DESIGN AND DEVELOPMENT OF A BIPED ROBOT

A Final Year Project Report

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by

Hassan Khalid

Abdullah Zafar

Ahmed Abdullah Shahid

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EXAMINATION COMMITTEE

We hereby recommend that the final year project report prepared under our supervision by:

HASSAN KHALID	00000271253
ABDULLAH ZAFAR	00000257373
AHMED ABDULLAH SHAHID	00000246759

Titled: “DESIGN AND DEVELOPMENT OF A BIPED ROBOT” be accepted in partial fulfillment of the requirements for the award of BACHELORS OF MECHANICAL ENGINEERING degree with grade ___

Supervisor: Yasar Ayaz, Dr. (Professor) Dept. of RIME, SMME	____________________ Dated:
Committee Member: Khawaja Fahad, Dr. (Asst. Professor) Dept. of RIME, SMME	____________________ Dated:
Committee Member: Sara Baber, Dr. (Asst. Professor) Dept. of RIME, SMME	____________________ Dated:

______________________ ___________

(Head of Department) (Date)

COUNTERSIGNED

Dated: ________________ __________________________

(Dean / Principal)

ABSTRACT

The RISE lab at SMME NUST has been continuously working on the research and development of robotics since its inception in the early 2000s. One of the major projects that has been worked on in the RISE lab has been the building of the concept of a humanoid bipedal robot and turning it into a reality. Named NUSTBOT-3, this humanoid bipedal robot was the work of one of the student's (Mr. Zaid Ahsan Shah) master's thesis, who fabricated this to prove his thesis of making a humanoid robot walk from a point to another while having its ankles unactuated. This concept is known as Decentralized Pattern Generator (DPG) and is one of the first major works done on a concept to generation walking patterns for any type of robot other than the commonly used Centralized Pattern Generator.

However, the results in hardware were not as expected and this specific humanoid robot did need actuated ankles to function properly and walk seamlessly from a point to another. This final year project thesis focuses on the evaluation of NUSTBOT-3, studying various actuated ankle and foot designs of different humanoid robots present globally and making modifications to allow it to be able to be put on NUSTBOT-3 without making significant changes to the lower limbs of the humanoid robot.

ACKNOWLEDGMENTS

Firstly, we would be sending all praise to Almighty Allah who bestowed his blessings upon us to successfully deliver the final year project despite the challenges faced throughout the length of the project. This project would have been impossible to be at this stage without the support and prayers of our parents and family, who stood beside us at all times, whether it was something positive or negative regarding the final year project.

We have our utmost gratitude for the faculty supervisor, Dr. Yasar Ayaz who has helped us from the start of this project, helped us in pursuing our dreams of working and researching in the exciting field of humanoid robotics. His motivation and willingness to guide, help and facilitate us at all times in whatever was necessary has been of paramount significance to help us through all the highs and lows of this project.

We thank our faculty members and co-advisors, Dr. Sara Baber, and Dr. Khawaja Fahad and the GEC members for their constant support and their valuable suggestions and practical guidelines to improve our work in whatever way possible.

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Lastly. we would like to SMME and NUST for the support, mentoring and guidance over the past four years which helped us to evolve into individuals as such who could take on challenging engineering problems and find cost-effective and feasible solutions to solve it.

ORIGINALITY REPORT

The Turnitin Plagiarism Report will be added as soon as the thesis below is approved by the faculty supervisor, and he runs it on Turnitin, after which the report will be attached.

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ABBREVIATIONS

ZMP	Zero Moment Point
COM	Centre of Mass
DOF	Degree of Freedom
SSP	Single Support Phase
LIPM	Linear Inverted Pendulum Model
DSP	Double Support Phase
CPG	Centralized Pattern Generator
DPG	Decentralized Pattern Generator
CAD	Computer Aided Design
3D	Three-dimensional
RBD	Rigid Body Dynamics
MBD	Multi Body Dynamics
LQR	Linear-Quadratic Regulator
MPC	Model Predictive Control
PID	Proportional Integral Derivative
XML	Extensible Markup Language
RISE	Robotics and Intelligent Systems Engineering
SMME	School of Mechanical and Manufacturing Engineering
NUST	National University of Sciences and Technology

NOMENCLATURE

P	Point on the contact plane
n	Unit vector
M^{gi}_P	Resultant moment of the inertial and gravity moments
F^{gi}	Resultant force of the inertial and gravity forces
ω	Natural frequency
g	Gravitational acceleration
h	Height
p_z	Position of zero-moment point
p_g	Position of center of mass

CHAPTER 1: INTRODUCTION

Motivation

The motivation behind this project is to develop the current two-legged humanoid robot which is present at RISE Lab, SMME so that it could overcome its current deficiencies and gets to a state where the humanoid robot can perform its most basic task of walking in a straight line without any hiccups.

Moreover, we wanted to play a role in the development in the ever-growing field of robotics especially at NUST so that further work could be carried out at RISE lab, making the humanoid robot that we are currently working on an example and an inspiration for the future robotics enthusiasts.

Problem Statement

Study of the existing humanoid robots from which suitable ideas could be taken and implemented in an existing humanoid robot by designing and developing it so that the issues in the existing humanoid robot could be minimized by the implementation of this modification for a better functioning humanoid robot, which could help into further work done on it over the upcoming years, benefitting the research community.

Objectives

The objectives that were laid in front of us in order to achieve the end goal of an improved humanoid robot are as follows

1. Analysis of existing humanoid robot structure

2. Design improvements / modifications

3. Development of new design

4. Testing of the designed system

5. Fabrication of the improved sections of the humanoid robot

From the start of the civilization, humans have been curious to build a replica of itself. A human designed by human who can walk like them and perform tasks like humans do. This dream has been turning into a reality step by step with the advancement of science in the past few centuries, which saw the development of the concept of "robots". The closest that humans have to build its replicas is in the 20^{th} and the 21^{st} century where the world has seen two-legged human-sized robots.

Since the first model of the humanoid robot was fabricated in the early second half of the 20^{th} century, the world has seen immense development and research going towards this domain, resulting in better and improved human-like robots which can be of varying shapes and sizes.

The most important aspect for a humanoid robot is movement to displace or move from a certain point to another, which in literature terms in the field of robotics, is also known as legged locomotion.

Locomotion is defined as an act of moving from one point to another point. Locomotion is found in every object regardless of it being a living or a non-living creature which can perform the task as mentioned in the definition. Locomotion can be divided into three main types

- Ground
- Aerial
- Underwater

The focus for the humanoid robots is legged locomotion which lies under the category of ground locomotion, along with wheeled and crawling.

Legged locomotion refers to any kind of motion that is performed with legs. This property has been seen in a multitude of biological creatures around us, being done as a common task on a daily basis. All of these creatures possesses locomotion up to a certain degree and is highly dependent on the shape and size of the leg, the number of joints and the position of the body in which the biological creature remains.

A humanoid robot includes the body shape closely resembling that of individual. This causes it to have the headway also control capacities like individual. It is normal that a humanoid robot might work or help individuals in the human-focused climate without a need to adjust or to alter the climate.

In this manner numerous researchers and engineers from around the world working at different research institutes and universities have put forth extraordinary attempts in this field.

Over the course of a mere few decades, humans have created different versions of the humanoid robot each better than the previous model. Examples of humanoid robots include ASIMO, WABIAN, HRP, QRIO, KHR, HRP3L-JSK, JOHNNIE, Atlas, THBIP, and BHR.

A number of events which promote the development of humanoid robots have been conducted at various levels in recent years which have encouraged the development and increase in research of the designs and tasks of humanoid robots. Two of the most popular events in this field are the DARPA Robotics Challenge and the International RoboCup which challenge developers and researchers to develop humanoid robots for tasks such as rescue and reconnaissance and multi-agent coordination.

Figure 1 Competitors for DAPRA Robotics Challenge 2015 SCHAFT by Google (left), Valkyrie by NASA (center), PETMAN by Boston Dynamics (right)

CHAPTER 2: LITERATURE REVIEW

Legged robotics (being a part of mobile robotics) is a field of study that trades data between biomechanics, control systems and mechatronics designs. Many of the ideas and concepts in legged robotics have been derived from perceptions from the creatures around us that can be subjective or quantitative in nature. These ideas and concepts require a strong grasp on the previously mentioned fields in order to achieve the end goals in this field.

Static vs Dynamic Locomotion

Static Locomotion Robots are always in a balanced state; their center of gravity always lies between the polygon formed by their ground contacts. Whereas in Dynamic Locomotion, the robot must always try to keep itself balanced through complex motion patterns i.e., gait patterns in case of humanoid robots like NUSTBOT-3.

Statically stable structures therefore do not require motion at every moment of time to maintain their stability. For example, a chair with 4 legs has the square area enclosed by its four legs as its support polygon. The chair is stable because the center of mass lies completely within this polygon.

Static stability is completely defined as the center of mass being within the boundaries of support polygon and polygon’s area being greater than zero, thus at least three contact points are needed to make a closed polygon. Consequently, a statically stable robot needs to have four legs, as one leg would need to be in the air for walking

Bipedal robots need to be dynamically stable as their support polygon is only formed by the footprint of their two legs. The feet are usually small, so this polygon almost approaches a line during double support phase and even a point during single support phase.

So, a bipedal robot must actively try to balance its center of mass between the footprints, but this is a very complex task to accomplish due to the intricacies associated with walking, like the force acting on the robot when its leg swings forward

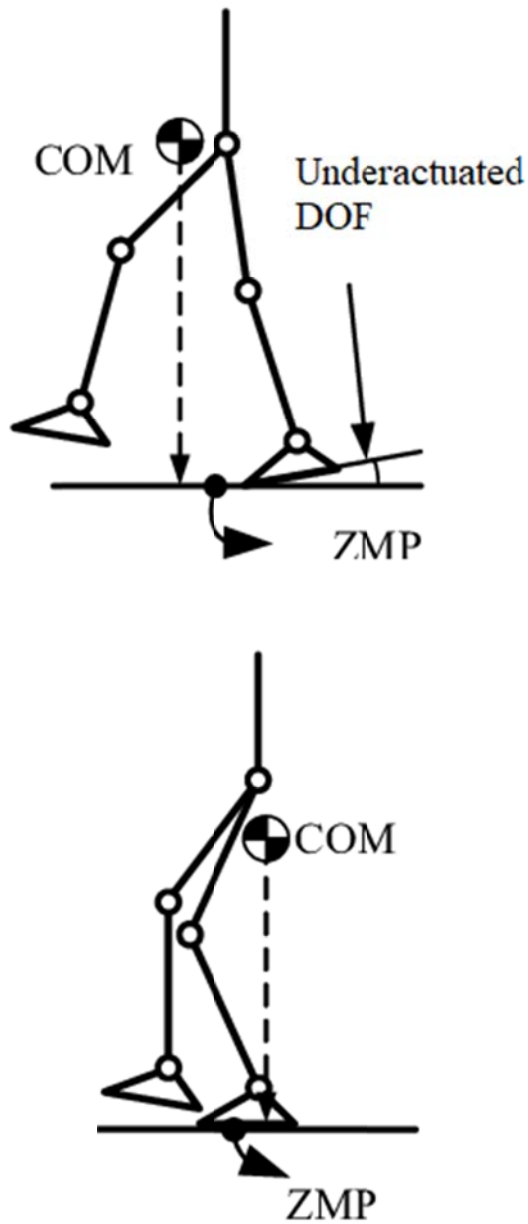

Figure 2 Pictorial representation of static locomotion (below) and dynamic locomotion (above)

Underactuated vs Actuated Robots

Underactuated robots are those which don't have all of their DOFs actuated. Formally a robot is said to be underactuated if in one or more states, it cannot be accelerated along any of its degrees of freedom. Such robots will have at least one joint that is not directly controllable.

Underactuated systems use the natural dynamics of the robot instead of cancelling it out and result in much more natural looking walking robots. But understanding the dynamics of a robot is a complex task.

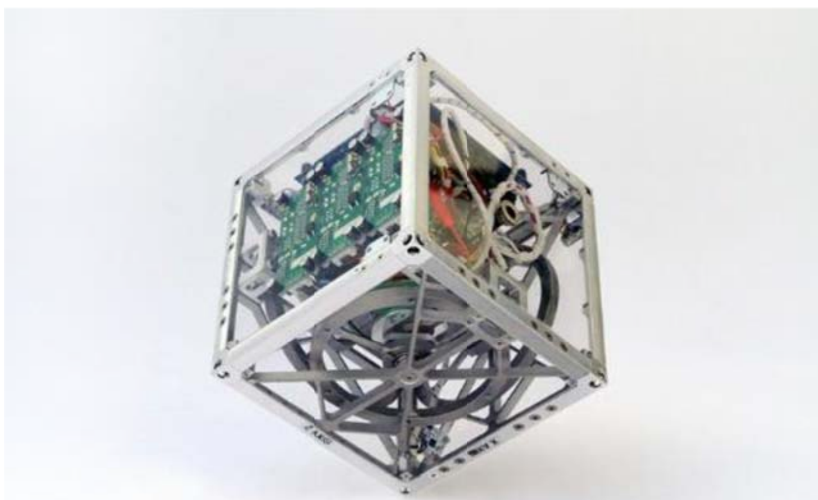

Figure 3 Cubli - An under-actuated robot by ETH Zurich

Fully actuated robots have all of their joints actuated and can accelerate along all of their degrees of freedom. Fully actuated systems use high gain feedback control to cancel out the natural dynamics of a system. This results in stiff (high torque) joints and a very robotic and unnatural movement.

Figure 4 ASIMO - A fully actuated humanoid robot by Honda

Single Support Position (SSP) and Double Support Position (DSP)

Single Support System (SSP) and Double Support System (DSP) are best understood from an overview of the general gait cycle. The gait is measured from the first instance of when a leg strikes the ground to the second instance the same leg strikes the ground again.

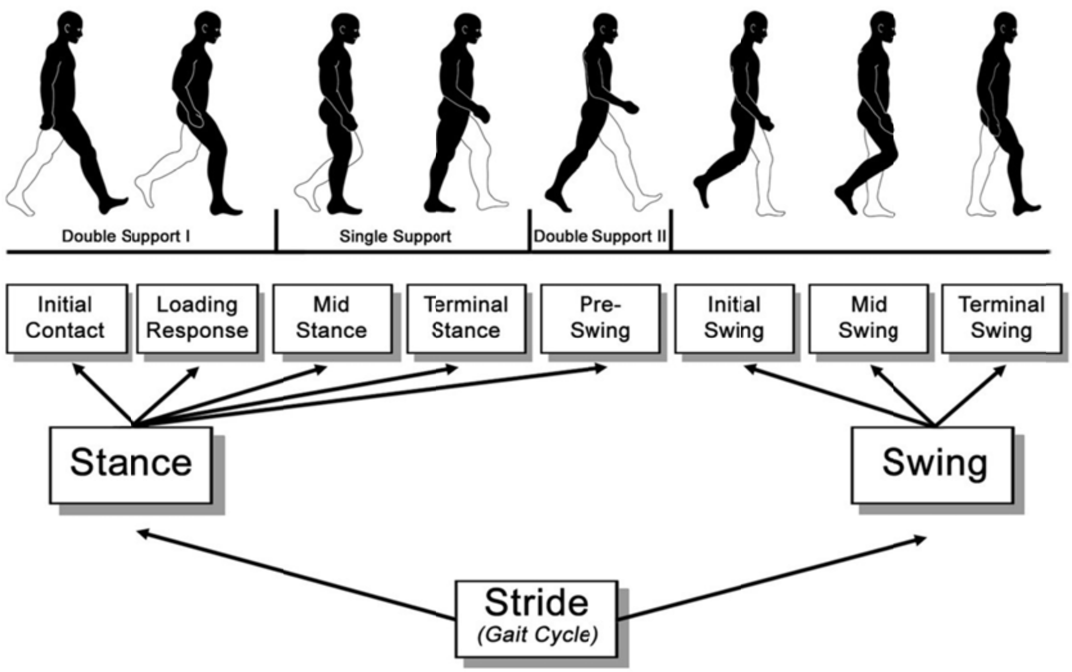

Figure 5 Depiction of walking cycle, showing the phases of single support and double support

Just as the 1st foot contacts the ground, the body starts to shift all its weight on that foot, as the 2nd foot begins to prepare for its swing. During this transfer of weight, both the feet are in contact with the ground for a brief period of time. This is known as the double support phase. Double support ends when the 2nd foot begins its swing. During the entire swing, the body balances on just 1st foot and this phase is known as the single support phase. Single support phase continues till the 2nd foot comes into contact with the ground. Then the 2nd support phase begins, and the cycle continues.

Gait Stability Polygon

For any two-legged robot, the stability polygon takes the following form

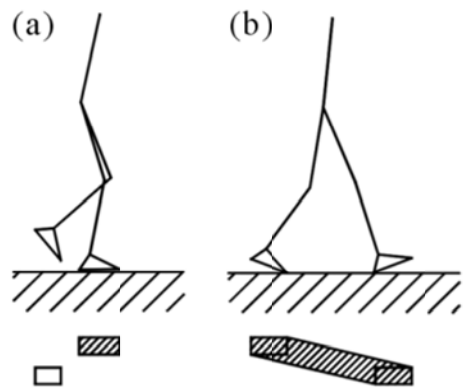

Figure 6 Gait Stability polygon during single-support phase (a) and double-support phase (b) of the walking motion

As discussed earlier in the section of Single Support System (SSP) and Double Support System (DSP), the polygon approaches a line during double support phase as it consists of a very narrow area, whereas during single support phase, the polygon is approximately equal to the area of a single foot

Zero Moment Point

Zero moment point is a concept relating with dynamics and control of legged locomotion, e.g., for humanoid robots. It specifies the point with respect to which dynamic reaction force at the contact of the foot with the ground does not produce any moment in the horizontal direction, i.e. the point where the total of horizontal inertia and gravity forces equals zero. The concept assumes the contact area is planar and has sufficiently high friction to keep the feet from sliding.

Mathematically it is given by

$$\overrightarrow{PZ} = \frac{n \times M_P^{gi}}{F^{gi} \cdot n}$$

Where P is a point on the contact plane, n is a unit vector perpendicular to the surface, $M^{gi}{}_P$ is the resultant moment of the inertial and gravity moments acting on the bipedal robot, and F^{gi} is the resultant force of the inertial and gravity forces acting on the bipedal robot.

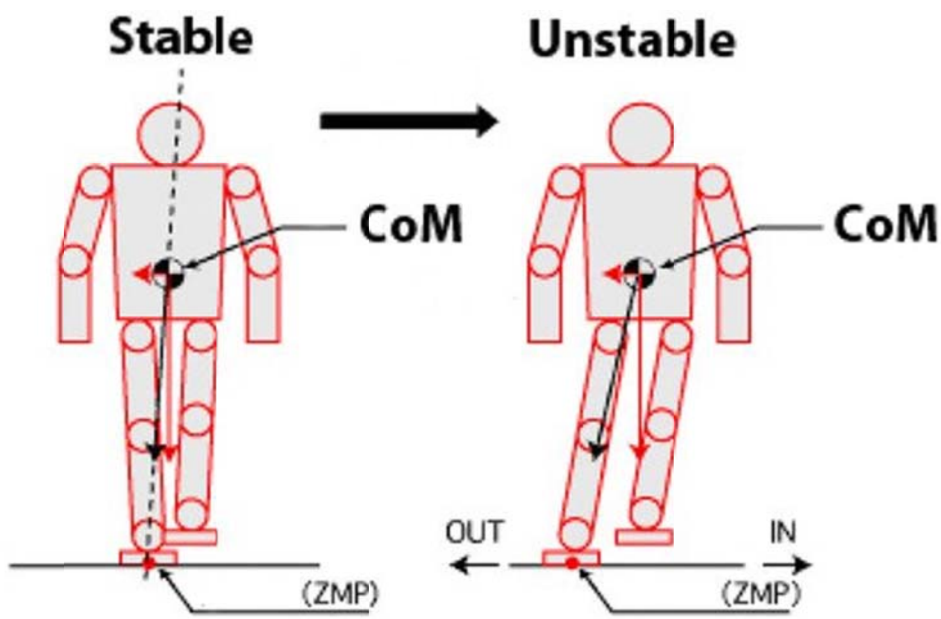

Figure 7 Importance of Zero Moment Point in biped robots

Centralized Pattern Generator (CPG) and Decentralized Pattern Generator (DPG)

Central pattern generators (CPGs) are neural circuits found in vertebrate and invertebrate animals that produce required oscillations for rhythmic movement patterns. When applied to robotics, they are often used as building blocks for the generation of walking controllers. centralized pattern generators generate the pattern generation by considering the entire robot as a single body, unlike in the decentralized pattern generator (DPG) where every link gets its pattern generated individually centralized pattern generators permit easy adjustment of gait speeds and gait transitions.

Also, centralized pattern generators allow better recovery from disturbances and an accurate model of the robot is often not required However a centralized pattern generator-based system becomes unstable or unsolvable at certain conditions, two of which are lack of actuation (reduction in number of actuated joints) and the zero-moment point moving outside the contact polygon.

The main aim for the literature review is to study the existing humanoid robot onto which the potential deficiencies are noted. Similar humanoid robots have been studied and points have been noted which could be applied onto the existing humanoid robot under consideration to have an improved version of it.

The first humanoid robot under consideration is NUSTBOT-3, a humanoid bipedal robot present at RISE Lab, NUST. This is the humanoid robot under consideration for finding possible deficiencies and improvements.

NUSTBOT-3

This thesis discusses the approach to walking pattern generation for a bipedal humanoid robot. The commonly used method is the central pattern generator, but this thesis explores and demonstrates the possibility and effectiveness of the relatively not as much used method called the decentralized pattern generator. This method is beneficial in overcoming two issues which are

- Underactuated Robots (reduction un the degrees of freedom of the robot)
- Zero Moment Point moving away from the contact polygon causing instability

These benefits were the main reason an underactuated robot was manufactured to test out in practical means the given theory. The manufactured robot consists of the lower limbs with the ankle having no actuation given the lack of motors for the said part.

The thesis mainly focuses on the formulation of the pattern generation problem as a multi-body dynamics problem which is a key part in deriving the decentralized pattern generator for under-actuated humanoid robots.

The construction of the degrees of freedom of the lower limbs of the humanoid robot NUSTBOT-3 when fully actuated is mentioned in detail in the below paragraph.

The hip pitch and roll joints are connected to a cross shaft inside the hip joint. The hip yaw joint is inside the thigh of the robot which rotates the knee. The knee joint is connected between the knee and the shin of the robot. The ankle joints are connected to the foot through a cross shaft inside the ankle of the robot. This is to note that NUSTBOT-3 has no motors or gears that make the ankle joint actuated.

The robot consists of the nine major body parts which are connected together through six or eight joints depending upon the reference topology that is used by the person examining the humanoid robot. All of the twelve degrees of freedom (DOFs) are actuated through motors which are fitted with torque controllers.

The (hip) yaw axis is highlighted in purple, the pitch axes are highlighted in blue, and the roll axes are highlighted in red as shown in Figure 7.

NUSTBOT-3 has been created as an underactuated robot which means not all of its joints are in a working position. In the case of NUSTBOT-3, it is the ankles which have not been actuated.

A major disadvantage of an underactuated ankle is its inability to keep the feet in a horizontal position when the biped robot is in single support phase while walking. This inability caused its toe end to be pointed downwards.

When the foot lands on the ground in this case instead of having the entire foot touching the floor at a single time, its toe end will touch the ground first, leading to poor pose recovery and maximizes the chances of the biped robot to fall over as the center of mass of the robot leaves the stability polygon.

To overcome this major flaw, it is proposed that the ankle is actuated, meaning that motors are attached onto the ankles. This will allow to keep the foot in a horizontal position when the biped robot is in the single support system and the issue of not having the entire foot on ground at the same time while going to double support system would be resolved, allowing better and more stable walking pattern. [1]

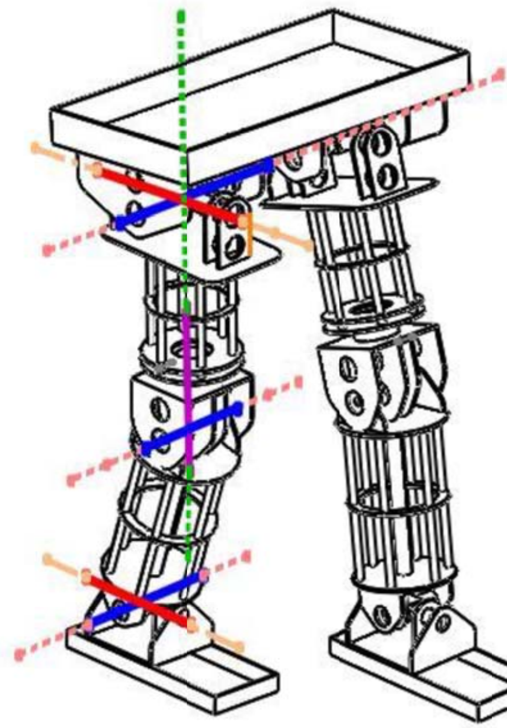

Figure 8 NUSTBOT-3 Revolute Joint Axes in right leg.

After identifying the major improvement that is the lack of actuation of the ankle which was found to cause the abnormality in the walking motion of the humanoid robot.

One of the robots whose mechanical design for the ankle part of the limb was inspired from the fifth generation of the Beijing Institute of Technology (BIT) Humanoid Robots which is also known as BHR-5 in its short form.