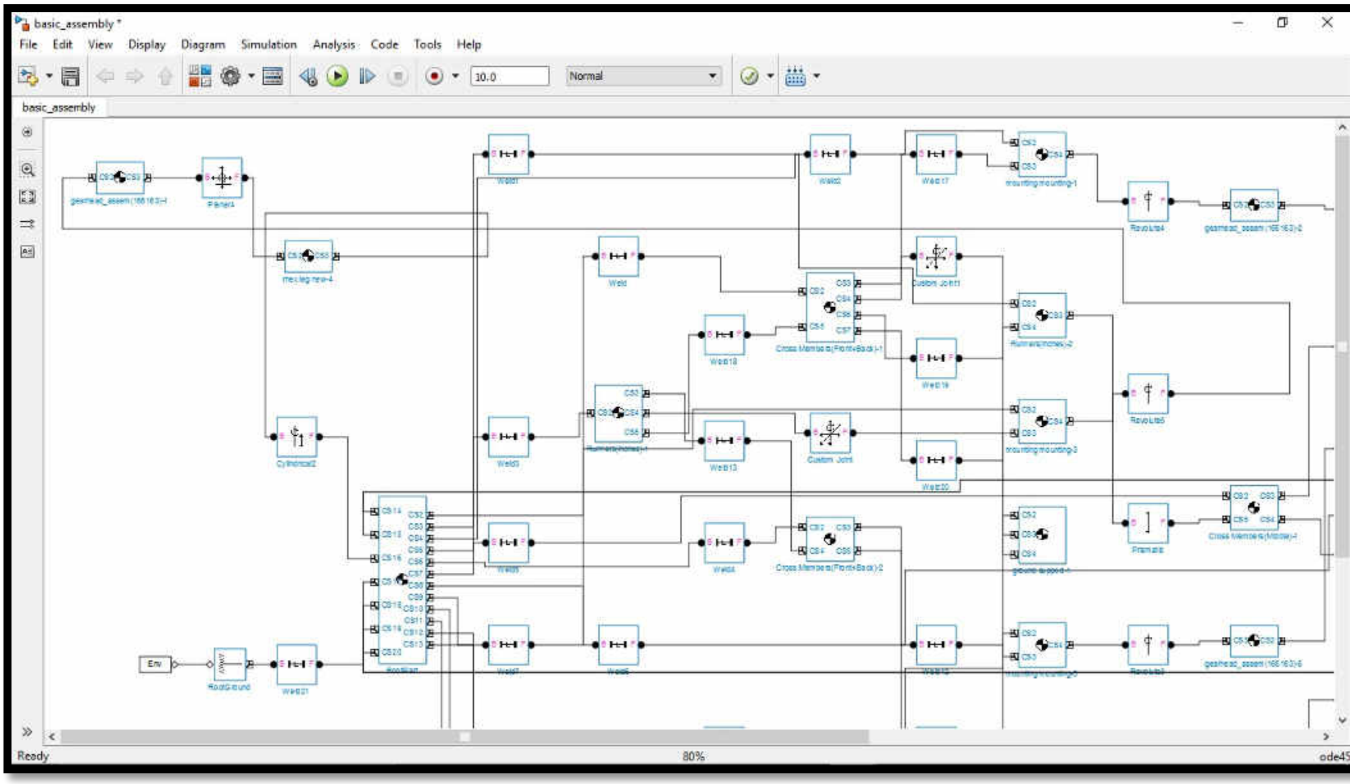
Init
InitDone
Move1
Move1D...
Move2
Move2D...
Move3
Move3D...
Move4
Move4D...
Move5
Move5D...
Move6
Move6D...
Init

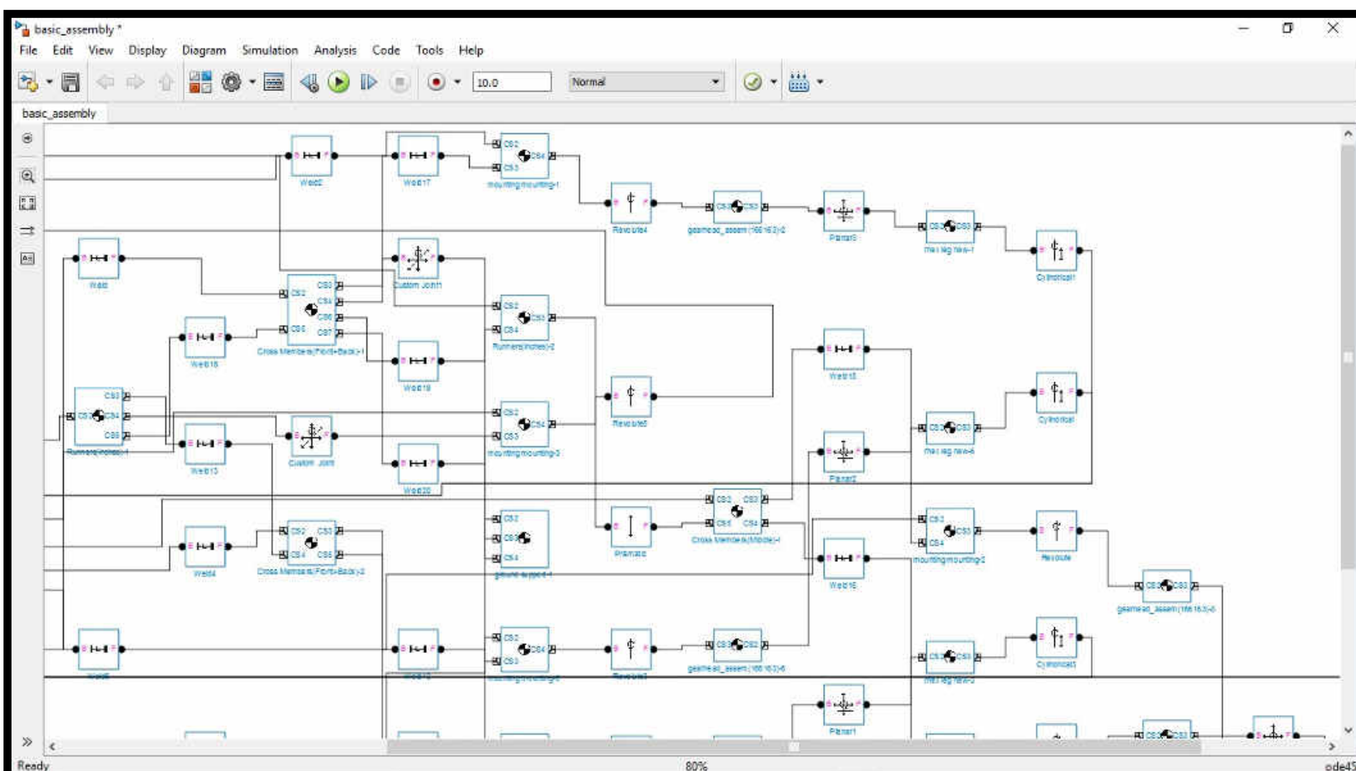
G) Proportional – Integral Controller (Position and Speed Control)

```
clc
clear all

J = 1.08*10^-6;                              % kgm^2
b = 6*10^-6;                                 % Nms
K = 0.0234;
R = 2.32;                                    % Ohm
L = 2.38*10^-3;                              % H
s = tf('s');
Tp_motor = K/(s*((J*s + b)*(L*s + R) + K^2));  % speed transfer
 fucntion
Kp = 5;                                      % Proportional Gain
Ki = 10;                                     % Integral Gain


for i = 1:3

     C(:,:,i) = pid(Kp,Ki);
end
sys_cl = feedback(C*Tp_motor,1);

dist_cl = feedback(Tp_motor,C)
step(sys_cl(:,:,1), sys_cl(:,:,2));
stepinfo(sys_cl(:,:,1))
ylabel('Position, (radians)')
title('Position Control')
grid
legend('Kp = 5', 'Ki = 10')


dist_cl(:,:,1,1) =

                            0.0234 s
  --------------------------------------------------------------
  2.57e-09 s^4 + 2.52e-06 s^3 + 0.0005615 s^2 + 0.117 s + 0.234


dist_cl(:,:,2,1) =

                            0.0234 s
  --------------------------------------------------------------
  2.57e-09 s^4 + 2.52e-06 s^3 + 0.0005615 s^2 + 0.117 s + 0.234


dist_cl(:,:,3,1) =

                            0.0234 s
  --------------------------------------------------------------
  2.57e-09 s^4 + 2.52e-06 s^3 + 0.0005615 s^2 + 0.117 s + 0.234

3x1 array of continuous-time transfer functions.
```

```
clc
clear all

J = 1.08*10^-6;                                    % kgm^2
b = 6*10^-6;                                       % Nms
K = 0.0234;
R = 2.32;                                          % Ohm
L = 2.38*10^-3;                                    % H
s = tf('s');
Ts_motor = K/(((J*s + b)*(L*s + R) + K^2));        % speed transfer fucntion
Kp = 0.2;                                          % Proportional Gain
Ki = 25;                                           % Integral Gain

for i = 1:3

     C(:,:,i) = pid(Kp,Ki);
end
sys_cl = feedback(C*Ts_motor,1);

dist_cl = feedback(Ts_motor,C)
step(sys_cl(:,:,1), sys_cl(:,:,2));
stepinfo(sys_cl(:,:,1))
ylabel('Anglar Velocity, (rad/sec)')
title('Speed Control')
grid
legend('Kp = 0.2', 'Ki = 25')


dist_cl(:,:,1,1) =

                       0.0234 s
  -------------------------------------------------
  2.57e-09 s^3 + 2.52e-06 s^2 + 0.005241 s + 0.585


dist_cl(:,:,2,1) =

                       0.0234 s
  -------------------------------------------------
  2.57e-09 s^3 + 2.52e-06 s^2 + 0.005241 s + 0.585


dist_cl(:,:,3,1) =

                       0.0234 s
  -------------------------------------------------
  2.57e-09 s^3 + 2.52e-06 s^2 + 0.005241 s + 0.585

3x1 array of continuous-time transfer functions.


ans =
```

H) SimMechanics Simulation Code:





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VITA

Abhishek is from Pune, India. He has done his Bachelors degree in Mechanical Engineering from The University of Pune. He has a Masters degree in Advanced Manufacturing and Enterprise Engineering from The University of Texas at San Antonio. He plans to work in field of Mechanical Design, Automation, Robotics and / or Robot Research. He also has plans of starting his own venture in one of this field in future.