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DETERMINATION OF JOINT ANGLES OF BIPEDAL ROBOT USING FORWARD AND INVERSE KINEMATICS AND ZERO MOMENT POINT MODELS

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Abstract: In recent years, robotics studies have gained great momentum in industry, medicine, education, agriculture, and in all areas of life along with rapid developments in electronics, computers, and control technologies. With the increase in robotic studies, the walking of biped robots has increasingly become similar to that of humans. Compared to other living creatures in nature, walking on two legs is one of the most important features of man. For this reason, this study aims to calculate joint angles of a bipedal robot using forward and inverse kinematics to imitate human-like walking. In this study, 12 state-of-the-art intelligent servo motors are used to make a bipedal robot.

Keywords: *Bipedal Robot, Servo Control, Forward and Inverse Kinematics, Zero Moment Point.*

INTRODUCTION

Robots are mechatronic systems designed with multifunctional manipulators and consists of electrical, electronic and computer parts, a microcontroller, sensors, and mechanical components and programed with various software to perform required tasks (Gu, E.Y., 2013).

Especially over the past 30 years, rapid advances in computer, electronics machine technologies, and microcontroller-aided device control technique have led to accelerated development of robotics technology. Due to this rapid development, robots have replaced human labor in the fields of industry, agriculture, education and medicine. With the development of robotics technology, researchers and scientists have given great weight to the development of bipedal robots as well. Moreover, even the most famous technology, electronics and defense companies have contributed and supported the development of bipedal robots, and competed in this field. In particular, Honda (Honda, HondaRobotics, 2016) and Toyota (Toyota, Partner Robot Family, 2016) in the automotive industry; Sony (Sony, Sony Robot, 2016) in the electronics industry; and Boston Dynamics (BostonDynamics, BostonDynamics Robots, 2016) in the defense industry are examples of such companies.

In designing bipedal robots or humanoid robots, they are inspired by humans-the only land mammal walking on two legs (Orthopaedic Prosthesis and Orthesis Gait Analysis, 2011). The walking conditions for a robot are similar to those for a man. That is, at least one foot should stay on the ground to go from one place to another. This is why it is very difficult for a robot to walk with balance on two legs without falling down. Because as soon as a robot enters the single support phase while walking, it shows a tendency to fall due to the movements of the manipulators mounted on it and to disturbing forces coming from the outside. In addition, the DoFs–there are at least 12 of them-on the bipedal robot must work in harmony. Because human walking in nature consists of rhythmic movements of legs and arms that are pleasant to the eye. This is why, complex mathematical and physics laws must be applied for modelling walking patterns of bipedal robots.

EXPOSITION

What is walking?

In order to be able to make a bipedal robot walk like a human, first it is necessary to analyze walking motion of a human in nature very well. This is because, the walking control algorithm of a bipedal robot can be revealed by thoroughly understanding human walk. In this context, first the walk of a human in nature was investigated. The mathematical and physical methods for our robot were determined from the obtained information.

Walking is the action of land mammals moving from one place to another. In essence, it can be expressed as moving. It is also referred to as walking style or behavior (Houglum, P.A. and D.B. Bertoti, 2011).

Like other land mammals, humans move from place to place by walking. Therefore, it is called walking when a human moves from one place to the other on an x-z axis, with the condition of standing on two feet in balance. This is because only humans have the ability to walk on two legs among land mammals. It was discovered by scientists that ‘Lucy’-- the oldest human skeleton found in evidence throughout human history--is about 3 million years old and can stand upright. Also, unlike other land mammals, humans use both legs for support and moving forward while keeping at least one foot always on the ground (Orthopaedic Prosthesis and Orthesis Gait Analysis, 2011 - Lovejoy, C.O., 1988).

Gait Cycle

The gait cycle is defined as the time it takes for the rhythmic movements of leg joints to occur from the moment when a heel touches the ground initially until the moment the same heel touches the ground again (Orthopaedic Prosthesis and Orthesis Gait Analysis, 2011). During walking, this cycle is repeated continuously in an order. If we take into consideration the gait cycle of the right leg, first the heel of the right leg touches the ground and the cycle continues until the heel of the right leg touches the ground again. Although the left leg does the same motion as the right leg, it comes from behind with a half-cycle phase difference (Whittle, M.W., 2014).

The gait cycle of a leg is divided into two phases. These are stance and swing phases. The stance and swing phases are divided once more by various methods. However, the terminology of these sub-phases has changed over time. This is why previous terminology may be encountered in different sources. In this study, the Rancho Los Amigos (RLA) terminology developed by Jacqueline Perry, as seen in Figure 1, is used (Houglum, P.A. and D.B. Bertoti, 2011).

The distribution of these phases is divided into two phases, which is Stance Phase and Swing phase. These phases are Stance Phase; i)Initial contact, ii)Loading response, iii)Mid stance, iv)Terminal stance, v)Pre swing , Swing phase; vi)Initial swing, vii)Mid swing, viii)Terminal swing, respectively.

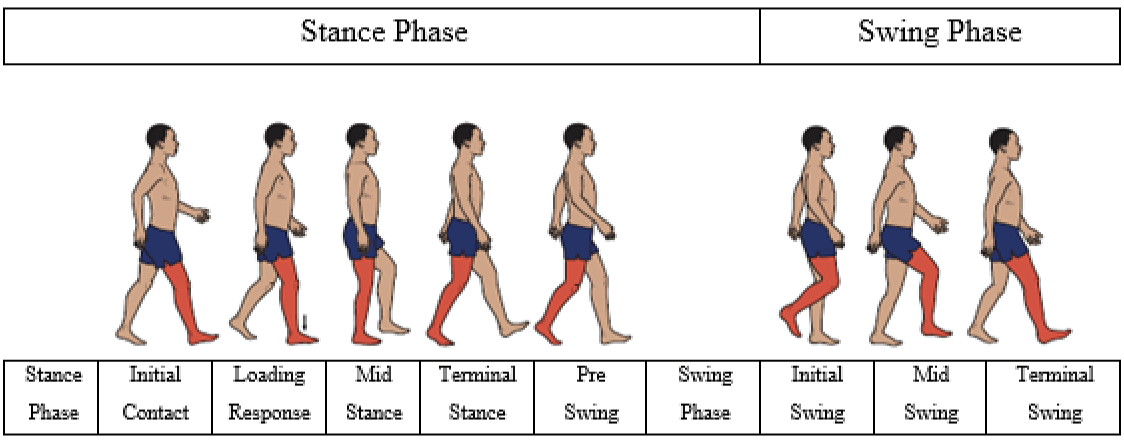

Fig. 1. Gait cycle and its phases (Houglum, P.A. and D.B. Bertoti, 2011).

The time distribution and relative durations required for each walking phase in the human gait cycle are shown below. The stance phase takes up 62% of one full gait cycle, The swing phase takes up 38% of one full gait cycle, The double support phase takes up 11% of one full gait cycle.

Walking Models in Bipedal Robots

The walking balance in biped robots is grouped into two categories: static walking and dynamic walking.

The most important feature of static walking is keeping the robot's balance while walking. Thus, it does not fall unless an external force is applied. The most well-known method of static walking is based on the fact that the center of gravity (CoG) of the robot is always inside the robot's support polygon. Since the center of gravity needs to continuously remain inside the support polygon, the step length is limited so that the robot can stay in balance. This is why static walking is the main disadvantage for a biped robot (Kajita, S., et al., 2014 - Wahde, M. and J. Pettersson, 2002 - Gökçe, B., 2009). Static walking is easy to apply to bipedal robots, but their speed remains slow.

In the dynamic walking of a bipedal robot, on the other hand, the robot uses the dynamic characteristics of its own joint movements in order to maintain its balance when a disturbing force is applied from outside. Control of dynamic walking motion is very difficult in biped robots. The most important advantage of dynamic walking is that the robot can walk at a higher speed (Yapıcı, K.O., 2008).

Using Forward Kinematics to Calculate Joint Angles

When joint angles of a robot are known or values are assigned to the angles, the position, angle and orientation of the robot's end-effector in the operation space are found using forward kinematics (Kajita, S., et al., 2014).

Using Inverse Kinematics to Calculate Joint Angles

If the coordinates of the end-point of a robot's arm or leg to the main frame in the operation space are known, the method used to calculate joint angles is known as inverse kinematics. It has nonlinear equations due to the structure of the joints it owns. Therefore, its computation is more difficult compared to the forward kinematics. The greater the number of rotating joints, the more difficult it is to find the values of the joint angles. Moreover, different joint angles can be mathematically found in the solution set for the end of a robot's leg that can reach the same coordinate value.

Zero Moment Point

The concept of Zero-Moment-Point or ZMP was first defined by Vukobratovic in 1969 for use in the control of humanoid robots (Vukobratovic, M. and D. Juricic,1969).

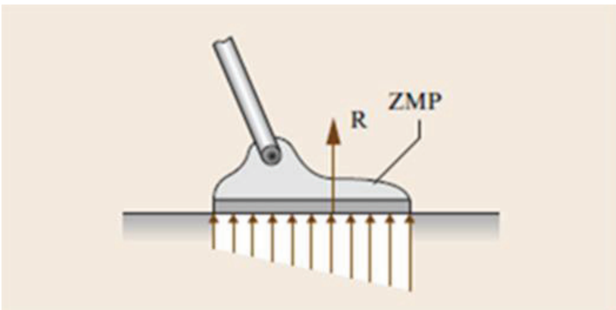

Fig. 2. Original demonstration of zero moment point (ZMP) (Kajita, S., et al., 2014)

An example of force distribution underneath a foot is shown in Figure 2. These forces can be simplified to R resultant force since all the forces acting under the foot are in the same direction, provided that they are applied to the points within the foot boundaries. Thus, the resultant force acting on the foot is shown as R-point zero-moment point or ZMP (Siciliano, B. and O. Khatib, 2008).

Creating Graphics of Biped Robot's Joint Angles

The joint angles and angle charts for each joint obtained from the walking model generated according to the ZMP conditions of the bipedal robot using forward and inverse kinematics are shown in Figure 3.

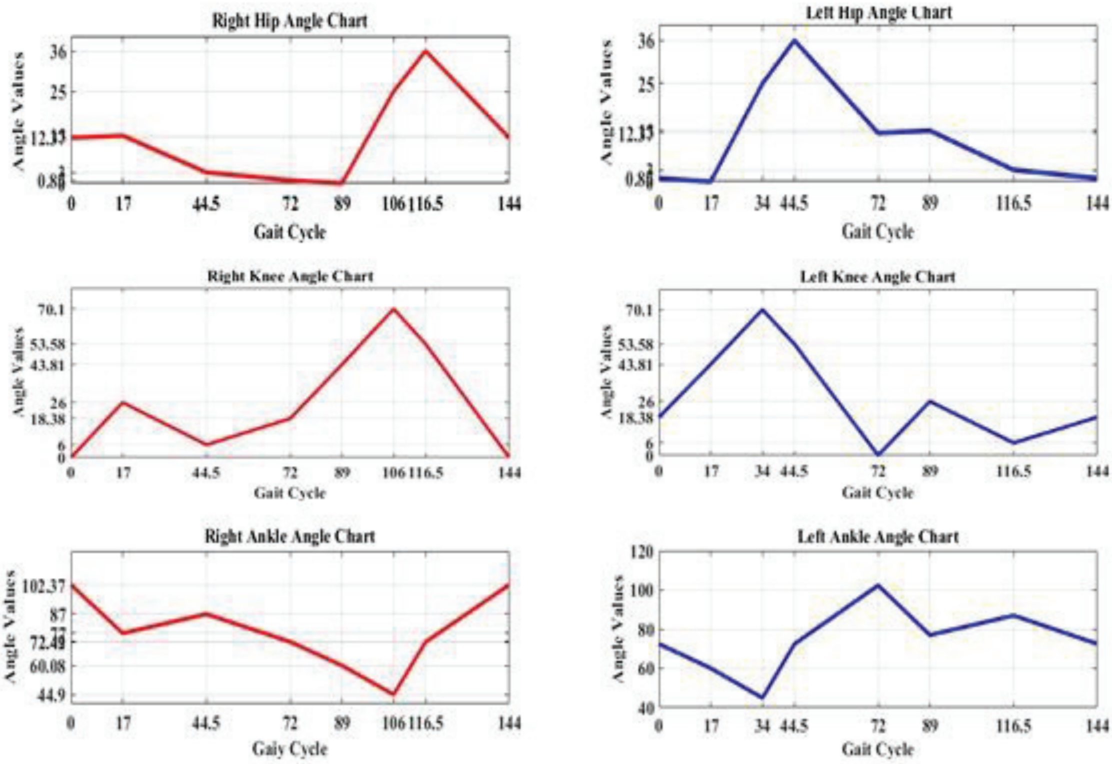

Fig. 3. Angle charts

Servo Motors

To providing joints motion of biped robot, smart servo motors, which called Dynamixel MX-64T, were used. The Dynamixel MX-64T servo actuators were developed by a Korean manufacturer ROBOTIS. (Robotis, Dynamixel MX-64T, 2016).

Main Control Board

To check a total of 12 servo motors in the biped robot, we used an OpenCM.9.04 control board, which allows open-source programming. Similar to the Arduino IDE shown in Figure 6, the Open CM.9.04 control board is also available for C/C++ programming (Robotis, OpenCM9.04, 2016).

Kinematics of Bipedal Robot

The biped robot must have at least 12 DoFs to be able to walk like a human being (Chevallereau, C., et al., 2013). Almost all designed biped robots have 6 DoF in one leg. These are 3 DoFs in the hip, 1 DoF in the knee and 2 DoFs in the ankle (Lohmeier, S., et al., 2009).

The joint and solid modeling of the bipedal robot made for this study is shown in Figure 9. A bipedal robot with 12 DoFs is assembled according to this model. There are 6 DoFs in one leg. These are 3 DoFs in hips, 1 DoF in the knee and 2 DoFs in the ankle. The height of the developed robot is 0.45 m and the width is 0.14 m. The robot has a total weight of 3.06 kg including a 0.51 kg battery(Figure 4).

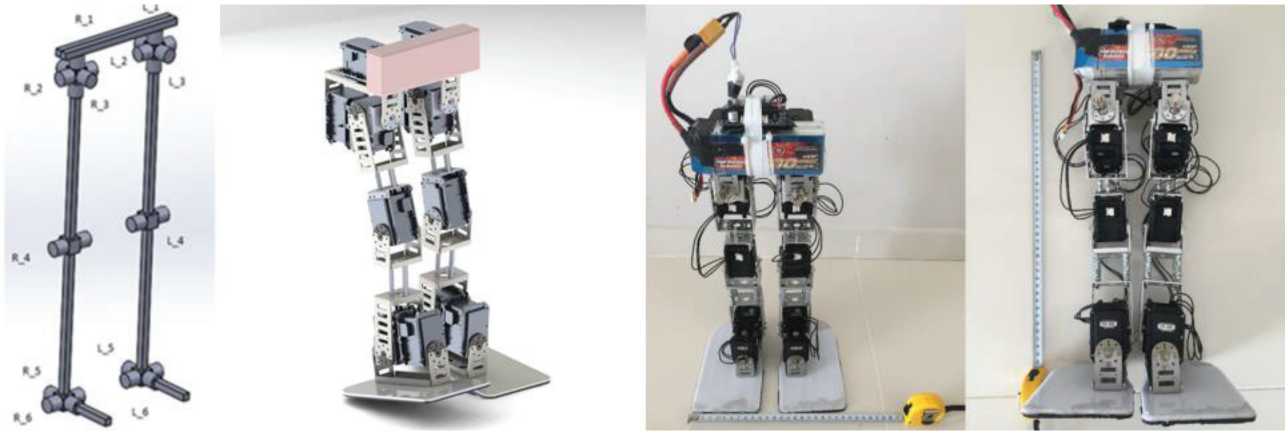

Fig. 4: Joint and solid modeling of the bipedal robot.

Application of the walking pattern and motion equations produced for the gait cycle of the bipedal robot's right leg

A walking pattern model is created for a gait cycle by bringing side by side the walking pattern angles produced for the bipedal robot's right leg as shown in Figure 5. When these angles are applied to an actual bipedal robot and its motions are compared as shown in Figure 5, it is seen that the bipedal robot walks like a human.

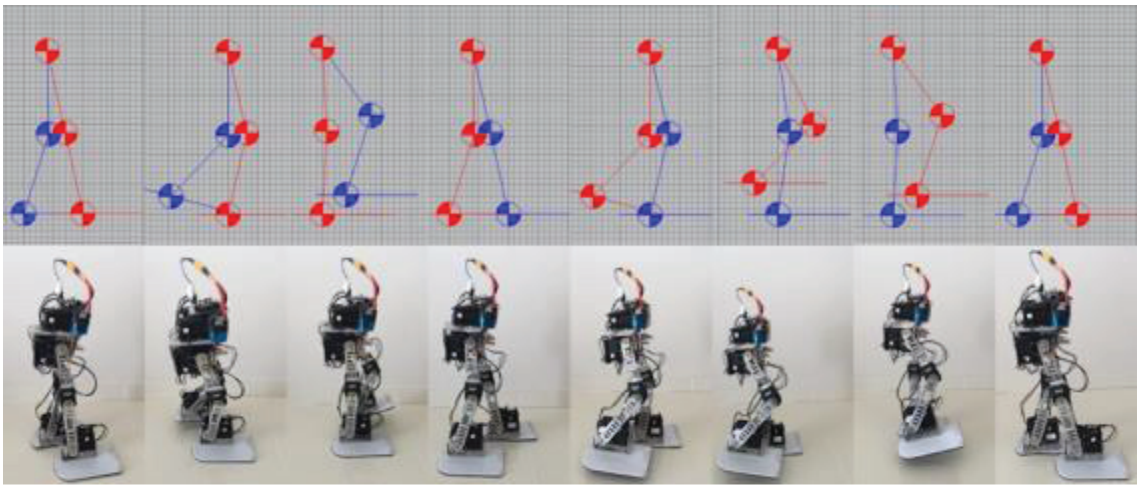

Fig. 5: Application of the walking pattern and motion equations produced for the gait cycle of the bipedal robot's right leg.

CONCLUSION

Two basic topics are discussed in this study for theoretical and empirical investigation of the designed bipedal robot's ability to walk in balance like a human being.

First, the motion functions of the servo motors in 12 DoFs of the biped robot are found. For this, the hip, knee and ankle joint angles are calculated by means of forward and inverse kinematics in a way to provide ZMP conditions of the robot for each phase. Then, these joint angle values are used and the servo motors are checked by a microcontroller programmed with embedded software. When theoretically calculated angle values are applied to the robot, it is determined that the joint angles move towards the desired position.

As a result, our bipedal robot, whose joint angle values are determined using forward and inverse kinematics in accordance with ZMP conditions of gait cycle, walk in balance like a human, performing harmonic movements in all the joints without falling down.

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