Design and Development of a Bipedal Robot with Adaptive Locomotion Control for Uneven Terrain

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Abstract

Bipedal robot is considered as more efficient, in terms of mobility and adaptation, than any other kind of robots. One of the most important problems in bipedal robot walking is the instability produced by the violent transition between the different dynamic phases of walking. In this research, a small size bipedal robot was designed and developed. A dynamic control algorithm for bipedal walking was also proposed and implemented. First, we designed mechanical, electrical and electronic aspects of the robot. Also, required firmware and software components were designed. Then we developed the full robotic system with hardware, firmware and software components. We tested the robot for walking and from experimental results we found that the robot could walk with certain degree of stability. In order to increase sophistication in the system further work is required. In particular, the dynamics of the system and trajectory patterns should be analysed based on the Augmented Model Predictive Control (AMPC) structure. Also, the Forward Kinematics (FK) and Inverse Kinematics (IK) of the bipedal system should be analysed with close attention. However, the output of this research will have the potentials in the field of education, research, and commercial uses.

Keywords: Robotics, Bipedal Robot, Augmented Model Predictive Control (AMPC), Forward Kinematics (FK), Inverse Kinematics (IK)

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1. Introduction

A Humanoid robot is a type of bipedal system that resembles a human. Study on bipedal robot locomotion has advanced due to the great interest of researchers in the last few decades. Biped locomotion and balancing are the principal studies in humanoid robotics. The motivation of research is that the bipedal robot has efficient mobility than the other types of legged robots and has flexibility due to a large number of Degree of Freedom (DoF). Adaptability while moving in unstructured environment leads to design of new walking and locomotion strategy for a bipedal robot. To achieve this target, it is more desirable to have a suitable humanoid platform and reliable algorithm to guide the humanoid in real-time operation. Moving on rough ground, for example: soft and uneven surfaces, bipedal robot has a huge potential advantage comparing with other types of robots, such as wheel robots. The problem of dynamic walking has attracted a number of researchers in order to understand the nature of bipedal locomotion in biological systems and to improve locomotion capabilities of bipedal robots. Though, the locomotion capabilities of existing bipedal robots are still restricted in flat surface environment, nowadays, some researches are being conducted to improve the dynamic behavior of bipedal walking on rough terrain. This research focuses to design and develop a bipedal robot and its locomotion strategies with suitable control mechanisms so that the robot can move on rough terrain in indoor environment. There are many scopes in the field of bipedal robotics in terms of mechanical design and control strategies for efficient bipedal locomotion. Basically, humanoid robot requires computationally advanced and efficient algorithms to solve the locomotion problem on uneven ground. Humanoid locomotion patterns are the accumulation of complex skills which requires extensive analysis for designing bipedal

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real platform. For the comprehensive study of the human locomotion pattern, biped platforms are designed to perform various postures, gestures, gaits, and certain physical abilities. So, the main objectives for this study are to design and develop a bipedal robot with implementation of an efficient control algorithm for adaptive locomotion on rough terrain in indoor environment. To achieve the target, the objective can be broken down into several sub objectives:

- To design and develop a small size bipedal robot.
- To conduct mathematical analysis in modelling the biped system and design an adaptive control architecture for the system with simulation.
- To implement the control architecture in the physical system and conduct experiments.
- To evaluate the performance of the overall system in terms of mechanical design and control strategies.

This manuscript is classified into five interconnected sections. The section two provides the background of the related works. Section three provides the method of this study along with the proposed working principles. Section four provides design procedures and the snapshots of the developed solution. Finally, section illustrates the conclusion of this manuscript.

2. Literature Review

Biped robot is able to perform its locomotion in almost any type of terrain and has a wide range of movable capabilities in environment with obstacles and uneven surface. For this reason, it is suitable to use biped robots in human environment. Many biped robots have been developed in recent years [1][2][3][4] and many researches are focusing in the development of control mechanisms for biped robots [5][6]. A series of bipedal robots were designed and developed by Honda since 90s. The series began with P1 model and continued to P3 and later on progressed to the design of ASIMO humanoid which is 1.4 meter in height having more than 25 DoF [3][7]. The Toyota humanoid robot is capable of playing musical instrument. The SONY Qrio robotics the first child sized bipedal robot introduced in 2003 [7].

The stable walking of biped robots can be characterized as Static walking and dynamic walking. In the case of static walking, biped robot maintains the projection of its Centre of Gravity (CoG) inside the support region. However, dynamic walking does not need to conserve the CoG in the support region, rather maintain the Zero Moment Point (ZMP) inside the support geometry. The strategy has been broadly used to design biped balance control algorithms [3][7]. Many researchers designed control algorithms by maintaining the hip trajectories to follow the ZMP criteria [3][7][8].

A recent paper presented a 12-DoF bipedal walking based on Quasi-Inverse Pendulum (QIP) model [9]. Direction and acceleration of CoM movement of the QIP model is determined based on the position of CoM relative to the Center of Pressure (CoP). Heel-contact and toe-off conditions were determined based on two custom design switches which were attached with heel and toe positions of each foot. Force sensors were also placed at the four positions of the plantar surface of each foot to detect ground contact and to measure pressure which leads to the calculation of CoP trajectory.

The paper also describes Forward Kinematic (FK) and Inverse Kinematic (IK) investigations of the bipedal robot where Denavit-Hartenberg (D-H) representation and Geometric-Trigonometric (G-T) formulation approach were applied [9][10]. Homogeneous coordinate transformation matrix was used by Lope et al. to describe the position and orientation of foot for biped robot [11]. Kinematic structure of the system used IK solution which was formulated based on Artificial Neural Network (ANN) by using two layered back propagation architecture. Zorjan and Hugel presented a modified D-Hconvention, called DHKK [12]. They applied geometric formulation only for knee joint and decomposed to calculate hip and ankle joint angles which eliminated IK singularity [12].

Cubic interpolation method was used for gait generation of many biped systems. Two separate researchers, conducted by Shih and Huang, have used cubic polynomials to generate the hip and foot trajectories for bipedal walking on uneven terrains [13] [14]. The work of Shih discussed only the static walking, while the work of Huang proposed a method for dynamic walking. V. Mastanaiah, et. al. [15] conducted a study on the design, fabrication and analysis of a bipedal robot. In this study, researchers have focused on the development of a strategy of balance control of bipedal robot during its walk. The researcher used cascading logic algorithm and control signal by the microcontroller for the servomotors placed in the links.

In this research, a small sized bipedal robot will be designed and developed with dynamic walking capability on uneven terrain in indoor environment. The research will also describe the mechanical design, and propose a control algorithm for dynamic walking of a bipedal robot.

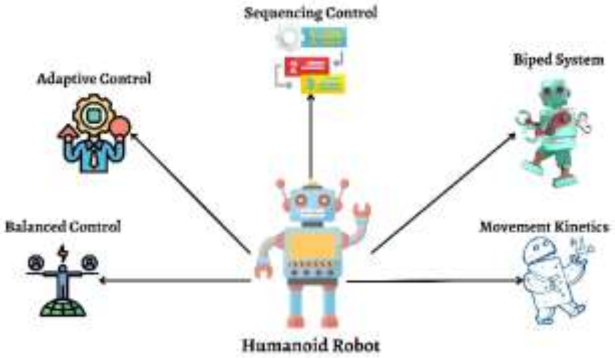

Fig. 1: Overall system illustration.

3. Method with Proposed Working Principles

This section presents the method of the study along with proposed working principles of the robot. Fig. 1 show the overall system illustration of the proposed biped robot with existing features. The robot is enriched with five interconnected features such as kinetic movement in both directions like forward and backward, sequencing controlling to move right direction, adaptive controlling to cope with current situation and finally balance controlling to hold on the extract position.

3.1. Sequence Control

A very important function of software plane was to plan sequence of actions for the robot. Every major robot movement has a corresponding sequence. Algorithm to realize action sequence for walking is illustrated in this subsection. Algo. 1 consists of a number of big steps. Each of these steps need sequence of micro steps. Sequences of micro steps required to realize steps 1, 2 and 5 are given in the Algo. 1-4. In addition, the Steps 2 and 3 involves similar actions.

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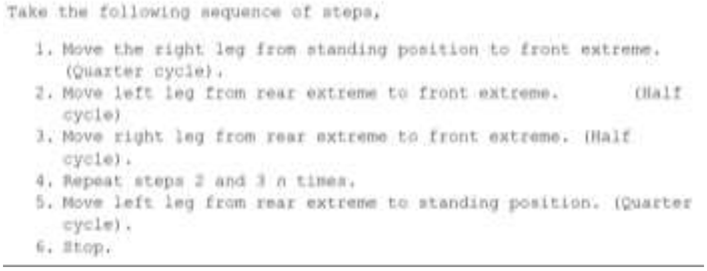

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Take the following sequence of steps,

   1. Move the right leg from standing position to front extreme.
      (Quarter cycle).
   2. Move left leg from rear extreme to front extreme.       (Half
      cycle)
   3. Move right leg from rear extreme to front extreme. (Half
      cycle).
   4. Repeat steps 2 and 3 n times.
   5. Move left leg from rear extreme to standing position. (Quarter
      cycle).
   6. Stop.
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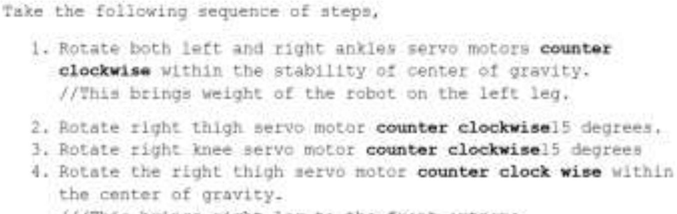
Algo. 1: Basic algorithm for walking sequence of the robot



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Take the following sequence of steps,

   1. Rotate both left and right ankles servo motors counter
      clockwise within the stability of center of gravity.
      //This brings weight of the robot on the left leg.

   2. Rotate right thigh servo motor counter clockwise15 degrees.
   3. Rotate right knee servo motor counter clockwise15 degrees
   4. Rotate the right thigh servo motor counter clock wise within
      the center of gravity.
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Algo. 2: Algorithm for forwarding right leg from standing position to front extreme

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Take the following sequence of steps,

   1. Rotate both left and right ankle servo motors clockwise within
      the stability of center of gravity.
      //This brings weight of robot on the right leg

   2. Rotate left thigh servo motor clockwise 15 degrees.
   3. Rotate left knee servo motor clockwise 15 degrees
   4. Rotate the left thigh servo motor clock wiseto bring left leg
      to neutral position.
   5. To bring left leg to front extreme, rotate
      i)    left knee counter clockwise and
      ii)   left thigh clockwise

   6. Bring back both ankles to neutral positions through rotation
      counter clockwise.
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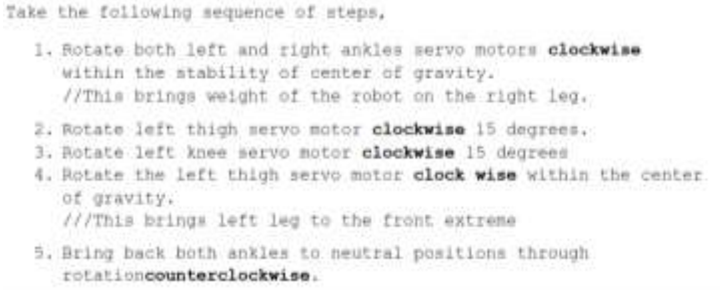
Algo. 3: Algorithm for moving left leg from rear extreme to front extreme.



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Take the following sequence of steps,

   1. Rotate both left and right ankles servo motors clockwise
      within the stability of center of gravity.
      //This brings weight of the robot on the right leg.

   2. Rotate left thigh servo motor clockwise 15 degrees.
   3. Rotate left knee servo motor clockwise 15 degrees
   4. Rotate the left thigh servo motor clock wise within the center
      of gravity.
      ///This brings left leg to the front extreme

   5. Bring back both ankles to neutral positions through
      rotationcounterclockwise.
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Algo. 4: Algorithm for moving left leg from rear extreme to standing position

3.2. Balance Control

In addition to the above-mentioned algorithms for robot walking, a sensor based sophisticated feedback control system has been proposed to keep accurate overall balance during walking. Robot being a sophisticatedly controlled automated system, it needs control at individual joint level as well as at overall system level. Overall control architecture of the proposed system is shown schematically in Fig. 2.

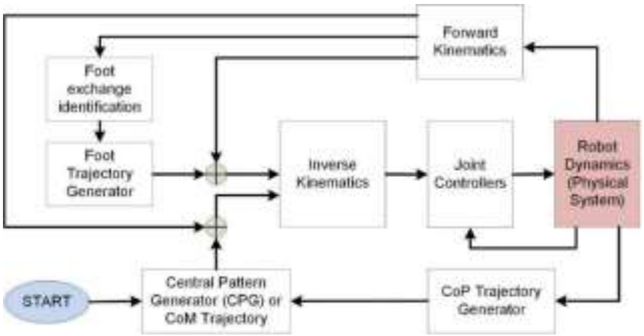

Fig. 2: The control architecture of the proposed system

In this control design, Centre of Mass (CoM) trajectory was generated based on the Central Pattern Generator (CPG) algorithm. There will was a feedback form the Centre of Pressure (CoP) trajectory. Because of any disturbance on CoM (considered as push), CoP trajectory could be adjusted dynamically. Similarly, any disturbance on CoP (because of rough terrain), CoM trajectory could also be adjusted dynamically. This philosophy led to the dynamic balancing of bipedal robot while walking on rough terrain. FSR data was feed to the joint motor control unit for the dissipation of Ground Reaction Force (GRF). Similarly, joint angles were feed to the control architecture to calculate FK and IK information of the system.

3.3. Adaptive Controlling

In order to make the control suitable for walking in the rough terrain, an Augmented Model Predictive Control (AMPC) was proposed for adaptive control of the robot motion. The set of sensor values provided the current state of the robot and a set of actuators modified the state of the robot to reflect a desired motion condition. An overall feedback control loop is shown in Fig. 3.

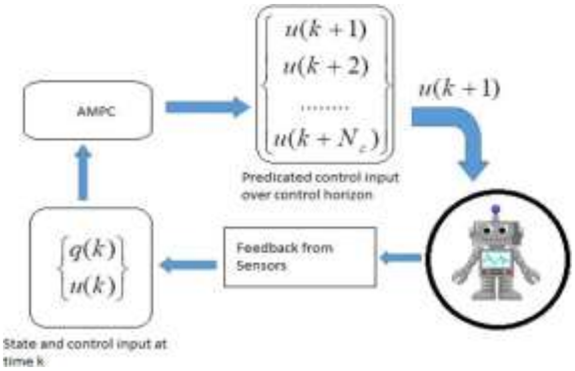

Fig. 3: Working mechanism of Adaptive Control

From this figure we can easily observed that q(k) places a significant role in adaptive role. Where, k denotes the state and control input at k time. Initially, the robot takes the feedback from the multiple sensors then using(k), sends the data to AMPC to overserve the predicted control input over control horizon. The following Eq. 1 shows mathematical annotations of the adaptive control.

$$q(k) = (x_{com} \times y_{com} \times z_{com})^k \qquad (1)$$

Where x_{com}, y_{com}, and z_{com} are x,y and z components of center of mass u(k). Presented the control input to the robot dynamical system. Zero moment point (ZMP) was calculated as follows:

$$x_{ZMP}=x_{com}-(z_{com}/g)\ddot{x}_{com} \tag{2a}$$

$$y_{ZMP}=y_{com}-(z_{com}/g)\ddot{y}_{com} \tag{2b}$$

Objective of the control system was to minimize the distance between CoM and ZMP of the dynamic robot.

3.4. Electrical, Electronic and Sensor Plane

A number of electrical and electronic components as well as sensors were incorporated in the robot design. These included a microcontroller board, a servo controller board, servo motors and different types of sensors such as Inertial Measurement Unit (IMU) sensors and pressure sensors. Also, this plane included power distribution network necessary to provide electrical power to microcontroller and servo boards and servo motors.

In order to properly regulate its motion and final position, the servomotors had to incorporate a closed-loop servomechanism. The movements in our concept were restricted to rotating motions exclusively. The servomotor contained a DC motor, motion control system, and position control system to meet these demands. Fig. 4 depicts the structural layout of a servomotor control system.

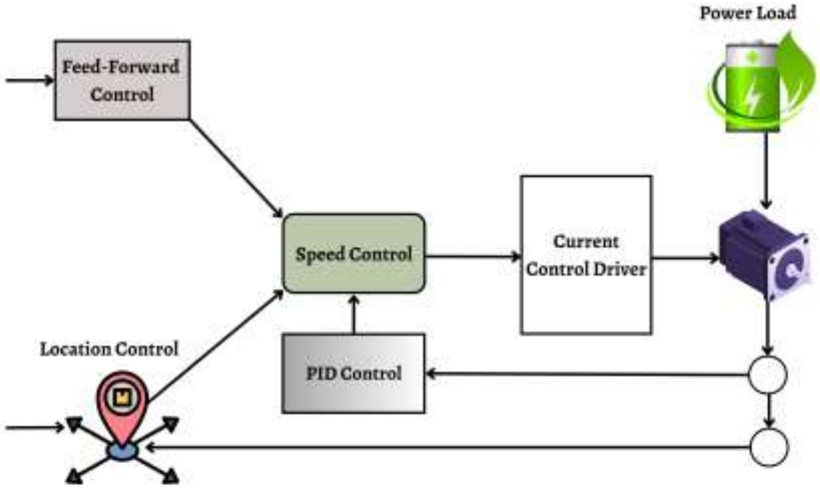

Fig. 4: Working mechanism of servo motor

In this figure, feedbacks from the DC motor was fed to the speed and position controllers. Also, there were options to specify desired position and to apply feed forward control. In order to facilitate decision-making high-level programs running in the microcontroller board with important information like acceleration, speed and orientation of robot and pressure on the feet, a number of sensors of different types were required. Components in electrical, electronic and sensor design plane constitute a closed circuit with feedback. Corresponding circuit diagram is shown in Fig. 5.

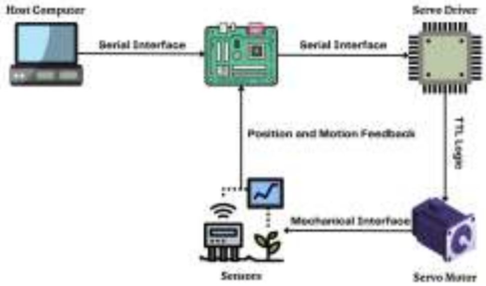

Fig. 5: Working mechanism of sensor with microcontroller.

4. Implementation and Results

This section provides the overall implementation process of the proposed biped robot with mechanical elements, multiples sensors. Also, this section provides snapshots of the developed prototypes

4.1. Implementation

The proposed system design was implemented to a good extent. The first three design planes, namely i) mechanical plane, ii) electrical, electronic and sensor plane, and iii) firmware plane were almost fully implemented. A significant portion of the software plane was also implemented.

In the mechanical plane, we have taken some discrete mechanical components for the embodiment of the robot as shown in Fig. 6. Then. We have assembled these components into a full-fledged bipedal robot.

Fig. 6. Mechanical components of the robot

In the electrical, electronic and sensor plane, we used well known Arduino microcontroller. Precisely, we used Arduino Meag 2560 as this is a low-cost microcontroller very suitable for dedicated embedded systems. For the servo control, we utilized SSC-32 servo controller. This servo controller can controller can control up to 32 servo motors, and therefore quite suitable for control our 17 servo motors in our 17 DOF robot system. For sensors, we purchased Arducam OV 7660 camera and HC-SR04 ultrasonic range sensor. Also, we procured inertial measurement unit (IMU) sensor MPU 6050 for sensing acceleration and angular orientations.

In the firmware plane, we used resident firmware in the Arduino Mega 2560 board and also the firmware resident in the SSC-32 servo controller board. In particular, the firmware resident in the SSC-32 servo controller contains all the firmware necessary to initiate, coordinate and control position and velocity of each servo motors in parallel. The control is done through timely generation of pulse width modulation (PWM) signal and application on the motors.

In the software plane, we wrote all the necessary programs. These included the following components.

- Serial communication components toward host computer and toward the servo controller.

- Calibration component for the servo motors.
- Procedure to move each motor to desired position.
- Procedure to make the robot walk.

The advanced level components for more sophisticated adaptive control are yet to be finished.

4.2. Snapshots of the Robot

This section presents experimental results of the robotic system we proposed. Initially, we have performed the taking ability test. Fig. 07 shows the desire movement when the robot talked to us effectively.

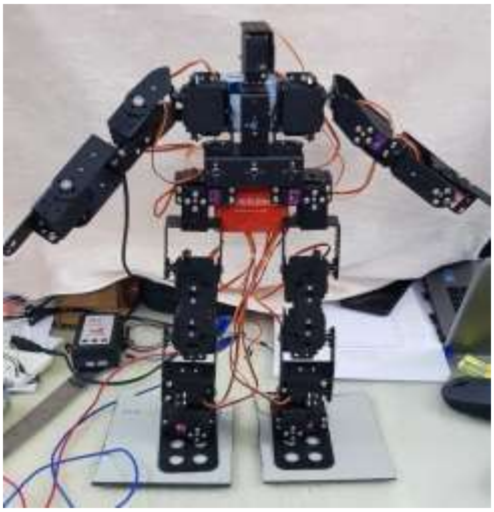

Fig. 7: Preparing for walking

Then we have performed the test on the robot movement whether the robot moves in accurate direction or not. Fig. 08 shows the robot movement of the right leg. After that, Fig. 9 shows the robot is again on the neural position. To move the robot we have also tested the left leg. Fig 10 shows the snapshot left leg movement.

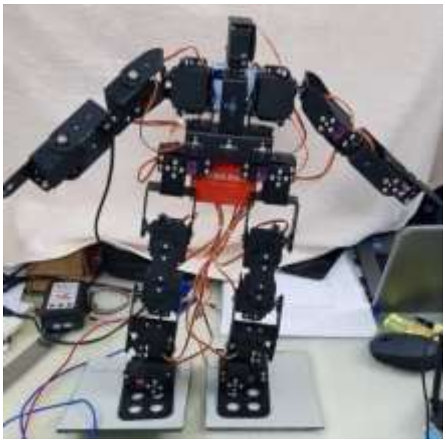

Fig. 8: The robot has inclined to the left and has started to move the right leg forward.

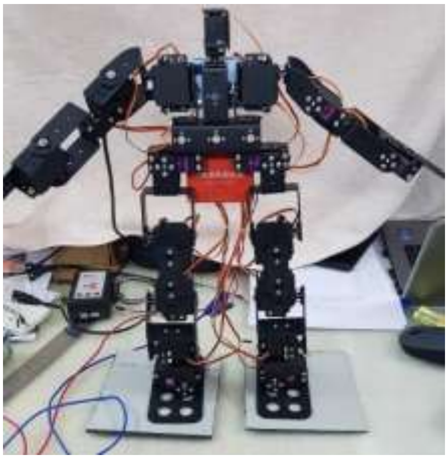

Fig. 9: The robot has come back to the neutral position

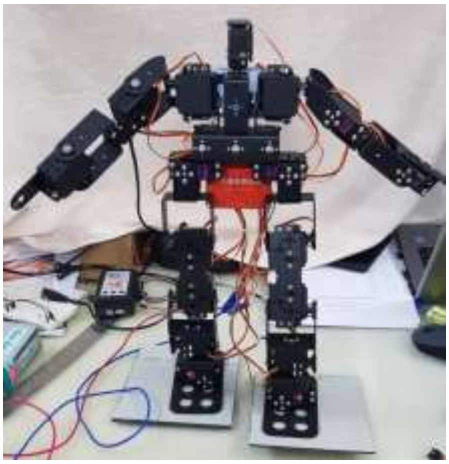

Fig. 10: The robot has moved the left leg forward

5. Conclusion

Bipedal robots are thought to be more effective than any other type of robot in terms of mobility and adaptability. The instability caused by the abrupt change in dynamic phases of walking is one of the most significant issues with bipedal robot walking. During this research, a little bipedal robot was created. Also suggested and put into practice was a dynamic control algorithm for bipedal walking. The robot's mechanical, electrical, and electronic components were first designed. The necessary software and firmware components were also created. After that, we created the whole robotic system, including its hardware, firmware, and software components. We put the robot through a walking test, and the findings showed that it could walk with a certain amount of steadiness. Further work is necessary to boost the system's complexity. The dynamics of the system and trajectory patterns, in particular, should be examined using the Augmented Model Predictive Control (AMPC) framework. The bipedal system's Forward Kinematics (FK) and Inverse Kinematics (IK) should also be thoroughly examined. In future, we will come up with more effective robotic solution utilizing the emergent technologies like Machine Learning, Deep Learning and Data Science. However, this research's findings have the potential to be used in teaching, research, and commercial applications.

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