Design of Biped Robot with Anthropomorphic Gait

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Abstract: - This research develops a biped robot and designs a new walking pattern in order to achieve dynamic gait stability. One of the most widely used methods for the synthesis of humanoid gait is the zero-moment point method, proposed by Vukobratović and Juričić. This method is investigated and evaluated through computer simulation of forward motion performed by a biped robot with 10 degrees of freedom. On the basis of the simulation results, a new walking model is proposed that is inspired by the human gait. The design of a real biped robot with 6 degrees is described in detail. The hardware and software components required for anthropomorphic gait synthesis and wireless control are evaluated in the execution of realistic use cases like forward and backward movement, left and right rotation and kicking a ball.

Key-Words: - biped robot, anthropomorphic gait, zero moment point, stability, robot operating system, simulation

1 Introduction

In recent years, the topic of anthropomorphic robots is one of the most widely studied in the field of robotics. The strong interest is due to the possibility of such robots to duplicate human movements [1]. This will allow humanoid robots to replace humans in repetitive, hard or risky human activities. They can work in the environment for humans as it is. They can walk easily on inclined terrain or surface with obstacles. Due to their ability to imitate human movements, humanoid robots are also suitable for assistants of the elderly or disabled people [2]. The biped robots are more efficient than the mobile robots, when they operate in a rough terrain or in unconstructed environment [3]. The first humanoid robots with stable gait walked at a very slow speed, over 10 seconds for one step. Later, scientists began to use the Zero Moment Point (ZMP) [4, 5], as a criterion for stability during a motion [6]. The method was first proposed by Vukobratović and Juričić [5]. For a long time, this method was the only one used to control biped robots. The model has improved the movement of humanoid robots, making it more dynamic and faster.

This paper considers the ZMP method as a measure of gait stability. This is discussed in section 2 and computer simulation is performed to verify the gait model. Section 3 presents the design of biped robot. The hardware components, the software, the body and the gait of the robot are described. Section 4 presents the experiments executed on the real biped robot and summarizes the results.

2 Problem Formulation

In contrast to industrial robots which base is fixed to the ground, the foots of the humanoid robots are constantly moving and most of the time make only temporary contact with their support. Therefore, it is necessary to ensure gait stability. The robot must move smoothly without risk of falling [7]. One approach for such gait is the ZMP method. This is one of the most commonly used methods to ensure a stable gait [5].

Let's consider an anthropomorphic robot with 10 degrees of freedom (J10). It has five degrees of freedom in each leg (hips, thighs, knees, ankles, foots). Local orthogonal coordinate systems $\{X_i, Y_i, Z_i\}$ are connected to each joint. Fig. 1 presents 3D model of the biped robot J10, the local coordinate systems and the direction of rotation of the joint angles.

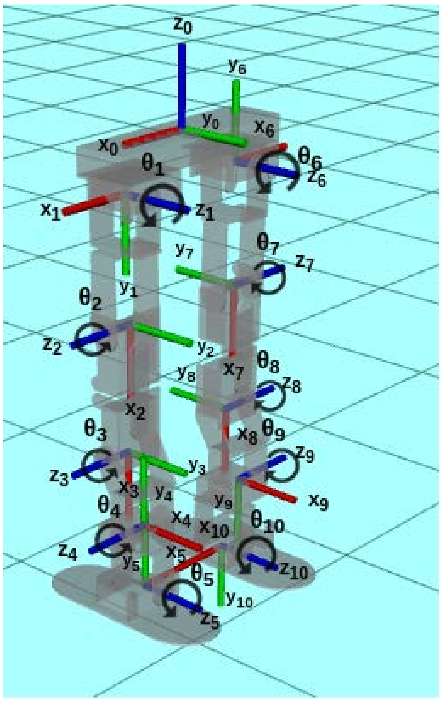

Fig.1: 3D model and coordinate systems of biped robot J10

Based on human gait studies [8], we propose the following position sequences that the robot must execute when moving forward (Fig. 2). The full cycle of motion consists of two types of phases:

Single support phase and double support phase. In the single support phase, the foot of the support leg is on the ground and the other leg is raised. During the double support phase, the two foots are in full contact with the surface on which the robot moves. The double support phase begins when a foot contacts the support and ends when the other foot detaches from the surface.

The ZMP is defined as the point in the ground where the sum of all the active moments of force is null [9]. According to the method, proposed by Vukobratović and Juričić [5], the ZMP for the foot of the support leg, in full contact with the surface, (Fig. 3) is determined by the following equations (1), (2) and (3):

$$\vec{\mathbf{R}} + \mathbf{F_A} + \mathbf{m_s g} = 0, \quad (1)$$

$$\overrightarrow{\mathbf{OP}} \times \vec{\mathbf{R}} + \overrightarrow{\mathbf{OG}} \times \mathbf{m_s g} + \mathbf{M_A} + \mathbf{M} + \overrightarrow{\mathbf{OA}} \times \mathbf{F_A} = 0, \quad (2)$$

$$M_x = 0, M_y = 0, \quad (3)$$

where **R** is the resultant force of all distributed reaction forces acting on the foot. **OP**, **OG** and **OA** are the radius vectors of the application points P, G and A, of the forces **R**, $\mathbf{m_s g}$, $\mathbf{F}_A$, relative to the point O, the origin of the O_{xyz} coordinate system. The biped robot is in equilibrium, therefore the equations (1), (2), (3) are fulfilled for every point on the foot.

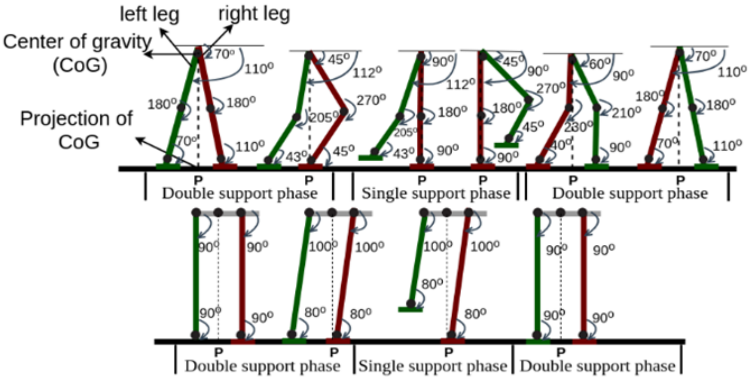

Fig.2: Forward movement

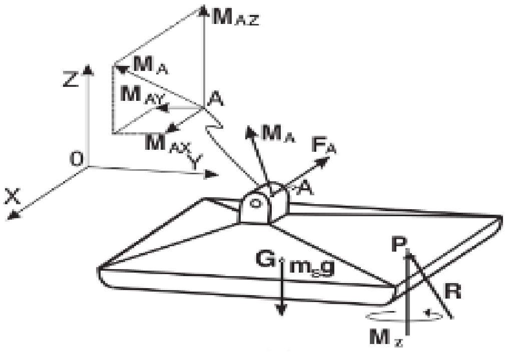

Fig.3: ZMP diagram of forces

Conditions (1) and (2) are too computationally expensive to calculate and therefore we will simplify them. Let us assume a one-point mass model of a biped robot and consider the motion of the center of mass, which is located in the center of gravity (CoG) (Fig. 2). The CoG of the J10 is located in the torso due to the location of the hardware components. We assume that the motion is constant at CoG speed. Thus, we can suppose that only the gravitational force **G** and the reaction force **R** acts on the robot. The ZMP is the projection of the CoG on the support [10], in point P in Fig. 2. At this point conditions (1), (2) and (3) for dynamic equilibrium gait are fulfilled. It is necessary to solve the inverse kinematics problem for each position that J10 executes during its forward motion. We know the lengths of the robot joints, so we can easily determine by the Law of Cosines theorem the angles for each position of the forward motion (Fig. 2).

After the computation of the desired angles, we can make a simulation of the humanoid robot J10 in

Robot Operating System (ROS) using the rviz tool. ROS is a widely used tool in the development of software for robotic systems [11], while rviz [12] is the standard 3D ROS visualization tool. Rviz requires a 3D model of the J10 robot. Such model is designed with the `OpenSCAD` [13] software. `OpenSCAD` allows the design of each joint as a separate module. Fig. 5 shows the robot J10 in each position during the simulation of the forward motion.

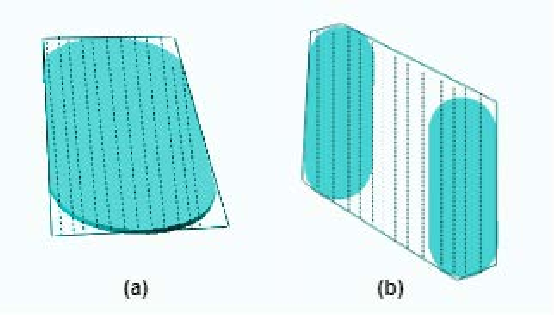

Fig.4: Support polygon in single and double support phase

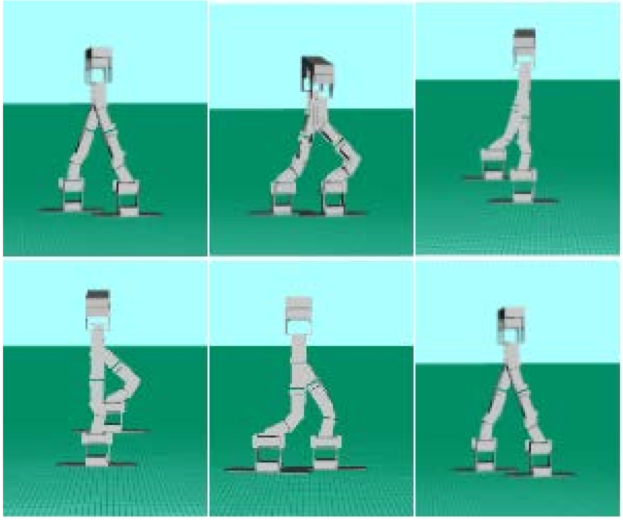

Fig.5: Forward motion simulation

The results of the J10 simulation show that the gait generated by the ZMP criteria differs significantly from the human natural gait. The motion is not smooth enough. In the next section we will design a walking pattern, that is more like a human gait. The movement performed by the biped robot must be smooth, stable and dynamic. Other researches also propose a gait that does not use the ZMP equations [14].

3 Biped Robot Design and Synthesis of Anthropomorphic Gait

Dropping the ZMP requirement allows further simplification of the biped robot model. Let's consider a new construction of an anthropomorphic robot (JOEY), in which each leg has three degrees of freedom instead of five. In the new construction the hips and the knees joints (first, third, sixth and eighth joint) from the model of J10 (Fig. 6) are dropped.

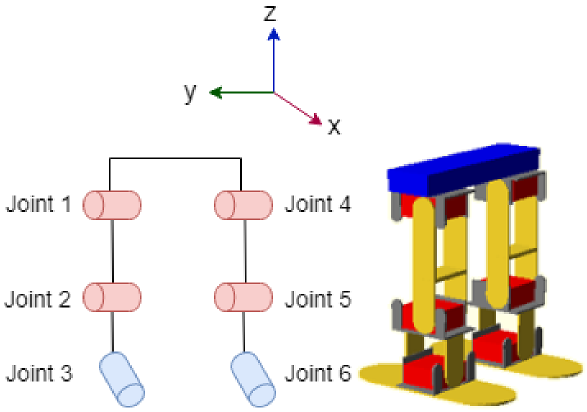

Fig.6: 3D Model of JOEY

Therefore, the number of motors is reduced, and JOEY is lighter in weight and easier to manipulate than J10. That will help us to achieve smooth and stable walking gait. The hardware components, that the robot uses and how they are connected are described below in full detail. A software application has also been developed for remote control of the robot. The following section provides information about the specific body construction, that was designed for the robot. Moreover, an anthropomorphic walking pattern is synthesized.

3.1 Hardware Components of the Robot

JOEY is powered by 6 MG996R servo motors. The servo controllers operate with analog feedback from the output shaft potentiometer. The control input is a digital - pulse width modulation signal. Pulse width modulation (PWM) is a technique for managing analog and digital circuits. PWM uses a rectangular pulse wave whose pulse width is modulated resulting in the variation of the average value of the waveform [16]. The servo motors have a maximum torque of 10 kgf.cm and have an operating voltage of 4.8 to 7.2 V.

The angle of rotation is determined by the pulse width from 0 to 20 ms.

The motors are controlled by a master controller (board) that controls up to 32 servo motors - USC32 Servo Motor Controller, ver 3.0. The operating voltage is 5V and the motor input voltage is between 4.2 and 7.2V, depending on the servo controllers. The master controller USC32 generates PWM to the inputs of the servo controllers of the motors and can be controlled via Bluetooth or another wireless module or serial via USB [16]. Robot motors are powered by 4-cell NiMH battery.

The master controller USC32 for servo motors receives commands to pass to the engines from a Raspberry Pi Zero W V1.1 single-board computer. The Raspberry Pi Zero W V1.1 has 512 MB of RAM. There is a memory card slot from which to boot the operating system. The robot is designed in such a way that the Raspberry Pi Zero connects via a web server to another computer or mobile device (e.g. smartphone).

The scheme used to connect the above described hardware components is shown in Fig. 7. JOEY can be controlled by sending a command from mobile device to Raspberry Pi Zero. The mobile device and the Raspberry Pi Zero are connected via a web server. Moreover, the Raspberry Pi Zero sends the commands to USC32 Servo Controller. They are connected by USB. Finally, the USC32 Servo Controller controls the 6 Servo Motors MG996R and they drive the biped robot JOEY.

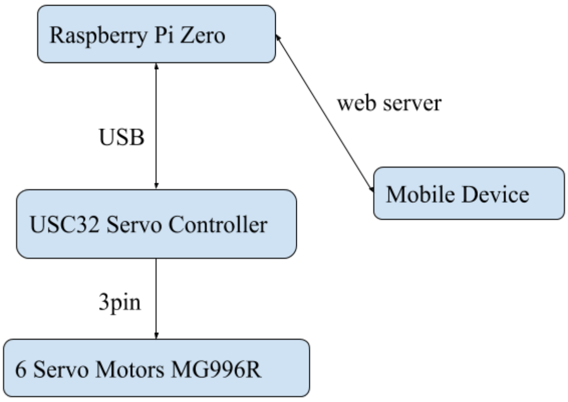

Fig.7: Hardware schema of a biped robot.

3.2 Software System of the Robot

Mobile application is developed. It provides remote control of the biped robot. The application allows control of every single robot joint. The user monitors in real time the changes occurring in the individual joints and at any moment can set the robot back to its starting position. The application makes it possible to create a sequence of movements, save them and execution on the robot. The application is developed using the Python programming language and using the micro framework Flask. The `roslibpy` library is used to allow Python to interact with the ROS. WebSockets are used to connect to `rosbridge 2.0` to publish or subscribe to a communication channel, tf transformations, and other important ROS functionality. The library does not require locally installed ROS, so it can be used on operating systems other than Linux [17].

3.3 Specific Body Construction

A custom outer cover for the robot is designed using the OpenSCAD program. It encapsulates and protects the batteries that power the motors and the single-board computer and the servo motor controller. Also, this contributes to better appearance of the anthropomorphic robot and at the same time all hardware components are hidden and protected from damage in the event of a fall of the robot. The cover is fully 3D printed. The material used for the manufacture of the body is polylactic acid (PLA).

3.4 Specific Body Construction

We propose a new gait, that does not meet the criteria of the ZMP model, and the forward movement is more like a human gait. The new gait is a combination of forward and lateral motion [14]. During the lateral motion, the biped robot is in the single support phase. The lateral motion represents the stance switch. The CoG is on the support leg. The forward motion represents the leg swing. The forward movement will be combination of stance switch and leg swing. As described in the previous subsections, the biped robot has 6 degrees of freedom. The lateral motion is controlled by 2 rotational joints which rotates along X axis. The forward motion is controlled by 4 rotational joints which rotates along Y axis (Fig. 6).

4 Experiments and Results

The robot’s forward movement consists of discrete sequence of joint angles. The cyclical repetition of this sequence represents the gait of the robot when it is moving forward. The discrete sequence that generates the JOEY forward gait is determined by demonstration of the first cycle of movement of the biped robot J10. The JOEY USC32 controller controls the motors, sending them PWM signals. The signals represent values between 700 and 2300. Table 1 shows the PWM values for each robot joint at each forward motion phase.

Table 1. PWM values.

Joint	Position 1	Position 2	Position 3	Position 4
1	1450	1450	1200	1450
2	1500	1500	1300	1500
3	1550	1700	1400	1550
4	1500	1250	1250	1650
5	1400	1200	1200	1500
6	1500	1650	1250	1250

The execution of forward motion of the biped robot with 6 degrees of freedom consists of 4 positions. The first position is the starting position in which the two legs of a robot are straight, parallel, and the projection of the CoG is in the middle of the support area. From this position, the robot can easily shift its weight to the left or right leg (Fig. 8 (a)).

During the second position JOEY shifts its weight onto its right leg, lifting its left leg. The projection of the CoG is on the right foot. The right leg remains in a straight position. The robot is at the single support phase (Fig. 8 (b)).

In the third position, the biped robot moves the left foot forward and steps to the ground. JOEY tilts its right leg forward, whereby the projection of the CoG and the ZMP leave out of the support polygon of the right foot. The robot loses momentary equilibrium, but when the left foot touches the ground, the robot again goes into equilibrium in a double support phase. The projection of CoG moves to the left leg (Fig. 8 (c)). In the fourth position, the biped robot goes again into the single support phase, the support leg is the left. The right leg is raised. The projection of CoG is on the left foot. To take a step forward with the right foot, the biped robot executes the second position again, but the legs are changed (Fig. 8 (d)). Images at each position of the forward motion of JOEY are shown in Fig. 8.

JOEY can perform backwards walking, turning left and right, and kicking a ball (Fig. 9). The way these movements are modeled similarly to the way forward movement is modeled. The joint angles are programmed by demonstration.

5 Conclusion

In this paper, we investigated the ZMP method as a gait stability criterion. For this purpose, a computer model of biped robot with 10 degrees of freedom was used. Computer simulation of forward motion with the ZMP method was made by using the ROS toolbox and the computer model of the robot.

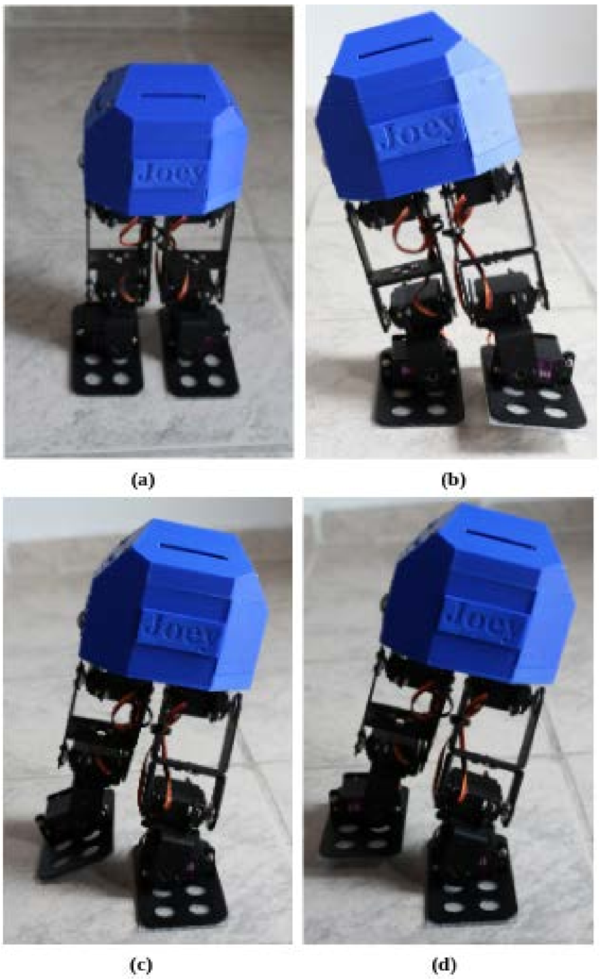

Fig.8: Forward motion.

Fig.9: Kicking a ball.

This computer simulation confirmed that the gait is not dynamic enough and does not resemble the human gait. Therefore, we suggested a new gait synthesis. The new walking pattern was motivated by the human gait. It consists of a combination of two movements - forward motion and lateral motion. The design of the robot was also changed. The new design consists from 6 degrees of freedom. Experiments have been done with the new gait on the real biped robot and the robot has now stable and dynamic gait. The biped robot can perform various movements such as forward and backward movement, left and right rotation and kicking a ball [18] and it can be controlled wirelessly through a mobile application. The mobile application can be used for any robotic system, regardless of its type. Further improvements can be done by creating additional movements such as climbing stairs or walking on surface with obstacles. Sensors of the foot of the robot can be also added. Moreover, the movement pattern can be improved by feedback correction from sensors.

Acknowledgment:
This work was supported by Grant No. 80-10-07/2019 of the Fund for Scientific Research at Sofia University “St. Kliment Ohridski”.

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