وزارة التعليم العالي والبحث العلمي

BADJI MOKHTAR- ANNABA UNIVERSITY
UNIVERSITE BADJI MOKHTAR ANNABA

جامعة باجي مختار- عنابـة

FACULTY OF SCIENCE AND ENGINEERING
DEPATMENT OF ELECTRONICS

MASTER THESIS

DOMAIN: SCIENCE AND TECHNOLOGY
BRANCH: ELECTRONICS
SPECIALTY: ELECTRONICS OF EMBEDDED SYSTEMS

Thesis

Biped Walking Robot Design and Control

Presented by:
DERRADJI Mohamed Lamine

Directed by:
Mme.Chaker Karima

JURY

MAB.Yahi Amira	Presedent,	Badji Mokhtar University-Annaba
MAB.Ait Izem	Member,	Badji Mokhtar University-Annaba
MCB.Boulebtateche Brahim	Member,	Badji Mokhtar University-Annaba

Promotion: June 2019

ACKNOWLEDGEMENTS

First, of course, to my family members who have put up with me spending a large proportion of our home time and have been very supportive on this project. I would like to personally thank all the people involved and a big thank to all the reviewers who spent time and effort reading and providing feedback. To my friends, especially Mouassa Abdennour, Madi Fateh ,Benaïssa Billel and Guebla Chems Eddine for their supporting and help.

A special thanks to Mr Frihi.M, Mr Boulebtateche.B and Mr Fezzari.M for their time, reviews and help. Finally, I would like to thank my supervisor, Mme. Chaker Karima for her help in this project.

CONTENTS

CHAPTER II: KINEMATICS FOR A BIPED WALKING ROBOT

CHAPTER III: BIPED WALKING ROBOT DESIGN AND CONTROL

List of figures

List of tables

Abstract

Robotics is a large field of study that brings together science and engineering and the practical application of this field is achieved through the structure called ROBOT.

In this project thesis, a 10 degrees of freedom biped walking robot is designed and built to imitate the human walking pattern. We have 2DOFs for each hip joint, 1DOF for each knee joint and 2DOFs for each ankle joint. The robot's locomotion and actions are controlled by a microcontroller board**.**

Electronic design's knowledge, programming and mechanical designing skills are required to achieve the main purpose of this project and also to reduce complexity level of humanoid robots.

ملخص

مجال الآلات مجال واسع يجمع بين العلم والهندسة, والتطبيق العملي لهذا المجال يتجسد من خلال الهيكل المسمى بالروبوت

في أطروحة هذا المشروع سنقوم ببناء روبوت ثنائي القدم يحمل عشر درجات من الحرية من أجل محاكاة نمط سير الإنسان. الروبوت يحمل درجتين من الحرية في كل مفصل الورك, درجة حرية واحدة لمفصل ركبة ودرجتين من الحرية لمفصل الكاحل لكل قدم. يتم التحكم بحركة وعمل الروبوت من خلال دارة المتحكم الصغري.

مهارات التصميم الإلكتروني, البرمجة والتصميم الميكانيكي مهارات مطلوبة لتحقيق الهدف الأساسي لهذا المشروع إضافة إلى تخفيض درجة تعقيد الروبوتات الشبيهة بالبشر.

Résumé

La robotique est un grand domaine qui combine entre la science et l'ingénierie et l'application pratique de ce domaine est réalisé à partir la structure nommée ROBOT.

Dans ce projet, un robot bipieds avec 10 degrés de liberté est réalisé. Nous avons 2 degrés pour chaque articulation de hanche, 1 degré de liberté pour chaque genou et 2 degrés pour chaque articulation de cheville. La locomotion du robot et ses actions sont contrôlées par une carte à microcontrôleur.

Des informations sur les circuits électroniques, la programmation et des mécaniques sont nécessaires pour réaliser le but principal de ce projet et diminué la complexité des robots humanoïdes.

INTRODUCTION

INTRODUCTION

The development of robotic technology after the mid-1920s went in at least two major directions. The first was in the development of larger (or smaller), more sophisticated devices capable of performing tasks difficult or impossible for humans. The second direction was in the development of humanoid robots that look and act more and more like humans. Experts have devised many ways and methods for the classification and categorization of robots, and the most useful way is based on the practical applications of these robots.

One of the most recent kind of robots in this century are the biped robots or the humanoid robots or androids. Two legged robot locomotion mechanisms are very popular and complex field of science. Engineers can't make robot legs so as it exists in biological systems, which are very successful and don't have any problems to walk, jump and run. However, there are a large number of two-legged robots that work on simpler principles than human legs.

People who suffer from stroke, spinal cord injury and other impediments, often after relearn how to walk as adults; robots are increasingly being used in rehabilitation treatment; with the robot teaching the patient how to walk again by retraining their gait. Therefore we need to take in consideration the time preparation for the biped Robot to imitate the human walk, in order to reduce rehabilitation period. In the other hand, to provide such sophisticated machine like a human-like robot to study the human walking pattern, in order to reduce the rehabilitation treatment period of time.

The first step to find the solution of this problem is by finding the appropriate locomotion walking gait cycle for a biped walking robot to be a human-like machine. Finding the balancing methods which are very similar to a human balancing method, while the high cost and complexity is very high to build this human-like robot.

In the first chapter of this thesis, brief knowledge information about mobile robots appearance and developments from the first appear until today's mobile robots technology development.

The second chapter consists of the study of a biped robot walking mechanisms and the difference between the balance methods to find which method is the most effective method for a human-like walking mechanism, while trying to understand the human walking pattern.

In the third chapter, a10 degrees of freedom (DOF) biped walking robot is built. We have 2DOFs for each hip joint, 1DOF for each knee joint and 2DOFs for each ankle joint. The robot's locomotion and actions are controlled by a microcontroller board.

Some software simulation programs are used to simulate algorithms and then the algorithms are implemented in real. Finally, we finish this project work by experimental results, perspectives and a conclusion for a future work.

CHAPTER I

I.1 Introduction

In recent years, the notion of the robot as a mechanical companion and servant has become a common concept, and the robots have captured the interest of more and more people. Compared to old mobile robots which were controlled by heavy, large and expensive computer systems, the new generation of mobile robots is built in small, light and inexpensive embedded computer systems containing numerous actuators and sensors which are carried on-board the robot. The mobile robots are used today at almost all universities in Information Technology, Computer Engineering and Mechatronics as a perfect tool for engineering education.

I.2 Definition

Robotics is a large and exciting field of study and application. A robot is an embedded system that moves or physically manipulates its environment or nearby objects. Some robots are made to move only via remote control; others are fully automatic. Both kinds are used in space exploration, factory automation, and a variety of other settings. Many dream of a future in which automated robots will make life easier, whereas equal numbers worry about robots later becoming sentient and banding together to overthrow their human masters. A variety of books and movies have explored these possibilities.

I.3 History of Mobile Robots

- In 1206, the most comprehensive book on automata of the time was created and published by **Ibn Al-Jazari** (The Book of Ingenious Mechanical Devices).
- The first appear of the word robot was in 1921 by the Czech playwright **Karel Čapek** in his play R.U.R, to describe androids that eventually take over the world [1].
- The three laws of robotics were created in 1942 by **Isaac Asimov**, to limit the extent to which robots could overtake human activities [4].
- The first social robot was built by the English neurophysiologist **William Grey Walter** in 1949. Walter's research was motivated by his belief that relatively simple connections between a limited numbers of neurons can result in complex human behavior[1], (see Fig 1.3.a)
- A mechanical robot called Unimate, which is developed by **George Devol** in 1961, was placed for the first time on the assembly line at General Motors in Ewing Township, New Jersey, (see Fig 1.3.b). After 3 years, the General Motors orders 66 Unimates to be used in its

assembly plant (see Fig 1.3.c). In 1975, Olivetti Company produces one of the first Cartesian coordinate robots, Sigma, for use in assembly lines. A Cartesian coordinate robot is one whose arms move in linear, rather than rotational, directions.

- The Japanese inventor **Hirose Shigeo** designed the original Titan walking robot in 1981. The Titan is of special interest because its robots are large enough to carry small loads, but not so big as to be unwieldy. (For an image of a later Titan model, see http://menzelphoto.photoshelter.com/image/I0000h31uUJ2zW1A/ .
- The MIT Department of Ocean Engineering produces a robot called Robotuna to simulate the mechanisms by which fish swim in 1996. It choose the fastest of all fish, tuna, around which to name the project. The goal of the project is not only to better understand swimming mechanisms in fish but also to develop the fastest and more efficient systems for ship propulsion.
- The product of a five-year research program which known as ASIMO (Advanced Step in Innovative Mobility), was released in 2000 by the Japan’s Honda Corporation (see Fig 1.3.d).
- After a decade of producing a variety of military robots, the iRobot manufacturing company released its first domestic product in 2002, the Roomba home vacuuming system.
- With research funding from DARPA (Defense Advances Research Projects Agency), the firm of Boston Dynamics develops Big Dog in 2005, a quadrupedal robot able to run at speeds of 10 km/h (6 mph), climb slopes of up to 35 degrees, walk across rubble, climb muddy hiking trails, walk in snow and water, and carry loads of up to 150 kg (300 lb). The firm also produced the most recent version of anthropomorphic robots in 2013, Atlas. The robot was funded to develop human-like machines.
- A new set of Robotic Laws were released in 2016 by Google Brain, to replace those first proposed by Isaac Asimov in 1942. At the same year, a nonprofit organization (FIRST) sponsored annual Olympics-style robotics competitions for young adults called the FIRST Global Challenge.
- In 2017, the Hanson Robotics’ new interactive robot, Sofia (shown in Fig 1.3.e), reinforces concerns about risks of ongoing developments in robot science and a research team at Gallaudet University produced the type for a new robot which is capable of teaching sign languages to babies as young as six months. The device has the ability to determine the point at which the babies are ready to learn the language by sensing their emotional state [1].

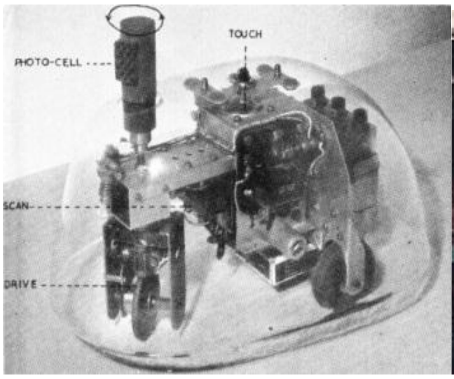


Fig 1.3.a Grey Walter's social robot. Fig 1.3.b Unimate (industrial robot).


Fig 1.3.c-General motors assembly plant. Fig 1.3.d Honda ASIMO.

Fig 1.3.e-Sofia (Hanson Robotics).

I.4 Types of Mobile Robots

I.4.1 Wheeled Robots

Wheeled robots are the simplest case of mobile robots; they comprise one or more driven wheels. Most wheeled robots designs require two motors to drive and steer (see Fig 1.4.a).

A special case of wheeled robots is the omnidirectional robot or “Mecanum Drive” which has four driven wheels with a special wheel design. [4]

All wheeled mobile robots have one disadvantage, which is that they require a sort of flat surfaces or a street to drive.

I.4.2 Tracked robots

They cannot navigate as accurately as wheeled robots. However they are more flexible and can navigate over rough terrains. Tracked mobile robots also need two motors to drive, one motor for each track (see Fig 1.4.b) [14].

I.4.3 Legged robots

Like tracked robots, legged robots can also navigate over rough terrains or climb up and down stairs. There are many designs for legged robots, depending on their legs number. [4]

Legged robots are the final category of land-based mobile robots, and more legs they have, the easier to balance, (see Fig 1.4.c). The biped robot is the most complex model of legged robots which require many techniques to be employed, in order to balance and to walk. More details will be discussed in Chapter II.

I.4.4 Flying robots

Flying robots like drones, helicopters and autonomous airplane models are more difficult than the previously discussed driving or walking mobile robots. This type requires a safety high level, more importantly to prevent endangering people on the ground and also because of the expensive equipment might be lost, (see Fig 1.4.d).

I.4.5 Underwater robots

Compared to other mobile robots designs, an underwater mobile robot requires an additional skill which is the water tightness. Especially for autonomous underwater mobile robots, this will be a challenge.

Underwater mobile robots can be used in various sub-sea surveillance and manipulation tasks for industry resource (see Fig 1.4.e). The disadvantage of this king of mobile robots is the communication method, which is sonar with a very low data rate; while other mobile robots can use any standard communication methods [14].

Fig 1.4.a: wheeled robot.

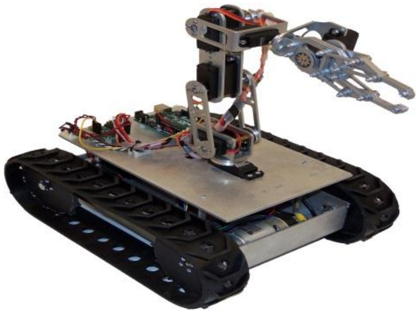


Fig 1.4.b: tracked robot.

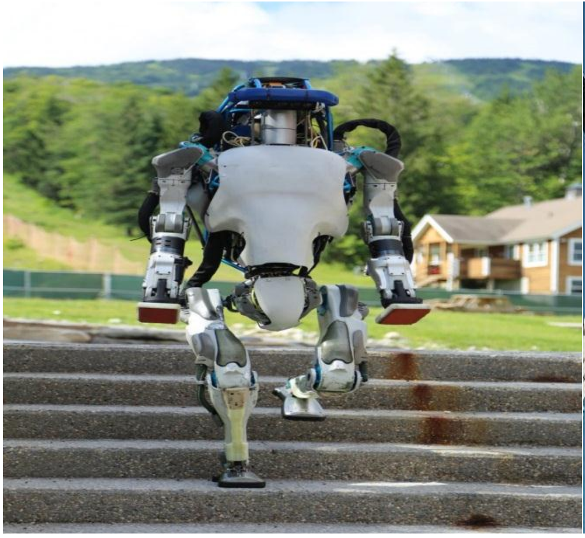


Fig 1.4.c: legged robot.

Fig 1.4.d: flying robot.

Fig 1.4.e: underwater robot.

I.5 Mobile Robots classification

For the classification of mobile robots categories; the useful and most interesting method is based on the practical applications of a robot. According to this method of classification we can classify the domestic robot application, medical application, service, military and space, entertainment, hobby and competition applications.

I.5.1 Domestic Robots

Domestic robots are designed to do many activities both inside and outside home (cleaning, ironing clothes and caring for babies), see Fig 1.5.a.

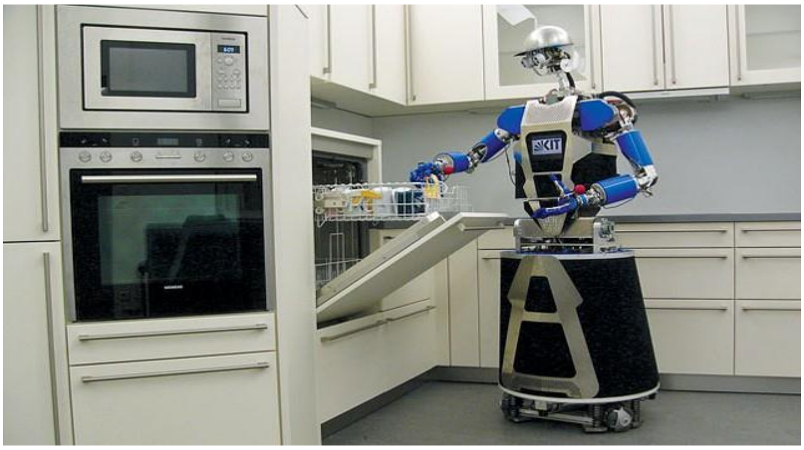


Fig 1.5.a: domestic robot.

I.5.2 Medical Robots

Robots are now designed and built to be used in variety medical applications like drawing of blood; exoskeletons for patients with spinal cord injuries. The most controversial applications are in the field of surgery, which can carry out many types of surgeries such as hip replacement and hysterectomies. [1]

I.5.3 Service Robots

Service robots may be classified into one of two categories: domestic robots [4], which are described earlier, and the industrial robots that are used in inaccessible or hazardous environments for humans, such as nuclear radiation or the search for disabling of land mines; which are very dangerous for humans to enter. Much of the work done in cleaning up after the Chernobyl nuclear power plant disaster of 1986 was done by robots [2].

I.5.4 military Robots

The national security and the highly developed character of modern warfare have resulted in the development of a host of robotic systems; these robots are typed under the military robots category, (see Fig 1.5.b). For the general public, the best known and most widely used robot of these systems are the flying robots called Drones, which are designed to attack targets of interest to a military unit after exploring and reporting on. The Goalkeeper CIWS is an example of a robot-controlled weapon system, which is a Dutch system introduced for the first time in 1979 [3].

Fig1.5.b- military service robot

I.5.5 Exploration Robots

Exploration of the Moon and Mars by humans is very difficult, and for this reason; space research is most obvious setting in which robots can be used, have been used and will continue to be used in the future. Researchers have been building devices which can travel and explore the outer space, even into its harsh conditions and as an example of the uses of space robots; in 2014 the Japanese Space Agency launched the first talking robot into the space. The robot was capable to respond to questions with no prerecorded responses but the responses were from its own internal vocabulary of words.

Fig 1.5.c: Exploration Robot.

I.5.6 Entertainment Robots

Entertainment robots have broadened to be available to the general public. Arguably, the leader in developing such robots has been the Walt Disney Company; by producing humanoid and animal-like robots in the 1960s (see Fig 1.5.d).

As an example of that event, an Abraham Lincoln talking robot that spoke to the audience about the great ideas of American history.

Fig1.5.d: Entertainment Robot.

I.5.7 Educational Robots

As participants in educational competitions, and hobbies is an increasingly popular application of robots. Often children or young adults, such activities are powerful tools in helping individuals. One of the most important examples of this field is the program known as FIRST ("For Inspiration and Recognition of Science and Technology") [1]. It was originally imagined by Dean Kamen in 1989, to encourage interest in robotics and their construction and use. The first global competition was in July 2017 in Washington, D.C, and teams from about 163 nations participated in the games.

I.6 First Humanoid Biped projects

I.6.1 Waseda

The first hardware humanoid robot was built by the humanoid robotics institute of the Waseda University. Teir current Wabian series started in 1968 and different versions of Wabot and Wabian series have been realized.

The latest model Wabian-RV which has 43 actuated and 8 passive joints is one of the most complex humanoids based on the sensing information, (see Fig 1.6.a). The whole body motion of the Wabian-RV is generated online and it can emotionally interact with humans by showing feelings like anger, sadness and happiness.

I.6.2 Honda Asimo

The success of the Honda humanoid series like P2, P3 and Asimo started in 1986. The latest model Asimo is one of the most advanced walking robots technologies and it disposes of a set of pre-calculated trajectories, (see Fig 1.6.b). The walking controller shows very fast and dynamic walking performance. The Asimo can recognize individual people by their faces and also react specifically to the person.

I.6.3 Sony QRio

As oppsed to the Asimo, the Sony QRio robot developed by industry is a small size robot focuses on implementing entertaining performances like singing or dancing synchronized between several robots, on the other side on creating an inexpensive platform, (see Fig 1.6.c).

This system accounts for external reaction forces, thus QRio can be taught to grab a ball and throw it away.

Fig 1.6.a: Wabian RIII.
Waseda University.

Fig 1.6.b: Honda Asimo.
Honda Motor Co.

Fig 1.6.c: Sony QRio.
Sony Corp.

I.6.4 HRP-2

The humanoid HRP-2 is developed by several Japanese research institutes and Kawada Industries Inc. The project is developed to provide a high quality research platform that can be turned into an industrial product, (see Fig 1.6.d).

A remarkable performance in a multitude of research problems has shown due to the large number of researchers working on this robot, like running or safe falling over and stepping over obstacles.

I.6.5 Johnnie

The humanoid Jonnie shown in (Fig 1.6.e) supported by the German Research Foundation (DFG), has been developed to enhance abilities in autonomous walking. The robot classifies obstacles into “possible to step on“, “possible to step over” and “not negotiable”. In order to reach the obstacle at a distance apt for negotiating it, the gait patterns are already adapted several steps in advance. [4]

I.6.6 UT-Theta

The university of Tokyo excels has developed the humanoid UT-Theta (shown in Fig.6.f) by some innovative ideas. The robot has double spherical hip joints and 6 rotation axes in order to maximize the motility of the robot to obtain a more natural looking gait and transferring the concept of passive walkers into actuated humanoids to mimic the human walking properties. [4]

Fig 1.6.d: HRP-2.
Kawada Industries.

Fig 1.6.e: Johnnie.
TU München.

Fig 1.6.f: UT-Theta.
University of Tokyo.

I.7 Conclusion

Over the history, humans have been interested in the concept of a robot and inventors have been led to create many robotic devices, from the simplest autonomous robot system of the traditional robotic devices and from the ancient history to the modern machines that are currently available in this century with a best-available program for the Artificial Intelligence.

One of the most commonly used mobile robots at this century is the biped robot or the humanoid robot.

CHAPTER II

II.1 Introduction

Walking is one of the most fundamental things we do as humans and when most people hear the term “Robot”, they think of biped walking robots (Humanoid robots) or android robots because of their resemblance to human beings. In this chapter we will discuss the different methods of walking mechanisms, trajectories and kinematics. Representing the humanoid moving mechanism of the biped robot using its legs and several facts that can be used to classify the walking approaches will be discussed.

Actually there are two walking modes:

- **Static balance:** The robot’s center of mass is at all times within the support area of its foot on the ground – or the combined support area of its two feet (convex hull), if both feet are on the ground.
- **Dynamic balance:** The robot’s center of mass may be outside the support area of its feet during a phase of its gait. In this chapter we will concentrate on dynamic balance methods [4],[5],[14].

II.2 Dynamic Balance Methods

II.2.1 Zero moment point (ZMP)

The implementation of this method requires the knowledge of all dynamic forces on the robot’s body plus all torques between the robot’s foot and ankle.
With all contact forces and all dynamic forces on the robot known, it is possible to calculate the “zero moment point” (ZMP), which is the dynamic equivalent to the static center of mass.

This knowledge of data can be determined by using accelerometers or gyroscopes within pressure sensors in the robot’s ankles [13],[4].

II.2.2 Inverted pendulum

The dynamic balance of the biped robot can be achieved by constantly monitoring the robot’s acceleration and adapting the corresponding leg movements because a biped walking robot can be modeled as an inverted pendulum[4],[14].

II.2.3 Neural Network

Neural networks can be used to achieve dynamic balance, but it needs all the sensors feedback used in the biped robot.

II.2.4 Genetic algorithms

The best performing robots are reproduced by using genetic algorithms for the next robots generation while a population of virtual robot is generated with initially random control settings. A mechanics system is required in this approach to evaluate each individual robot's performance and also several CPUs are required to evolve a good walking performance.

II.2.5 PID control

As similar to static balance, the classic PID control is used to control the robots leaning front/back and left/right. To achieve this leaning, the following parameters can be set to standard walking gate:

- Step length.
- Height of leg lift.
- Walking speed.
- Amount of forward lean of torso.
- Maximal amount of side swing.

II.2.6 Fuzzy control

For the dynamic balance, an adaptation of the PID control to replace the classic PID control by fuzzy control logic.

II.2.7 Artificial horizon

There is no need to use any of the kinetics sensors of other approaches in this innovative approach, but it needs a gray scale camera which is placed in the visual field of the robot to measure the robot's orientation.

A more powerful controller for image processing, there will be no need for the artificial horizon to be used to apply the same principle as the artificial horizon, just a general optical flow can be used to determine the robot' movements [13].

II.3 Kinematics

II.3.1 Forward Kinematics

The most commonly used convention for selecting reference frames to solve the forward kinematics problem or even inverse kinematics problem is the Denavit-Hartenberg (D-H) convention [5]. The Fig 2.3.1 shows the scenario that the right foot is on the floor while the left one is in the air.

In this case, the left leg is considered as the end-effector and that is a single-support phase with right leg support. The scenario is modeled by 13 links to indicate the location of the biped robot with respecting the frame 0. In general, we have 14 frames for the robot model (0 to 13). All the 13 links starts from link 1 to 13. The joint Oi is the point in space where links I and i+1 are connected. The i-th joint variable is the rotating angle θi.

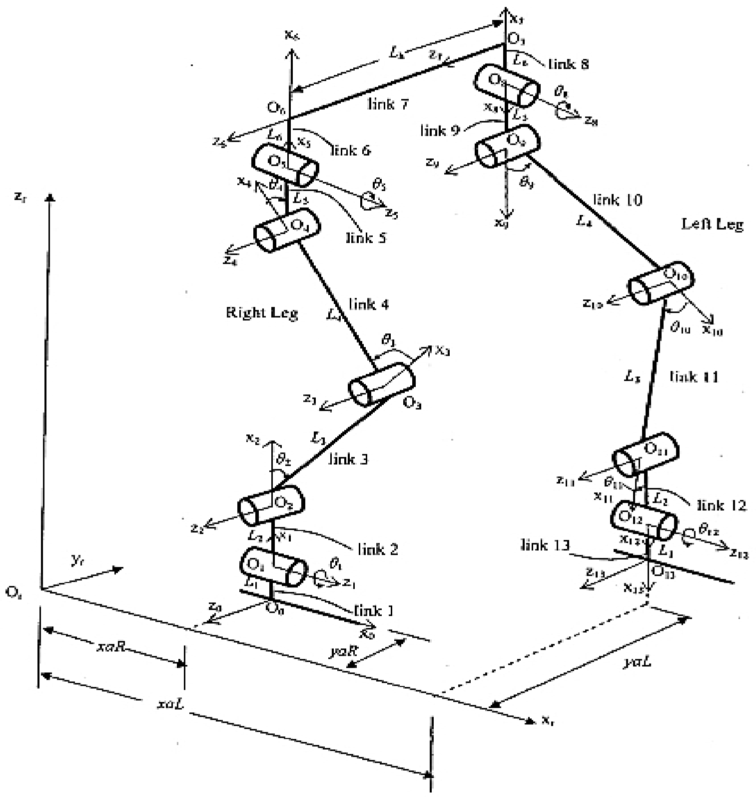


Fig 2.3.1-D-H representation of single support phase with right leg support.

The joint variables in this 10 DOF biped robot are θ1- θ5 and from θ8 to θ12, which are the rotating angles for joints O1-O5 and O8 to O12 respectively, (see Fig 2.3.1). Joint variables are represented in (Tab 2.3.1).

			Joint	Joint Variable
Hip	Left	Pitch	O_9	θ_9
		Roll	O_8	θ_8
	Right	Pitch	O_4	θ_4
		Roll	O_5	θ_5
Knee	Left	Pitch	O_{10}	θ_{10}
	Right	Pitch	O_3	θ_3
Ankle	Left	Pitch	O_{11}	θ_{11}
		Roll	O_{12}	θ_{12}
	Right	Pitch	O_2	θ_2
		Roll	O_1	θ_1

Tab 2.3.1: Joint variables list.

The Table 2.3.2 represents the D-H parameters list for the models in Fig 2.3.1.

Link	a_i	d_i	α_i	θ_i	A_i
1	L_1	0	90°	90°	A_1
2	L_2	0	-90°	θ_1	A_2
3	L_3	0	0°	θ_2	A_3
4	L_4	0	0°	θ_3	A_4
5	L_5	0	90°	θ_4	A_5
6	L_6	0	-90°	θ_5	A_6
7	0	$-L_h$	0°	0°	A_7
8	L_6	0	-90°	180°	A_8
9	L_5	0	90°	θ_8	A_9
10	L_4	0	0°	θ_9	A_{10}
11	L_3	0	0°	θ_{10}	A_{11}
12	L_2	0	-90°	θ_{11}	A_{12}
13	L_1	0	90°	θ_{12}	A_{13}

Tab 2.3.2: D-H parameters for single-support phase with right leg support.

Each homogeneous transformation Ai which transforms the coordinates of a point from frame i to frame i-1 can be represented as:

$$A_i = Rot_{z,\theta_i} Trans_{z,d_i} Trans_{x,a_i} Rot_{x,\alpha_i}$$
$$= \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & 0 \\ \sin\theta_i & \cos\theta_i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & a_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha_i & -\sin\alpha_i & 0 \\ 0 & \sin\alpha_i & \cos\alpha_i & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
$$= \begin{bmatrix} \cos\theta_i & -\sin\theta_i \cos\alpha_i & \sin\theta_i \sin\alpha_i & a_i \cos\theta_i \\ \sin\theta_i & \cos\theta_i \cos\alpha_i & -\cos\theta_i \sin\alpha_i & a_i \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(1).

The four quantities ai, di, αi and θi are the parameters of the link i and joint i. ai is the lengh, which is the distance along xi from Oi to the intersection of xi and Zi-1 axes. di is the offset, which is the distance along Zi-1 from Oi-1 to the intersection of xi and Zi-1 axes. αi is called the twist and it is the angle between Zi-1 and Zi measured about xi. Θi is the angle between xi-1 and xi meqsured about Zi-1.

The matrix that transforms the coordinates of a point from the frame j to the frame I is the transformation ${}^{j}_{i}T$

$${}^{j}_{i}T = A_{i+1} A_{i+2} \ldots A_{j-1} A_j, \quad if \quad i < j$$ (2).

For the 10 DOF biped robot, the transformation matrix that transforms the coordinates from the frame 0 to the reference frame (r with the origin Or) need to be obtained. It is determined as

$${}^{0}_{r}T = Rot_{x,\frac{\pi}{2}} Trans_{x,x_{aR}} Trans_{z,y_{aR}}$$
$$= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & x_{aR} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -y_{aR} \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & x_{aR} \\ 0 & 0 & -1 & y_{aR} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$ (3).

The forward kinematics for the single support phase with right leg support can be performed as in (4) and the transformation matrices can be calculated as in (5), where $(A_i)^{-1}$ is the inverse matrix of Ai.

$$\begin{cases} {}^{1}_{r}T = {}^{0}_{r}TA_1 \\ {}^{2}_{r}T = {}^{1}_{r}TA_2 \\ {}^{3}_{r}T = {}^{2}_{r}TA_3 \\ {}^{4}_{r}T = {}^{3}_{r}TA_4 \\ {}^{5}_{r}T = {}^{4}_{r}TA_5 \\ {}^{6}_{r}T = {}^{5}_{r}TA_6 \\ {}^{7}_{r}T = {}^{6}_{r}TA_7 \\ {}^{8}_{r}T = {}^{7}_{r}TA_8 \\ {}^{9}_{r}T = {}^{8}_{r}TA_9 \\ {}^{10}_{r}T = {}^{9}_{r}TA_{10} \\ {}^{11}_{r}T = {}^{10}_{r}TA_{11} \\ {}^{12}_{r}T = {}^{11}_{r}TA_{12} \\ {}^{13}_{r}T = {}^{12}_{r}TA_{13} \end{cases} \quad (4).$$

$$\begin{cases} {}^{12}_{r}T = {}^{13}_{r}T\left(A_{13}\right)^{-1} \\ {}^{11}_{r}T = {}^{12}_{r}T\left(A_{12}\right)^{-1} \\ {}^{10}_{r}T = {}^{11}_{r}T\left(A_{11}\right)^{-1} \\ {}^{9}_{r}T = {}^{10}_{r}T\left(A_{10}\right)^{-1} \\ {}^{8}_{r}T = {}^{9}_{r}T\left(A_{9}\right)^{-1} \\ {}^{7}_{r}T = {}^{8}_{r}T\left(A_{8}\right)^{-1} \\ {}^{6}_{r}T = {}^{7}_{r}T\left(A_{7}\right)^{-1} \\ {}^{5}_{r}T = {}^{6}_{r}T\left(A_{6}\right)^{-1} \\ {}^{4}_{r}T = {}^{5}_{r}T\left(A_{5}\right)^{-1} \\ {}^{3}_{r}T = {}^{4}_{r}T\left(A_{4}\right)^{-1} \\ {}^{2}_{r}T = {}^{3}_{r}T\left(A_{3}\right)^{-1} \\ {}^{1}_{r}T = {}^{2}_{r}T\left(A_{2}\right)^{-1} \\ {}^{0}_{r}T = {}^{1}_{r}T\left(A_{1}\right)^{-1} \end{cases} \quad (5).$$

${}^{13}_{r}T$ can be determined as

$$ {}^{13}_{r}T = Rot_{x,\frac{\pi}{2}} Rot_{z,-\frac{\pi}{2}} Trans_{y,x_{aL}} Trans_{z,-y_{aL}} \quad (6)$$

$$= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & x_{aL} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -y_{aL} \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & x_{aL} \\ 0 & 0 & -1 & y_{aL} \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

II.3.2 Inverse Kinematics

The inverse kinematics for the 10 DOF biped robot is very complicated, and for a given desired position and orientation for the end-effector of the robot, a set of joint variables that achieve the desired position and orientation can be determined by the inverse kinematics.

- **Calculate θ2 θ3 and θ4**

The x, y and z coordinates for the right ankle joint O2 and right hip joint O4 are determined as follow

$$\text{Right Ankle: } \begin{cases} x_{O_2} = x_{aR} \\ y_{O_2} = y_{aR} \\ z_{O_2} = l_{an} \end{cases} \quad (7).$$

Right Hip: $\begin{cases} x_{O_4} = x_{aR} - L_3 \sin\theta_2 - L_4 \sin(\theta_2 + \theta_3) \\ y_{O_4} = y_{aR} \\ z_{O_4} = l_{an} + L_3 \cos\theta_2 + L_4 \cos(\theta_2 + \theta_3) \end{cases}$ (8).

Where lan=L1+L2.

From the equations (7) and (8) we have :

$$\begin{cases} x_{O_4} - x_{O_2} = -(L_3 + L_4 \cos\theta_3)\sin\theta_2 - L_4 \sin\theta_3 \cos\theta_2 \\ z_{O_4} - z_{O_2} = (L_3 + L_4 \cos\theta_3)\cos\theta_2 - L_4 \sin\theta_3 \sin\theta_2 \end{cases} \quad (9).$$

By calculating (xO4 –xO2) + (zO4 –zO2), cosθ3 can be calculated as

$$\cos\theta_3 = \frac{(x_{O_4} - x_{O_2})^2 + (z_{O_4} - z_{O_2})^2 - L_3^2 - L_4^2}{2L_3L_4} \quad (10).$$

θ3 is 0≤θ3<π range from Fig.4.1 and Table.4.2, so that

$$\sin\theta_3 = \sqrt{1 - \cos^2\theta_3}$$

Then θ3 can be calculated as:

$$\theta_3 = \tan^{-1}\left(\frac{\sin\theta_3}{\cos\theta_3}\right)$$

The solution of cos θ2 and sin θ2 is obtained from (9) as follow:

$$\begin{cases} \sin\theta_2 = -\dfrac{(x_{O_4} - x_{O_2})(L_3 + L_4\cos\theta_3) + (z_{O_4} - z_{O_2})L_4 \sin\theta_3}{L_3^2 + L_4^2 + 2L_3L_4\cos\theta_3} \\ \cos\theta_2 = \dfrac{(z_{O_4} - z_{O_2})(L_3 + L_4\cos\theta_3) - (x_{O_4} - x_{O_2})L_4 \sin\theta_3}{L_3^2 + L_4^2 + 2L_3L_4\cos\theta_3} \end{cases} \quad (11).$$

Then θ2 can be determined by (11.a).

$$\theta_2 = \tan^{-1}\left(\frac{\sin\theta_2}{\cos\theta_2}\right) \quad (11.a).$$

The geometric relation among joint variables θ2, θ3 and θ4 are shown in Fig 2.3.2 and according to Fig2.3.1 and Table 2.3.2, θ4 can be determined by
θ4 = - θ2 - θ3.

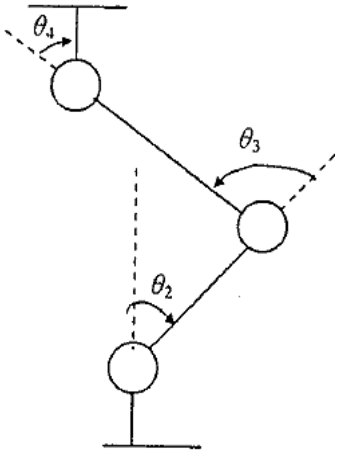


Fig 2.3.2-Geometric relation among θ2, θ3 and θ4.

- **Calculate θ9, θ10 and θ11**

The x, y and z coordinates for the left ankle joint O11 and left hip joint O9 are determined as follow

Left Ankle:

$$\begin{cases} x_{O_{11}} = x_{aR} - L_3\sin\theta_2 - L_4\sin(\theta_2+\theta_3) + L_4\sin(\theta_2+\theta_3+\theta_4+\theta_9) \\ \qquad + L_3\sin(\theta_2+\theta_3+\theta_4+\theta_9+\theta_{10}) \\ y_{O_{11}} = y_{aR} + L_h \\ z_{O_{11}} = L_1 + L_2 + L_3\cos\theta_2 + L_4\cos(\theta_2+\theta_3) - L_4\cos(\theta_2+\theta_3+\theta_4+\theta_9) \\ \qquad - L_3\cos(\theta_2+\theta_3+\theta_4+\theta_9+\theta_{10}) \end{cases} \quad (12).$$

$$\text{Left Hip:}\quad \begin{cases} x_{O_9} = x_{aR} - L_3 \sin\theta_2 - L_4 \sin(\theta_2+\theta_3) \\ y_{O_9} = y_{aR} + L_h \\ z_{O_9} = L_1 + L_2 + L_3\cos\theta_2 + L_4\cos(\theta_2+\theta_3) \end{cases}$$ (13).

And
$$\begin{cases} x_{O_9} - x_{O_{11}} = -(L_4 + L_3\cos\theta_{10})\sin(\theta_2+\theta_3+\theta_4+\theta_9) - L_3\sin\theta_{10}\cos(\theta_2+\theta_3+\theta_4+\theta_9) \\ z_{O_9} - z_{O_{11}} = (L_4 + L_3\cos\theta_{10})\cos(\theta_2+\theta_3+\theta_4+\theta_9) - L_3\sin\theta_{10}\sin(\theta_2+\theta_3+\theta_4+\theta_9) \end{cases}$$

(14).

As a result, we found:

$$(x_{O_9} - x_{O_{11}})^2 + (z_{O_9} - z_{O_{11}})^2 = L_3^2 + L_4^2 + 2L_3L_4\cos\theta_{10}$$ (15).

Therefore,(-π<θ10≤0),

$$\theta_{10} = \tan^{-1}\left(\frac{\sin\theta_{10}}{\cos\theta_{10}}\right),$$

$$\text{where,}\quad \begin{cases} \cos\theta_{10} = \dfrac{(x_{O_9} - x_{O_{11}})^2 + (z_{O_9} - z_{O_{11}})^2 - L_3^2 - L_4^2}{2L_3L_4} \\ \sin\theta_{10} = -\sqrt{1-\cos^2\theta_{10}} \end{cases}$$

From equation (14), θ2+ θ3+ θ4 + θ9 can be solved as

$$\begin{cases} \sin(\theta_2+\theta_3+\theta_4+\theta_9) = -\dfrac{(x_{O_9} - x_{O_{11}})(L_4 + L_3\cos\theta_{10}) + (z_{O_9} - z_{O_{11}})L_3\sin\theta_{10}}{L_3^2 + L_4^2 + 2L_3L_4\cos\theta_{10}} \\ \cos(\theta_2+\theta_3+\theta_4+\theta_9) = \dfrac{(z_{O_9} - z_{O_{11}})(L_4 + L_3\cos\theta_{10}) - (x_{O_9} - x_{O_{11}})L_3\sin\theta_{10}}{L_3^2 + L_4^2 + 2L_3L_4\cos\theta_{10}} \end{cases}$$ (16).

Which means that:

$$\theta_9 = -\theta_2 - \theta_3 - \theta_4 + \tan^{-1}\left(\frac{\sin(\theta_2+\theta_3+\theta_4+\theta_9)}{\cos(\theta_2+\theta_3+\theta_4+\theta_9)}\right)$$ (17)

According to Fig 2.3.1 and the Table 2.3.2, Fig 2.3.3 represents the geometric relation among joint variables θ9, θ10 and θ11

Θ11 can be solved as follow: θ11 = - θ9 - θ10 .

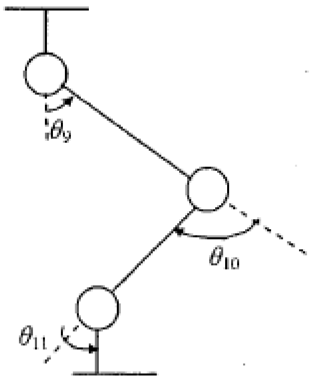


Fig 2.3.3-Geometric relation among θ9, θ10 and θ11.

II.4 Walking Trajectory

For each joint, the desired trajectory has to be properly designed for a biped robot to be able to walk stably. The existing research results show that the biped robot can walk stably if the ZMP is maintained within the contact area between the feet and the ground.

There are two main methods for walking pattern planning. One is to design the desired ZMP trajectory and then generate the joint trajectories. The second method based on designing the desired joint trajectories and the test if the desired joint trajectories result in a stable walking pattern by calculating the ZMP [5],[13],[14].

The biped robot walking is a periodic motion as similar to human walk. Two phases are used to a complete walking cycle: a double support phase and a single support phase. The first one is the period during which both feet are in contact with the ground, while the single support phase is the period during one foot is on the ground stationary and the other foot swings from rear to the front.

The double support phase is designed so that the weight is shifted to the support leg in order to avoid the biped robot from falling.

The walking cycle divided into the following movements to facilitate the design of walking trajectories:

- Shift the weight to the left leg and stay there for a short period of time.
- Lifting the right leg and swing it forward and landing it on the ground then stay there for a short period of time.

- Shift the weight back and stay for a short period of time.
- Shift the weight towards the right leg for a short period of time.
- Lift the left leg and swing it forward, land it on the ground for a short period of time.
- Shift the weight back and stay for a short period of time [5],[12].

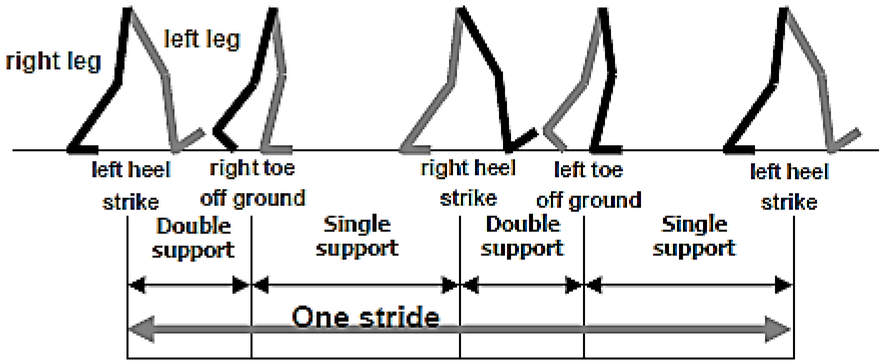


Fig 2.4.1-walking gait cycle.

II.4.1 Third Order Spline Interpolation:

The main advantage of spline interpolation is the stability and calculation simplicity. This method can be used to find a polynomial, which goes exactly through the given points.

In this thesis, we will use the third order spline interpolation, because of its ability of generating the smooth curve for the given points and possessing the property of: the first and derivatives are continuous and the first derivatives are zero at the start and end points.

For three given points, point 1 (t1, v11), point 2 (t2, v12) and point 3 (t3, v13), the curve p (t) which goes through these points is:

$$p(t)=\begin{cases} v_{11} & t=t_1 \\ v_{12} & t=t_2 \\ v_{13} & t=t_3 \end{cases}$$ (17).

By using the third order interpolation method, the curve p (t) is composed of two parts, p1 is the curve from point 1 to point 2 and p2 is the curve from point 2 to point 3, they can be expressed as

$$\begin{cases} p_1(t)=c_1+c_2(t-t_1)+c_3(t-t_1)^2+c_4(t-t_1)^3, & t_1\le t\le t_2 \\ p_2(t)=c_5+c_6(t-t_2)+c_7(t-t_2)^2+c_8(t-t_2)^3, & t_2\le t\le t_3 \end{cases}$$ (18).

We can find that:

$$\begin{cases} c_1 = p_1(t_1) = v_{11} \\ c_5 = p_2(t_2) = v_{12} \end{cases} \quad (19).$$

To determine the rest of coefficients, the following conditions can be used:

- p1 passes through (t1, v12) and the polynomial p2 passes through (t3, v13):

$$\begin{cases} f_1 = c_2 h_1 + c_3 h_1^2 + c_4 h_1^3 \\ f_2 = c_6 h_2 + c_7 h_2^2 + c_8 h_2^3 \end{cases} \quad (20).$$

Where h1 = t2 –t1, h2 =t3 –t2, f1 = p1 (t2) – p1 (t1), f2 = p2 (t3) – p2 (t2).

- The first derivatives match at the middle points:

$$\left.\frac{dp_1(t)}{dt}\right|_{t=t_2} = \left.\frac{dp_2(t)}{dt}\right|_{t=t_2}$$

$$c_2 + 2c_3 h_1 + 3c_4 h_1^2 - c_6 = 0 \quad (21).$$

- The second derivatives match at the middle points :

$$\left.\frac{dp_1^2(t)}{dt^2}\right|_{t=t_2} = \left.\frac{dp_2^2(t)}{dt^2}\right|_{t=t_2}$$

$$2c_3 + 6c_4 h_1 - 2c_7 = 0 \quad (22).$$

- The first derivatives vanish at the end points:

$$\left.\frac{dp_1(t)}{dt}\right|_{t=t_1} = 0, \quad \left.\frac{dp_2(t)}{dt}\right|_{t=t_3} = 0$$

$$\begin{cases} c_2 = 0 \\ c_6 + 2c_7 h_2 + 3c_8 h_2^2 = 0 \end{cases} \quad (23).$$

The coefficients ci can be calculated from the equations (19) to (23) as:

$$A\begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \\ c_6 \\ c_7 \\ c_8 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ f_1 \\ 0 \\ f_2 \\ v_{11} \\ v_{12} \end{bmatrix} \qquad A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 2h_1 & 3h_1^2 & 0 & -1 & 0 & 0 \\ 0 & 0 & 2 & 6h_1 & 0 & 0 & -2 & 0 \\ 0 & h_1 & h_1^2 & h_1^3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 2h_2 & 3h_2^2 \\ 0 & 0 & 0 & 0 & 0 & h_2 & h_2^2 & h_2^3 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}$$

The coefficient ci can be determined as

$$\begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \\ c_6 \\ c_7 \\ c_8 \end{bmatrix} = A^{-1}\begin{bmatrix} 0 \\ 0 \\ 0 \\ f_1 \\ 0 \\ f_2 \\ v_{11} \\ v_{12} \end{bmatrix} = \begin{bmatrix} v_{11} \\ 0 \\ \frac{1.5}{h_1(h_1+h_2)}\left(2f_1 + \frac{f_1h_2}{h_1} - \frac{f_2h_1}{h_2}\right) \\ -\frac{0.5}{h_1^2(h_1+h_2)}\left(4f_1 + \frac{f_1h_2}{h_1} - 3\frac{f_2h_1}{h_2}\right) \\ v_{12} \\ \frac{1.5}{h_1+h_2}\left(\frac{f_1h_2}{h_1} + \frac{f_2h_1}{h_2}\right) \\ -\frac{3}{h_1+h_2}\left(\frac{f_1}{h_1} - \frac{f_2}{h_2}\right) \\ -\frac{0.5}{h_2^2(h_1+h_2)}\left(\frac{f_2h_1}{h_2} - 3\frac{f_1h_2}{h_1} + 4f_2\right) \end{bmatrix} = \begin{bmatrix} v_{11} \\ 0 \\ 1.5c_a\left(2a_{11} + a_{12} - a_{21}\right) \\ -0.5c_a\left(4a_{11} + a_{12} - 3a_{21}\right)/h_1 \\ v_{12} \\ 1.5c\left(a_{12} + a_{21}\right) \\ -3c\left(M_1 - M_2\right) \\ -0.5c_b\left(a_{21} - 3a_{12} + 4a_{22}\right)/h_2 \end{bmatrix}$$

$$\text{where} \begin{cases} a_{11} = f_1, & a_{22} = f_2 \\ M_1 = \dfrac{f_1}{h_1}, & M_2 = \dfrac{f_2}{h_2} \\ a_{12} = M_1h_2, & a_{21} = M_2h_1 \\ c = \dfrac{1}{h_1 + h_2}, & c_a = \dfrac{c}{h_1}, \quad c_b = \dfrac{c}{h_2} \end{cases}$$

II.4.2-Ankle Trajectories:

The position of the ankle on the leg is changing with time during forward swing. The movement of the ankle can be illustrated in Fig 2.4.2

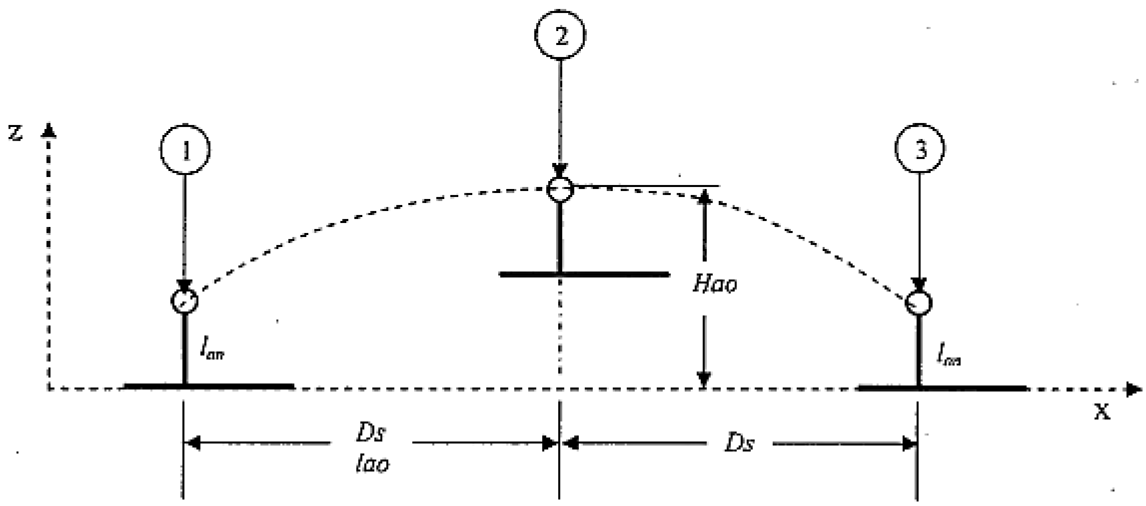


Fig 2.4.2-Walking parameters for ankle.

II.4.3 Hip Trajectories:

For simplicity, the y coordinate is assumed to be constant and only the x and z coordinates are considered for the hip trajectory design. The Fig 2.4.3 shows the walking parameters for the hip trajectory [5].

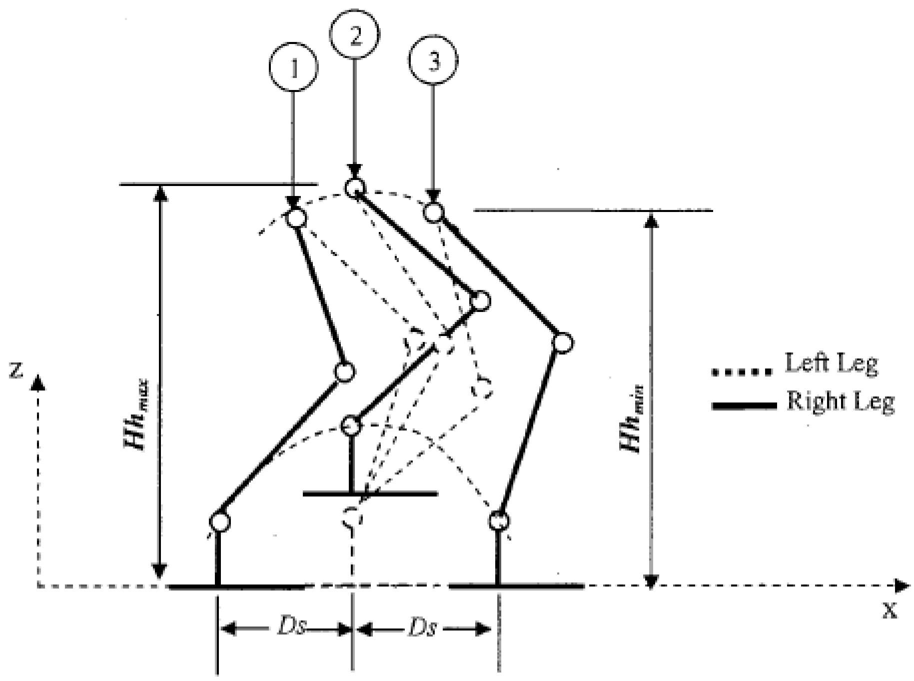


Fig 2.4.3-Hip walking parameters.

II.5 Conclusion

In walking mobile robots study, the more legged robot has the advantage of stability. This gives the static balance to the robot while walking like in six legged robots or even four legged robots but this is not the case in biped walking robots which are using dynamic balance. Biped walking robots are the most difficult to balance. Static balance can be achieved for the biped walking robots if the feet are relatively large but this is not the case in human-like robots, which require dynamic balance for walking.

The main focus of the humanoid robot study is to maintain and achieve a human-like motion and walking stability during walking gait cycle.

CHAPTER III

III.1 Introduction

Generally, robots are built to conceive the ideas of human being and take the modernization to an advanced level. In this chapter, we will try to develop a mechanism that will balance the biped robot structure while it tries to walk. Due to keep the complexity level low, very commonly found components where firstly chosen for this operation. A simple and flexible implementation of this mechanism is also one of the prime objectives. To match with this trend, a simple and easily understandable process of walking should now be developed.

III.2 Project Description

The structure was basically designed to provide the joints necessary for walking. As the purpose is to mimic the walking nature of human, so all the necessary joints with relevant degrees of freedom was provided. The locomotion was achieved through the actuators which consist of servomotor, gears and holders. The structural designs are discussed first followed by the working principle of all the devices and at the end prototyping is discussed. A balancing biped walking model can be presented that response intelligently for the walking process. This model will have the provision to be edited and adapted to different type of robot structure as per requirement.

III.3 Robot Prototype Design

In this project, the biped walking robot of 10 DOF is composed of mechanical design and electrical design. The block diagram shown in figure 3.1 represents the composition of the biped walking robot. The robot prototype composed of two basic parts:

Hardware which contains the materials used to construct and build the robot design, and software part which consists of the programming and simulation programs. The two parts are complementary in this biped walking robot project.

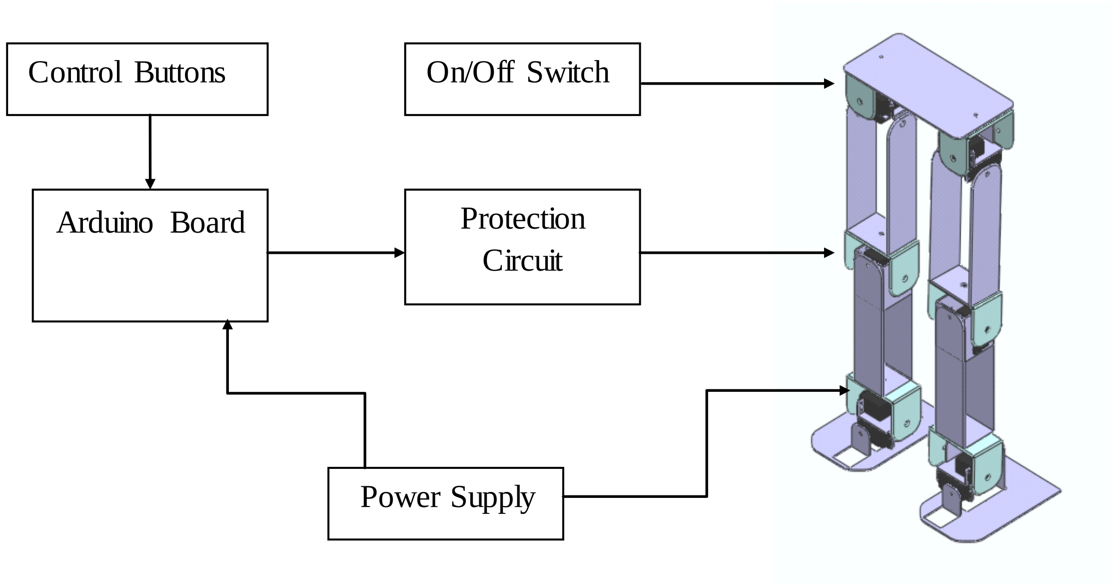


Fig 3.1: Block Diagram of the 10 DOF Biped Robot.

III.3.1 Mechanical Design

The robot's structure should be lightweight, simple and easy to assemble, for this reason a thin Aluminum is chosen to structure the 10 DOF biped robot materials because it is easy to machine to the desired shape and also light. The design of the biped robot is designed so that it can hold the whole control circuit board.

The biped robot has two legs and a flat surface so that it can hold the circuit board. Each leg of the robot is composed of two ankle joints, one knee joint and two hip joints.

The table 3.1 represents a comparison between the different joints of human leg's degrees of freedom and this biped walking robot [16].

Joint name	DOF(prototype)	DOF(human)
Ankle	2	2
Knee	1	1
Hip	2	3

Tab3.1: Degree of freedom of different joints of human.

The structure of the biped robot must contain adequate degrees of freedom in the same directions as per the human leg. It is to be noted that not all the joints are targeted for implementation. Only the joints necessary for performing and viewing the balancing logic at work are to be implemented in the prototype. For a 3D visualization of DOF of the robot (See Fig.3.1.1 and Fig3.1.2).

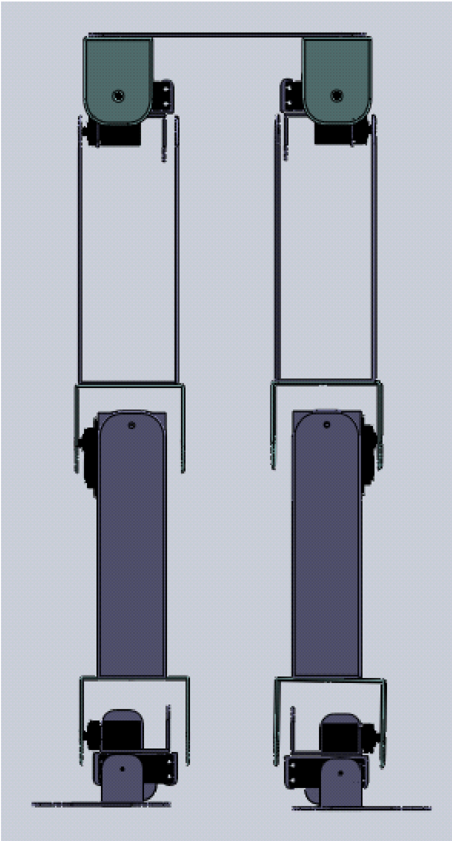


Fig3.1.1: 3D front view of the robot.

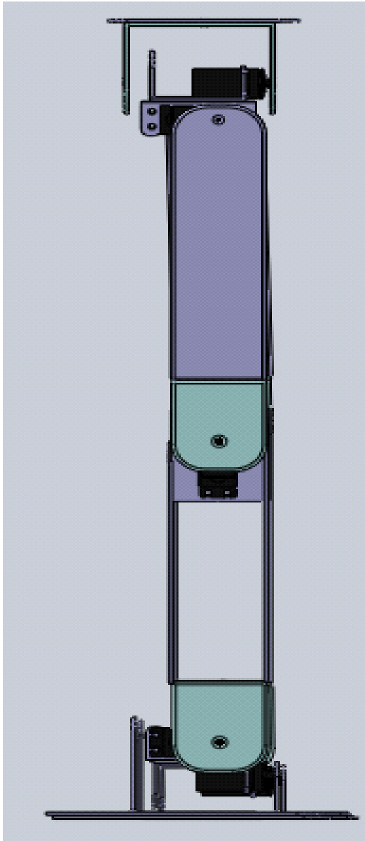


Fig 3.1.2: 3D side view of the robot

The 3D design of the biped walking robot was designed by the SolidWorks simulation software. To do the mechanical design of this biped walking robot, the same simulation software (SolidWorks) is used for that with the real parts dimensions. See Appendix for the detailed mechanical drawings of the robot parts.The figures 3.1.a to 3.1.f shows the real parts of the biped robot with real dimensions.

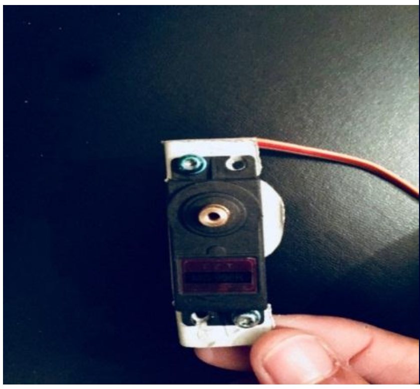


Fig 3.1.a: Placing servomotor.

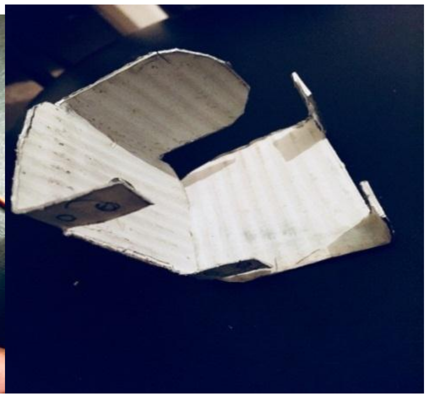


Fig 3.1.b: The ankle joint.

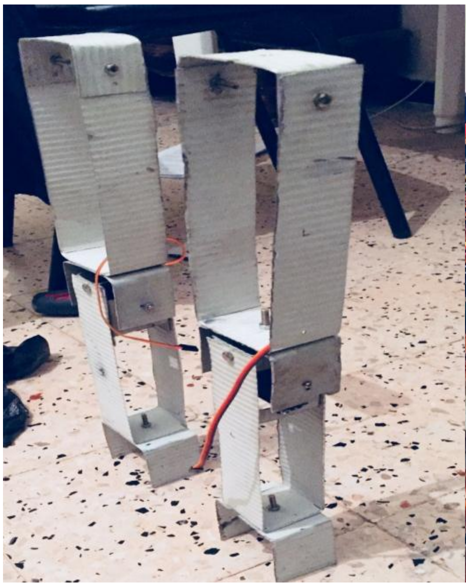


Fig 3.1.c: hip and knee links. Fig 3.1.d: Hip, knee and ankle links.

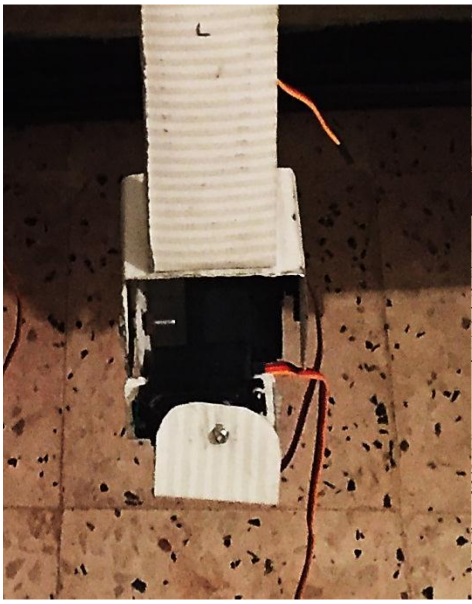


Fig 3.1.e: ankle joint servomotors. Fig 3.1.f: total robot after assembling.

The figures Fig3.1.3, Fig3.1.4 and Fig3.1.5 represent the robot knee, hip and ankle joints servomotors placement.

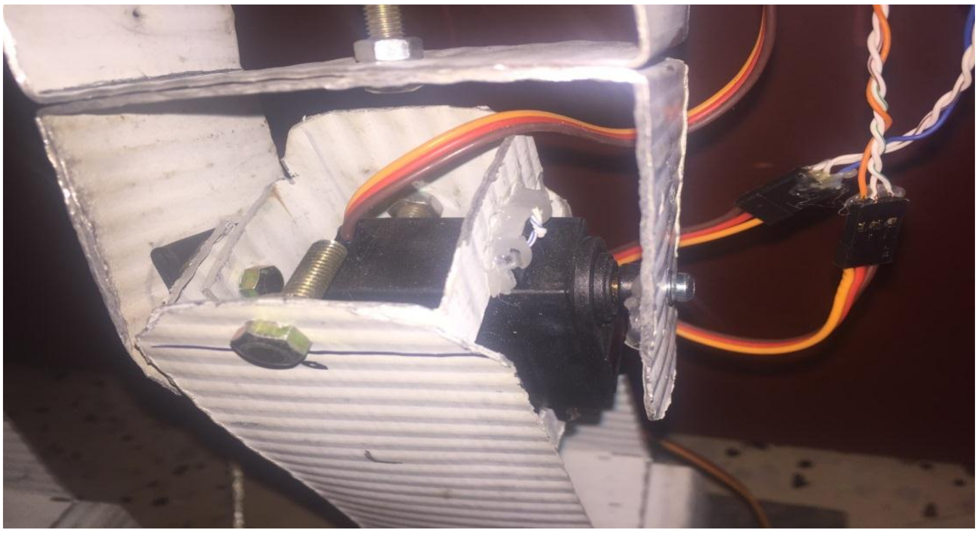


Fig 3.1.3: The knee joint.

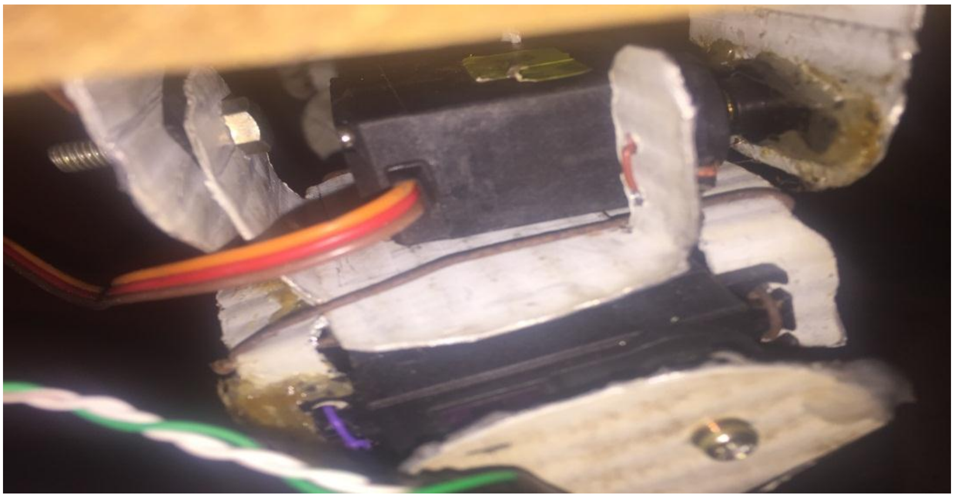


Fig 3.1.4: The hip joints.

Fig3.1.5: The ankle joints.

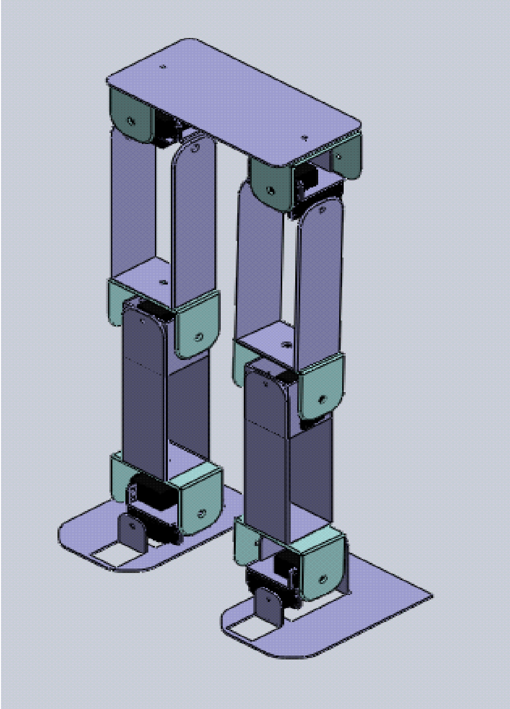
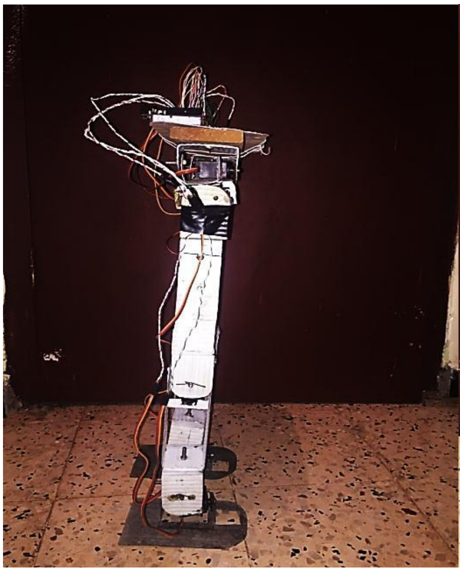


Fig3.2: the total robot 3D structure design.

The height of the robot prototype is 524.72 mm, with a width of 281.92 mm and a depth of 160.01 mm. See Appendix for the detailed mechanical design drawings of the robot prototype structure. The structural design meets all the requirements for mimicking the human leg and the biped walking. It has all the required degrees of freedom mentioned earlier. The figures 3.2.1 and 3.2.2 show the real structure design of the biped walking robot with all the required 10 DOF.



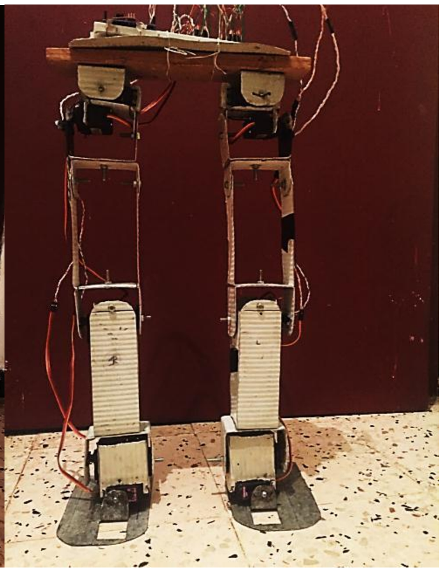


Fig3.2.1: Side view for the Biped Robot Fig3.2.2: Front view for the Biped Robot

III.3.2 Electrical Design

The Robot's detailed schematic (Fig.5.2) and parts list is included at the end of this topic.

III.3.2.1 Microcontroller

Microcontroller is very similar to a microprocessor, except that it is designed specifically for use in embedded systems. Microcontrollers typically include an integrated CPU, memory (a small amount of RAM, ROM, or both), and other peripherals on the same chip. Common examples are Microchip's PIC, the 8051, Intel's 80196, and Motorola's 68HCxx series [6].

The Atmega 328 microcontroller is used to control all sub-systems and make the decision. It works at a clock of 16MHz crystal. The figure (Fig.3.2.3) shows the Atmega 328 microcontroller with its peripherals in the Arduino Uno board, which is used in this biped walking robot.

Fig.3.2.3: The Arduino Uno board.

III.3.2.2 Servomotors

A motor with a shaft that can be positioned to specific angular positions, called a servo for short. As long as the coded signal exists on the input line, the servo will maintain the angular position of the shaft. As the coded signal changes, the angular position of the shaft changes. In practice, servos are used in radio-controlled airplanes to position control surfaces like the elevators and rudders. They are also used in radio-controlled cars, puppets, and of course, robots. Servomotors use a variable pulse–length input to control their position [6].

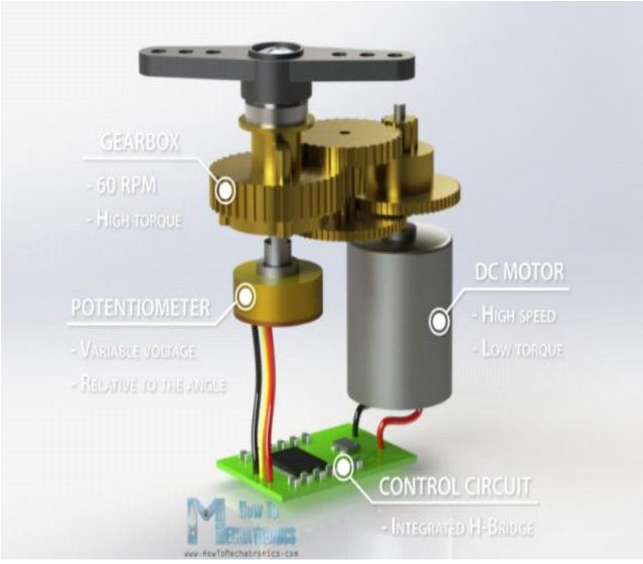


Fig.3.2.4: Metal gear servomotor parts.

The High-Torque MG996R Digital Servo features metal gearing resulting in extra high 10kg stalling torque in a tiny package.

The MG996R is essentially an upgraded version of the famous MG995 servo, and features upgraded shock-proofing and a redesigned PCB and IC control system that make it much more accurate than its predecessor [7]. The ten servomotors which are used in this biped walking robot are controlled by the microcontroller (Atmega 328) of the Arduino Uno board previously defined.

III.3.2.3 Optical-Isolator

In some references it is also called an optoisolator or optocoupler. An optical isolator is an IC used in many applications such as isolating high voltages from logic levels, and reducing noise between circuits. The optical isolators provide extremely high levels of isolation by coupling signals via light, see (Fig3.2.5).

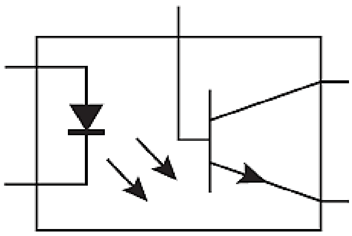


Fig3.2.5: Optical-isolator. The LED illuminates the light-sensitive transistor.

The optical isolator used in this project circuit is the PC817 optoisolator IC. The main function of this component in the circuit is to block the high voltages and voltage transients, so that a surge in one part of the system will not disrupt the rest of the system parts [6]. you can find more information about the PC817 optoisolator in its Datasheet.

III.3.3 Robot Structure

The structure is well within the dimensions of the firstly propose structure and has a weight under 1.5kg (without circuitry and power source).

The main board of the robot's locomotion operation as we have discussed at the beginning of this chapter is the Arduino Uno board using the Atmega 328 microcontroller to control the servomotors used for the joint movements. The robot has in total 10 servomotors, which will require 10 pins to achieve the rotation of each motor using protection circuit for the microcontroller board which is the optoelectronic component (optocoupler) which is the PC817 for each servomotor. The right leg servomotors are connected to the Arduino board pins IO4-IO8, while the left leg servomotors are connected to the board from pin IO9 to IO13. All the servo motors have their own power supply and are separated from the microcontroller board via the optoisolator ICs. The circuit shown in Fig.3.3 represents the total robot circuit.

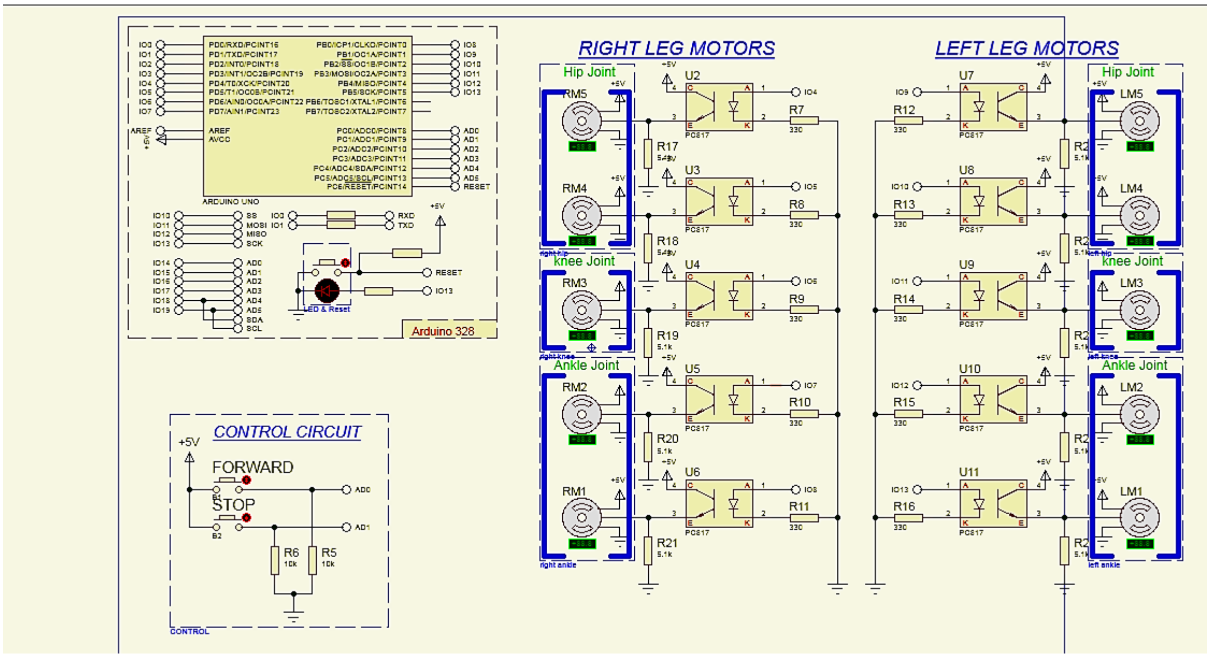


Fig.3.3: control circuit board with servomotors implementation.

Item	Description	Designator
1	microcontroller	Arduino Uno board
2	Metal gear servomotor MG996R	RM1-RM5, LM1-LM5
3	10 Kohm Resistor	R5,R6
4	PC817 Optoisolator	U2-U11
5	5.1Kohm Resistor	R17-R26
6	330 Ohm Resistor	R7-R16
7	Push Button	B1 and B2

Tab3.3: The main circuit parts.

Item	Description	Quantity	Price per part
1	Arduino Uno board	x1	3200DA
2	MG996R Servomotor	x10	1900DA
3	PC817 Optoisolator	x10	
4	10Kohm Resistor	x2	-
5	5.1Kohm Resistor	x10	-
6	330 Ohm Resistor	x10	-
		Total:	22200DA

Tab 3.4: Robot parts with price.

III.3.4 Software

After the hardware parts system are completed and implemented; now we will need to implement the software system to bring life to the microcontroller and to the whole robot system body parts. The software is the part of the system which doesn't need to be 100% working until long after the hardware ships, if ever, while he basic principle of this software is based on source code (C++) which uses the multitasking method[16],[6].

Multitasking is the ability to execute multiple separate tasks in a fashion that is seemingly simultaneous [6]. The main program is represented by the diagram (Fig 3.4.1).

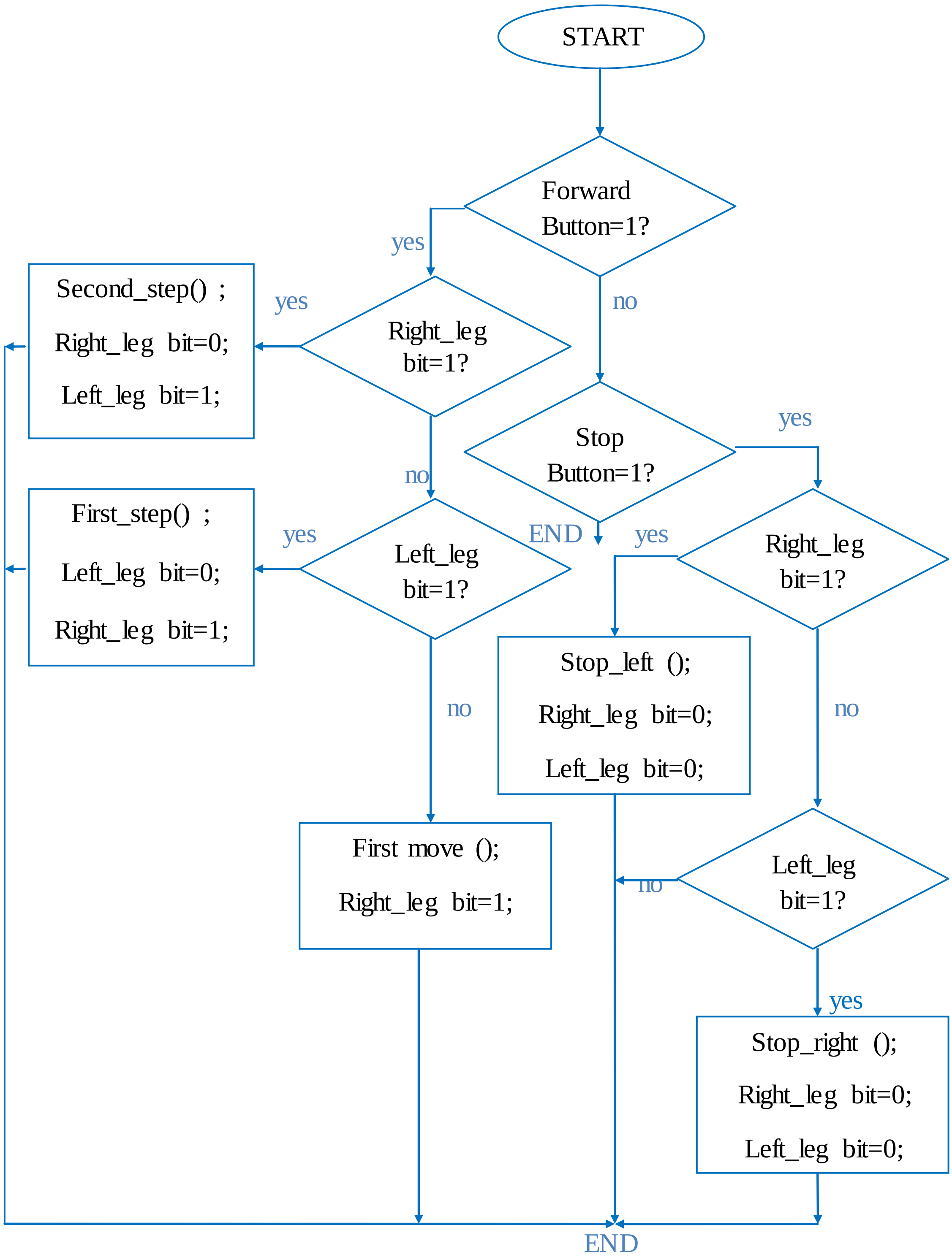


Fig 3.4.1: The main program Algorithm.

When the main program starts, it needs to check the status of the command as discussed in block diagram in hardware design (Fig3.1). As we have seen in the hardware description of the biped robot system, there are two switch buttons for the control of the robot movements. Each button has its own Function subsystem.

If one of the two buttons has pressed, the main program will automatically save its context and goes to do the corresponding process and returns to the main program when the subsystem ends. When the moving forward process starts, there are two bits to check; one for the right leg (Right_leg bit) and the other one for the left leg (Left_leg bit). These two bits are wsed to check which leg is in the front (the previous status) to know what the next step is.

If the Right_leg bit is high, the subsystem calls the corresponding function (Second_step()) to move the next leg, and the same process is for the left leg (as shown in Fig3.4.1). The two functions (First_step() and Second_step()) contain the joints angles movements.

To stop the robots walking movement, the corresponding subsystem will automatically breakpoint the main program to execute this subsystem when the stop button is pressed.

The main goal of this program software is to make the robot hardware take human like steps. For that it is required to design some movement pattern for each joint [17] to enable the robot to walk in biped motion. The movement should be calculated so that the robot doesn't lose its balance or falls down while it tries to walk; and these movements will be done in series (one after one another), to make the robot takes successive steps.

The main program was created in C++ language using the Arduino IDE software and the Proteus 8 simulator. When the program was created, checked and debugged in Arduino IDE, it is implemented to the circuit board in Proteus 8. After simulation is done well, the program is transferred to the Arduino Uno board to see the real biped robot walking movements.

III.4.1 Arduino IDE

The Arduino Integrated Development Environment - or Arduino Software (IDE) - contains a text editor for writing code, a message area, a text console, a toolbar with buttons for common functions and a series of menus. It connects to the Arduino and Genuino hardware to upload programs and communicate with them [8].

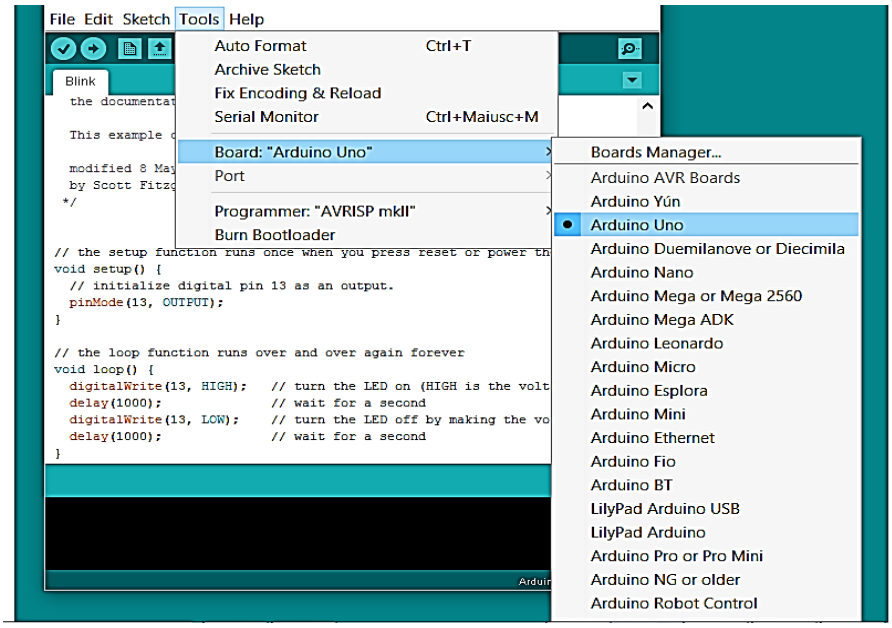


Fig 3.4.2: Arduino IDE interface. Selecting an Arduino Uno board

III.4.2 Proteus 8

Proteus 8 is a single application with many service modules offering different functionality (schematic capture, PCB layout, etc.). The wrapper that enables all of the various tools to communicate with each other consists of three main parts [9].

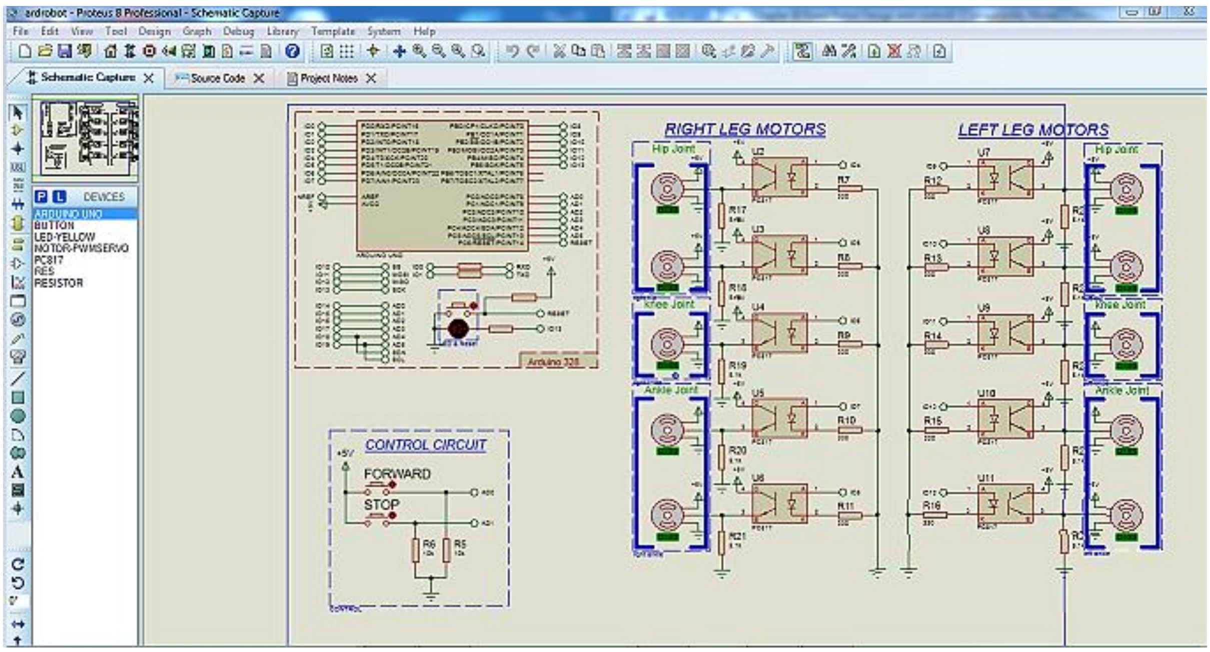


Fig 3.4.3: Proteus 8 software simulator interface.

III.4.3 SolidWorks

SOLIDWORKS, developed by the SOLIDWORKS Corporation, USA, is a feature based, parametric solid modeling mechanical design and automation software. SOLIDWORKS is the first CAD package to use the Microsoft Windows graphic user interface. The use of the drag and drop (DD) functionality of Windows makes this CAD package extremely easy to learn. The Windows graphic user interface makes it possible for the mechanical design engineers to innovate their ideas and implement them in the form of virtual prototypes or solid models, large assemblies, subassemblies, and detailing and drafting[18].

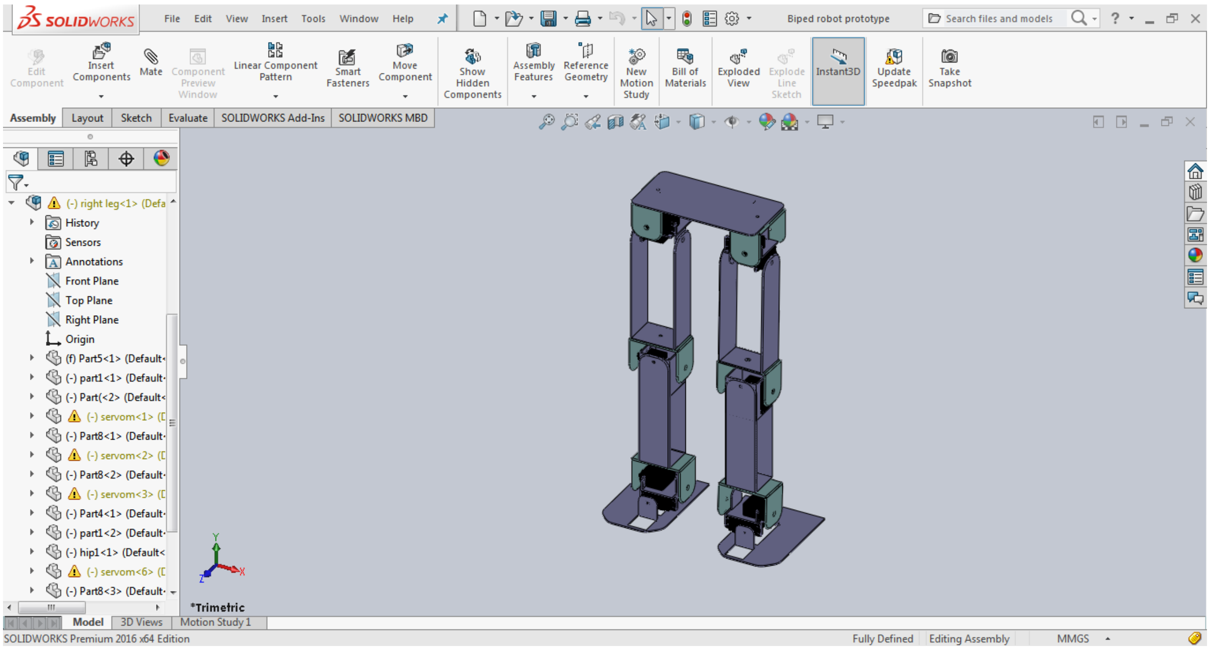


Fig 3.4.4: SolidWorks 3D design interface software.

III.4 Conclusion

The biped robot structure designed and built in this chapter was built to create an adaptive mechanism to balance; it is based on actuators and simple algorithms which can be easily used for any structure of any size and weight with few modifications. This model of Robot has the provision to be adapted to different type of robot structure as per requirements.

CHAPTER IV

IV.1: Introduction

After implementation, programming and tests in the previous chapter and the walking pattern discussed in chapter II .the final results are discussed in this chapter.

IV.2: Tests and Results

The figures 4.1 and Fig4.2 represent the initial position of the biped robot



Fig4.1: side view. Fig4.2: front view. Fig4.3: First sequence of a step.

- The first sequence consists of shifting weight to the right (RM1, RM5 and LM1, LM5 are actuating).


Fig4.4: side view of sequence 2. Fig4.5: front view of sequence 2.

- The second sequence shown in Fig4.4 and Fig4.5 (LM3 and LM2 are actuating).
- In the third sequence (Fig4.6), the robot's left leg is off from the ground and almost all the body weight is on the right leg.

Fig4.6: sequence 3of a step.

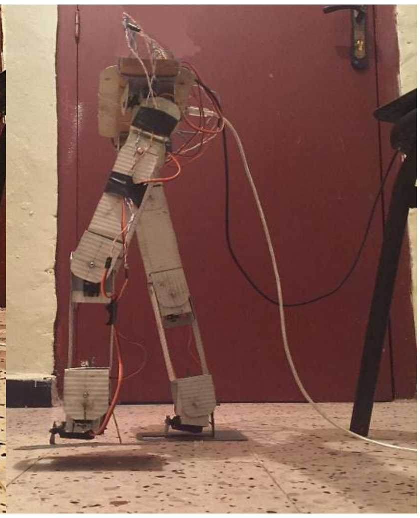


Fig4.7: side view for the fourth sequence.

- In sequence 4, LM3, LM2 actuate so that the left leg moves forward (see Fig4.7).

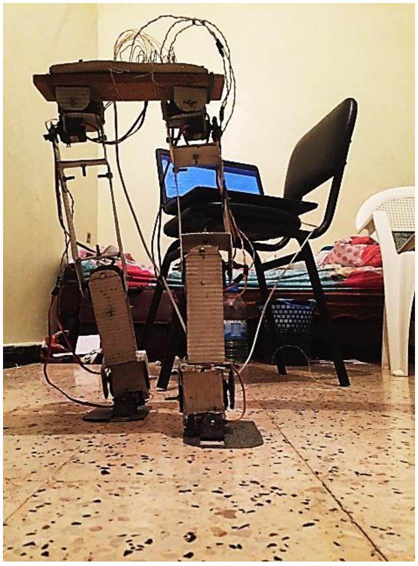


Fig4.8: sequence 5.puting the left leg on the ground.

- In sequence five, the robot tilts forward to put the left leg on the ground (RM2 and LM3 are actuating), see Fig4.8.
- The sixth sequence consists of shifting the eight of the robot back to the center.

The figure 4.9 shows that. In this sequence the servomotors RM1, RM5 and LM1, LM5 are actuating.

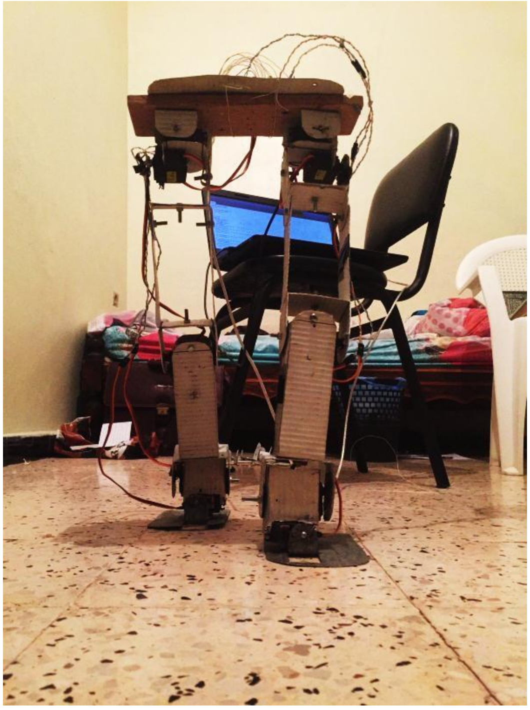


Fig4.9: sequence 6.shifting weight back to center.

The same sequences are the same to move the right leg forward. The maximum angle between the right leg and the left leg must be under 43°, to avoid falling down.

Some movements are removed because of the vibration of the servomotors, which makes the robot not stable enough for long.

IV.3: Conclusion

One of the problems that occurred during movements is that the robot can't stand on one foot for a long period of time when it tries to hold off its leg from the ground to move forward. Higher torques servomotors are recommended to solve this problem, due to no availability of better servomotors, these servomotors are used. Another limiting factor would be the time as it takes numerous design and correction steps to get to a final design capable of the objectives stated for this project.

CONCLUSION AND PERSPECTIVES

CONCLUSION

As advanced research goes into finding more efficient ways to make a man-made robot structure move like man himself, the emergence of biped walking robots and balancing robots are increasing rapidly. Most of these researches include use of complex sensors such as accelerometers, gyroscopes, force meters etc. The complexity of the structures and designs increase as a more natural flow of walking a running is researched. This project tries to move a little bit away from that flow and tries to implement that same balancing mechanism in a simpler manner with components that are very common.

PERSPECTIVES

- The complexity level is very low in this project and is suitable for any application where the high end accuracy and stability is not required.
- This process of balancing also has high potential of being redesigned with other parametric enhancements for a very balancing very efficiently.
- It is very easy to implement this logic in practical practice and one can add to this project with similar enhancements or can diversify this project through adding extra features such as an upper body structure.
- The main concept is simple; it takes less time to understand the concept and on can devote more time on future developments or adding extra features.

REFERENCES

[1] *David E. Newton "*Robots A Reference Handbook ", 2018.

[2] Robot inside Chernobyl's [sic] Sarcophagus 2009.

[3] Goalkeeper CIWS Gun System 2006.

[4] *Dirk Wollherr* "Design and Control Aspects of Humanoid Walking Robots".

[5] *Wigang Gu* "Design and Control of a 10 DOF Biped Robot", 2009.

[6] *Jack Ganssle; Michael Barr* "Embedded Systems Dictionary", 2003.

[7] MG996R Datasheet.

[8] Arduino/reference/www.arduino.cc/en/Guide.

[9] Proteus 8 help guide.

[10] *Jens Wittenburg "*Kinematics Theory and Applications".

[11] Biped Walking Robot {https://sites.google.com/site/bipedwalkingrobott/}.

[12] *Jung-Yup Kim, Ill-Woo Park and Jun-Ho Oh*"Walking Control Algorithm of Biped Humanoid Robot on Uneven and Inclined Floor".

[13] *Thomas Bräunl* "Embedded Robotics Mobile Robot Design and Application with Embedded Systems", (Third Edition),2008.

[14] *E Bahdi -University of Denver* "Development of Locomotion and Balancing Strategy for Humanoid Robots".

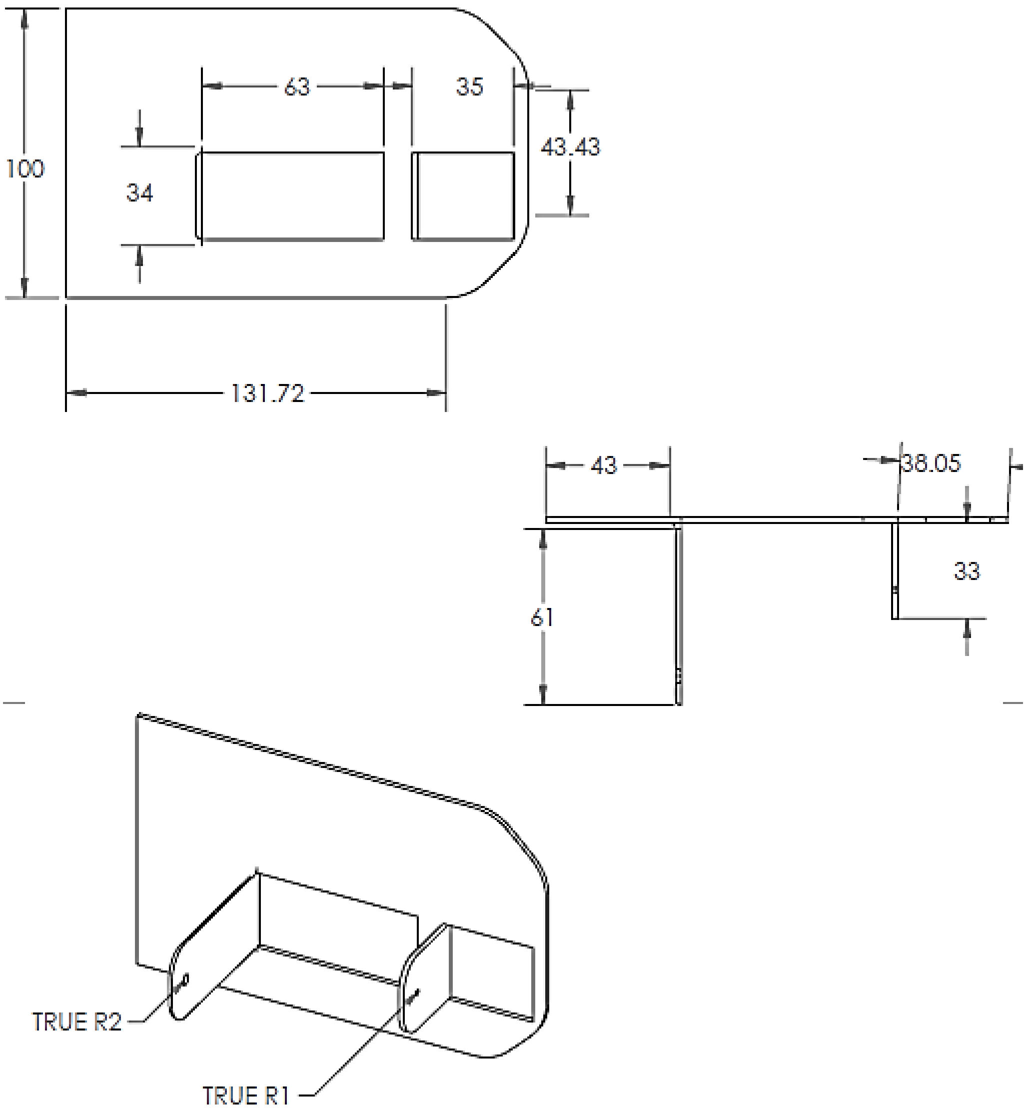
[15] *Keith E. Courtis* "Embedded multitasking", 2006.

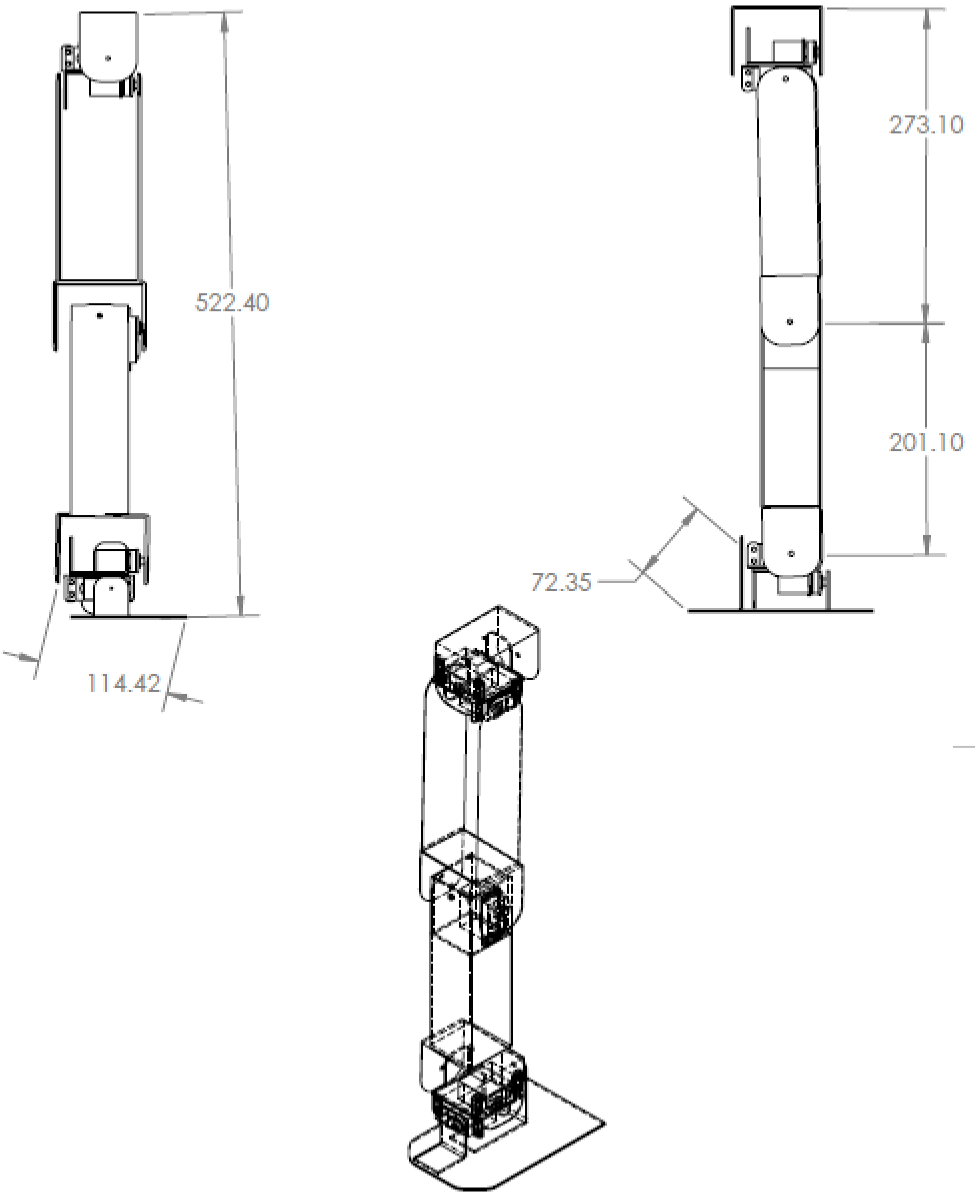
[16] *Andrew N. SLOSS; Dominic SYMES; ChrisWRIGHT* "ARM System Developer's Guide".

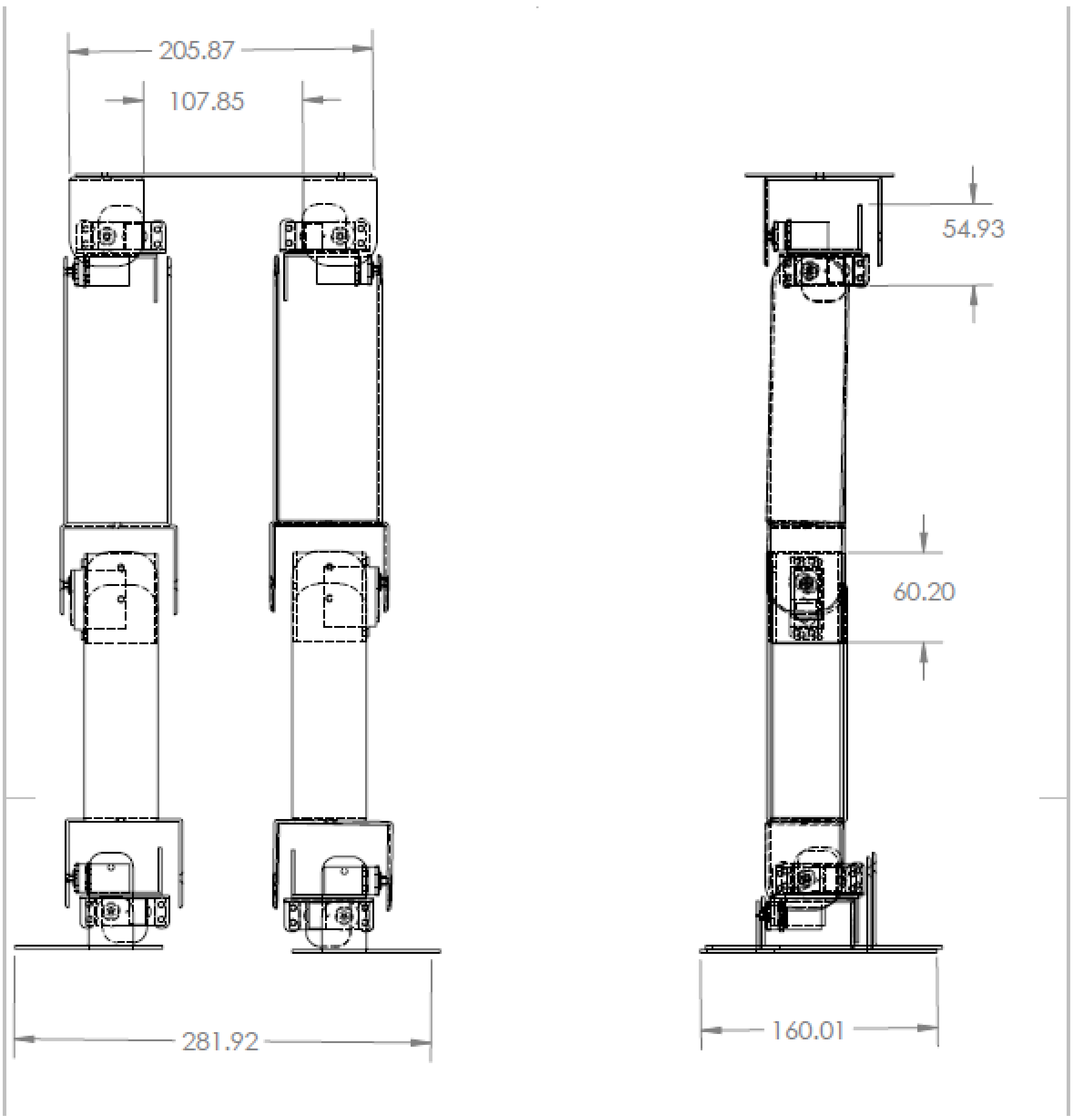
[17] *Fred R. Sias, Jr. and Yuan F. Zheng* "How many degrees of freedom does a biped need?" IEEE International Workshop on Intelligent Robots and Systems IROS '90.

[18] *Andrews Drive* "SOLIDWORKS 2016 for Designers" (14th Edition) CADCIM Technologies 525 St.

APPENDIX


100
63
35
43.43
34
131.72
43
38.05
33
61
TRUE R2
TRUE R1


522.40
114.42
273.10
201.10
72.35


205.87
107.85
54.93
60.20
281.92
160.01