Synthesis and Analysis of a Walking Machine (Robot) Leg Mechanism on a Rough Terrain

JIMMA UNIVERSITY
Jimma Institute of Technology
Faculty of Mechanical Engineering

By
TESFAYE OLANA TEREFE

Jimma, Ethiopia
October, 2018

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Thesis submitted to the

School of Graduate Studies of Jimma University

in Partial Fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering (Design of Mechanical System)

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Declaration

By my signature below, I declare and affirm that this thesis is my own work. I have followed all ethical and technical principles in the literature review, kinematic synthesis and analysis, geometric modeling and motion analysis, and assembling of this thesis. Any scholarly matter that is included in the thesis has been given recognition through citation.

....**Tesfaye Olana Terefe**......	....	....
Name	signature	date

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Approval sheet

As a member of the Examination Board of the final Master of Science open defense, we certify that we have read and evaluated the thesis prepared by Tesfaye Olana Terefe entitled **"Synthesis and Analysis of a Walking Machine (Robot) Leg Mechanism on a Rough Terrain"**. We recommend that it could be accepted as a fulfilling the thesis requirement for the Degree of Master of Science in Mechanical Engineering (Design of Mechanical System).

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Title of the thesis: **Synthesis and Analysis of a Walking Machine (Robot) Leg Mechanism on a Rough Terrain**

Degree awarded: Masters of Science in Mechanical Engineering
(Design of Mechanical System)

Dedicated
to
my beloved family!

Abstract

In today's human life, there is a high demand to automate labor work. The high cost of this labor work and its low efficiency puts major pressure on the competitiveness of automated machines. The present robotization of this labor entered a high level of technological willingness with a greater significance of sustainable productivity in economic development. Walking machine (robot) is a type of locomotion that operates by means of legs and /or wheels on rough terrain or flat surface. The performance of legged machines is greater than wheels or tracked walking machines on the unstructured terrain. These machines are used for data collections in a variety of areas such as large agricultural sector, dangerous and rescue areas for a human. The leg mechanism of a walking machine has a different joint in which a number of motors are used to actuate all DOF of the legs. Due to this, the weight of an individual motor of the machine leg results in high energy consumption for driving.

The main objective of this study is synthesis and analysis of a walking machine (robot) leg mechanism on rough terrain. The leg mechanism is developed using integration of linkages through kinematic synthesis to reduce the complexity of the design. The developed leg mechanism enables the robot to walk on rough terrain. Among others, its kinematic mechanisms are analyzed using Denavit-Hartenberg (DH) convention approach. Symbolic computations are also implemented to parametrically optimize the motion parameters of the robot leg mechanism. The equation of motion is derived from the dynamic analysis using the Euler-Lagrange method which involves kinetic and potential energy expressions. In order to validate the performance of the robot leg mechanism and motion behaviors, kinematic motion analysis in SolidWorks and MATLAB (academic licensed) are used. The leg mechanism used is effective for rough terrain areas because it is capable of walking on terrain with different amplitude due to surface toughness and aerodynamics.

Finally, the design developed as part of this thesis is better in terms of its simple mechanism, less energy consumption, easy to manufacture, easy to walk on rough terrain, though it has limitations such as detail analysis which is planned to be considered in its future work.

Keywords: *Walking machine, Leg mechanism, Kinematic synthesis and analysis, motion analysis.*

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I would like to thank first the almighty God for giving me this opportunity. Next, it is my pleasure to express the deepest appreciation his excellency to **Prof. Hirpa G. Lemu** (PhD, Professor of Mechanical Design Engineering at University of Stavanger, Norway) for exposing me to such an indispensable work. Without his continuous support and guidance, as well as his encouragement during difficult periods the completion of this thesis work would not possible.

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Table of content

List of figures

Acronyms

3D	:	Three dimensional
AI	:	Artificial Intelligence
ASV	:	Adaptive Suspension Vehicle
CAD	:	Computer Aided Design
CAN	:	Controller Area Network
CARD	:	Computer Aided Remote Driving
DC	:	Direct Current
DH	:	Denavit Hartenberg
DOF	:	Degree of freedom
GEWT	:	General Electric Walking Truck
GPS	:	Global Positioning System
JiT	:	Jimma Institute of Technology
JPL	:	Jet Propulsion Laboratory
MEMS	:	Micro Electro Mechanical System
MIT	:	Massassuchet Institute of Technology
MSL	:	Mars Science Laboratory
NASA	:	National Aeronautics and Space Administration
OSU	:	Ohio State University
RPI	:	Rensselaer Polytechnic Institute
SLRV	:	Survey Lunar Rover Vehicle
SMR	:	Soviet Mars Rover
ULB	:	Universit´e Libre de Bruxelles
UoW	:	University of Waseda
USA	:	United States of America
VMC	:	Virtual Model Control
VUB	:	Vrije Universiteit Brussel

Symbols

ω : Angular velocity
r : Crank radius
X : Displacement
ft : Feet
C_d : Gear center to center distance
d : Gear diameter
G : Gravitational energy
g : Gravity
h : Height
U : Homogenous transformation matrix
hr : Hour
I : Inertia
J : Jacobian
kg : Kilogram
km : Kilometer
K : Kinetic energy
$\mathcal{J}$: Lagrange
l : Length
v : Linear velocity
m : Mass
M : Mass matrix
m : Meter (Italic)
N : Newton
n : Number of variables
P : Position matrix
V : Potential energy (Italic)
lb : Pound
R : Rotational matrix
s : Second
τ : Torque
δ : Translational distance
V : Voltage

Chapter One

Introduction

1.1. Background

In the present day, the expansion of using robots in human life is becoming a more stimulating area of several investigators. This expansion has led many researchers to start advancing automated machinery aimed at different applications. Over the past periods, science and technology in robotics from fiction to reality in design and production of robots become improved. Different applications with disciplines of study areas such as computer science, medical application, fields of engineering and automation played a great role in robotics [1, 2]. A locomotion over a soft or hard surface by means of limbs, legs and/or wheels at low speed can be defined as a Walking. The design and development of walking machines or robots are widely studied by NASA for planetary exploration since the 1960s to the current status of its development [3]. Based on the surface on which they operate NASA developed and used three basic types of walking machines; namely wheeled, tracked and legged walking machine or robot [4-7].

Walking machine operates under different conditions are used for planetary, medical, engineering, agricultural task, etc. [8, 9]. These machines are types of locomotives automated machinery to speed up or replace human works [10]. The establishment of the walking machine technology started since in the ancient time of human civilization for conquering the walking machine on rough terrain surface. During the civilization of the Greek era mechanically powered walking machine traced from animals and humanlike appearance. In Europe, conceptual design and schematic drawing of humanlike artificial systems and mechanisms were developed [11]. The development in improving the technology of walking machine was later technologically advanced. In the walking machine research, the continuous efforts for the design and control of walking robots had contributed new aspects in the technology from the ancient Greek until now [11].

Among the walking robot systems, it is the rocker-bogie suspension for the wheeled system and legged walking machine that was introduced and used by NASA for the planetary application. The rocker-bogie suspension system enables to keep the six-wheeled robot passively in contact with the ground driving severely on rough terrain not more than its wheel diameter. Additionally, while climbing over rough terrain all six wheels on the ground will receive equal pressure even if they are slow resulting in damage of the rover at high speed. For Mars rover application NASA used rocker-bogie suspension in its favored design of Sojourner and later extended to a suspension of rover wheel [12].

The main drawbacks of the wheeled suspension system are that need flat surface and their mobility performance over rough terrain is very less compared to the legged mechanism. Even those designed for rough terrain cannot pass over obstacles or holes greater than their wheel diameter. Due to track system also damages the contact surface over which it operates, it is not feasible to make them applicable on rough terrain. Compared to these, legged mechanism is the most suitable design for rough surface, in addition, by replacing labor work with automation, to conduct data collection, inspecting dangerous areas and areas not possible for wheeled or tracked system, it is better to introduce and advance by designing a leg mechanism of walking machine (robot).

The legged walking machines recently introduced also use complex mechanisms. The leg of the machines uses independent motors which required to actuate all DOF. Thus increases the overall weight of the machine resulting in use of high energy consumption and low-speed operation. The complexity of the legs to make suitable to assemble actuators at its DOF increases the manufacturability costs.

The main purpose of this thesis is synthesis and analysis of a walking machine (robot) leg mechanism on a rough terrain and determining its kinematic behavior in SolidWorks motion analysis to determine its responses. To achieve the objectives of this research applying all the required procedures starting from literature review, defining functional requirements, kinematic synthesis and analysis, applying motion analysis in SolidWorks and MATLAB 2016a. Finally, the results of its kinematic behavior responses are analyzed to formulate conclusion and recommendation for its future works.

1.2. Statement of the problem

In the recent human life, the interest in using robots to improve productivity, safety, flexibility, controllability and accuracy that has a potential significant is becoming more popular. The legged mechanism of walking machine is suitable for the application that cannot be accomplished with tracked and wheeled walking machines.

Today's micro legged robot whose construction uses the individual motor at each joint for actuation. Basically single leg of most legged walking machines has three different types of joints in which a number of motors are used to actuate all its DOF of the legs. Due to this, the weight of an individual motor and the machine leg results in large weight which brings also high energy consumption for driving, very low speed due to the complex controlling system and needs also controlling algorithm since it cannot be stable statically.

Design of this machine for a different application that will speed up or replaces the manual work or life risk areas and dangerous to a human being has a great role. The use of automation in human life is mostly a crucial application. Need for automation of manual work in different applications, using a walking machine is important. Considering the rough terrain, modeling the leg mechanism of a walking machine is kinematically to solve the stated problems is recommended.

1.3. Objective

1.3.1. General objective

The general objective of this study is synthesis and analysis of leg mechanism of a walking machine (robot) that can travel on rough terrain to determine or investigate its kinematic responses.

1.3.2. Specific objective

The specific objectives of the study include:

- Kinematic synthesis of a leg mechanism of the walking machine to walk on rough terrain using integration of linkages
- Kinematic analysis of leg mechanism of a walking machine to formulate the equation of motion
- Determining the kinematic response of its CAD (Computer Aided Design) geometric model in a SolidWorks motion analysis

1.4. Significance of the study

In fact, when atomizing is intensive and highly remunerative culture, it is easier to ensure the economic return that compensates for higher investments. Developing of this robot would be to make some valuable contribution to achieve the stated problems. In the synthesis and analysis of the walking machine leg mechanism, simple integration of linkages is used to transfer motion to provide a walking mechanism for the walking machine. The number of actuators used is decreased and this will be the reason behind to decrease the overall weight of the walking machine and consumes less energy for driving. To conduct detail analysis and design of walking machine leg mechanism, the kinematic synthesis and analysis is important to continue with designing and manufacturing of the leg mechanism for a walking machine.

In addition to the contribution of advancing the leg mechanism in a legged walking machine, generally, the study will be a base for next research work on design of walking machine with linkage mechanism.

1.5. Scope and limitation of the study

1.5.1. Scope of the study

The scope of this thesis is constrained to the kinematic modeling of a walking machine leg mechanism based on the integration of linkages to walk on rough terrain and determining its kinematic response in SolidWorks motion analysis. This study is focused on kinematic synthesis and analysis of a leg mechanism to determine its kinematic behavior or responses such as position, velocity, acceleration and torque in SolidWorks motion analysis by considering input rotational motion without considering the impact on the leg, joint frictional force and external load on the walking machine leg mechanism.

1.5.2. Limitation of the study

Based on the objective of this thesis to kinematically conduct synthesis and analysis of the leg mechanism of the walking machine external factors such as impact force, frictional force in the joints did not be included.

1.6. Research methodology

This study is concerned with the synthesis and analysis of a walking machine (robot) leg mechanism based on the theoretical works and principles reviewed from works of different literature. In the literature review, a lot of scientific papers and journal articles are reviewed and part of it considered in the study from reliable catalogs of relevant literature. Kinematic synthesis and analysis of a walking machine leg mechanism are conducted using the Denavit-Hartenberg (DH) convention approach. The equation of motion is derived from dynamic analysis using a Euler-Lagrange method which involves the expression of kinetic energy and potential energy. Further geometric modeling of a walking machine leg mechanism is constructed using SolidWorks software and its kinematic responses are determined in SolidWorks motion analysis. The numerical data from SolidWorks motion analysis is exported into MATLAB and analyzed graphically.

Therefore, the objectives of the research are achieved in accordance with the methodology discussed below in Fig. 1.

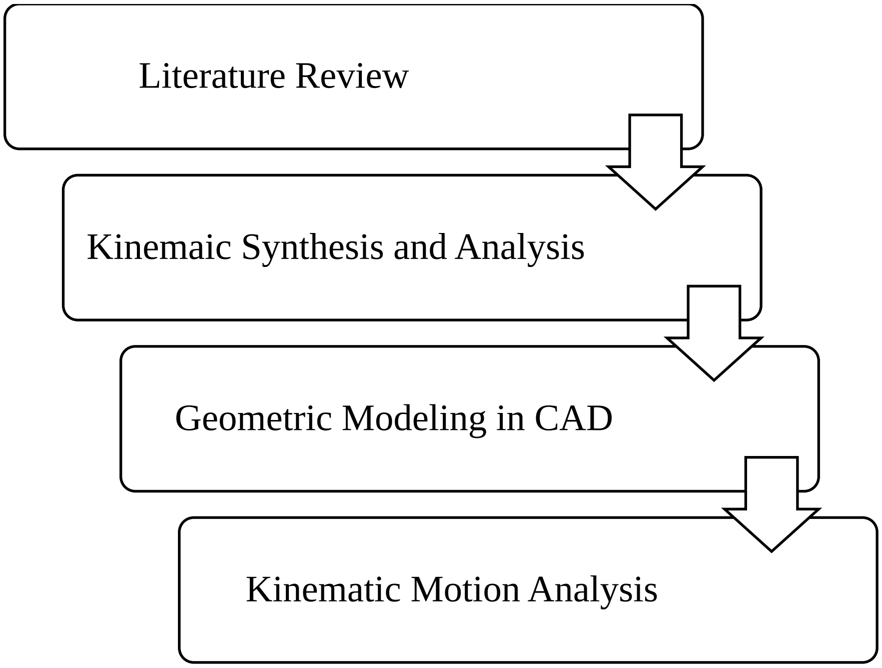


Fig. 1. Research Methodology

1.7. Outline of the thesis

This thesis report has been organized in a manner that is complete. The entire research work is organized into five chapters:

Following the Introduction part in **Chapter 1**, the previous work related to this study: the historical outlook of walking machine and its classification including their comparative advantage reviewed in **Chapter 2**. In **Chapter 3** the background of basic theoretical principles of a leg mechanism and its component, the functional requirement of the walking machine leg mechanism is defined. The kinematic synthesis and analysis of the integration of linkages that form a leg mechanism, dynamic analysis to derive the equation of motion using the Euler-Lagrange method from the expression of kinetic and potential energy are discussed. Further, the CAD geometric model constructed in SolidWorks. **Chapter 4** deals with result and discussion obtained from motion analysis of the CAD geometry of walking machine leg mechanism. The kinematic response is carried out in motion analysis and exported data are analyzed in MATLAB 2016a. Lastly, **Chapter 5** deals with the overall description of the thesis work summary. Furthermore, the conclusions of the thesis are summarized and recommendations are given for its future works. Reference and Appendix are mentioned at the end of the document.

Chapter Two

Literature Review

This chapter provides a review of the literature on historical outlook and general application areas of the walking machine. The main purpose of this literature review is to inaugurate the academic and research areas that are related to the topic studied.

2.1. Robotics

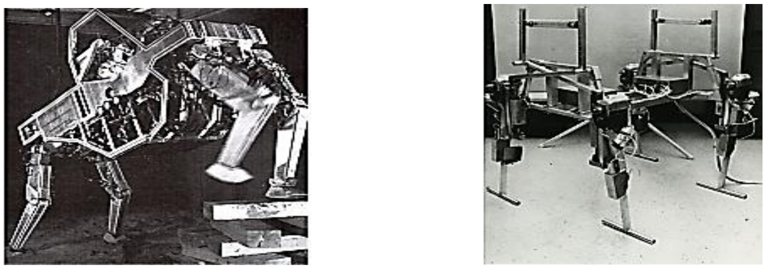
Leonardo da Vinci was the first person who developed the first mechanical armored knight used to charm royalty in 1495 [2]. It was designed to sit up, wave its arms and move its head. Jacquard [2] created the operational robot based on the Da Vinci's work which is an automated show controlled by punch cards during 1801. The word *"Robot"* was introduced by Karel Capek in 1921 while developing mechanical men *Rossum's Universal Robots* which works in a factory assembly to release human labors from a dangerous atmosphere. The origin of the word robot is derived from the Czech word *robota*, which means *forced labor* [2, 3, 13, 14]. In 1942, the term Robotics was initially declared by a Russian science-fiction author named Isaac Asimov in America. He stated '*Robotics is science that study robots*' which has a meaning of supportive servants of man and created three laws of Robotics. These three laws are: robot should not harm or injure, must comply or obey with all orders and must take care or protect of its own integrity respectively [2, 3].

Over the past periods, robotics advanced from fiction to reality becoming the science and technique that elaborated in the design, production and use of robots [1, 2, 15]. According to the current researches, robotics and artificial intelligence (AI) will saturate wide sections of human's daily life by 2025 with enormous allegations for a series of activities such as transport and logistics, consumer service, health precaution and home repairs [16].

2.2. Historical outlook of legged walking machine

Depending on the nature of the terrain, the locomotion mechanism can be categorized into three basic types, namely: wheeled (rover), tracked and legged (walking robot) [4]. From these categories, the main focus of this review is on the legged walking machine.

Edgeworth [17] constructed a wooden horse that has eight legs and jumps over high walls in 1770, on the other hand, more than 40 years' experiments weren't successful in constructing such mechanisms. The Russian mathematician, Chebyshev [18] designed and presented a fixed leg model for mechanical motion using clever linkage-based in the mid-1800's that moves in a straight path while the legs move up and down. In the mid-1960s Mosher [18, 19] developed quadruped machine a size of an elephant in General Electric Walking Truck (GEWT) shown in Fig. 2 (a) which is legged machine approached only by electromechanical means. Its mechanical design was good and reliable even if it was limited to the flat surface.



(a) (b)

Fig. 2. Quadruped robots: (a) GEWT [18] (b) McGhee and Frank Walking machine [19]

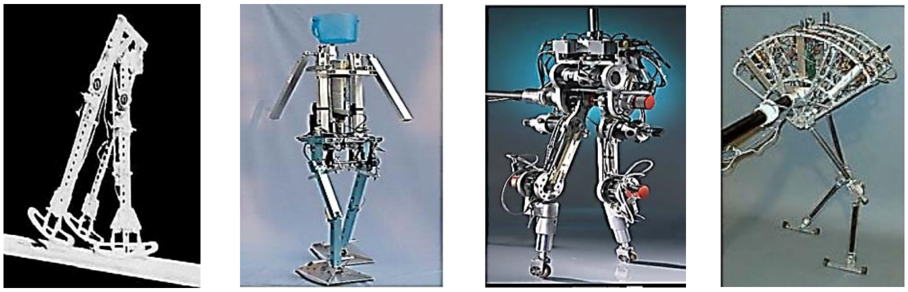
In the late 1960s, Frank and McGhee [18] introduced digitally controlled series of hexapod and quadruped robots in University of Southern California (USC), Fig. 2 (b). In Japan, the first anthropomorphic legged robot called WABOT1, by two famous researchers, Kato and Vukobratovic [19] demonstrated using simple control scheme which able to realize a few slow steps in static equilibrium at University of Waseda (UoW) in 1973. Then at Ohio State University (OSU) in the 1970s, they developed a robot that performs a variety of basic gaits, ability to turn and walk sideways given in Fig. 3 (a) [18], and in the 1980s computer-controlled walking machine shown in Fig. 3 (b) with Adaptive Suspension Vehicle (ASV), a human carrying hexapod vehicle walking machine developed. It weighs 2700 kg and can reach up to 3.6 m/s. It carries an operator who provides supervisory level commands, it specifically performs long-range sensing, path selection and navigation [6, 19, 20].

(a) (b)

Fig. 3. Vehicle Walking machine (a) The OSU Hexapod [18] (b) The ASV robot [20]

In the early 1990s, McGeer [21] introduced the concept of natural cyclic behavior in a purely passive mechanical system in terms of orbital stability in Simon Fraser University. He demonstrated that passive machines are capable of walking at various speeds and down hills in two dimensions. Several researchers have followed his truck by adding different extensions like feet and knees given in the Fig. 4 (a) which is Underactuated systems, RABBIT walking robot [6]. RABBIT was developed in the 1990s by Westervelt in France. Collins and Ruina [18] developed based on the McGeer concept, Cornell Biped robot, Fig. 4 (b), which has energetic efficiency with a human.

Using the Virtual Model Control (VMC) in the late 1990s, Pratt [21] developed Spring Flamingo walking robot which is the most impressive planar walking machine to date given in Fig. 4 (c).



(a) (b) (c)

Fig. 4. 2D Walking machines: (a) McGeer's Walker [6] (b) Collins and Ruina robot [18] (c) RABBIT walking robot [21]

At Jet Propulsion Laboratory (JPL) legged walking beam (robot) built by Marietta Corporation aimed at the exploration of planetary, composed of two frames with seven legs which retracts and extend vertically in a telescoping mode, shown in Fig. 5 (a) has a mobility system. Its three legs are placed with six-meter distance at the outer frame, at the angles of equilateral triangles creation and the inner frame consists of the other four legs placed at the angles of square creation [7]. AMBLER is another automated legged robot similar to walking beam designed for Mars exploration in unstructured environments. It consists of six orthogonal legs arranged at each side of the robot as shown in Fig. 5 (b) capable of rotating and extending in horizontal, and extending in vertical directions [7].

(a) (b) (c)

Fig. 5. NASA legged robots [7]: (a) Marietta walking beam (b) AMBLER (c) Dante II

The walking Robot in Fig. 5 (c), attempted by Dante II from NASA Science Internet to construct eight legs supplied power of 1000 V robot talented of crossing rough terrain autonomously to check the hardware and software methods appropriate for mars and moon exploration in Pittsburgh sponsored by NASA to Carnegie Mellon University's Robotics Institute. It descended in July of 1994, five days' operation to take samples and collect data from the crater of an Alaskan Volcano [3, 6, 7]. The design of its leg is based on the pantographic leg mechanism which involves four-bar linkage for an intrinsic stepping motion. Each leg can individually adjust its height, compounding the stepping motion and enabling to avoid obstacles and adapt to terrain [22].

From 1986 to 1990, Raibert [23] studied dynamically stable locomotion system to build single leg Hopping robot at Carnegie Mellon University. This Hop robot was only moving on a flat surface vertical, horizontal and rotational motion in the plane from point to point under velocity or position control when pushed. A computer controlled Pogostick designed by adding the legs to have sideways motion, greater speed and able to balance itself while hopping. The development of this robot became a base for developing biped and quadruped system with prismatic legs based on the similar design given in Fig. 6 [23].

(a) (b) (c)

Fig. 6. Hopping robots [24]: (a) single leg (b) two legs (c) four legs

Multi-legged robots recently introduced by different researchers widely used locomotion principle in a biological system to achieve the surface mobility [24]. The legs of the robots have three degrees of freedom which perform walking motions by adapting the body system to surface structure. In the history of the walking machine, Massassuchet Institute of Technology (MIT) contributed widely to the development of walking machines design including the hopping robot. MIT humanoid Robotics group developed the concept of subsumption architecture which is based on that basic layer is based on a strong coupling between actuators and sensors, promoting a more reactive behavior than in the classical control approaches. Based on this concept in 1989 and 1990 six-legged walking machines are designed as shown in Fig. 7 (a) and (b) respectively.

(a) (b)

Fig. 7. MIT multi-legged Walking machines (Robots) [25]

Scorpion IV eight-legged robot which is capable of traverse unstructured terrain and steep inclinations shown in Fig. 8 (a), designed by Kirchner [25] during 2000 in Germany. Its leg kinematic is inspired from biology by the spider and insect legs design [5, 26]. It uses a walking pattern inspired by the movement of scorpions coupled with reflexes that will help the robot to free a stuck leg, among other things.

The engine driven that has hydraulic actuating system robot walks, runs, climbs and carries heavy loads on rough terrain named as Bigdog shown in Fig. 8 (b). It has four legs articulated like animals and its legs are composed of shock absorber about 3 ft long, 2.5 ft tall, and weighs 240 lb by recycling energy from one step to the next. It has the ability to walk around 20 miles without refueling, it is inborn powerlessness to utilize the natural dynamics and not to communal with gait competently and also has extreme performance description [23]. Its design and development was based on power autonomous, capable of carrying significant loads (50 kg), operating outdoors, statically and dynamically stable, fully integrated sensing etc.

(a) (b)

Fig. 8. Legged Walking machines [23]: (a) Scorpion robot (b) Bigdog robot

Six-legged walking robot based on synthesis and analysis of linkage mechanism was designed with two DOF to achieve simplicity in mechanism and low weight which moves on a straight line [27]. Hexapod robots with six legs controlled with a degree of autonomy able to move on the irregular surface. This robot design (Fig. 9 (a)) aimed at identifying design issues and limitations that affect technical achievability and their performances [12].

Tokyo Institute of Technology in a research lab built a robot called PVII, [28] Fig. 9 (b) in 1978 using the Pantograph mechanism and advancing its kinematic control. Titan XI robot introduced again in 1996 in Japan which is a quadruped robot. Titan III, [29] Fig. 9 (c) which used improved pantomec legs mechanism increased at mobility range and reduced weight by using carbon fibre composite plastic. Whisker sensor equipped with its legs and signal processing system made up of wire to measure ground contact status is integrated.

(a) (b) (c)

Fig. 9. Recent Micro-rovers: (a) Hexapod robot [12] (b) WARP robot [28]

(c) PVII robot [29]

In Spain, Institute of Industrial Automation of Madrid worked on a walking machine in a hazardous environment and humanitarian demining. SILO4 and SILO6 quadruped walking machines in Fig. 10 (a) and (b) designed in medium size for educational and basic research development has four legs. This robot has capable of moving on the irregular surface up to 0.25 m obstacles and travels 0.025 m/s. The construction of the robot was aimed at small in size, easy to handle, a reliable robot with terrain adaptability and omnidirectionality [30].

(a) (b)

Fig. 10. Multi-leg Walking machines [30]: (a) SILO4 robot (b) SILO6 robot

Zielinska and Heng [31] designed legged autonomous vehicular agent (LAVA) walking machine in 2000 in Fig. 11 the leg swinging and lifting functions are based on the differential gear drive system. Each leg is incorporated into three DOF maximum flexibility with prices turning functions.

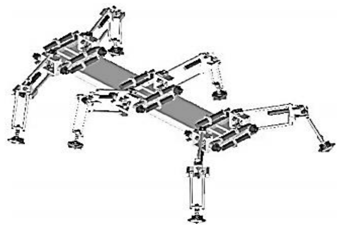


Fig. 11. LAVA Walking machine (Robot) [31]

In 2011, a six-legged robot with hexagonal architecture designed by Bombled [32] called ARMUR5 built by Royal Military Academy of Belgium in collaboration with the VUB (Vrije Universiteit Brussel) and the ULB (Universite Libre de Bruxelles) given in Fig. 12 (a). The robot has 34 kg weight and 1.4 m outer diameter. The maximum reachable velocity on flat ground is about 0.03 m/s the legs with three DOFs, rotation about the vertical axis, movement of up and down motion, and back forth motion. DC motor has been used to actuate each DOF of the robot leg using a pantographic mechanism which allows better efficiency and easier foot trajectory.

(a) (b)

Fig. 12. Multi-leg Walking Machines [32, 33]: (a) ARMUR5 (b) Underactuated robot

Kanner and Rojas [33] designed (Fig. 12 (b)) a passively adaptive three DOF multi-legged robot with Underactuated legs during 2015 in Boston, USA. They showed the use of adaptive under actuation techniques with constrained design-based tools which allows lighter and simple mobility that can adapt to rough terrain.

Most recently, the Micro-Electromechanical System (MEMS) technology designing millimeter scale walking robot within a very improved fabrication process, called Micro-lithographic techniques. MITRE Nanosystems group designed a walking robot which involves MEMS technology as shown in Fig. 13 which has six legs having two DOF each [34].

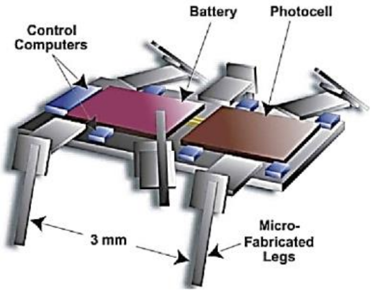


Fig. 13. High-level design of micro-robot [34]

2.3. Comparative advantages of a legged walking machine

A legged mechanism of walking machine has many advantages over wheeled or tracked by the following main points:

- In wheel mechanism, the wheels have continuous contact with the ground over which they travel but in the legged mechanism, the machines place their feet and frictional forces prevent further movement of the leg.

- The dynamics of the machine body is determined by the leg kinematics, in wheeled walking machines the body position is continuously affected by the contour of the road surface.
- In walking machines, the total ground area touched is considerably less than the area moved by wheeled or tracked. The average ground pressure it exerts is extremely small, in wheeled, the diameter of the wheels covers more area over which the pressure is high. Tracked walking machines have also a large ground contact area and hence legged walking machines are preferred to be used for their low ground pressure.
- Wheeled walking machines are subjected to slip, especially when applying high tractive effort on loose, slippery or wet surface. A legged walking machine with sharp feet could apply more tractive effort.

Some disadvantages of legged walking machines compared to wheeled or track:

- Complicated design of components which involves kinematic links,
- Inefficient since they operate at slow speeds,
- The high cost of construction related to its complexity and
- They are not familiar with the public.

2.4. Summary of literature review

The current development of legged walking machines (robots) is reviewed focusing on the ability to operate on rough terrain. Its field of operation mostly focused on space exploration, human assistance, large agricultural data collection, risky places for human and indoor environments. From the literature, the leg mechanism of walking machines is:

- The most advantageous locomotion over rough terrain to walk on obstacles and holes.
- Complex profile and requires high manufacturing cost
- Use a number of different joints and requires a number of actuators for its walking mechanism of the walking machine
- Large in overall weight which consumes higher energy for the driving mechanism
- Provides high mobility in challenging environments through reconfiguration of its legs mechanism.

Due to this, legged walking machine kinematically controlled with a simple mechanism which can operate on rough terrain to overcome the stated problems is a better approach.

Chapter Three

Theoretical Basis and Kinematic Modeling

This chapter deals with the theoretical basis of mechanisms, its historical development, the kinematic synthesis and analysis of the walking machine as well as the derivation of the equation of motion from the dynamic analysis for the leg mechanism. The development of working principles of the leg mechanism is synthesized by special type of four bar mechanism. The DH convention approach is used for the kinematic analysis of a leg mechanism. Then its dynamic equation of motion is derived using the Lagrangian method. Geometric modeling for the leg mechanism of the walking machine is constructed in CAD.

3.1. Mechanisms and historical development of kinematics

Motion can be converted into some desirable patterns through a mechanism in which it develops very small forces and to transmit little power. Mechanisms are part of the machine which is aimed to deliver significant forces and power. The main objective of developing and designing a mechanism for transferring motion in a specific system is one of its mechanical advantages. Synchronizing the input and output motion is a typical problem existing in a design of mechanisms. The designed mechanism is expected to give an output as a function of input called function generation which is capable of creating output that established an extensive diversity of application [35].

A machine is a system that transmits forces in a predetermined manner to accomplish work through different mechanisms. A mechanism is a heart of a machine that converts one motion to another type of motion through interconnected series of moving parts which provide the specific motions and forces to do the work for which the machine is designed [36]. These machines are driven by a motor which supplies a constant speed and power. The mechanism within the machine converts this applied motion into the form needed to accomplish a vital job. With the incredible benefits prepared in the design of instruments, automatic controls, and automatic tools, the study of mechanisms takes on a novel consequence.

After a requirement for a machine or mechanism with given characteristics is identified, the design process begins. A complete analysis of displacements, velocities and accelerations is typically mandatory. Kinematics is the study of motion in machines, which considered from the two different points of view generally identified as kinematic synthesis and kinematic analysis. In the synthesis of kinematics certain motion specifications that fulfill the mechanism is determined. The motion characteristic of a mechanism is determined through kinematic analysis [36].

Mechanisms and machines cannot be discussed independently and clearly but differ in degree. If a device is subjected to a force or energy that has a significance on it, we can consider it as a machine, if not it is a mechanism. Arrangements of elements in one system arranged to transmit motion in preset delegates the working definition of mechanisms. This definition can be used for a machine by adding the word force or energy after motion. Mechanisms considered as a kinematic device at low-speed operation condition within non-significant loading in which it can be analyzed without considering the force kinematically only. For machines, if mechanisms are running at high speed they are possessing a large amount of force, so that first kinematic analysis of their positions, velocities and accelerations must be performed by treating as a mechanism. Then the principles of kinematics will be used to analyze their dynamic condition due to static and dynamic forces caused by those accelerations.

Mechanisms were analyzed by Reuleaux [37] primarily in machine elements by studying their combinations and exposed those laws of operation which organized the early science of machine kinematics. In its work of “Theoretische Kinematik” of 1875 Reuleaux offered many sights of discovering general acceptance and his second book “Lehrbuch der Kinematic” (1900), merged and extended earlier ideas, and philosophies in mechanisms. His comprehensive and orderly views mark a high point in the improvement of kinematics. He dedicated most of his work to the investigation of machine elements.

In the one hundred years that followed Reuleaux, the contributions of scientists such as Hartmann, *et al.* [38] developed the science of constructing mechanisms to satisfy specific motions, namely, kinematic synthesis. The techniques they used was based on mechanics and geometry. It was not until 1940 that Svaboda [39] developed numerical methods to design a simple but versatile mechanism known as four-bar linkage to generate the desired function using enough precision for engineering resolutions. The scale to input crank indicates the values of the parameter of a function, and that on the output crank indicates the result of the function. Naturally, this four-bar linkage can generate only a partial amount of tasks because of the nature of the linkage itself. In 1951, the publication by Hrones and Nelson [40] of an

“Atlas” containing approximately 10,000 coupler curves offered a very practical approach for the design engineers. The Kinematics of mechanisms has progressively developed as popular investigation area in an engineering field.

3.2. Components of walking machine leg mechanism

In the past centuries, mechanisms have been configured into machines. The development of kinematics of mechanisms in the past forty years as an engineering science, regular terminologies and explanations were demanded to support study and communication. As mechanism was defined by Reuleux [37] an arrangement of inflexible or rigid bodies so designed and coupled that they move up on each other with definite relative motion.

In the study of kinematics analysis of the walking machine leg mechanism, distinguishing the definitions and the roles of some terminologies such as links, linkages, frame, joints and, high and lower pairs are important. These terminologies are briefly explained below.

Links are the individual parts of the leg mechanism which considered as a rigid body and linked with supplementary links to transfer motion and forces. In a theoretical principle, a true rigid body does not change its shape during motion due to strains in walking machines members. In the similar method true rigid body doesn’t exist, it is an idealization used in mechanisms that do not consider small deflections or they are designed to minimally deform and are considered as a rigid body. In a different textbook for modeling of a real machine member’s links can be considered as a perfectly rigid body [41, 42].

Linkage is a mechanism where rigid body parts are connected together to form a chain. Four bar mechanism special types are a combination of a number of pair elements connected by rigid pieces or links, connecting them by pin or pivoted joints in order to allow between their parts a relative motion. If kinematic chains are needed to be observed deprived of regard to its ultimate use, an assemblage of rigid bodies connected by kinematic joints of lower pairs is termed as a linkage. Thus, both mechanisms and machines can be taken as a link. However, in general, the term linkage is limited to kinematic chains made lower pairs [35, 36].

Frame is a part which serves as the frame of reference for the motion of all parts. It is typically part that not exhibit motions. It is stationary or a fixed link in a leg mechanism, and when there is no link it is actually fixed link which considered as being fixed and determine the motion of the other links relative to it. It is the reference from which all motions of the leg mechanisms are accounted for [36, 43].

Joints are movable connections used to allow relative motions between links of the leg mechanism of the walking machine. Each joint reduces the mobility of a system. The joint between a crank and connecting rod of the slider-crank mechanism, for instance, is called a revolute joint or pin joint. The revolute joint has one DOF in that if one element is fixed, the revolute joint allows the other only to rotate in a plane [36].

Lower and Higher Pairs: Connection between rigid bodies can be categorized as lower and higher pairs of elements. The gear and pinion which used in the leg mechanism to transfer motion have a lower pair have theoretical surface contact with one another, while the two elements in the higher pair have theoretical point or line contact. Lower pairs include revolute or pin connections [41].

3.3. Selection of DOF and functional requirements of a walking machine leg mechanism

Any mechanical system can be classified according to its number of independent parameters which are needed to uniquely define the position in its space at any instant of time; i.e. degrees of freedom (DOF). The number of joints in a robot roughly translated to the DOF. In the design process, three different possibilities were considered. However, the up-down and forward-back motion is approximately linear and provides a method to propel forward or backward while adjusting to some uneven terrain.

For the leg mechanism of the walking machine, the general Gruebler-Kutzbach criterion can be applied to find DOF which is given

$$DOF = 6(n-1) - 2p - h \quad \text{………………………………......(3.1)}$$

Where: n - Number of linkages

p - Number of lower pairs

h - Number of higher pairs

It is a desired that a walking machine has the flexibility required for walking on rough terrain while it can still achieve fast locomotion and require minimal actuation for walking on a flat terrain. For a walking machine to be capable of walking on various terrains, each leg requires three DOF to carry out the back and forth motion, up and down motion, and turning motion. Since the turning motion can be separated from other two motions in a leg mechanism, a two DOF planar mechanism which provides the back and forth and the up and down motions are of interest. If all three DOF needs simultaneously actuated for a rough terrain walking, then the walking machines can be slow. On the contrary, if a leg mechanism is designed such that only one DOF is required to be actuated for normal walking, then the speed of the walking machine can be fast.

The following points are the functional requirements of the walking machine leg mechanism:

- The leg mechanism, in addition to being able to move forward and backward, should have the capability to lift the foot point up and down
- The back and forth motion of the leg is to be driven by continuous rotary motion using gear train rather than linear motion in primary mover, moving either in forwarding or backward direction
- The up and down motion of the leg is to be driven by crank slider motion
- The means of transferring motion should be using one driving unit; the integration of linkages would be the means of transferring motion between links
- To make more stable at least three legs of the walking machine should touch the ground at the same time while others legs are performing back and forth, up and down motion simultaneously
- The linkages of leg mechanism should be considered as a rigid body to permit motion and force transferring, and minimal power consumption
- Ability to walk on rough terrain
- Statically balanced, so that no balance control system is required
- Uniform velocity while legs are in contact with terrain

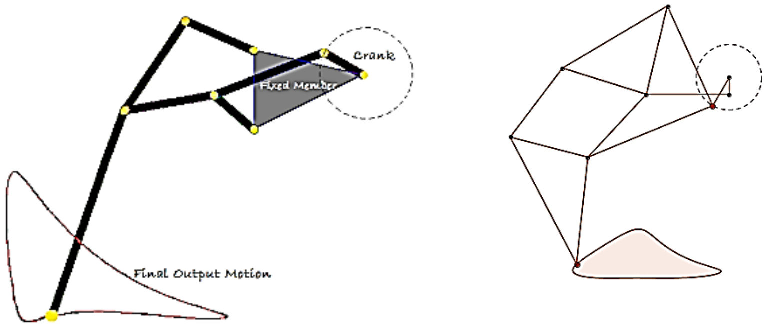
3.4. Kinematic synthesis of a walking machine leg mechanism

The motion of the leg mechanism can be described in terms of position, velocity and acceleration of its all components without regard to the forces or torques that cause the motion. The components of the leg mechanism can be connected together by different types of joints which bounds how the components are movable relative to each other. This interconnection indicates that the motion between components constrained relative to each other. This geometry of leg mechanism can be studied by kinematics.

In order to change previously body under motion, Newtonian mechanics states that there should be another external force need to be applied to it. These forces are classified as constraint force, which limits the force and generalized force, the force that causes motion on the body. Without the regard of these two forces, the interconnection between the bodies components can be described by kinematics through space, i.e. the dynamics of the system. This idea undertakes that each of the components of a mechanical system is preserved as a rigid body. In the rigid body, the distance between any point within the components is fixed and cannot move relative to each other. The geometric configuration of the leg mechanism can be defined by generalized coordinates in which all points are allotted to generalized coordinate values indicated at the point. Identifying the configuration of a leg mechanism with a minimum number of generalized coordinates is called as a geometric DOF. It helps to determine the motion of the leg mechanism by identifying all the generalized coordinates as a function of one single variable that aids generating motion curve for all points in the mechanism of walking machine leg.

Usually, the Cartesian coordinate system is used as a fixed frame relative to earth known as an inertial frame or world frame based on the framework. Other frames can be defined for each of the components to fix the orientation of a specific frame relative to a specific component and the frame will rotate with the component relative to the inertial frame. Once the generalized coordinate values are given then the configuration of the leg mechanism will be specified, this method is taken as direct kinematics; it is a generally straightforward problem. On the other side, the most difficult one is inverse kinematics, in which the position of the points in the leg mechanism is given and generalized coordinates of all points should be formulated or determined. In this method, for a single point different set of values of generalized coordinates can be obtained [44].

Different mechanisms like Klann mechanism and Jansen linkages are widely used types of leg mechanisms for different walking machines. Klann mechanism is a type of tabular mechanism to simulate the gait of leg-like animal and performance as a wheel replacement. It consists of a frame, cranks and two grounded rockers, and two couplers connected by a pivot joint, eight bar kinematic chain (Fig. 14 (a)). It provides several advantages in walking machines application; step over curbs, climb stairs, travel into areas which are not accessible with wheels which don't need microprocessor control or a large amount of actuator mechanism [45].



(a) (b)

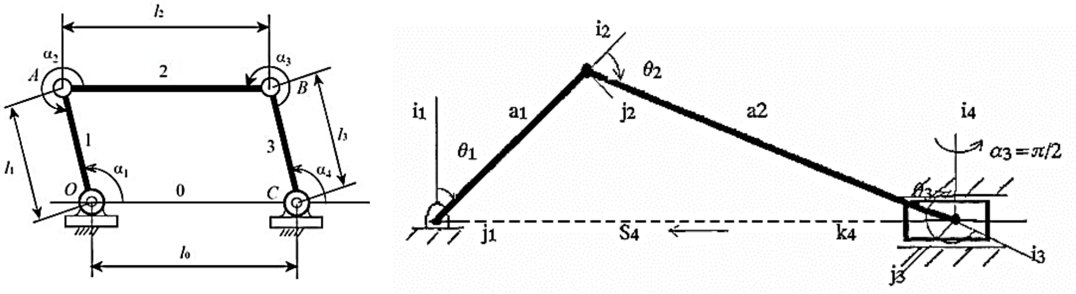
Fig. 14. Alternative leg mechanisms: (a) Klann mechanism (b) Jansen linkage

Jansen's linkage mechanism is used for smooth walking motion for its ingenious simulation of walking motion using a simple rotary input. It is one DOF planar, 11 mobile link leg mechanism that converts the rotational motion of a simple crank mechanism into a stepping motion, (Fig. 14 (b)) [46]. The popularity of Jansen mechanism is due to its scalable design, efficient in energy, low payload and deterministic foot trajectory [47]. Presently, the major use of the Jansen linkage is a walking motion used in legged robotics.

By integrating a combination of linkages the walking mechanism can be developed. Basically, in this thesis, special types of four-bar mechanism; change a point four-bar and inline slider crank mechanism is proposed to create a mechanism that can be used in a legged walking machine to walk on a rough terrain.

An important property of a classification system would be the aid it could furnish a designer in finding the forms and best-suited arrangements to satisfy certain conditions. The planar four-bar mechanism which consists of four pin connected rigid links gains its importance as a basic mechanism because it is one of the simplest of all mechanisms to produce. The four-bar linkage derives its renown from the fact that the members of a three-bar linkage are incapable of relative motion and a linkage composed of more than four bars has indeterminate motion with a single input. Though it may assume many forms, often with little resemblance to the usual representation, a four-bar linkage consists of two members in pure rotation about fixed axes, called the driving and follower crank; a coupler in combined motion, which joins the moving ends of the cranks; and a fixed frame, which establishes the relative position of the stationary crank centers. The special type change point four-bar mechanism in Fig. 15 (a) which enables its links became collinear is used. With this property considering only the first link grounded the other links can develop a rotating motion if some constraints are added.

The simplest and most common closed loop linkage mechanism is the four-bar linkage. One link is designated as a frame with four pin joint for a single degree of freedom of controlled motion. It has also special configurations created by making one or more links infinite in length. Slider-crank mechanism is a four-bar chain with a slider replacing an infinitely long output link, Fig. 15 (b). It is connected by three pin joints and one sliding joint [48].



(a) (b)

Fig. 15. Types of four bar (a) four-bar mechanism (b) Inline slider crank mechanism

Kinematic synthesis is a process of designing a mechanism to accomplish the desired task which includes both choosing the type as well as dimensions of the mechanism. For the leg mechanism of the walking machine, the mechanism is composed of special types of four-bar change point and inline slider mechanisms in which both are integrated together to develop the required motion of back and forth, and up and down motion respectively. The change point four-bar mechanism is used for the motion of the back and forth of the walking machine leg. “Changepoint mechanism is the sum of the two sides is the same as the sum of the other two. Having this equality, the change point mechanism can be positioned such that all of the links become collinear” [36]. The parallelogram linkage is given in Fig. 16 (a). is a widely used type of change point mechanism. The frame and coupler are the same lengths, and so are the two pivoting links. Thus, the four links will overlap each other. In that collinear configuration, the motion becomes intermediate. The motion could stay in a parallelogram arrangement. For this reason, we call it a singularity configuration.

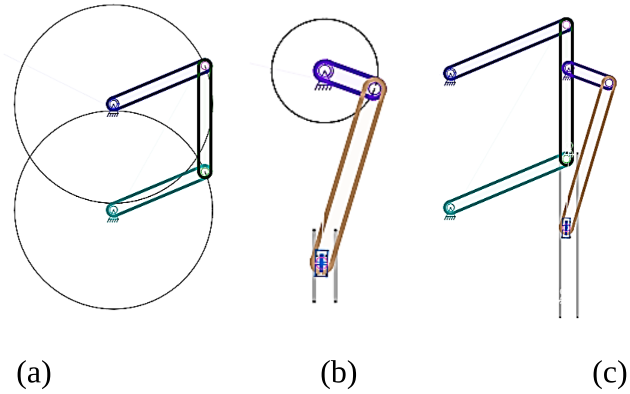

(a) (b) (c)

Fig. 16. Synthesis of leg mechanism

For the up and down motion, the inline slider-crank mechanism is assembled on the coupler of change point four-bar linkage which rotates together simultaneously while providing up and down motion of the leg as shown in Fig. 16 (b) and (c). The coupler of the change point four-bar mechanism is extended beyond and be used as a fixed frame for the slider mechanism.

The leg mechanism for up and down motion is developed from the mechanism of the inline slider-crank mechanism. This mechanism provides reciprocating linear sliding motion and it has the crank pivot coincident with the axis of the sliding motion. The stroke is defined as the linear distance that the sliding link exhibits between the extreme positions. Because of the crank and connecting arm motion is symmetric about the sliding axis, the crank angle is mandatory to perform a forward stroke as the same as the return stroke. For this reason, the inline slider-crank mechanism produces balanced motion. The length of the connecting arm does not affect the stroke of an inline slider-crank mechanism. However, a shorter connecting arm yields greater acceleration values [36].

The gear assembly is used to transfer motion between links from single central input rotary motion. The arrangements of the gears are designed to provide input motion for the change point four-bar mechanism and the inline slider-crank mechanism. The coupler of the change point four-bar mechanism is used as a fixed frame for the inline slider-crank mechanism having a prismatic joint at its one end which helps the connecting arm of the slider to slide in to develop the up and down motion of the leg.

3.5. Dimensional synthesis of a walking machine leg mechanism

Dimensional synthesis deals with the determination of kinematic (link lengths, offsets, etc.) of the leg mechanism to satisfy the required motion characteristics. Graphical methods, as well as analytical methods, are available for dimensional synthesis. For the leg mechanism developed a dimensional analysis of both change point four-bar and inline slider-crank mechanisms are formulated analytically. The relation between them also given in a parametric equation.

With this mechanism, the drive crank and follower crank are the same lengths and the connecting rod or coupler and the ground pivots are the same lengths. The drive crank and the follower crank will always have the same angular velocity. There are two positions in the cycle when the system is not constrained; when the follower link, the drive crank and the connecting rod are co-linear. At these two positions, called dead points or dead center, the follower could begin to rotate in a direction opposite to that of the drive crank. Inertia, springs, gravity or constraints usually prevent the reversal at the dead point. In this mechanism Grashof's rule is not satisfied, no matter the configuration of links, only a double-rocker mechanism with oscillating couplers is attained.

The dimensional synthesis of the change point four-bar evaluates the most perfect structure that can provide the maximum workspace. The dimensional synthesis is carried out by controlling the following geometrical parameters such as the link length, and the angle between the link as given in Fig. 17. The typical structures with the dimensions are drawn and, the angle and the displacements are identified.

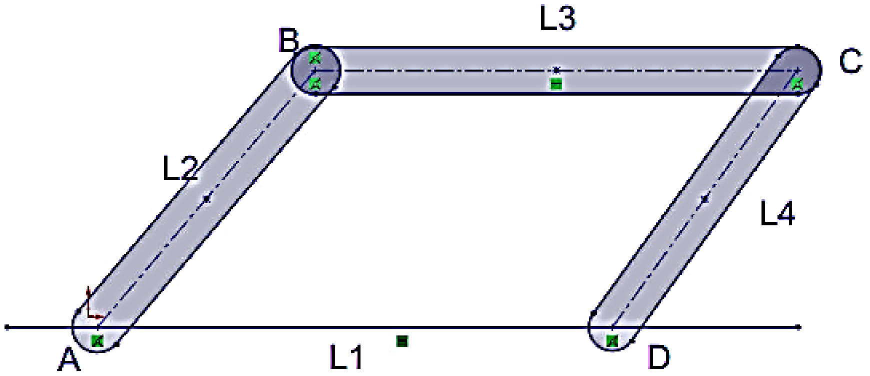


Fig. 17. Change point four-bar dimensional synthesis

$$Link\ AB\ = link\ CD, Link\ BC =\ link\ AD, AB//CD, BC//AD,$$

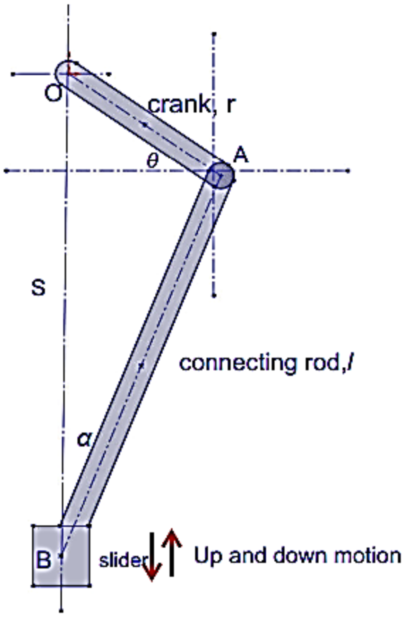
$$\overline{AD} = l1, \overline{AB} = l2, \overline{BC} = l3, \overline{CD} = l4$$

$$\overline{AB} + \overline{BC} = \overline{BD} + \overline{AD}\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

By the following steps analytically the dimensions of the linkages for the change point four-bar mechanism will be obtained as

$$l1 + l2 = l3 + l4\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.3)$$

One or more data about the frequency of oscillation, the speed at different positions and range of motion of the slider may be provided and the requisite task will be finding the dimensions of the members of the leg mechanism and position of the slider such as to have the desired motion of the leg mechanism. The relation between the length of the links are determined from Fig 18 parametrically to formulate the general equation of its dimensions.



$$s = l\cos\alpha + r\cos\theta\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.4)$$

$$r\sin\theta = l\sin\alpha\ \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.5)$$

$$l^2 = r^2 + s^2 - 2rs\cos(\theta)\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.6)$$

$$l^2 = r^2 + s^2 - 2rs\cos(\theta) + r^2((\cos^2\theta + \sin^2\theta) - 1)$$

$$l^2 - r^2 - r^2\sin^2\theta + r^2 = s^2 - 2rs\cos(\theta) + r^2\cos^2\theta$$

$$l^2 - r^2 - r^2\sin^2\theta + r^2 = (s - r\cos\theta)^2$$

$$\sqrt{l^2 - r^2\sin^2\theta} = s - r\cos\theta$$

$$s = r\cos\theta + \sqrt{l^2 - r^2\sin^2\theta}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.7)$$

Fig. 18. Inline Slider-crank dimensional synthesis

3.6. Kinematic analysis of walking machine leg mechanism

Kinematic analysis of a leg mechanism is an investigation based on the mechanism geometry and known characteristics such as angular velocity, angular acceleration, etc. The motion of the leg mechanism building the walking machine results in the required output. The kinematic quantities such as position, velocity and acceleration have a great importance. The position and velocity give an insight into the functional behavior of the leg mechanism. The acceleration, on the other hand, is related to stresses and deformations in the leg components. The linkages are assumed to be fully rigid bodies for the kinematic analysis of the leg mechanism.

3.6.1. Direct kinematic analysis of a leg mechanism

There are two basic types of methods for analysis of mechanisms. Namely; graphical and analytical. Denavit and Hartenberg (DH) [38] convention approach is another method used for more complex mechanisms. These methods involve different techniques for the analysis of mechanisms, in which the techniques are suitable for a particular category of mechanisms. Due to the sophisticated development of computer program, some engineers in designing of mechanisms desire to work with the analytical approach. For preferable solution analyzing mechanisms using the graphical approach to visualize the working mechanism is still useful.

Graphical method of analyzing a mechanism involves starting with the position analysis of the mechanisms linkages by simply drawing in scale. Then the angular position of the links is determined and based on the result on the position analysis, and then velocity analysis is implemented. So that to determine the acceleration analysis of the links its angular velocity needs to be executed before. This is a method through which the analysis of kinematics is performed; i.e. position analysis, velocity analysis and acceleration analysis. The approach of using graphical analysis involves different techniques such as velocity and acceleration polygon, inversion techniques, relative velocity and acceleration, and instant center of velocity [35, 48].

The other method used for analysis of mechanism is the analytical approach. This method is used when the repetitive and broad analysis is required for a mechanism so that the solutions and equations obtained analytically programmed on a computer conveniently. The approach involves the formulation of position, velocity and acceleration equations in a vector based on the fact that the loops connecting the points in the path. By simplifying the equations, it can be programmed on computer and solutions are obtained by using variable parameters.

When mechanisms are becoming more complex and a number of generalized coordinates are too much another type of analysis techniques are preferred to be used; the Denavit-Hartenberg (DH) convention approach [38, 49, 50]. In a walking machine construction, links are assumed as a rigid body and connected together by joints. When a walking machine leg mechanism is placed in a three-dimensional space it has three DOF in position and three DOF in the orientation which has six DOF totally. Denavit and Hartenberg [38] suggested that it is imaginable to use four parameters to achieve kinematic analysis of robots in multi-degree of freedom for the first time, in which links are connected by rotary or prismatic joints. This DH convention approach is used to represent, model the leg mechanism and drive its equation of motion. This representation is now used as a standard approach for the kinematic analysis of the walking machine leg mechanism. It simplifies ways of modeling the leg mechanism arrangement, irrespective of its order and difficulty or complexity [51, 52].

The significance of kinematic study overviews the presence of a technique which permits numerous locations of end-effector to be defined in a reliable and definite means. The DH concept technique says that each joint of the robot is assigned to a coordinate frame. Under this assumption, it is possible to simplify complex kinematic structures. To model the walking machine leg mechanism with DH representation [49] first, assign a local reference frame for every single joint i.e. assign a z-axis and an x-axis. In DH representation y-axis cannot be used.

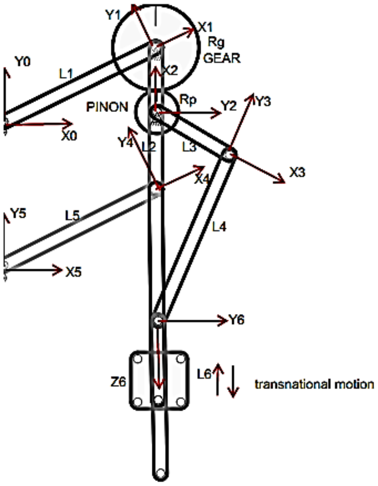


Fig. 19. DH convention of leg mechanism

Designation in Fig. 19 : α_i =offset angle, θ_i = joint angle, l_i = link length and d_i = link offset distance

The performance of a walking machine is analyzed by calculating the position, velocity and acceleration of points on the different parts of the leg mechanism and tracing the trajectory they follow. In this representation, each homogenous transformation matrix is represented as a product of basic transformations obtained for each link of the leg mechanism. This DH representation in Fig. 19 allows constructing the direct kinematics function by decomposition of the individual transformations into a homogeneous transformation matrix. By multiplying each individual homogenous matrix together, the kinematic function can be generated.

Since the links lies on the same axis offset angle and offset distance (excluding prismatic) between them is insignificant. The forward kinematic analysis is used to determine the position and orientation of the end point of the leg that touch ground relative to the base frame of the walking robot in terms of the joint variables which are the link extensions in the case of sliding or prismatic joint, and the angle between the links in the case of rotational or revolute joints.

The kinematic relationship between two frames involving a translation and a rotation can be represented by a position vector and a $3x3$ rotation matrix. Hence the transformation of moving the frame with respect to a fixed frame can be represented by a homogeneous transformation matrix,

$$[A] = \begin{bmatrix} n_x & o_x & s_x & p_x \\ n_y & o_y & z_y & p_y \\ n_z & o_z & s_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \text{.................................(3.8)}$$

Where: $R_{3x3} = \begin{bmatrix} n_x & o_x & s_x \\ n_y & o_y & z_y \\ n_z & o_z & s_z \end{bmatrix}$ Rotational matrix

$P_{3x1} = \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix}$ Translational matrix

$3x1 = [0 \quad 0 \quad 0]$ Perspective matrix and

[1] Global scale

Rotation matrix R is orthogonal $R^T R = I$ three independent entries using Euler angles $\psi, \theta\ and\ \alpha$. Hence any homogeneous transformation could be denoted in terms of the products of special transforms.

Once the coordinate systems are rigidly fixed to each link of the leg mechanism and the link joint parameter is formed, coordinate-transformation matrices are specified. Coordinate transformation matrices contain information about the links and the displacements (both sliding and rotation) between coordinate frames in the form of dual angles.

Using the transformation matrix along the z -axis, the overall transformation matrix is given by:

$$[A]_0^n = [A]_0^1\ [A]_1^2\ [A]_2^3[A]_3^4\ [A]_4^5\ [A]_5^n, \qquad n \text{ is a number of joints} \ldots\ldots\ldots.. \ (3.9)$$

Determination of the homogeneous transformation matrix for all the joints

For $n = 1$ revolute joint, exhibit rotational motion

The homogeneous transformation matrix is given by

$$A_0^1 = \begin{bmatrix} cos(\theta_1) & -sin(\theta_1) & 0 & a_1 * cos(\theta_1) \\ sin(\theta_1) & cos(\theta_1) & 0 & a_1 * sin(\theta_1) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \ (3.10)$$

For $n = 2$ revolute joint, exhibit rotational motion

$$A_1^2 = \begin{bmatrix} \cos(\theta_2) & -\sin(\theta_2) & 0 & a_2 * \cos(\theta_2) \\ \sin(\theta_2) & \cos(\theta_2) & 0 & a_2 * \sin(\theta_2) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \ (3.11)$$

For $n = 3$ revolute joint, exhibit rotational motion

$$A_2^3 = \begin{bmatrix} \cos(\theta_3) & -\sin(\theta_3) & 0 & a_3 * \cos(\theta_3) \\ \sin(\theta_3) & \cos(\theta_3) & 0 & a_3 * \sin(\theta_3) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \ (3.12)$$

For $n = 4$ revolute joint, exhibit rotational motion

$$A_3^4 = \begin{bmatrix} cos(\theta_4) & -sin(\theta_4) & 0 & a_4 * cos(\theta_4) \\ sin(\theta_4) & cos(\theta_4) & 0 & a_4 * sin(\theta_4) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots.. \ (3.13)$$

For $n = 5$ revolute joint, exhibit rotational motion

$$A_4^5 = \begin{bmatrix} \cos(\theta_5) & -\sin(\theta_5) & 0 & a_5 * \cos(\theta_5) \\ \sin(\theta_5) & \cos(\theta_5) & 0 & a_5 * \sin(\theta_5) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots.. \ (3.14)$$

For $n = 6$ prismatic joint, exhibit translational motion

$$A_5^6 = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_6 \\ 0 & 0 & 0 & 1 \end{bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.... (3.15)$$

As a result, the overall homogeneous transformation matrix defining the last link in touch with the ground with respect to the robot body is given by:

$$[A]_0^n = \begin{bmatrix} n_x & o_x & s_x & p_x \\ n_y & o_y & s_y & p_y \\ n_z & o_z & s_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} A_0^n & P_0^n \\ 0 & 1 \end{bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.... (3.16)$$

The homogeneous transformation matrix is coded in MATLAB (Appendix A)

Where $A_0^n = \begin{bmatrix} n_x & o_x & s_x \\ n_y & o_y & s_y \\ n_z & o_z & s_z \end{bmatrix}$ and $P = \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix}$

Both the position vector and rotation matrix are functions of joint position θ, the p_x, p_y, p_z leg tip position can be directly obtained from the position vector P_0^n. The rotation matrix A_0^n represents the orientation of the tip leg point relative with respect to the body of the robot.

Formulation of the homogeneous transformation matrix for n number of joints

$$[A]_0^n = \begin{bmatrix} n_x & o_x & s_x & p_x \\ n_y & o_y & s_y & p_y \\ n_z & o_z & s_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.... (3.17)$$

3.6.2. Inverse kinematic analysis of a leg mechanism

In inverse kinematic modeling of mechanisms of the walking machine, we determine the value of a joint position in terms of the position and orientation of the tip leg point inverse kinematics method is applied. Thus the homogeneous transformation matrix defining the walking leg with respect to the body of the walking machine is calculated as:

$$[A]_0^n = \begin{bmatrix} A_0^n & P_0^n \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.... (3.18)$$

Assuming $[A]_0^n = U_0$, $$U_0 = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.... (3.19)$$

All elements of the matrix U_0 is known according to the homogeneous transformation matrix given (Appendix B). In fact, determining the joint position θ directly from the equation of the homogeneous transformation matrix is very difficult. So, by pre-multiplying successively the two equation by the matrices $({}^{j-1}A_j)^{-1}$, for $j = 1, \ldots, n$ set of a new equation can be obtained.

$$U_0 = [A]_0^n = [A]_0^1\,[A]_1^2\,[A]_2^3[A]_3^4\,[A]_4^5\,[A]_5^n \text{ ………….……... (3.20)}$$

In a similar way, a new set of equations are given as for $n = 6$

$$U_1 = ([A]_0^1)^{-1}U_0 = [A]_1^2\,[A]_2^3[A]_3^4\,[A]_4^5\,[A]_5^n$$

$$U_2 = ([A]_1^2)^{-1}U_1 = [A]_2^3[A]_3^4\,[A]_4^5\,[A]_5^n$$

$$U_3 = ([A]_2^3)^{-1}U_2 = [A]_2^3[A]_3^4\,[A]_4^5\,[A]_5^n$$

$$U_4 = ([A]_3^4)^{-1}U_3 = [A]_3^4\,[A]_4^5\,[A]_5^n$$

$$U_5 = ([A]_4^5)^{-1}U_4 = [A]_4^5\,[A]_5^n$$

$$U_6 = ([A]_5^6)^{-1}U_5 = [A]_5^n$$

Where: $U_j = ({}^{j-1}A_j)^{-1}U_{j-1}$, and these equations are named forward equations.

By equating the position matrix from the homogeneous transformation matrix, the position of the tip of the leg touching the ground can be determined. This analytical approach considers the initial assumption that

$$P_0^n = \begin{bmatrix} P_x^n \\ P_y^n \\ P_z^n \end{bmatrix} \quad \text{and} \quad [R]_0^n = \begin{bmatrix} A_0^n & P_0^n \\ 0 & 1 \end{bmatrix} \text{……………………. (3.21)}$$

$$\text{Where} \quad R_0^n = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \quad \text{and} \quad P_0^n = \begin{bmatrix} P_x^n \\ P_y^n \\ P_z^n \end{bmatrix}$$

$$\mathrm{R}_0^{\mathrm{n}} = \text{rotation matrix and}$$

$$\mathrm{P}_0^{\mathrm{n}} = \text{position matrix}$$

3.6.3. Instantaneous kinematic analysis of leg mechanism

To derive the velocity relationships between the operational coordinates and the joint coordinates the direct kinematic model which can express the linear velocity (v_x, v_y, v_z) and angular velocities $(\omega_x, \omega_y, \omega_z)$ of the tool frame in terms of the Jacobian matrix and the derivatives of the joint variables, is yielded by the differentiation with respect to time of the forward position kinematics equation.

$$\dot{X} = \begin{bmatrix} v_x \\ v_y \\ v_z \\ \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} = \begin{bmatrix} \frac{\partial f_1}{\partial \theta_1} & \cdots & \frac{\partial f_1}{\partial \theta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_m}{\partial \theta_1} & \cdots & \frac{\partial f_m}{\partial \theta_n} \end{bmatrix} \begin{pmatrix} \dot{\theta}_1 \\ \vdots \\ \vdots \\ \dot{\theta}_n \end{pmatrix} \text{.......................... (3.22)}$$

Where n is the number of joints and we can simply denote as

$$\dot{X} = J(\theta)\,\dot{\theta} \text{ .... (3.23)}$$

where $\dot{X} = \left[v_x, v_y, v_z, \omega_x, \omega_y, \omega_z\right]^T$ denotes the vector of operational velocity, which is the velocity of the origin of the tool frame combined with its angular velocity with respect to the fixed Cartesian coordinate frame and $\dot{\theta} = \left[\dot{\theta}_1\ \dot{\theta}_2\ \dot{\theta}_3\ \dot{\theta}_4\ \dot{\theta}_5\ \dot{d}_6\right]^T$ is the vector of angular velocity. The 6×6 matrix $J(\theta)$ is the Jacobian matrix of the tool frame with respect to the base frame. The Jacobian matrix $J(\theta)$ is composed of two parts: the upper half of the Jacobian $J_v(\theta)$ can calculate the linear velocity v, and the lower half of the Jacobian $J_\omega(\theta)$ is able to calculate the angular velocity ω. Thus, the Eq. 3.22 can be rewritten as:

$$\begin{bmatrix} \mathrm{v} \\ \omega \end{bmatrix} = \begin{bmatrix} J_v(\theta)_{(3x6)} \\ J_\omega(\theta)_{(3x6)} \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \\ \dot{\theta}_4 \\ \dot{\theta}_5 \\ \dot{d}_6 \end{bmatrix} \text{.................................... (3.24)}$$

The elements of the Jacobian matrix can be obtained by differentiating the direct geometric model $X = J(\theta)$ with respect to joint position θ as:

$$J_{ij} = \frac{\partial f_i\,(\theta)}{\partial \theta_j} \text{ .... (3.25)}$$

To compute the Jacobian matrix, using the DH frames, i.e.

$$J_v(\theta) = \begin{cases} \mathrm{Z}_0^{\mathrm{i}-1}, & \text{for prismatic joint} \\ \mathrm{Z}_0^{\mathrm{i}-1} * [\mathrm{O}_0^{\mathrm{i}} - \mathrm{O}_0^{\mathrm{i}-1}] & \text{for revolute joint} \end{cases}$$

$$J_\omega(\theta) = \begin{cases} 0, & \text{for prismatic joint} \\ \mathrm{Z}_0^{\mathrm{i}-1} & \text{for revolute joint} \end{cases}$$

The Jacobian matrix formulated in the form of

$$\begin{matrix} J_v(\theta)_{(3x6)} \\ J_\omega(\theta)_{(3x6)} \end{matrix} = ? \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.26)$$

$$= \begin{bmatrix} R_0^1 \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} X(P_0^6 - P_0^1) & R_0^2 \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} X(P_0^6 - P_0^2) & R_0^3 \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} X(P_0^6 - P_0^3) & R_0^4 \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} X(P_0^6 - P_0^4) & R_0^5 \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} X(P_0^6 - P_0^5) & R_0^6 \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \\ R_0^1 \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} & R_0^2 \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} & R_0^3 \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} & R_0^4 \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} & R_0^5 \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} & R_0^6 \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \end{bmatrix}$$

From the homogeneous transformation matrix, the rotation matrix and position matrix can be extracted as:

$$\text{For } n = 1, \quad R_0^1 = \begin{bmatrix} \cos(\theta_1) & -\sin(\theta_1) & 0 \\ \sin(\theta_1) & \cos(\theta_1) & 0 \\ 0 & 0 & 1 \end{bmatrix} \text{ and } P_0^1 = \begin{bmatrix} a_1 * \cos(\theta_1) \\ a_1 * \sin(\theta_1) \\ 1 \end{bmatrix} \ldots\ldots \quad (3.27)$$

$$\text{For } n = 2, \quad R_1^2 = \begin{bmatrix} \cos(\theta_2) & -\sin(\theta_2) & 0 \\ \sin(\theta_2) & \cos(\theta_2) & 0 \\ 0 & 0 & 1 \end{bmatrix} \text{ and } P_1^2 = \begin{bmatrix} a_2 * \cos(\theta_2) \\ a_2 * \sin(\theta_2) \\ 1 \end{bmatrix} \ldots\ldots \quad (3.28)$$

$$\text{For } n = 3, \quad R_2^3 = \begin{bmatrix} \cos(\theta_3) & -\sin(\theta_3) & 0 \\ \sin(\theta_3) & \cos(\theta_3) & 0 \\ 0 & 0 & 1 \end{bmatrix} \text{ and } P_2^3 = \begin{bmatrix} a_3 * \cos(\theta_3) \\ a_3 * \sin(\theta_3) \\ 1 \end{bmatrix} \ldots\ldots \quad (3.29)$$

$$\text{For } n = 4, \quad R_3^4 = \begin{bmatrix} \cos(\theta_4) & -\sin(\theta_4) & 0 \\ \sin(\theta_4) & \cos(\theta_4) & 0 \\ 0 & 0 & 1 \end{bmatrix} \text{ and } P_3^4 = \begin{bmatrix} a_4 * \cos(\theta_4) \\ a_4 * \sin(\theta_4) \\ 1 \end{bmatrix} \ldots\ldots \quad (3.30)$$

$$\text{For } n = 5, \quad R_4^5 = \begin{bmatrix} \cos(\theta_5) & -\sin(\theta_5) & 0 \\ \sin(\theta_5) & \cos(\theta_5) & 0 \\ 0 & 0 & 1 \end{bmatrix} \text{ and } P_4^5 = \begin{bmatrix} a_5 * \cos(\theta_5) \\ a_5 * \sin(\theta_5) \\ 1 \end{bmatrix} \ldots\ldots \quad (3.31)$$

$$\text{For } n = 6, \quad R_5^6 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \text{and} \quad P_5^6 = \begin{bmatrix} 0 \\ 0 \\ d_6 \end{bmatrix} \ldots\ldots\ldots\ldots \quad (3.32)$$

NB: joint six is prismatic and the others are revolute joints.

The acceleration can be obtained by differentiating equations

$$\frac{d}{dt}(\dot{X}) = \frac{d}{dt}\left(J(\theta)\dot{\theta}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.33)$$

$$\ddot{X} = J(\theta)\ddot{\theta} + \left(\frac{d}{dt}J(\theta)\right)\dot{\theta} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.34)$$

3.7. Dynamic analysis of a walking machine leg mechanism

In the study of the dynamics of the leg mechanisms, we consider the forces and/or torques required to cause motion of the mechanisms. The kinematics of the leg mechanisms is derived in the previous section of this chapter using DH convention approach without consideration of the forces and moments producing the motion. Under this section, the dynamic analysis is carried out to formulate the parametric equation of motion which describe the relationship between force and motion.

The dynamics of mechanisms can be obtained in various ways namely using a Newton-Euler dynamic formulation, a Lagrangian formulation, Kane's Method, and others. The Newton-Euler method is based on Newton's second law of motion with its rotational analog called Euler's equation. It describes how forces and moments are related to acceleration. In the iterative Newton-Euler algorithm, the position. velocity and acceleration of the joints are known. With these as input and assuming that the mass properties of the manipulator and any externally acting forces are known, the joint torques required to cause this motion can be calculated.

Dynamics of the walking machine can be divided into two basic categories: forward and inverse dynamics. Forward dynamics deals with finding the response of a given rigid body influenced by force and torques applied on it which carried out in a computer simulation by giving link length and rotating angle to determine the position [50]. On the other hand, the opposite procedure to find the force and torques by which motion is created in the system through inverse dynamic analysis. The link length and position is given to determine the angle of rotation of the links. This method widely used in the control system of a motion [53]. In general, for the analysis and modeling of dynamic equations of complex mechanism in robot design subjected to holonomic constraints Newton-Euler and Euler-Lagrange formulations are a common one. The Lagrangian equation formulation involves the kinetic and potential energy of the system.

For the walking machine, kinematic motion analysis is of the leg mechanism and the consideration of the equation of motion is crucial. To perform forward dynamic analysis some assumptions needs to be made. Then furthermore the generic dynamic equation can be formulated as an equation of motion for the leg mechanism.

The following assumptions are considered in the dynamic analysis:

1. The links are rigid
2. The friction in the joints are ignored
3. The leg mechanism is assumed to be at a constant velocity with no inclination terrain
4. When the leg comes into contact with the ground it is assumed to have zero impact

3.7.1. Euler-Lagrange equation of the leg mechanism

Let $\theta_1, \ldots, \theta_n$ be generalized coordinates that completely locate a dynamic system. Let K and V the total kinetic and potential energy stored in a dynamic system respectively. The Lagrange method is based on describing the scalar energy functions of the system, including the kinetic energy $K(\theta, \dot{\theta})$ and the potential energy $V(\theta)$. The two energy functions can be expressed in terms of the joint positions θ and the joint velocities $\dot{\theta}$.

Lagrange equation can be defined as:

$$\mathcal{L}(\theta_i, \dot{\theta}_i) = K - V \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.35)}$$

Since the kinetic and potential energies are as a function of θ_i and $\dot{\theta}_i$, $(i = 1, 2, 3, \ldots. n)$, using the Lagrangian equation of motion the dynamic system is given by

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{\theta}_i} - \frac{\partial L}{\partial \theta_i} = \tau_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.36)}$$

Where, τ_i= externally applied generalized force $L = K - V,$ and $V = V(\theta)$ is the potential energy, $i = 1, \ldots, n$ $K = K(\theta)$ is the kinetic energy.

3.7.2. Kinetic and potential energy expression

To use the Euler Lagrange equations, the kinetic and potential energy has to be expressed for the leg mechanisms. After the derivation of kinetic and potential energy for each link, the Lagrangian of the leg mechanisms is the summation of the individual Lagrangian. The overall kinetic energy is given by Eq. 3.37.

$$K = K_t + K_r = \frac{1}{2} m \dot{v}^T \dot{v} + \frac{1}{2} I \dot{\omega}^T \dot{\omega} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.37)}$$

$$K_i = \frac{1}{2} v^T M v \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.38)}$$

For n linkages, the kinetic energy expression can be expressed as

$$K = \sum_{i=1}^{n} K_i = \frac{1}{2} \sum_{i=1}^{n} (v^T M\, v)_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.39)}$$

This becomes $K = \sum_{i=1}^{n} \frac{1}{2} J(\theta)\dot{\theta}^T M\, J(\theta)\dot{\theta} = \frac{1}{2}\dot{\theta}^T M(\theta)\dot{\theta}$……………..……………. (3.40)

Where: $M(\theta) = \sum_{i=1}^{n} J(\theta)^T M\, J(\theta)$

where M is a generalized inertial matrix of mass and moment of inertia, symmetric and positive definite matrix

Kinematic properties of the rigid body are fully described by its mass, principal axis and moments of inertia. Inertia Tensor I_J can be made diagonal as

$$I_J = RIR^T = \begin{bmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{yx} & I_{yy} & I_{yz} \\ I_{zx} & I_{zy} & I_{zz} \end{bmatrix} \text{ and } M = \begin{bmatrix} m_{xx} & m_{xy} & m_{xz} \\ m_{yx} & m_{yy} & m_{yz} \\ m_{zx} & m_{zy} & m_{zz} \end{bmatrix} \text{………………. (3.41)}$$

Where R is a rotational matrix of the homogenous transformation matrix

Considering the coordinate axis and principal axis aligned together, the inertial tensor would be only diagonal:

$$M(\theta) = \begin{bmatrix} m_{xx} & 0 & 0 & 0 & 0 & 0 \\ 0 & m_{yy} & 0 & 0 & 0 & 0 \\ 0 & 0 & m_{zz} & 0 & 0 & 0 \\ 0 & 0 & 0 & I_{xx} & 0 & 0 \\ 0 & 0 & 0 & 0 & I_{yy} & 0 \\ 0 & 0 & 0 & 0 & 0 & I_{zz} \end{bmatrix} \text{……………….... (3.42)}$$

By summing the translational and rotational kinetic energy of the link,

$$K = \sum_{i=1}^{n} \left(\frac{1}{2} m_i \dot{v}_i{}^T \dot{v}_i + \frac{1}{2} I_i \dot{\omega}_i{}^T \dot{\omega}_i\right) \text{ …………………….... (3.43)}$$

Where $\dot{x}$ denotes the velocity of the center of mass of the rigid link, $\dot{\omega}$ is the angular velocity vector and I is the inertia matrix.

In the case of the rigid body, the source of potential energy is gravity due to the mass of the links. In most cases, the potential energy defined along the unit vector acting through the center of mass of each link. The potential energy is expressed as:

$$V(\theta) = \sum_{i=1}^{n} m_i g^T h_i(\theta) \text{………………………….... (3.44)}$$

In Eq. 3.43 and 3.44 we have computed an expression for kinetic and potential energy given in respectively $\mathcal{L}(\theta_\mathrm{i}, \dot{\theta}_\mathrm{i}) = \mathrm{K} - \mathrm{V}$ ……..……………..……... (3.45)

$$\mathcal{L}(\theta_i,\dot{\theta}_i)=\frac{1}{2}\dot{\theta}^T M(\theta)\dot{\theta}-V(\theta)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.46)}$$

Using the Euler Lagrange equations that describe the dynamics for each of the generalized coordinates are then, $$\frac{d}{dt}\frac{\partial L}{\partial\dot{\theta}_i}-\frac{\partial L}{\partial\theta_i}=\tau_i\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.47)}$$

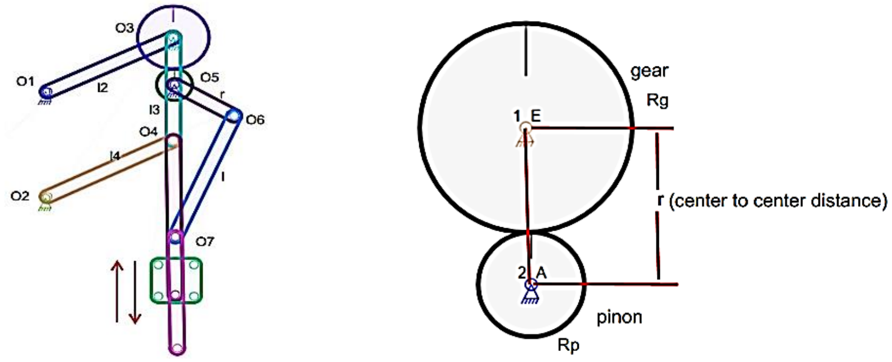
Where, τ_i= externally applied generalized force, $L = K - V,$ and $V = V(\theta)$ is the potential energy, $i = 1,\ldots,n,\ K = K(\theta)$ is the kinetic energy. Recalling the equations and inserting them into the Lagrange equation given in Eq. 3.47 and taking its derivative required by considering that Potential energy does not depend on $\dot{\theta}$ yields [54]:

$$M(\theta)\ddot{\theta}+C(\theta,\dot{\theta})\dot{\theta}+G(\theta)=\tau_i\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.48)}$$

Where M and C summarizes inertial properties (inertial matrix and Coriolis effect), and G represents gravity terms.

3.8. Kinematics of gear assembly

The spur gear train assembly used to transfer motion between links is selected. The gear is assembled on the four-bar of the input link and coupler link connecting pin joint. It has the rotational speed of the input link of the change point four-bar, to provide motion for the inline slider-crank mechanism input link pinon is assembled on the pin joint of the fixed frame and input link of the inline slider crank mechanism. In the dimensional analysis, the distance of O_3 to O_5 is equal to the distance of O_5 to O_6 (input link of slider-crank). Center to center distance (C_d) of the gear assembly is considered between point O_3 and O_5. In Fig. 20 the r is considered as C_d.



(a) (b)

Fig. 20. Schematic drawing of leg mechanism (a) Leg model (b) Gear assembly

The module m of the gear which indicates the size of the gear is the ratio of reference diameter d of the gear divided by the number of teeth z.

The mutual relationship between the module and the reference diameter is given as:

$$m = d/z \tag{3.49}$$

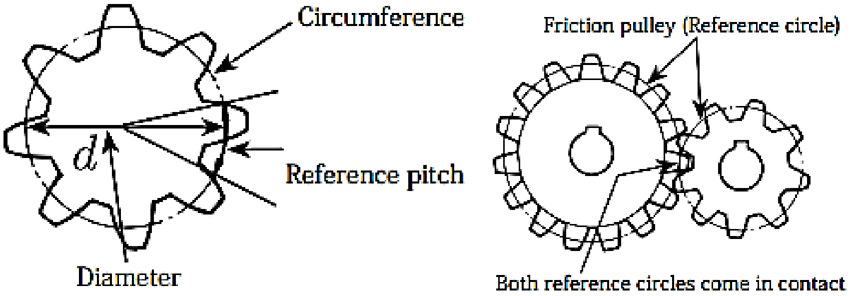


Fig. 21. Spur gear geometry

Other key relationships in design of gear transmission are:

Reference diameter	$d = mz$
Number of teeth	$z = d/m$
Reference pitch	$p = \pi m$
Center distance	$C_d = (R_g + R_p)/2$
Gear ratio	$R = R_g/R_p$

3.9. Geometric modeling of a leg mechanism in CAD

Geometric modeling involves assembly drawing and preparation of the design. After some analysis is carried throughout the drawings, the final assembly drawing made from part drawings. Part drawing contains all the information such as size, shape, dimension, notes, material specifications and other descriptions. Geometric modeling of the three dimensional CAD is modeled using SolidWorks V2018. The procedure followed in geometric modeling and motion analysis is shown as a general in Fig. 22.

SolidWorks is a Parasolid-based solid modeler and utilizes a parametric feature-based approach to create models and assemblies. It is capable of carrying out numerous tasks ranging from simple components physical modeling up to simulation, motion study and sustainability analysis of a more complex assembly.

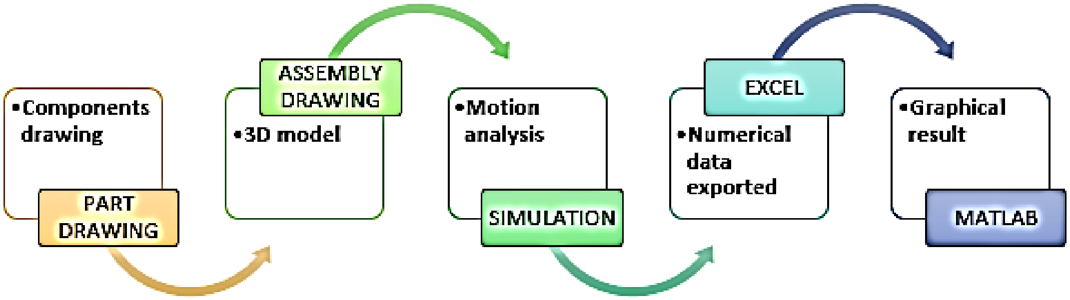


Fig. 22. Geometric modeling procedure in CAD

However, in this thesis work the use of SolidWorks is limited, for creating a 3D digital model of the walking machine components for part drawing, creating assembly drawing and finally motion analysis. Solid modeling techniques can be used in obtaining all mass properties and center of mass, assuming that the material and geometry of body or link are precisely known.

In the design of a walking machine leg mechanism, the components are combinations of linkages and gears. Once the solid model is positioned with respect to the reference frame, the properties of mass with respect to the user coordinate system can be determined by considering the density of the material (Appendix D). The components are assembled together in an assembly drawing tool of SolidWorks V2018. The detail drawing including the overall dimensions, quantities and other specification of the walking machine given (Appendix E). The constructed geometric model (Fig. 23) is further used for simulation in motion analysis.

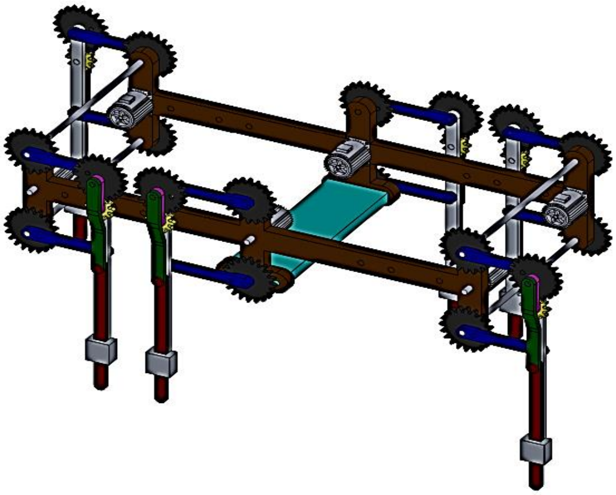


Fig. 23. Walking machine assembly

The leg mechanism for the walking machine enables to move on rough terrain without controlling system. The walking machine leg mechanism is synthesized in a manner that it can overcome to walk on rough terrain. The leg mechanism developed from the integration of linkages for a walking machine can be advantageous to decrease the number of motors used for actuating each joint of the leg mechanism of walking machines discussed in the literature review.

From literature, at least three motors are required for a single leg to provide a required motion. In this design single motor is needed to generate a motion path that enables to walk the leg mechanism on rough terrain. The integration of the linkages is settled in a manner that it can transfer motion between links. This reduction of the number of motors reduces the weight of the machine and resulted in less power consumption to derive the leg mechanism. The leg mechanism components are not complex to manufacture. This decreases the high cost required for manufacturing the leg components. Major point required to be focused is on the precision of the measurements of the links. The stability problem encountered and its complexity to design for walking machine can be also simplified in the design of the arrangement of the movement of legs. To perform the stability of the walking machine, the three legs are touching the ground, so that it is stable while it is in a motion.

In this thesis, the kinematic synthesis and analysis of a leg mechanism for a walking machine from combination of linkages are conducted. Further work should be aimed to carry out the detailed analysis of the walking machine leg mechanism for rough terrain developed in this thesis work.

Chapter Four

Result and Discussion

This chapter deals with discussion of the results obtained to determine effects of its kinematic behavior in motion analysis tool of the leg mechanism responses. The CAD geometry of the walking machine is analyzed in SolidWorks kinematic motion analysis. The data are exported to excel and interpreted with MATLAB. The results obtained from the kinematic motion analysis explained briefly.

4.1. Kinematic motion analysis in SolidWorks

A kinematic motion analysis is the imitation of the operation of a real-world process or system over time. It is a tool to evaluate the kinematic response of a system, existing or proposed, under different configurations of interest and over long periods of real time. The behavior of a system that evolves over time is studied by developing a kinematic model. The motion analysis consists of building a computer model that describes the behavior of a system with this model to reach conclusions that support decisions. It uses the mathematical model to determine the response of the system in different situations. Types of motion analysis in SolidWorks are classified into three basic categories, namely: Animation, basic motion and motion analysis (Fig. 24).

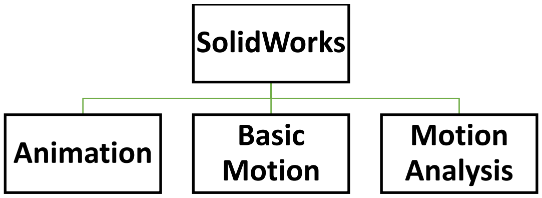


Fig. 24. Types of Motion analysis in SolidWorks

Motion analysis is the most sophisticated motion analysis tool reflecting all required analysis features such as inertial properties, external forces, contacts, mate friction etc. [55]. In the simulation procedure of motion analysis:

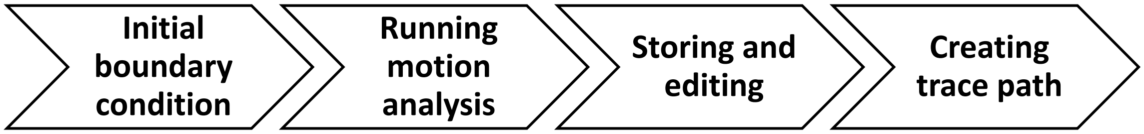


Fig. 25. Kinematic analysis procedure

The kinematic analysis is performed in SolidWorks motion analysis to determine the displacement, velocity, acceleration and torque responses. MATLAB 2016a is used to analyze the data obtained by importing and performing the leg responses in plots. The motion analysis is performed based on constant input function and fluctuating input function as flat and rough terrain respectively.

4.2. Motion analysis of walking machine leg mechanism

SolidWorks motion analysis is used to determine the response of the walking machine leg in terms of displacement, velocity and acceleration based on the input provided. Motion path generated in Fig. 26 shows the typical single leg motion path of the walking machine. The forward and backward motion and the up and down motion of the leg helps to move over a rough terrain. Based on this the height of the obstacle or the amplitude of the rough terrain over which the walking machine come over can be identified. So that in this analysis based on the assumed boundary conditions, it can climb over a rough terrain having up to 150 mm height and horizontal distance of 130 mm distance (Fig. 26).

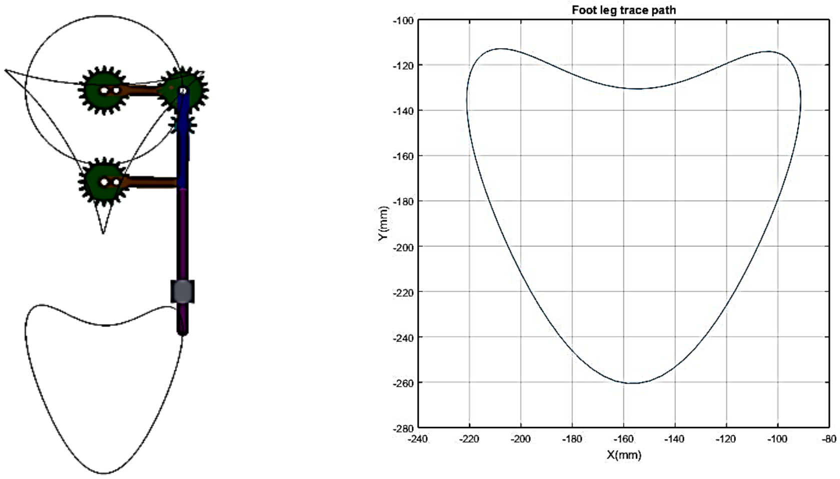
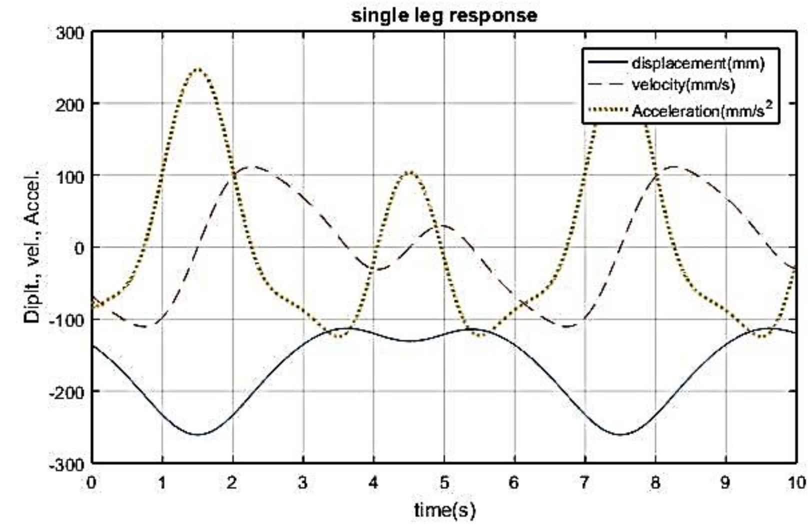
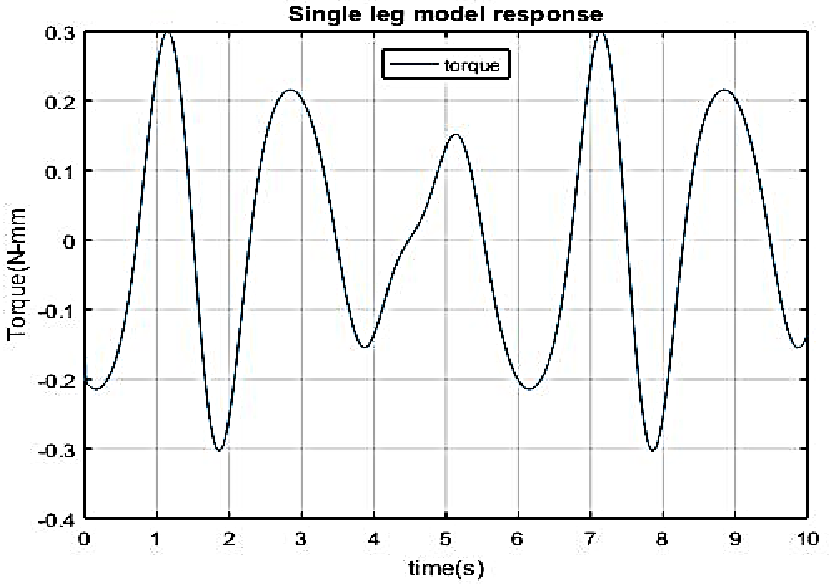


Fig. 26. Motion path generation of leg mechanism

From Fig. 27 (a) the response of the single leg shows the smooth profile of its kinematic behavior with no external input function. As the displacement increasing or decreasing the velocity and acceleration are increasing or decreasing having the direct relationship. Theoretically, it is proved that the relationships between displacement, velocity and acceleration is directly proportional and time-dependent.



(a) Displacement, velocity and acceleration response

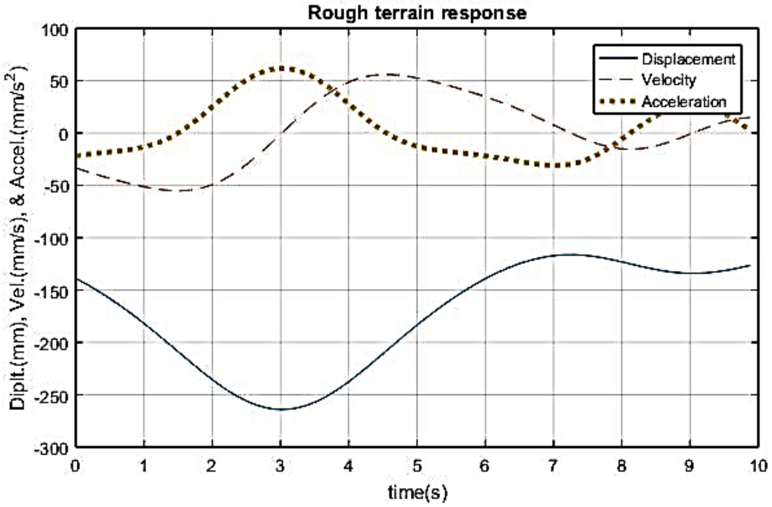


(b) Torque profile

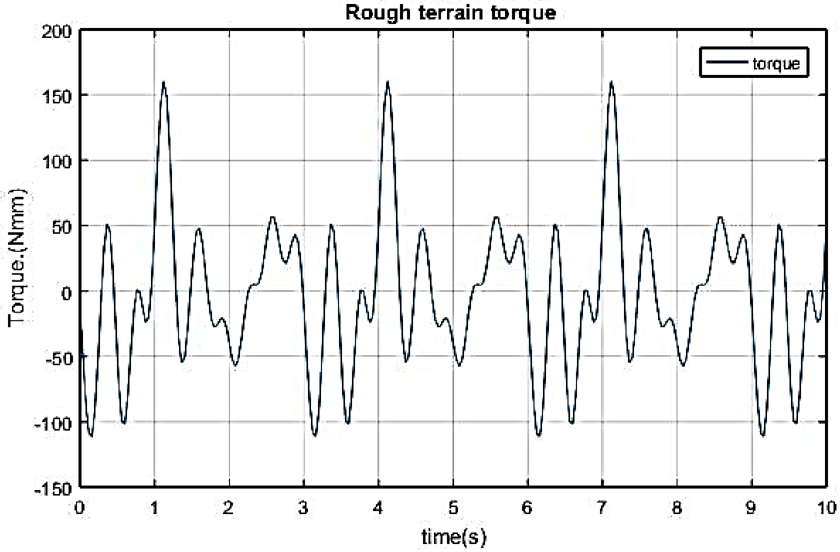
Fig. 27. Leg mechanism response of walking machine

From Fig. 27 (b) the torque profile generated shows that the graph is smooth and repeats the same path over motion patterns. The degree of smoothness can determine the behavior of the motor that will be used in the system. As the smoothness of the torque graph decreasing the motor behaves unwanted motion fluctuation that damages the motor. So generating the torque profile graph is basically used to determine the specification of the motor to be used. The maximum torque recorded here is 0.3 N-mm and minimum of 0.17 N-mm within the initial boundary considered in this motion analysis. The peak value obtained in the motion analysis describes the point at which high torque is required. Based on the mechanism when the leg mechanism starts to move in the up direction while rotating it needs a large amount of torque.

In the motion analysis, the derived equation of motion parameters is considered to show the responses. The gravitational energy, the mass matrix from the property of material assigned to it in modeling, the external force as input from the motor and the properties of rough terrain as an external input which affects the motion of the walking machine legs.



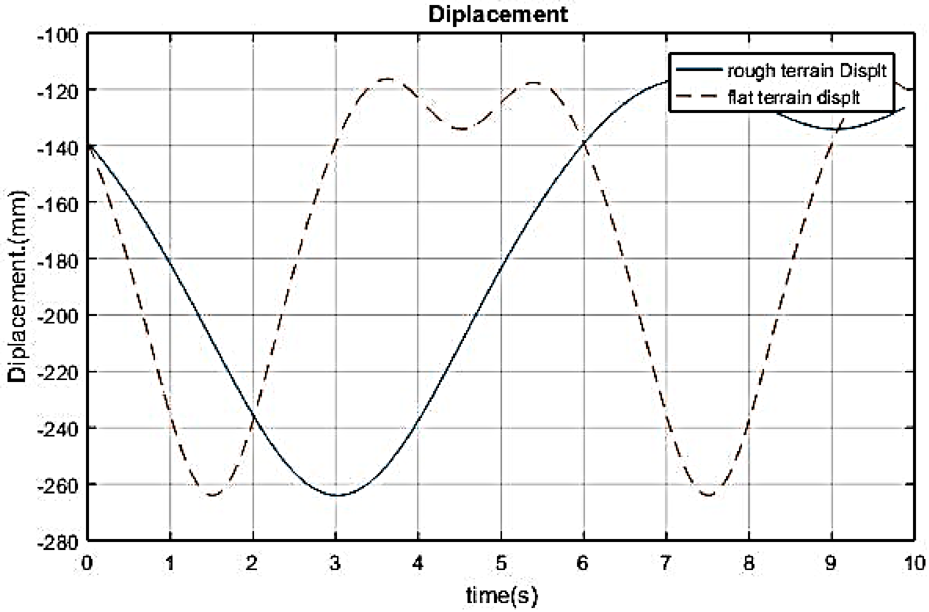
(a) Displacement, velocity and acceleration response



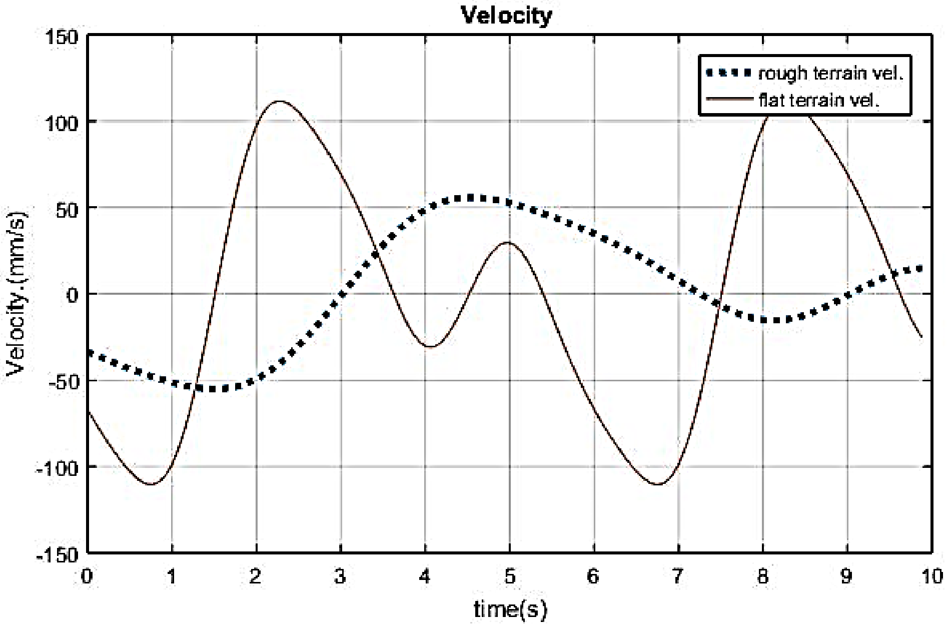
(b) Torque response of fluctuating input function

Fig. 28. Leg mechanism response of walking machine

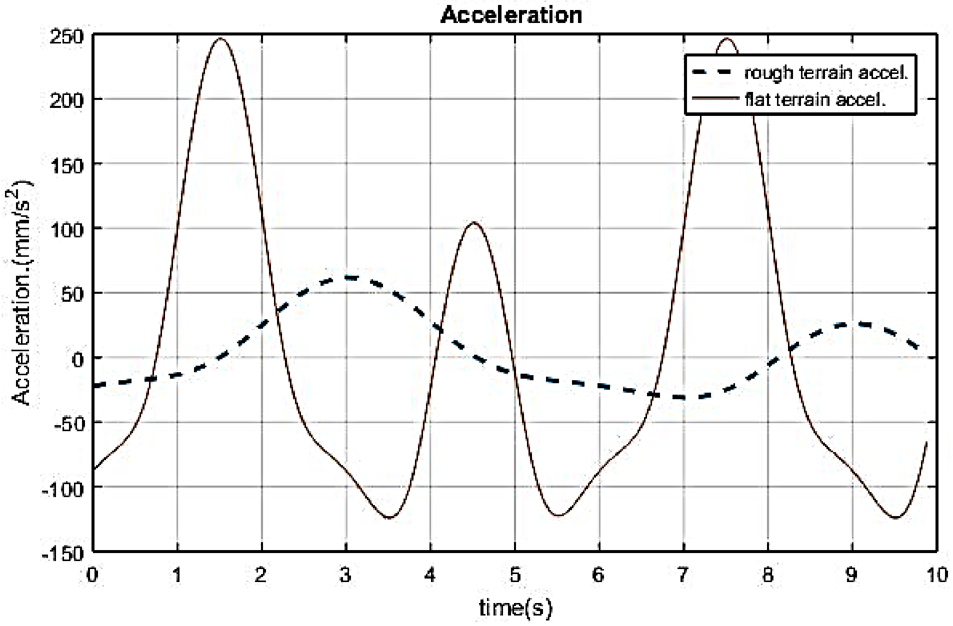
From Fig. 28 (a) and (b) the motion analysis result considering fluctuating input function from the ground by means of force shows that as the amplitude of the input force is fluctuating, the torque required to drive the mechanism against the force varies. This can be theoretically validated because torque and force have a direct relationship.



(a) Displacement comparison



(b) Velocity comparison



(c) Acceleration response

Fig. 29. Comparison between constant and fluctuating input function

In Fig. 29, the comparison between constant input function and fluctuating input function has been shown in terms of its displacement, velocity, acceleration and torque responses. Generally, with different terrain parameters, the leg mechanism behaves different responses. This is shown clearly in the motion analysis result from a constant input function and fluctuating input function, Fig. 27 and Fig. 28 respectively, on rough terrain the displacement, velocity and acceleration obtained take time when compared to the flat surface. This shows that the performance of the walking machine can be affected due to the terrain topology. As the amplitude of the rough terrain variation increases the performance of the walking machine can be affected much more.

4.3. Kinematic response of a walking machine leg mechanism

The motion gait of the walking machine takes place in two parts consecutively. The order of leg movement depends on touching the ground at the same time.

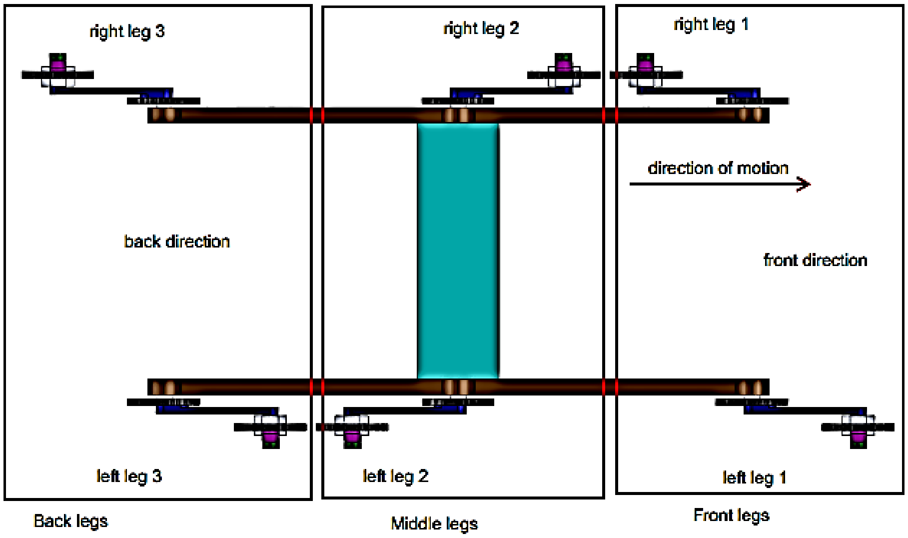


Fig. 30. Walking machine top view leg designation order

Based on the leg designation order given in Fig. 30 the three legs of left leg 1, right leg 2 and left leg 3 touch the ground at the same time while the right leg 1, left leg 2 and right leg 3 is suspended up and moving forward direction to perform the next touching with the ground.

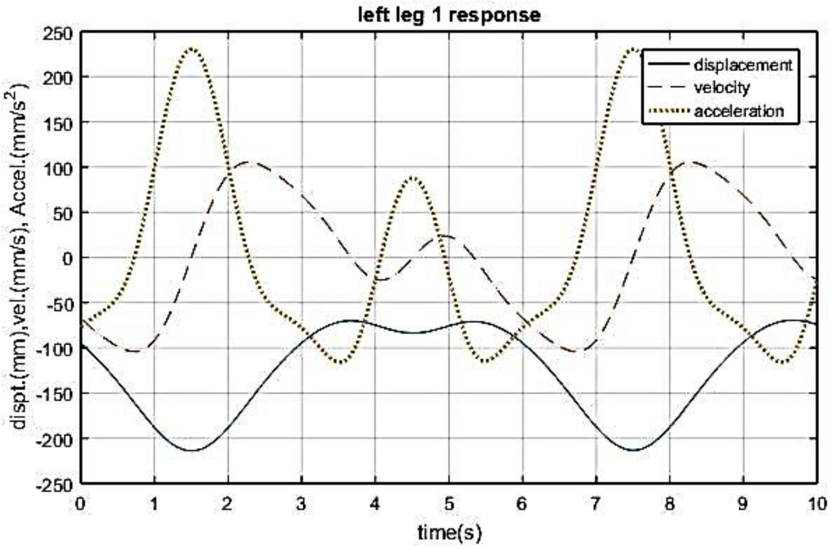
(a) (b)

Fig. 31. Motion path for CAD model: (a) First three legs (b) Second three legs

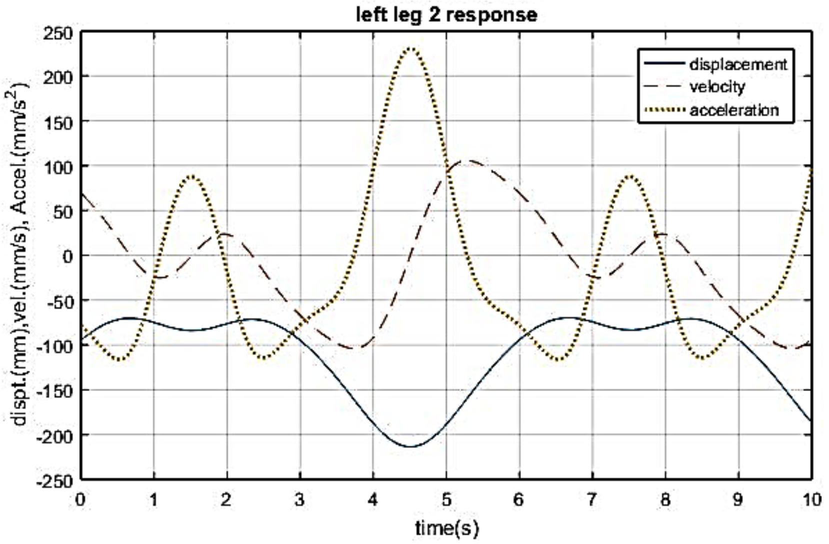
In Fig. 31 (a) and (b) the motion of the walking machine on a straight line is shown. Clearly, the leg arrangements to touch the ground in a pre-planned requirement of the walking machine design is obtained. So that at the same time three legs of the walking machine from one side, two legs and from the other side one leg, Fig. 31 (a) in a longitudinal symmetry touches the ground and the other three legs, Fig. 31 (b) repeats the same procedure to continue the motion. This arrangement helps to keep the walking machine balanced while in a motion statically. The legs are forming triangular shape while touching the ground, as three-point is required for any rigid body on a plane to be stable, the stability of the robot is controlled by its arrangements of the legs of the machine touching the ground at the same time.

4.3.1. kinematic response of each leg mechanisms

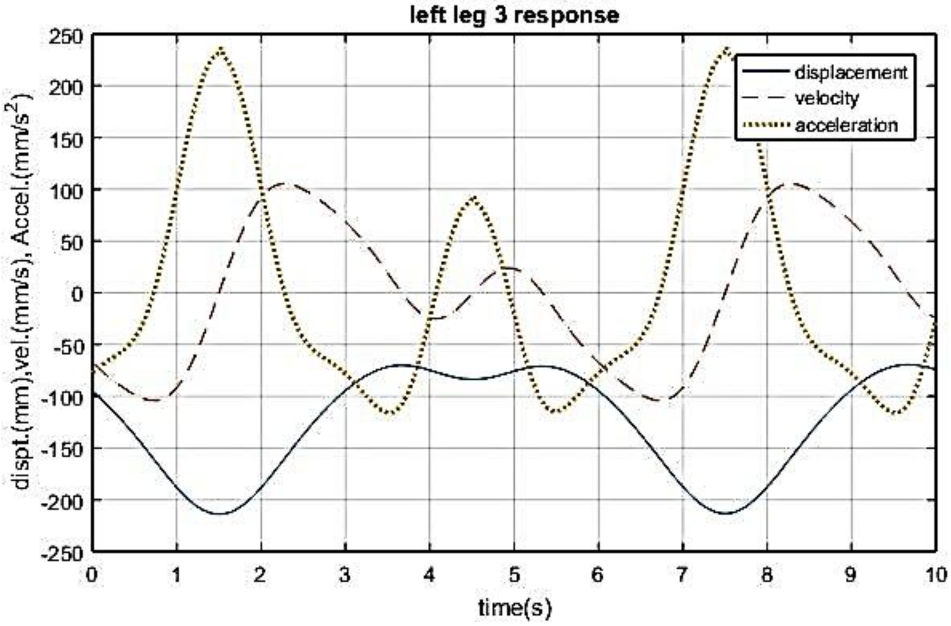
Responses of a moving object can be described and quantified through space over a time. Displacement, velocity and acceleration describe the motion of moving objects. The kinematic simulation of the waking machine for the displacement, velocity and acceleration responses are determined to show the responses of all legs for comparison. The plots are MATLAB 2016a output based on the data imported from SolidWorks motion analysis.



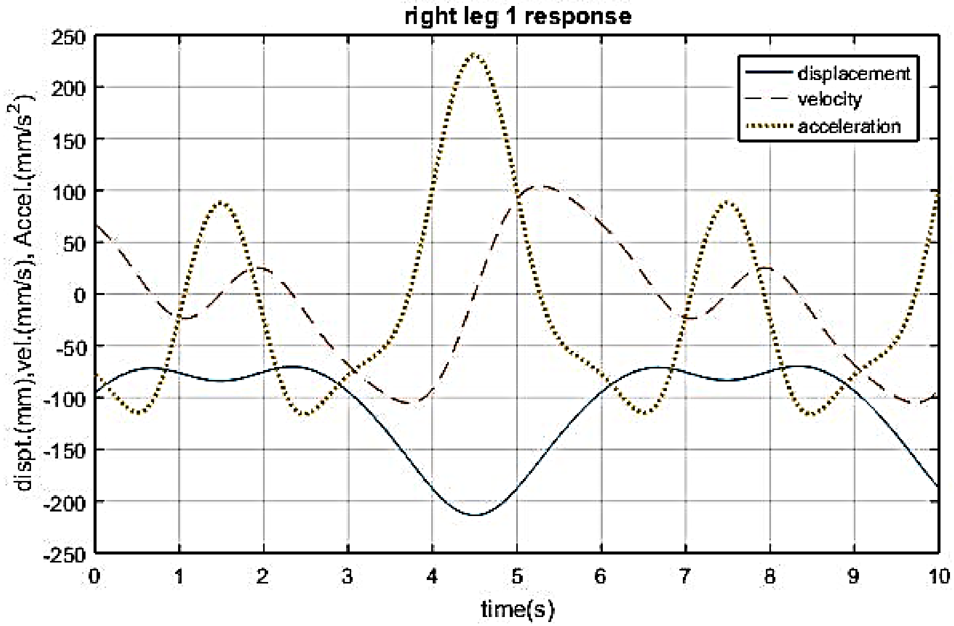
(a) Left leg 1 response



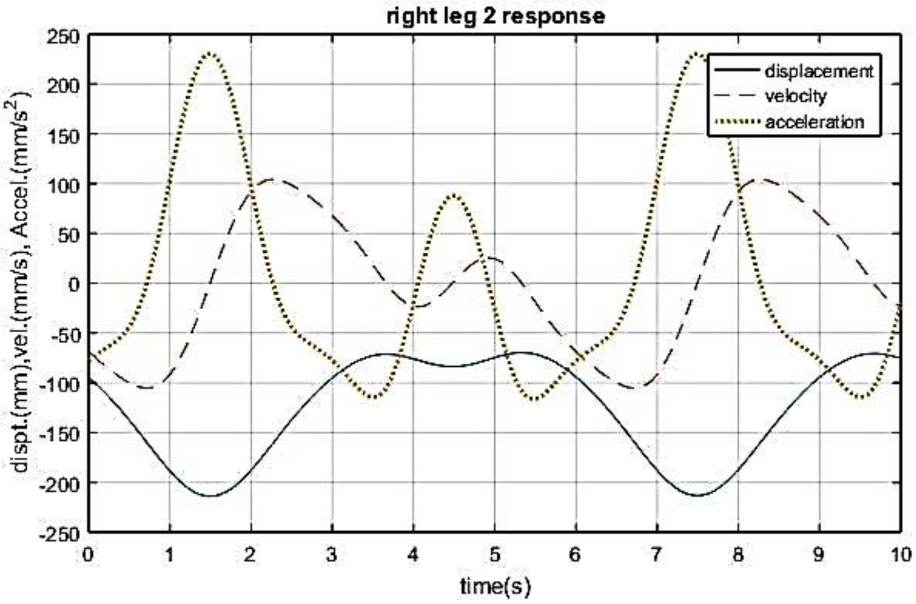
(b) Left leg 2 response



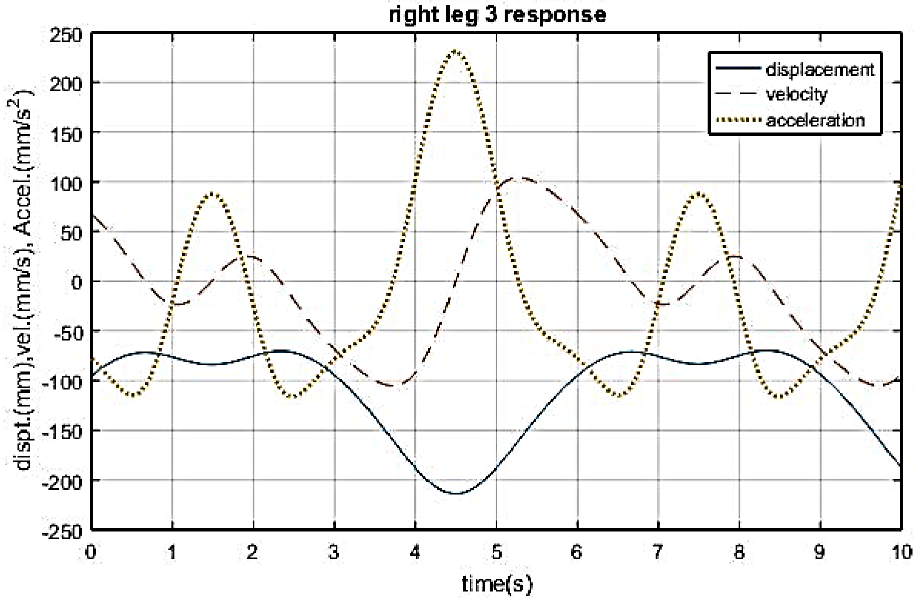
(c) Left leg 3 response



(d) Right leg 1 response



(e) Right leg 2 response



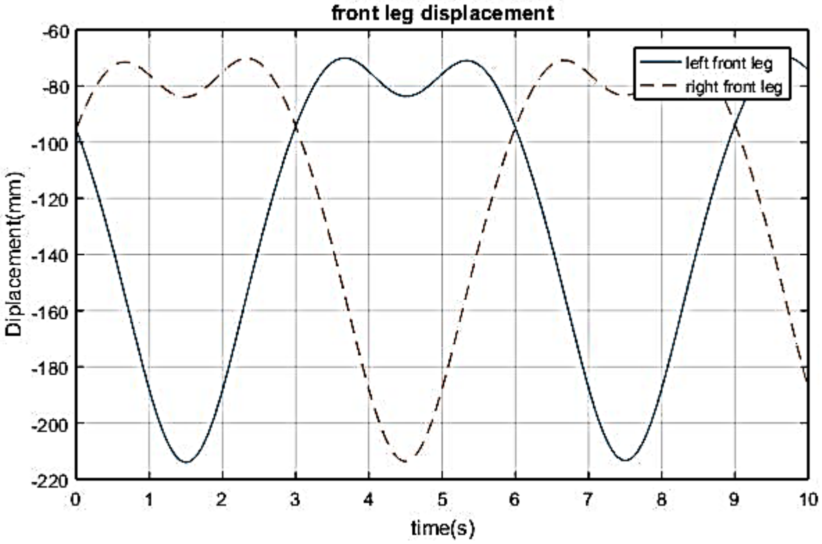
(f) Right leg 3 response

Fig. 32. Displacement, velocity and acceleration responses of individual legs

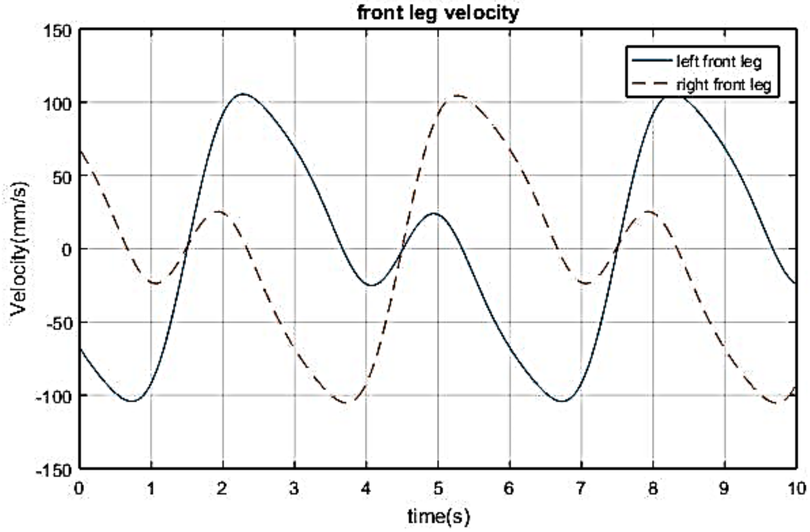
From Fig. 32 the response of each leg is clearly shown in terms of their displacement, velocity and acceleration for the leg of the walking machine. In Chapter 3.6. the homogeneous transformation based on the Denavit-Hartenberg approach obtained and further extended to compute the position of the leg which is in contact with the ground. From Fig. 32 (a), (c) and (e) the responses of the first three legs touching the ground at the same time, we visualize the same response. And for the three legs also Fig. 32 (b), (d) and (f) the same output is observed. The lagging of the legs between Fig. 32 (a), (c), (e) and Fig. 32 (b), (d), (f), can be also observed and similar output is obtained. Generally, this verifies the motion path generated in Fig. 31 (a) and (b) on straight-line.

4.3.2. Comparison of the motion of parallel legs response

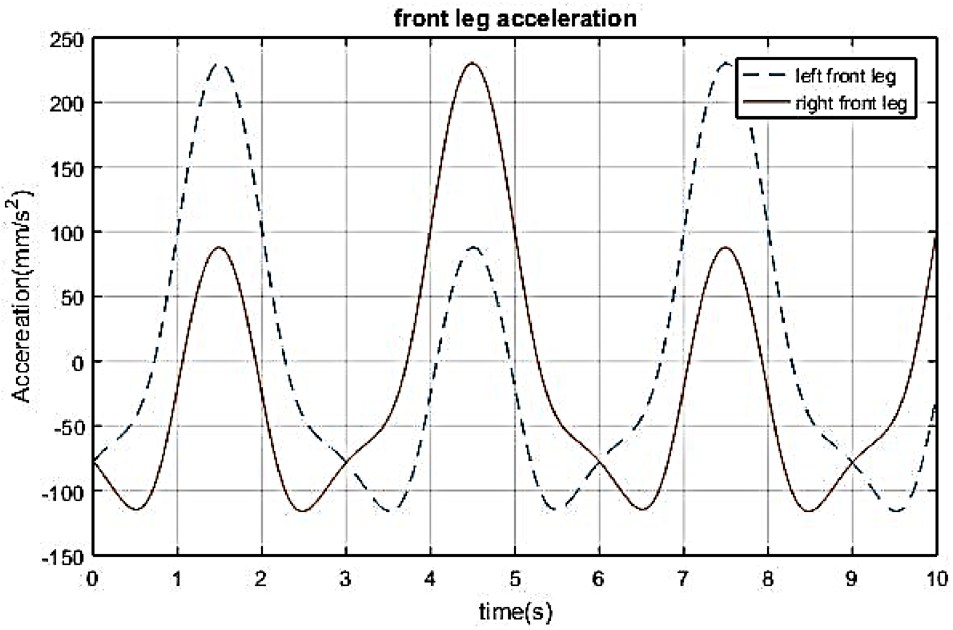
Based on the sequence of the motion of each leg the comparison made considering their displacement, velocity and acceleration. The first two front legs responses in Fig. 33 (a), (b) and (c) it can be observed that based on the motion since all legs are having the same responses, parallels legs are having opposite motion over the same time.



(a) Displacement response

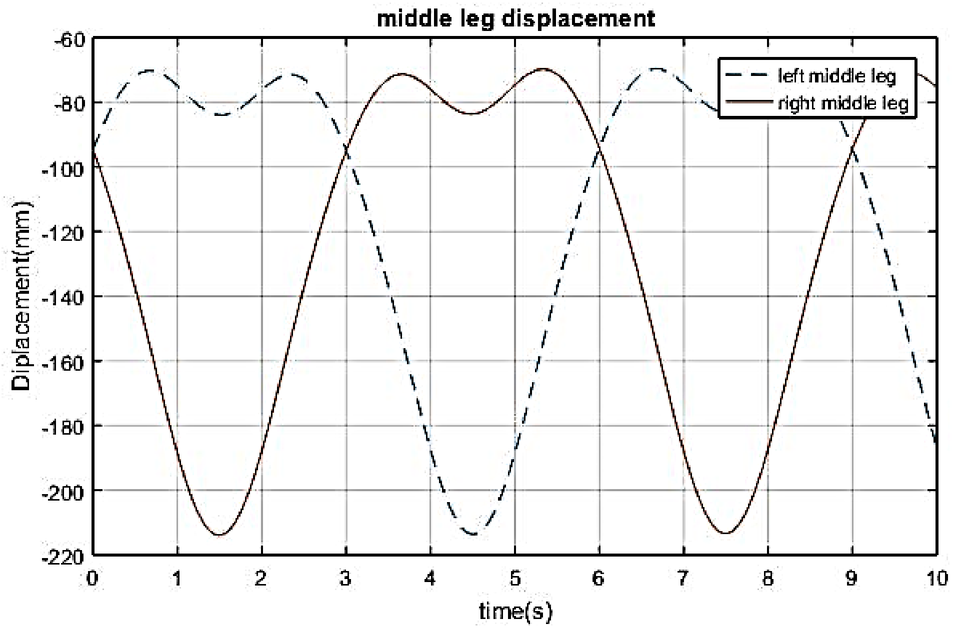


(b) Velocity response

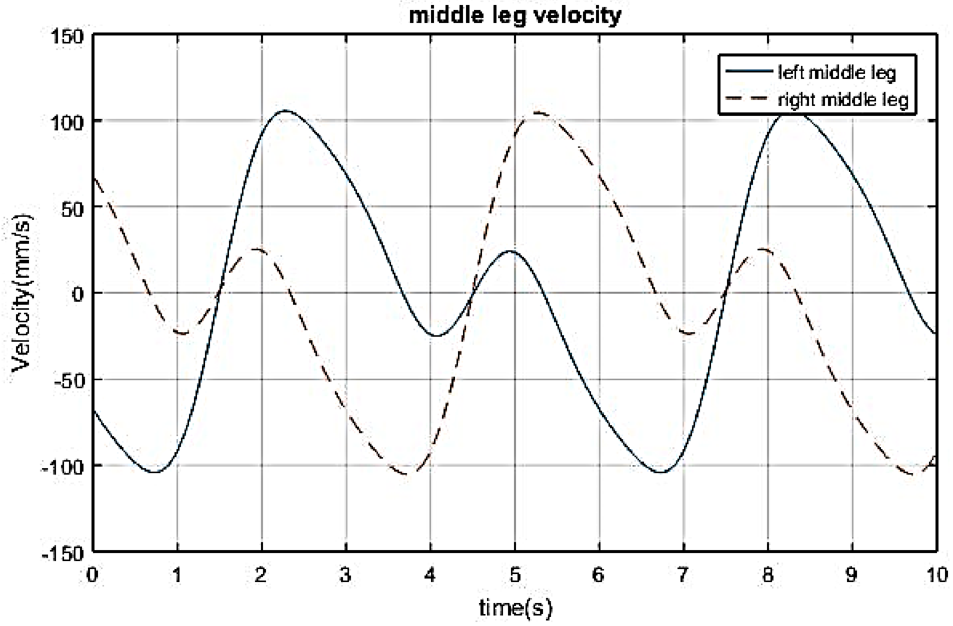


(c) Acceleration response

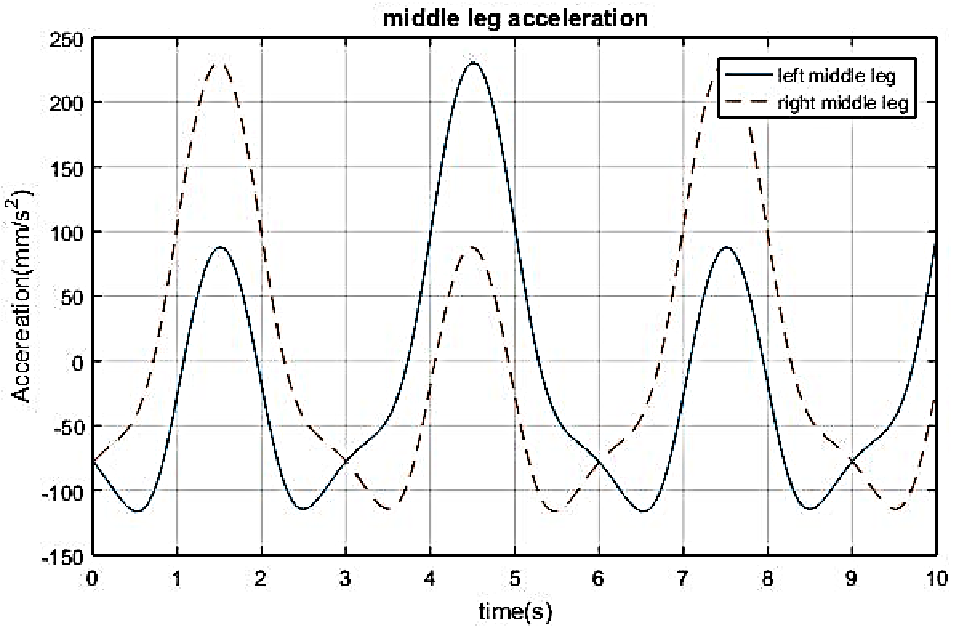
Fig. 33. Front legs response comparison



(a) Displacement response

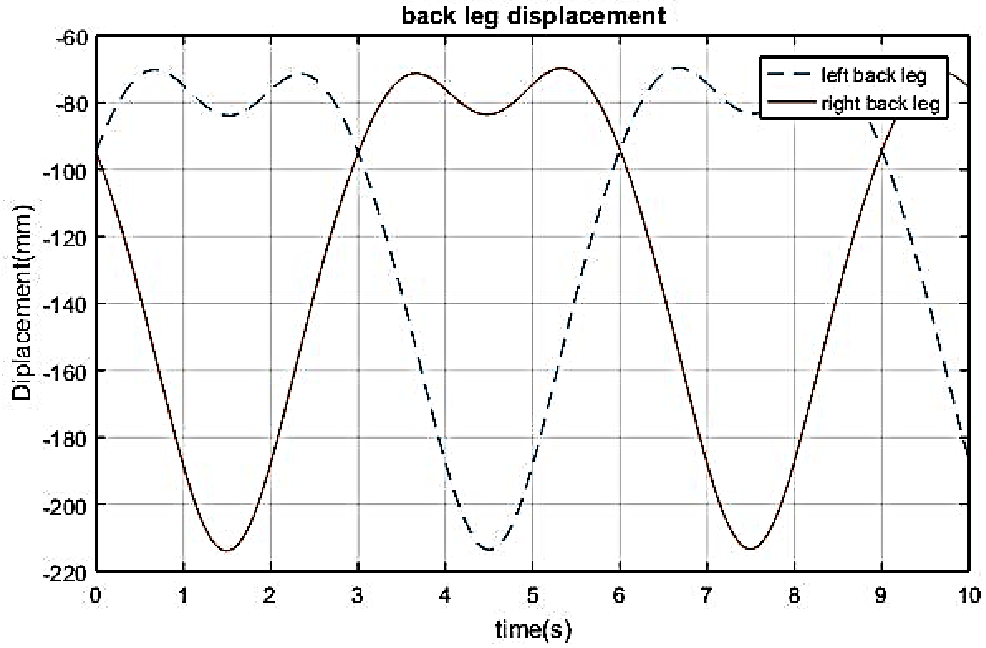


(b) Velocity response

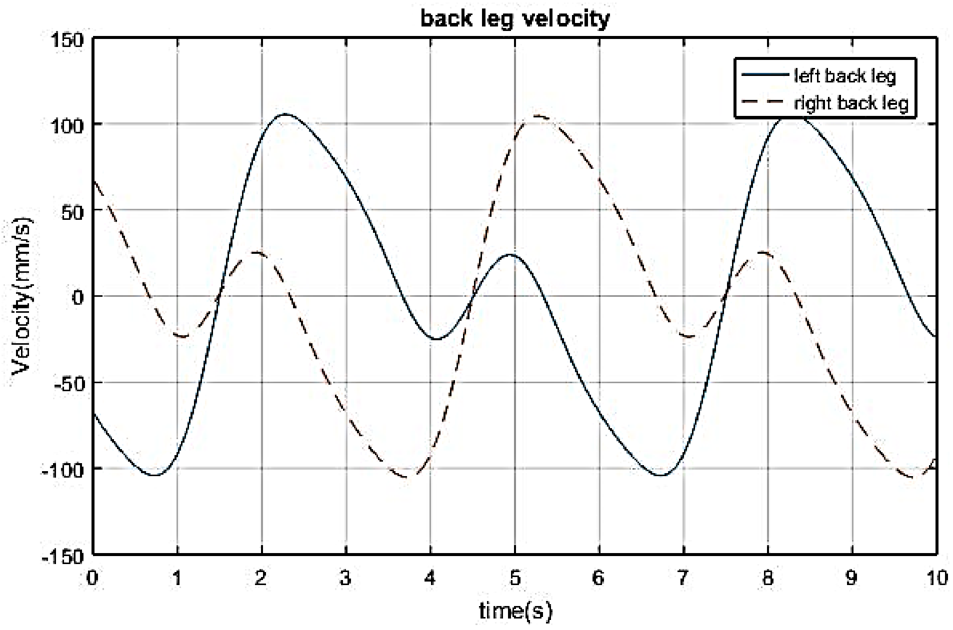


(c) Acceleration response

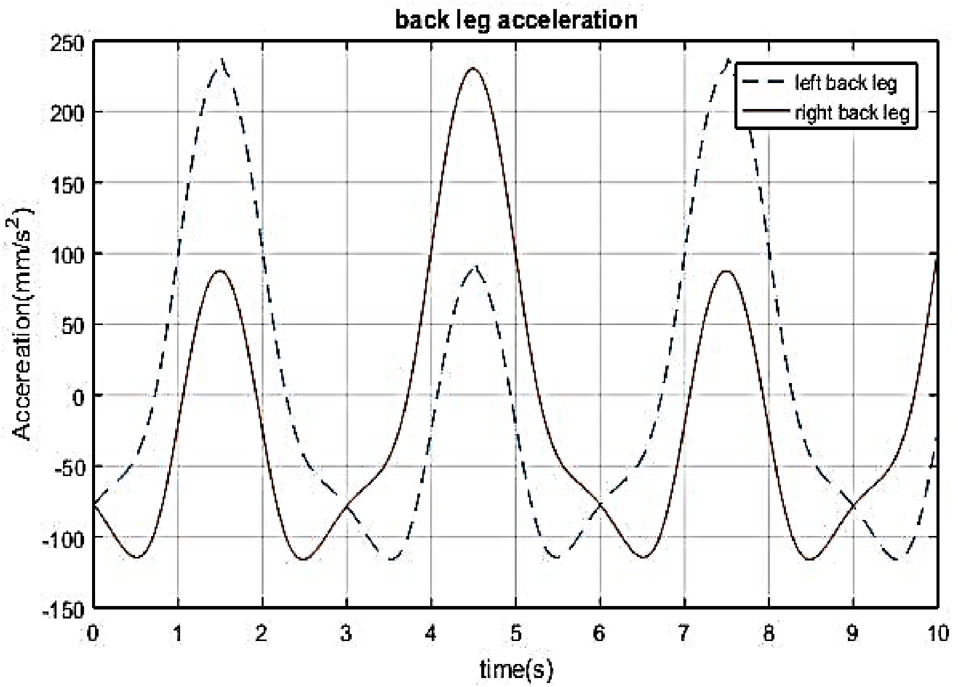
Fig. 34. Middle legs response comparison



(a) Displacement response



(b) Velocity response



(c) Acceleration response

Fig. 35. Back legs response comparison

Generally, the responses obtained by the front legs, middle legs and back legs of Fig. 33, Fig. 34 and Fig. 35 based on the name assigned in Fig. 30 the comparison given above shows the sequence of motion patterns in terms of displacement, velocity and acceleration.

4.3.3. Torque response of a walking machine leg mechanism

The torque outputs for all the legs operating at the same time is given in Fig. 36. The peak value observed in the simulation indicates the maximum torque is required when the three legs operating at the same time start to move up direction motion. Due to the gravity while the legs are moving in the downward direction rotating simultaneously the mechanism exhibit less amount of torque. This variation is occurred due to the effect of gravity on the legs mechanism.

The kinematic behavior of the leg mechanism is determined in motion analysis using input parameters as a constant input and fluctuating function. The motion path generated for the leg fulfills the functional requirements mentioned in the previous Chapter 3 in a manner that it can walk on the rough terrain. The effects of the input function on the leg mechanism in terms of kinematic properties are discussed from the results obtained.

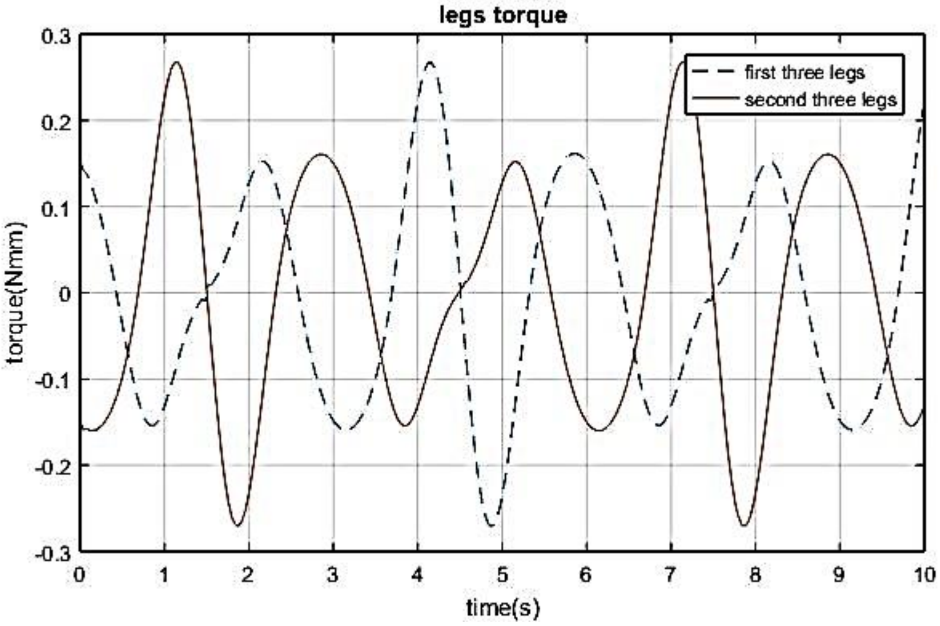


Fig. 36. Torque profile of a walking machine leg mechanism

Chapter Five

Conclusion and Recommendation

This chapter is the last part of the thesis and focuses on the summary to formulate the conclusion and recommendation for the future work to enhance the research.

5.1. Summary

- Various scientific papers have been reviewed and it is found that the leg mechanism over wheels or track mechanism is a comparatively better solution for rough terrain. The mechanism of the leg is modeled kinematically using integration of linkages without multiple uses of motors at each actuating DOF. This reduced number of motors has a great effect on the energy consumption. The leg mechanism developed also enables to walk on rough terrain while statically stable. A number of the component is less and simple design, it needs minimum cost for the machine to be manufactured.
- From kinematic synthesis and analysis, dimensional synthesis parametrically derived for the leg mechanisms, using forward kinematic and inverse kinematic the position analysis is carried out in a vector form. The DH convention approach applied to analyze the mechanisms using Transformation matrix for the formulated relation between position, velocity and acceleration analysis is using Jacobian Matrix. The dynamic analysis carried out using Euler-Lagrange method considered the kinetic energy and potential energy expression and then the equation of motion is derived.
- The part and assembly geometric modeling in SolidWorks V2018 is done. From the motion analysis result, the exported data is analyzed in MATLAB 2016a to show displacement, velocity, acceleration and torque responses. The effect of variation of the rough terrain on the kinematic behavior of the leg mechanism is explained.

5.2. Conclusion

The work presented here in this thesis has been to advance the walking machine leg mechanism. The following conclusions are drawn from the research work:

- Special types of four bar mechanisms are used for the walking machine leg mechanism for walking operation
- Simple linkage integration is proposed in the synthesis to the generated motion path for the leg mechanism of a walking machine
- The parametric equation helps to scalable the design to any size for constructing the machine is derived
- Number of actuator is decreased for a leg mechanism which reduces the energy consumption

5.3. Recommendation and its future work

In this thesis, a leg mechanism for a six-legged walking machine for the walking machine is synthesized and analyzed. The kinematic modeling conducted in this thesis is basic for its further work. So careful attention is paid to the main design issues and constraints that influence the technical feasibility and performance of the leg mechanism.

In the dynamic analysis, the effect of impact loads, frictional loads at joints and other external factors are not considered. Further analysis is required by considering these parameters in the design of the leg mechanism.

Particularly for a specific application, it is better if the following areas are carried out for its future work:

- Detail design of the walking machine leg mechanism
- Design for controlling and navigation of a leg mechanism integrated with communication system of the walking machine (robot)
- Designing the walking machine using the leg mechanism for under water application
- Fabrication and experimental validation of the walking machine leg mechanism

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Appendix A: MATLAB code Homogeneous transformation matrix

```
% for the multiplication of rotation matrix symbolically and each
rotation matrix is defined and computed in MATLAB
q=sym('c1'); % cos theta 1
b=sym('s1'); % sin theta 1
c=sym('c2');
d=sym('s2');
e=sym('c3');
f=sym('s3');
g=sym('c4');
h=sym('s4');
i=sym('c5');
j=sym('s5');
k=sym('c6');
l=sym('s6');

x=sym('a1'); % link length
y=sym('a2');
z=sym('a3');
m=sym('a4');
n=sym('a5');
p=sym('a6');

o=sym('d6');

A=[q -b 0 a*x; b a 0 b*x; 0 0 1 0; 0 0 0 1]; % transformation matrix of
joint 1
B=[c -d 0 c*y; d c 0 d*y; 0 0 1 0; 0 0 0 1]; % transformation matrix of
joint 2
C=[e -f 0 e*z; f e 0 f*z; 0 0 1 0; 0 0 0 1]; % transformation matrix of
joint 3
D=[g -h 0 g*m; h g 0 h*m; 0 0 1 0; 0 0 0 1]; % transformation matrix of
joint 4
E=[i -j 0 i*n; j i 0 j*n; 0 0 1 0; 0 0 0 1]; % transformation matrix of
joint 5
F=[1 0 0 0;0 1 0 0; 0 0 1 o;0 0 0 1];% transformation matrix of joint 6
G=A*B*C*D*E*F
Z=[G(1,4); G(2,4); G(3,4)]
% to determine each elements of the homogeneous transformation matrix
a11=G(1)
a21=G(2)
a31=G(3)
a41=G(4)
a12=G(5)
a22=G(6)
a32=G(7)
a42=G(8)
a13=G(9)
a23=G(10)
a33=G(11)
a43=G(12)
a14=G(13)
a24=G(14)
a34=G(15)
a44=G(16)
```

Appendix B: Homogeneous Transformation matrix elements

a_{11} = c5*(c4*(c3*(c1*c2 - s1*s2) - s3*(c1*s2 + c2*s1)) - s4*(c3*(c1*s2 + c2*s1) + s3*(c1*c2 - s1*s2))) - s5*(c4*(c3*(c1*s2 + c2*s1) + s3*(c1*c2 - s1*s2)) + s4*(c3*(c1*c2 - s1*s2) - s3*(c1*s2 + c2*s1)))

a_{21} = c5*(c4*(c3*(c1*s2 + c2*s1) + s3*(c1*c2 - s1*s2)) + s4*(c3*(c1*c2 - s1*s2) - s3*(c1*s2 + c2*s1))) + s5*(c4*(c3*(c1*c2 - s1*s2) - s3*(c1*s2 + c2*s1)) - s4*(c3*(c1*s2 + c2*s1) + s3*(c1*c2 - s1*s2)))

a_{31} = 0

a_{41} = 0

a_{12} = - c5*(c4*(c3*(c1*s2 + c2*s1) + s3*(c1*c2 - s1*s2)) + s4*(c3*(c1*c2 - s1*s2) - s3*(c1*s2 + c2*s1))) - s5*(c4*(c3*(c1*c2 - s1*s2) - s3*(c1*s2 + c2*s1)) - s4*(c3*(c1*s2 + c2*s1) + s3*(c1*c2 - s1*s2)))

a_{22} = c5*(c4*(c3*(c1*c2 - s1*s2) - s3*(c1*s2 + c2*s1)) - s4*(c3*(c1*s2 + c2*s1) + s3*(c1*c2 - s1*s2))) - s5*(c4*(c3*(c1*s2 + c2*s1) + s3*(c1*c2 - s1*s2)) + s4*(c3*(c1*c2 - s1*s2) - s3*(c1*s2 + c2*s1)))

a_{32} = 0, a_{42} = 0, a_{13} = 0, a_{23} = 0, a_{33} = 1, a_{43} = 0,

a_{14} = a1*c1 + a5*c5*(c4*(c3*(c1*c2 - s1*s2) - s3*(c1*s2 + c2*s1)) - s4*(c3*(c1*s2 + c2*s1) + s3*(c1*c2 - s1*s2))) - a5*s5*(c4*(c3*(c1*s2 + c2*s1) + s3*(c1*c2 - s1*s2)) + s4*(c3*(c1*c2 - s1*s2) - s3*(c1*s2 + c2*s1))) + a2*c1*c2 - a2*s1*s2 + a4*c4*(c3*(c1*c2 - s1*s2) - s3*(c1*s2 + c2*s1)) - a4*s4*(c3*(c1*s2 + c2*s1) + s3*(c1*c2 - s1*s2)) + a3*c3*(c1*c2 - s1*s2) - a3*s3*(c1*s2 + c2*s1)

a_{24} = a1*s1 + a5*c5*(c4*(c3*(c1*s2 + c2*s1) + s3*(c1*c2 - s1*s2)) + s4*(c3*(c1*c2 - s1*s2) - s3*(c1*s2 + c2*s1))) + a5*s5*(c4*(c3*(c1*c2 - s1*s2) - s3*(c1*s2 + c2*s1)) - s4*(c3*(c1*s2 + c2*s1) + s3*(c1*c2 - s1*s2))) + a2*c1*s2 + a2*c2*s1 + a4*c4*(c3*(c1*s2 + c2*s1) + s3*(c1*c2 - s1*s2)) + a4*s4*(c3*(c1*c2 - s1*s2) - s3*(c1*s2 + c2*s1)) + a3*c3*(c1*s2 + c2*s1) + a3*s3*(c1*c2 - s1*s2)

a_{34} = d6

a_{44} = 1

Appendix C: Material property

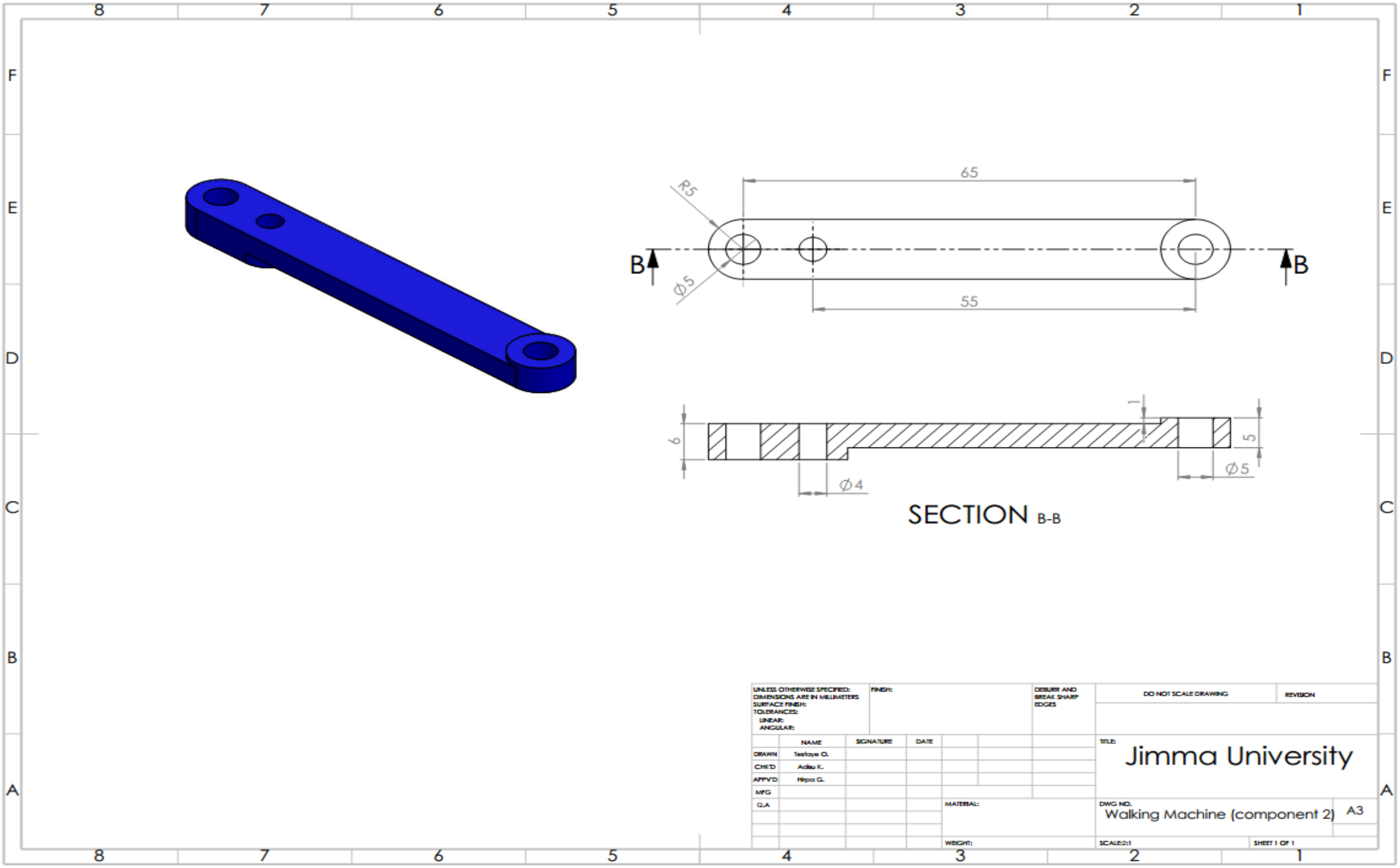
No.	Property of Al Alloy 1060	Value	Units
1	Elastic Modulus	6.9e+010	N/mm^2
2	Poisson's Ratio	0.33	N/A
3	Shear Modulus	2.7e+010	N/mm^2
4	Mass Density	2700	kg/mm^3
5	Tensile Strength	68935600	N/mm^2
6	Compressive Strength		N/mm^2
7	Yield Strength	27574200	N/mm^2
8	Thermal Expansion Coefficient	2.4e-005	/K
9	Thermal Conductivity	200	W/(mm·K)
10	Specific Heat	900	J/(kg·K)
11	Material Damping Ratio		N/A

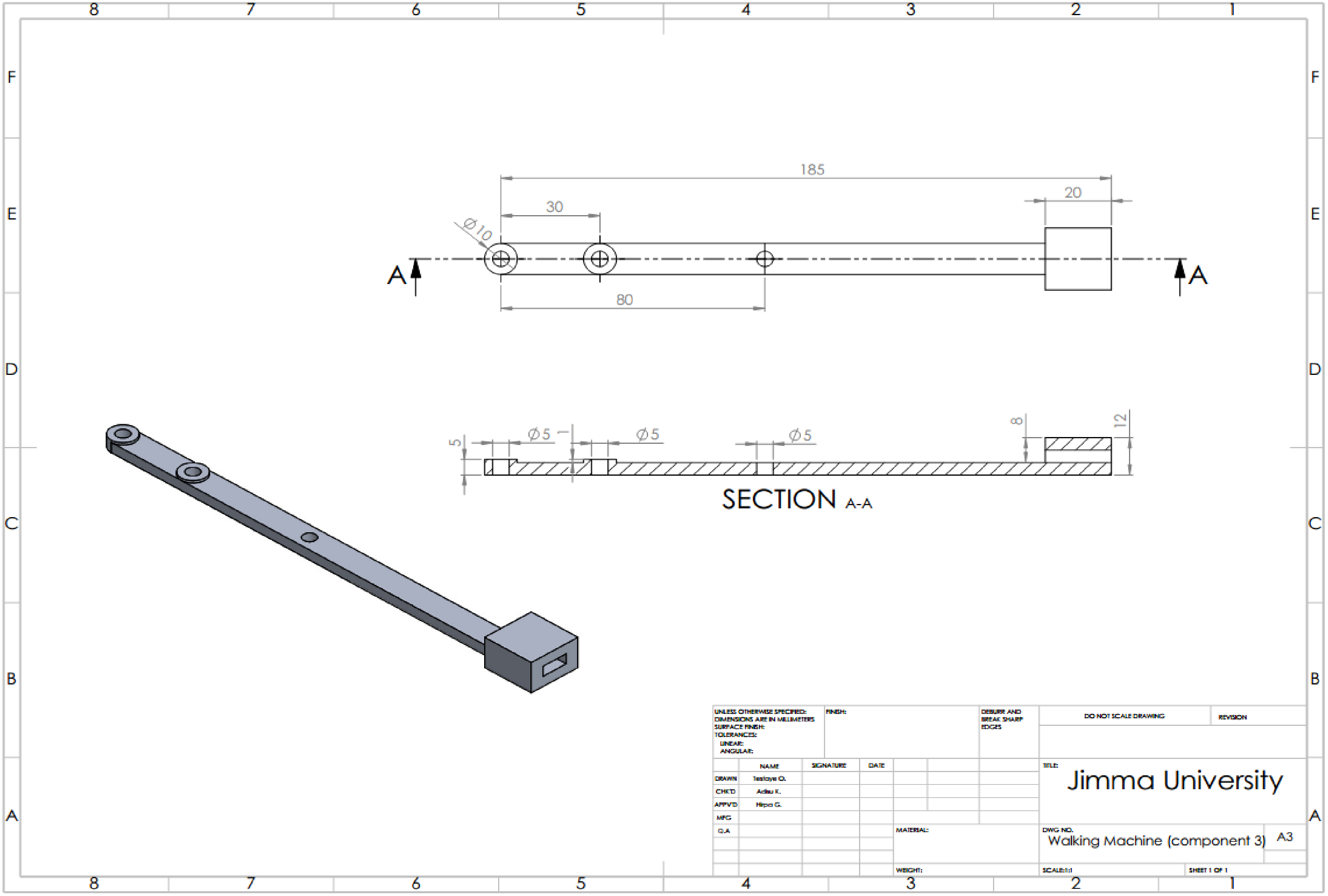
Appendix D: Mass properties

```
Mass properties of Walking Machne (Main Body)
    Configuration: Default
    Coordinate system: -- default --

Mass = 1613.48 grams

Volume = 607474.37 cubic millimeters

Surface area = 305595.22  square millimeters

Center of mass: ( millimeters )
                    X = -58.53
                    Y = 46.43
                    Z = 449.10

Principal axes of inertia and principal moments of inertia: ( grams *  square
millimeters )
Taken at the center of mass.
                     Ix = ( 1.00,  0.00,  0.07)    Px = 16092066.04
                     Iy = ( 0.07,  0.00, -1.00)    Py = 31379137.61
                     Iz = ( 0.00,  1.00,  0.00)    Pz = 40408707.73

Moments of inertia: ( grams *  square millimeters )
Taken at the center of mass and aligned with the output coordinate system.
                    Lxx = 16176318.60   Lxy = -562.52         Lxz = 1131758.05
                    Lyx = -562.52       Lyy = 40408707.71 Lyz = 262.39
                    Lzx = 1131758.05    Lzy = 262.39          Lzz = 31294885.07

Moments of inertia: ( grams *  square millimeters )
Taken at the output coordinate system.
                    Ixx = 345078863.89  Ixy = -4385481.68   Ixz = -41280210.72
                    Iyx = -4385481.68   Iyy = 371360202.82Iyz = 33645434.68
                    Izx = -41280210.72  Izy = 33645434.68   Izz = 40300897.50
```

Appendix E: Part drawing and Assembly drawing

a) Part drawing





UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	Tesfaye O.		
CHK'D	Adisu K.		
APPV'D	Hirpa G.		
MFG			
Q.A			

TITLE: Jimma University

MATERIAL:

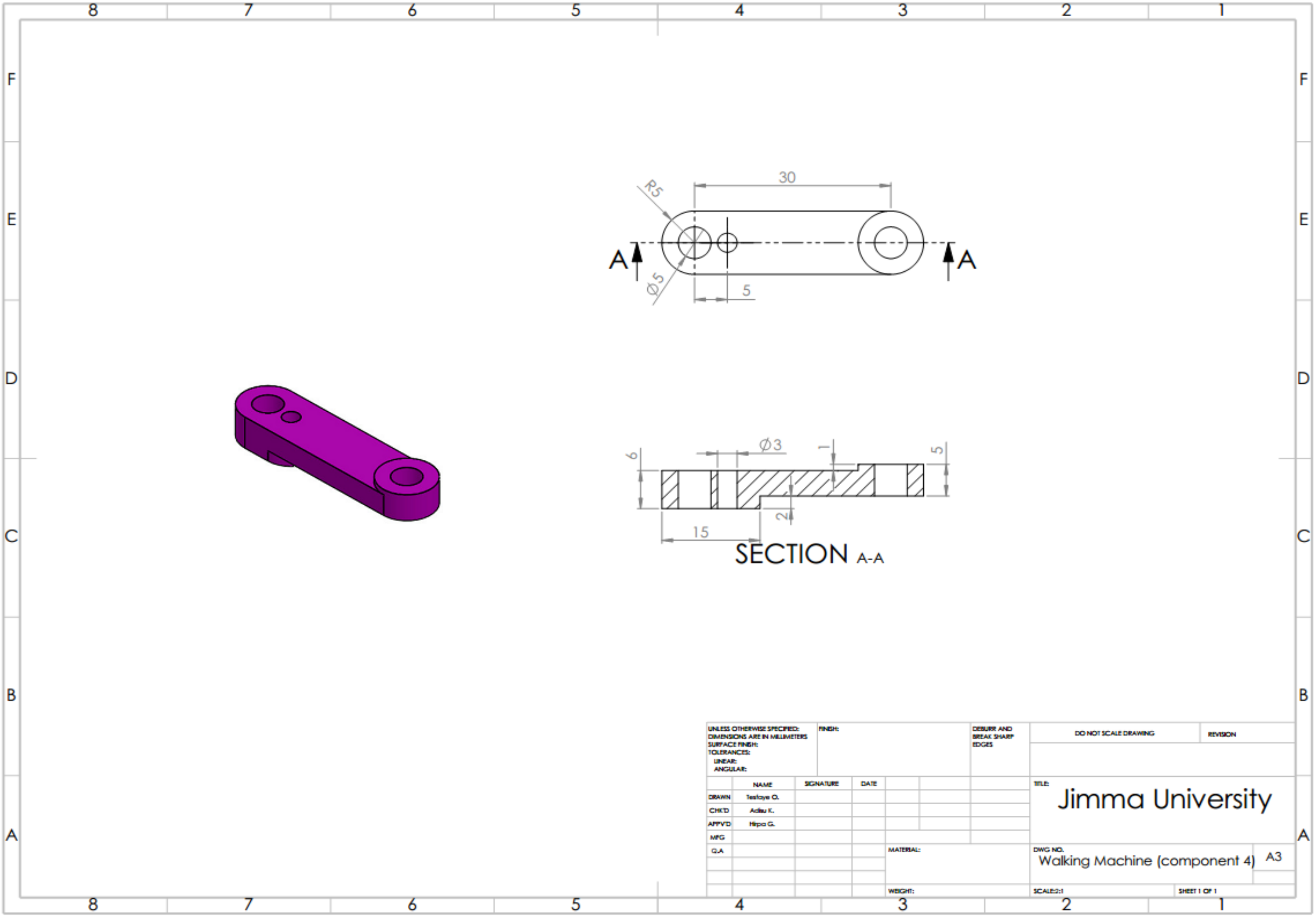
DWG NO. Walking Machine (component 3)

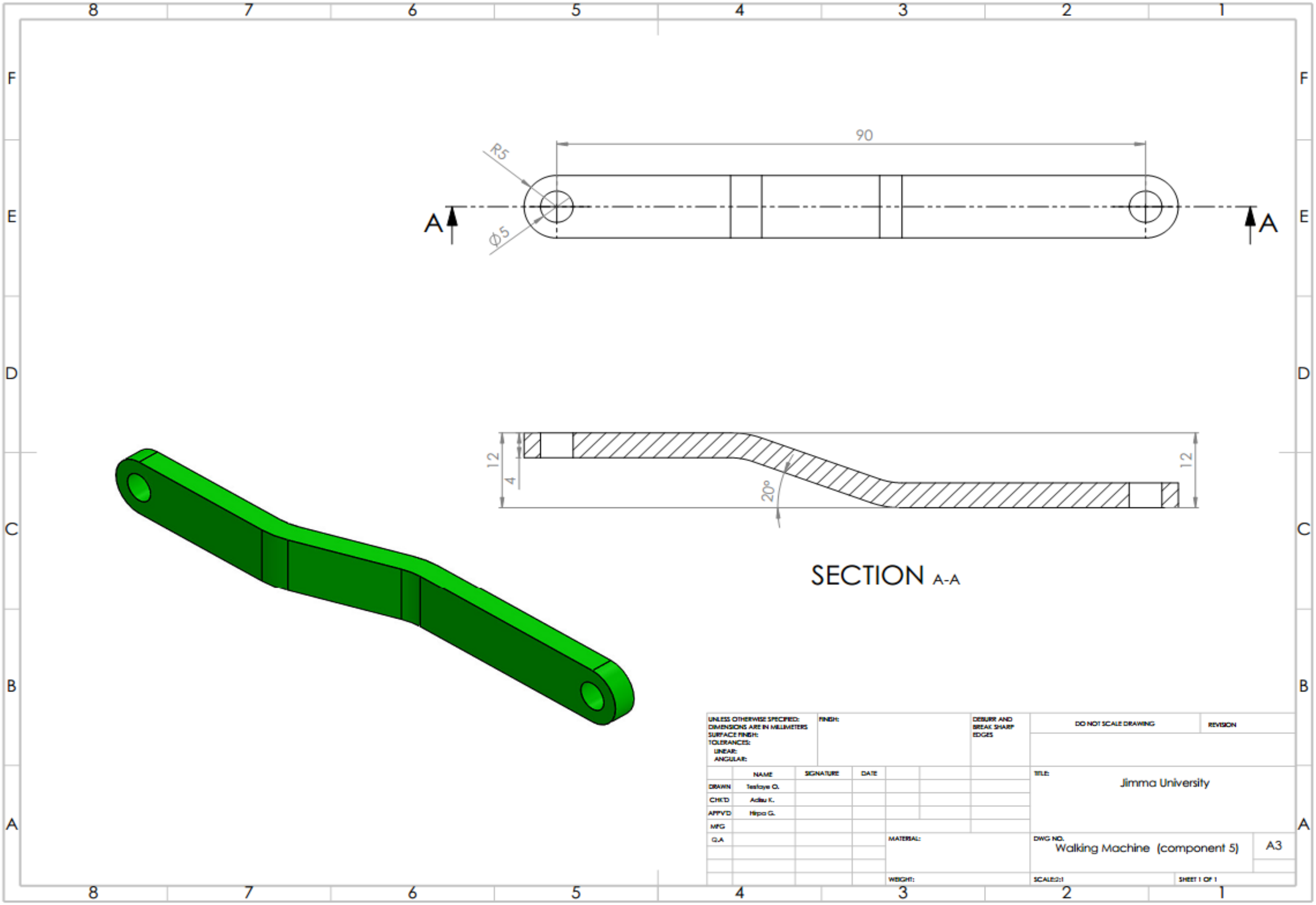
A3

WEIGHT:

SCALE:1:1

SHEET 1 OF 1


30
R5
A
A
∅5
5
∅3
1
5
6
2
15
SECTION A-A
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN Tesfaye O.
CHK'D Adisu K.
APPV'D Hirpa G.
MFG
Q.A
MATERIAL:
WEIGHT:
TITLE:
Jimma University
DWG NO.
Walking Machine (component 4)
A3
SCALE:2:1
SHEET 1 OF 1



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SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

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REVISION

	NAME	SIGNATURE	DATE
DRAWN	Tesfaye O.		
CHK'D	Adisu K.		
APPV'D	Hirpa G.		
MFG			
Q.A			

TITLE: Jimma University

MATERIAL:

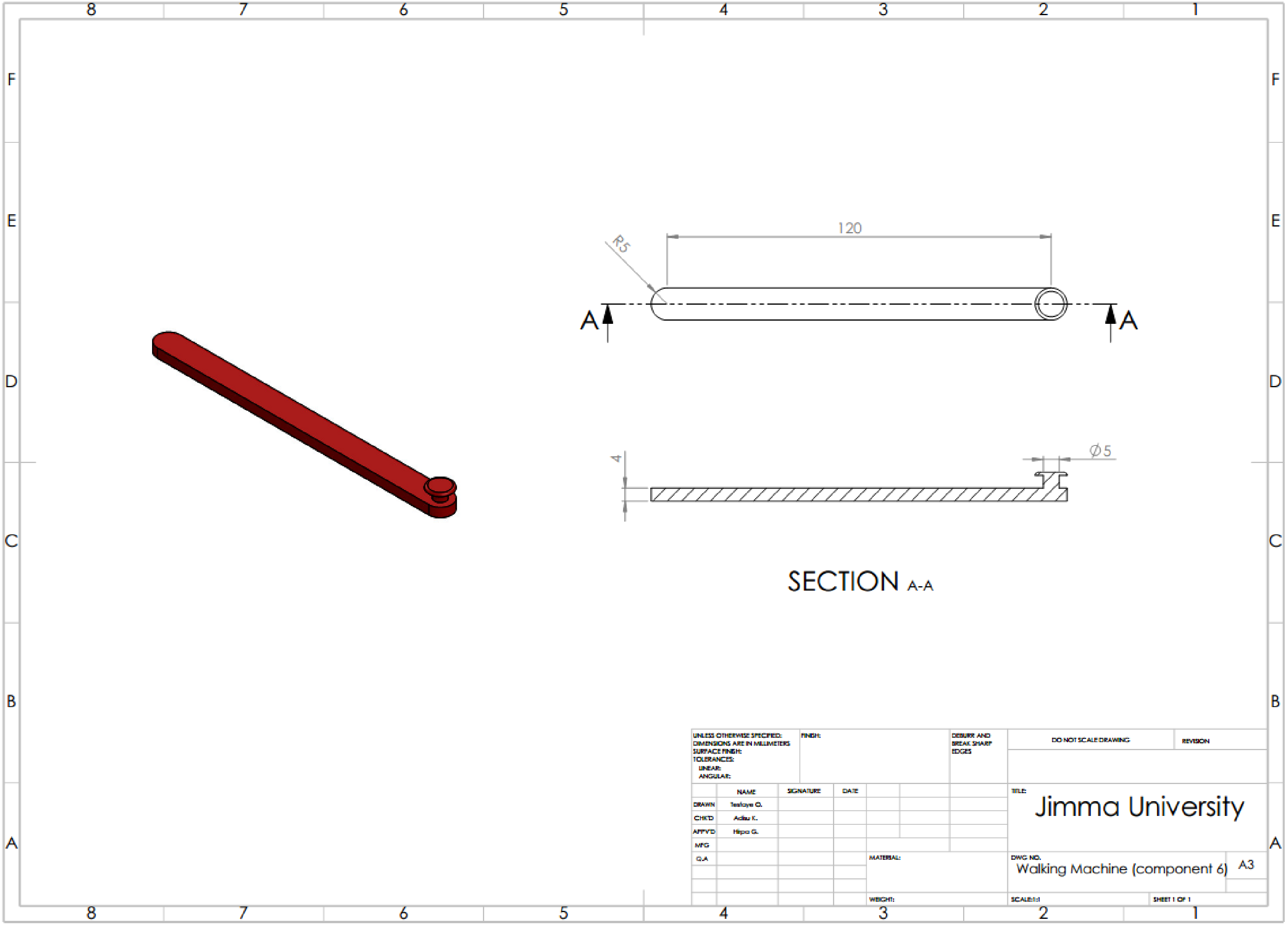
DWG NO. Walking Machine (component 5)

A3

WEIGHT:

SCALE:2:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
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SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	Tesfaye O.		
CHK'D	Adisu K.		
APPV'D	Hirpa G.		
MFG			
Q.A			

TITLE: Jimma University

MATERIAL:

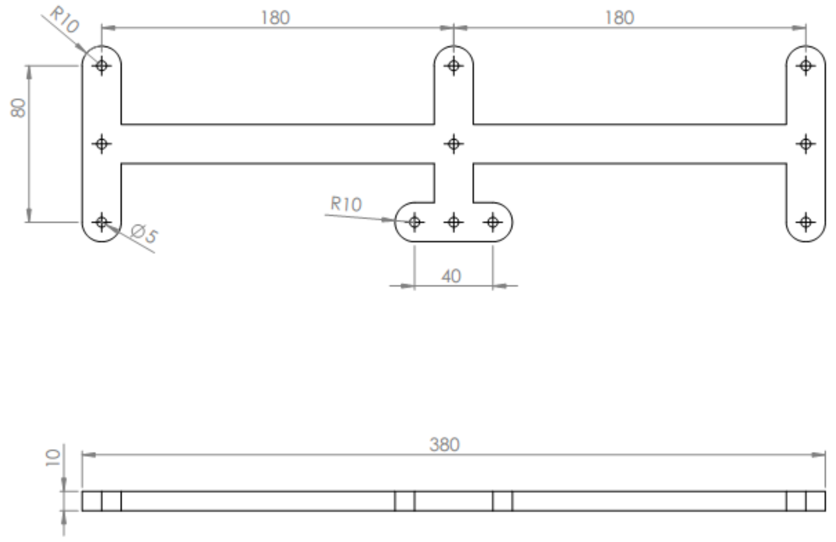
DWG NO. Walking Machine (component 6)

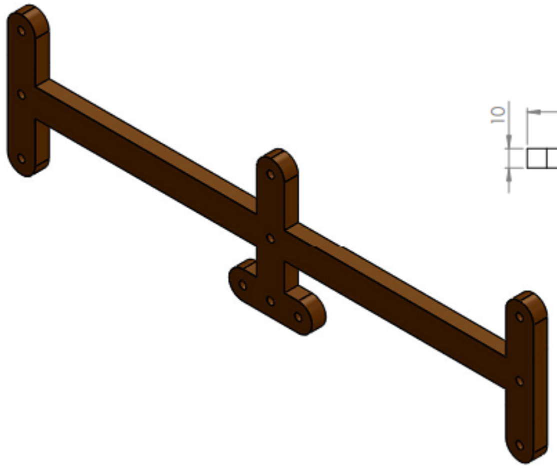
A3

WEIGHT:

SCALE:1:1

SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	Tesfaye O.		
CHK'D	Adisu K.		
APPV'D	Hirpa G.		
MFG			
Q.A			

TITLE: **Jimma University**

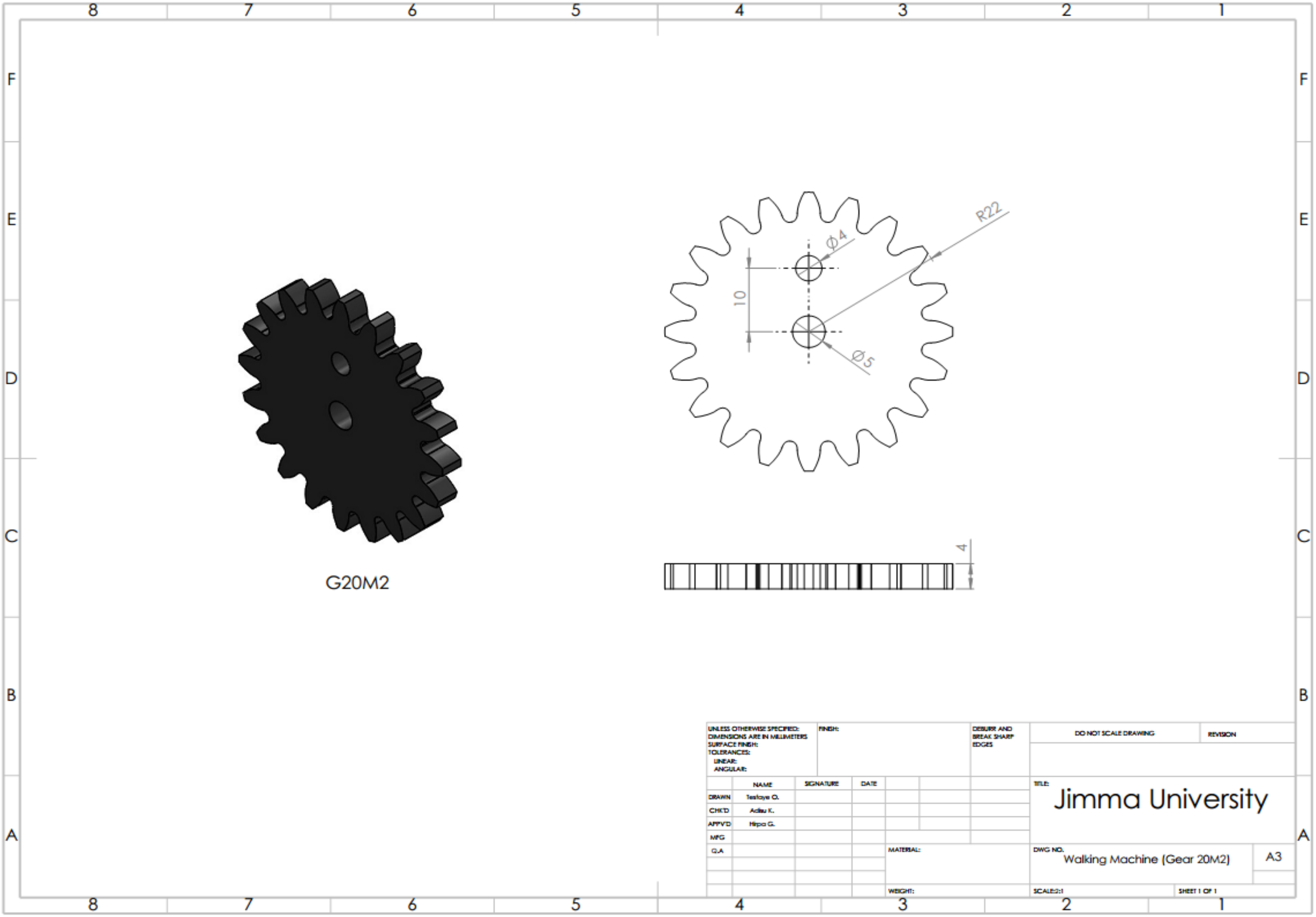
MATERIAL:

DWG NO. Walking Machine (Body Structure) A3

WEIGHT:

SCALE:1:2

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

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REVISION

	NAME	SIGNATURE	DATE
DRAWN	Tesfaye O.		
CHK'D	Adisu K.		
APPV'D	Hirpa G.		
MFG			
Q.A			

TITLE: Jimma University

MATERIAL:

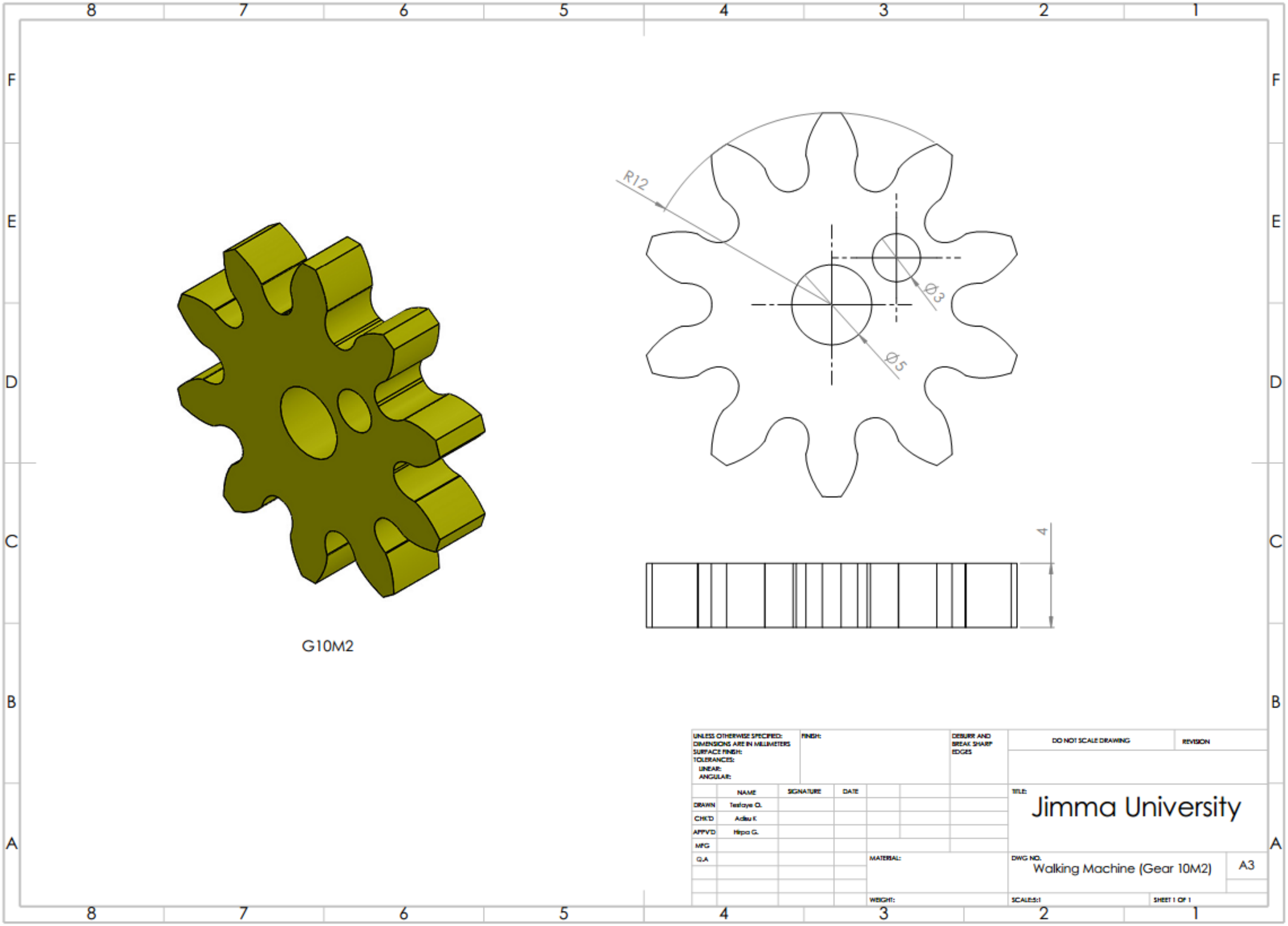
DWG NO. Walking Machine (Gear 20M2)

A3

WEIGHT:

SCALE:2:1

SHEET 1 OF 1



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DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	Tesfaye O.		
CHK'D	Adisu K		
APPV'D	Hirpa G.		
MFG			
Q.A			

TITLE: Jimma University

MATERIAL:

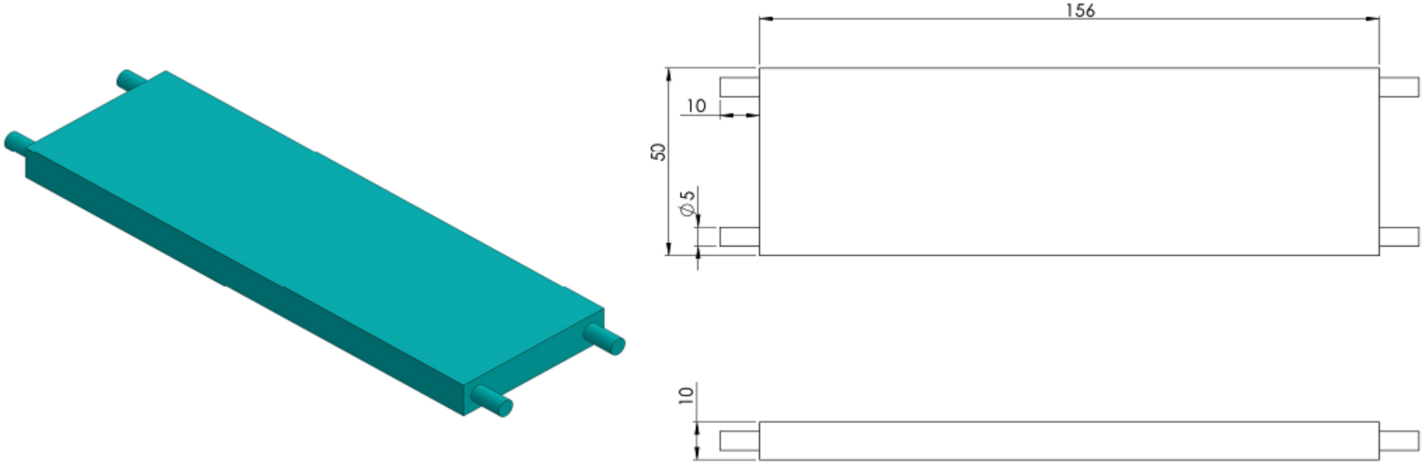
WEIGHT:

DWG NO. Walking Machine (Gear 10M2)

A3

SCALE5:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	Tesfaye O.		
CHK'D	Adisu K.		
APPV'D	Hirpo G.		
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:
Jimma Uiversity

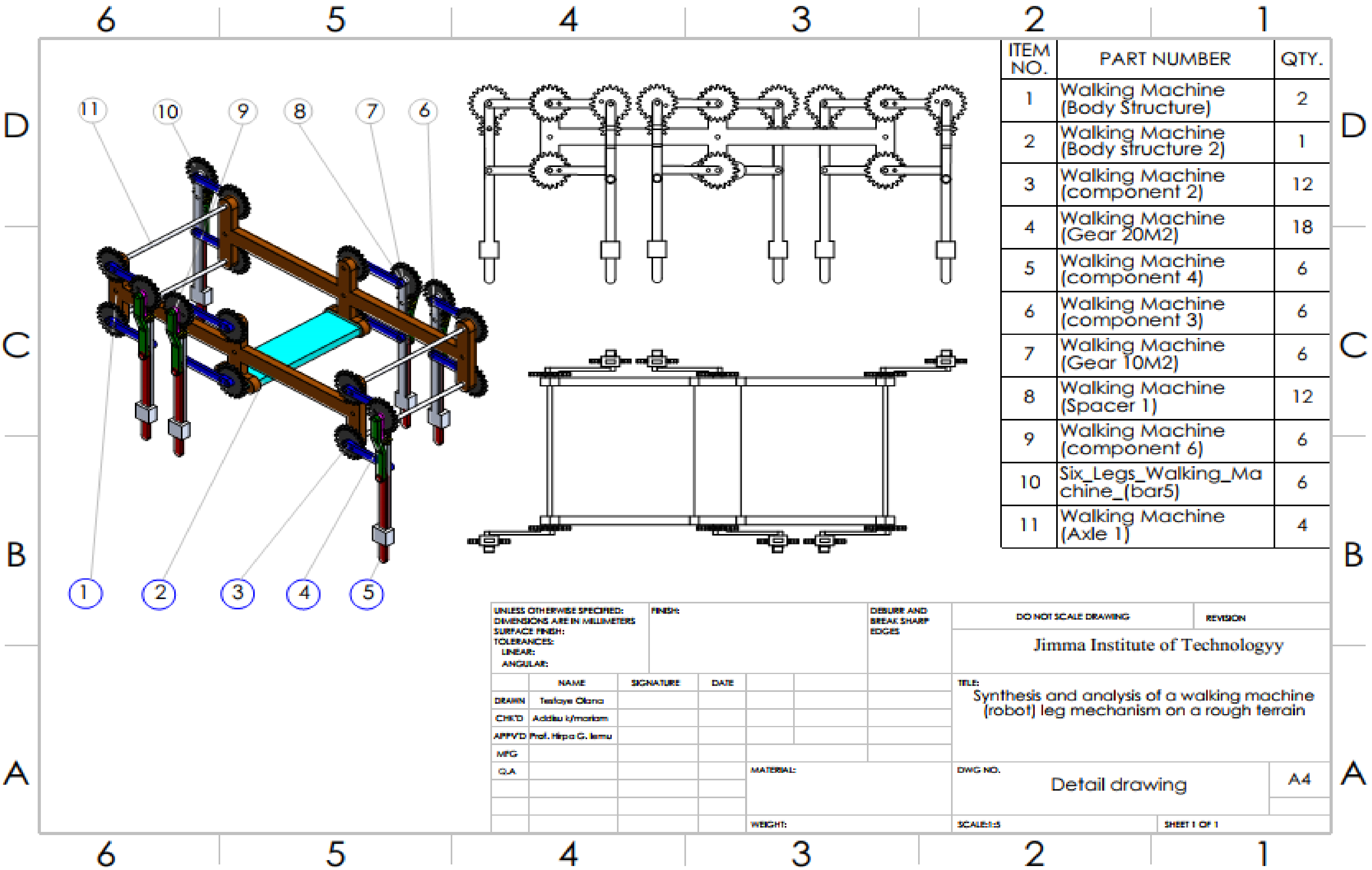
DWG NO.
Walking Machine (Body structure 2)

A3

SCALE:1:1

SHEET 1 OF 1

b) Assembly drawing



ITEM NO.	PART NUMBER	QTY.
1	Walking Machine (Body Structure)	2
2	Walking Machine (Body structure 2)	1
3	Walking Machine (component 2)	12
4	Walking Machine (Gear 20M2)	18
5	Walking Machine (component 4)	6
6	Walking Machine (component 3)	6
7	Walking Machine (Gear 10M2)	6
8	Walking Machine (Spacer 1)	12
9	Walking Machine (component 6)	6
10	Six_Legs_Walking_Machine_(bar5)	6
11	Walking Machine (Axle 1)	4

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

Jimma Institute of Technologyy

	NAME	SIGNATURE	DATE
DRAWN	Tesfaye Olana		
CHK'D	Addisu k/mariam		
APPV'D	Prof. Hirpa G. lemu		
MFG			
Q.A			

TITLE:
Synthesis and analysis of a walking machine (robot) leg mechanism on a rough terrain

MATERIAL:

DWG NO.
Detail drawing

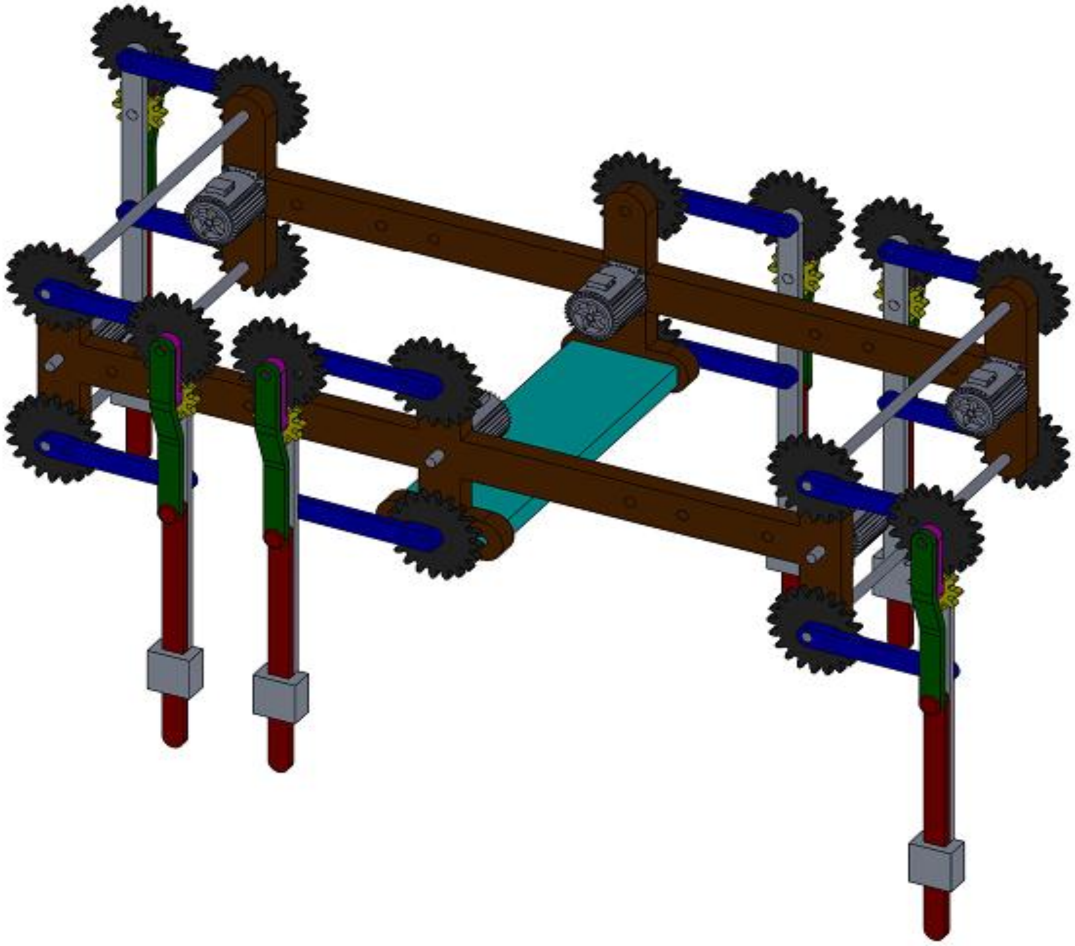
A4

WEIGHT:

SCALE:1:5

SHEET 1 OF 1

3D Assembly
Six Leg Walking machine



Authors’ previous publication

Thesis:

Tesfaye O., Gemechu G. and Tsega T., “Design of impact stone crusher machine”, Lambert Academic Publishing (LAP), November 14, 2017 Edition, p147. ISBN-10: 6202060468, ISBN-13: 978-6202060462 https://www.lap-publishing.com/catalog/details/store/fr/book/978-620-2-06046-2/design-of-impact-stone-crusher-machine?search=crusher

Journal Articles:

Tesfaye O., “Review of Basic Principles of Embodiment Design”, International Journal of Business Intelligent. 2017; 6(1): pp1-5. DOI: 10.20894/IJBI.105.006.001.001, ISSN: 2278-2400. https://www.ijbui.com/abstract_temp.php?id=V6-I1-P1

Tesfaye O. Terefe, “Design and development of manually operated reaper machine”, International Journal of Advanced Research and Publications (IJARP). 2017; 1(2): pp15-21. http://www.ijarp.org/online-papers-publishing/aug2017.html,

Tesfaye O. Terefe and **Hirpa G. Lemu,** “Solution Approaches to Differential Equations of Mechanical Systems Dynamics: A case study of car suspension system”, Advances in Science and Technology Research Journal. 2018; 12(2): pp226-273. DOI: 10.12913/22998624/85662

http://www.astrj.com/solution-approaches-to-differential-equations-of-mechanical-system-dynamics-a-case,85662,0,2.html