Design and Development of a Robot Transformable between Biped Waking and Wheeled Modes

J. Singh, D.Gandhi, N. Reddy

Abstract

In this paper, a novel robot is designed such that it possesses walking as well as wheeled motion. Wheeled locomotion is most widely used mechanism for mobile robots on even terrain whereas walking mechanism is suitable for mobility of robots on uneven terrain. Unlike quadruped robots or hexapod robots, biped robots can serve as a replacement of humans for many hazardous tasks. To achieve advantages of wheeled as well as biped robot, we designed a robot with both mobility mechanisms. First, a 6-degree of freedom (DoF) biped robot has been constructed with 3 DoF on each leg. A gait pattern for walking mechanism is designed based on kinematic analysis of robot and simulations were done to visualize the walking gait. Furthermore, the actuation angles are provided based on foot trajectory and inverse kinematics of the robot. Every degree of freedom has been actuated by a motor with inbuilt PID controller. Two designs are proposed for the biped robot, one having springs between ankle and foot and the other entirely rigid. Next, the task is to transform from walking mode to wheeled mode. A setup was designed to bring four wheels in contact with the ground and lift the feet from the ground simultaneously. In the wheeled mode, rear wheels are active and front caster wheels are passive. Experiments were carried out in which the prototype is made to move with both mobility mechanisms.

Keywords: quadruped robots, hexapod robots, biped robots, degree of freedom, gait, PID

1 Introduction

In recent years, focus of several researchers in robotics community has been directed towards developing robots which can provide fast mobility on varied terrain. Legged robots present an appealing solution to navigate a robot on uneven terrain or climb stairs. Among the legged robots, biped robots have been an intensive point of research because of their ability to efficiently replace humans in performing tasks which are potentially hazardous to their health [2]. Also, a useful by-product of research into bipedal robotics will be the enhancement of prosthetic devices. The first reason why legged robots are more mobile is that they can use isolated footholds separated by unusable terrain to optimize support and traction [7]. However, the major disadvantage of biped robots lies in the fact that they are less efficient, slow and subject to falls or toppling. The wheeled robots, on the other hand, have the advantage of fast mobility, increased stability and smooth traversal. The disadvantage associated with wheeled robots is that they are generally useful only on even terrain. The idea of incorporating advantages of both biped and wheeled robots served as a motivation to design a robot which can navigate in both these modes.

Earlier, static stability was used in controlling a biped robot. It was the concept of Zero Moment Point (ZMP) which served as a milestone in walking of biped robots. It proposed that even if center of mass exits the convex hull of support polygon, the biped robot will not fall as long as the ZMP is inside that hull. Miomir studied the emergence of ZMP concept and published it in his paper 'ZERO-MOMENT POINT — THIRTY FIVE YEARS OF ITS LIFE' [5]. The first biped robot to be successfully created and use dynamic balance was developed by Kato in 1983 [8]. However Miura and Shimoyama [9] abandoned static balance entirely in 1984 when their stilt biped BIPER-3, which was modelled after a human walking on stilts, showed true

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J. Singh
Mechanical Engineering, IIT Guwahati, , E-mail:jagjeetsingh774@gmail.com.

D. Gandhi
Mechanical Engineering, IIT Guwahati, , E-mail:g.prakashchand@gmail.com.

N. Reddy
Mechanical Engineering, IIT Guwahati, , E-mail:annem@iitg.ernet.in.

active balance. After years of progress, C. Hernández proposed a new architecture for a biped robots that are equipped with flat feet which allows a robot to walk in a more natural way [6]. Further, many researchers used compliance in different parts of their biped robots. Abhishek et al proposed a new design of an 8-DoF biped robot with compliant links for walking [1]. Keon developed a biped robot which has compliant ankle joints. Simulated version of a human ankle joint was built using springs and mechanical constraints, which gave a flexibility of joint and compliance against the touching ground [4]. The advantages of wheeled locomotion on smooth terrain are clear from the fact that all modes of travel and transportation involve wheels. Masaaki proposed the leg-wheel locomotion of a biped robot. In the design proposed by him, the feet of the robot consisted of wheels that move forward with the periodic motion of a leg under a double-leg support [3]. Nakano's Chariot series [10] have two large active wheels on the body that assist the legs in supporting robot weight while traversing uneven terrain and helping the robot travel smoothly without the legs on flat ground. Several approaches have been developed with biped robot using wheels mounted on their feet. Hashimoto's WS-2/WL-16 [11] and Weiguo's GoRoBot [12] have motor-driven wheels on each foot. They can switch between walking on foot and wheel locomotion.

This paper presents design of a robot which can switch between walking mode and wheeled mode as well as analyzes the use of compliance at the foot of the robot. In the following section, we explain the walking mechanism and the walking gait adopted for the biped robot. Forward Kinematics of the robot is presented using DH parameters which are followed by trajectory generation using toe, knee and hip angles. Simulation results for the walking gait are displayed. Following this is the design part wherein two different designs are proposed and compared based on the effect of adding leaf springs at the foot. For walking, the advantages and disadvantages of having springs connecting feet to the ankle instead of a rigid joint were analyzed based on static stability and the ability to overcome obstacles Prototype is developed for the spring-less design and experiments are carried out. It is followed by the transformation mechanism where a novel setup is designed to convert the robot from one mode to the other. Finally, wheeled mode of mobility for the proposed design is explained.

2 Walking Mechanism

Biped walking is a periodic phenomenon. A complete walking cycle is composed of two phases: a double-support phase and a single-support phase [1].As shown in Fig. (1), at the start of walking, the robot is in double support phase as both the feet are in contact with the ground. As soon as one of the feet is lifted off the ground, the robot enters the single support phase. Balancing a biped robot in single support phase is a complicated task as the convex hull of the foot in contact with the ground is less. The robot tends to fall as soon as the Zero Moment Point exits this region.

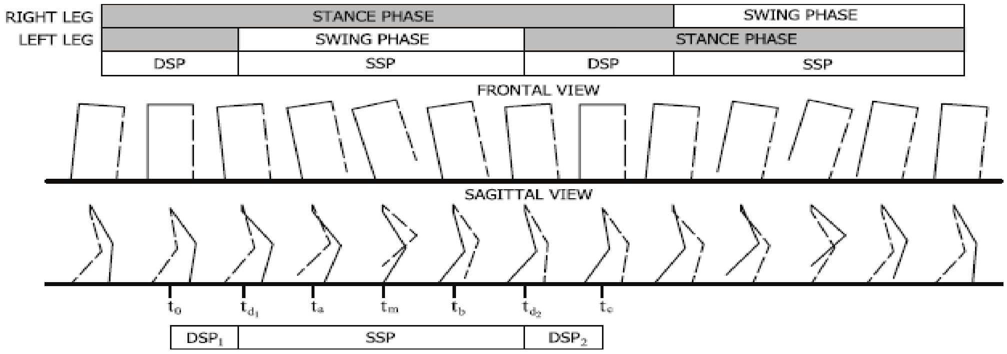


Figure 1: Frontal and Sagittal views of a complete walking cycle of a biped robot [1]

In the walking gait used, first step is the lifting up of the foot to move from double support phase to single support phase. The toe degree of freedom is used to tilt the robot sideways. The range of angles for which the ZMP would lie within the convex hull of contact area was found to be between 14.7 degree to 45.5 degree. The toe motor was actuated by 30 degree which is approximately the mean of these two angles. Also, the motor needs to be actuated fast enough to avoid falling down of the robot. From experiments, the time was found to be 0.5 seconds during which the motor would be actuated by 30 degrees.

The next step in walking is to actuate the hip and knee motors on the stance leg. During this phase the center of mass (COM) of the robot rotates about this contact point in the manner of an inverse pendulum, while the other leg known as the swing leg translates in preparation to come in contact with the ground for the next double support phase[2]. In this case also it is to be ensured that the ZMP stays within the convex hull of contact area. This limits the maximum step size of the bot, which was found to be 4 cm. From the second step onwards each motor in the two hip joints and two knee joints have to be actuated by 2θ. Also time period of 2 seconds was found to be appropriate for completing this step. This time will decide the speed of walking.

2.1 Forward Kinematics

In this section, the position and orientation of the end-effector is obtained from the configuration of the active joints of the robot. This paper focuses on the lower body of a humanoid biped robot. It consists of two 3 DOF legs, namely a 1 DOF hip, a 1 DOF knee, a 1 DOF ankle. The total system is modelled as a kinematic chain with 7 links connected by 6 revolute joints. The model specifications are shown in Table 1.

Table 1: Model Specifications for forward kinematics

Link	**Length(m)**
Toe(L_0)	0.05(centre)
Shank(L_1)	0.15
Thigh(L_2)	0.15
Hip Link(L_3)	0.12

The local frame (X_i, Y_i, Z_i) is assigned to each joint according to the Denavit-Hartenberg (DH) convention. The base frame (X_0, Y_0, Z_0) is attached at the centre of the foot which is at rest in the starting motion. The DH parameter specifications of the model are shown in Table 2.

Table 2: DH parameters for the forward kinematic model

Link i	$\boldsymbol{\theta_i}$	$\boldsymbol{\alpha_i}$	$\boldsymbol{a_i}$	$\boldsymbol{d_i}$	**Initial** $\boldsymbol{\theta}$
1	0	$\pi/2$	$-L_0$	0	0
2	θ_1	$\pi/2$	L_1	0	$\pi/2$
3	θ_2	π	L_2	0	0
4	θ_3	0	0	L_3	0
5	θ_4	π	L_2	0	π
6	θ_5	$-\pi/2$	L_1	0	0
7	θ_6	0	L_0	0	$\pi/2$

For the visualization of the DH parameters, the RoboAnlyzer tool, provided by mechatronics lab of Indian Institute of Technology, Delhi. The visualization is shown in Fig. (2).

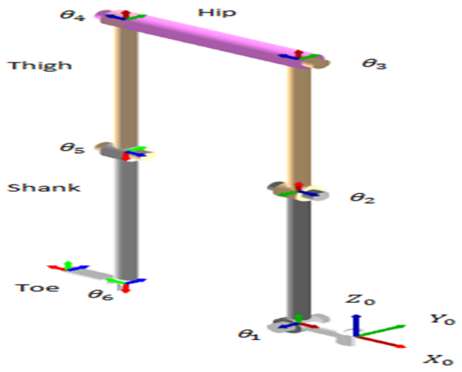


Figure 2: Visualization of D-H parameter

Using the D-H parameter, general link transformation matrix relating the i-th coordinate frame to the (i-1)th coordinate frame is obtained by,

$$T_i^{i-1} = \begin{bmatrix} c\theta_i & -s\theta_i \cdot c\alpha_i & s\theta_i \cdot s\alpha_i & a_i \cdot c\theta_i \\ s\theta_i & c\theta_i \cdot c\alpha_i & -c\theta_i \cdot s\alpha_i & a_i \cdot s\theta_i \\ 0 & s\alpha_i & c\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where, $s\theta_i = sin\theta_i, c\theta_i = cos\theta_i, s\alpha_i = sin\alpha_i, c\alpha_i = cos\alpha_i$ and parameters are corresponding to the i^{th} link. The total transformation matrix, connecting the 7th frame to the base frame is obtained by multiplying the individual matrices.

2.2 Trajectory Generation

The gait implemented on the robot for the walking purpose follows a specific sequence of actuation. First toe joint (θ_1 or θ_6) is actuated to lift one foot from the ground. After that, knee & hip joints ($\theta_2, \theta_3, \theta_4, \theta_5$) are actuated in such a way that the lifted foot remains at a constant height from ground during the whole motion. This actuation of knee & hip joint is responsible for moving the robot in the forward direction. Again the toe joint is actuated to get lifted foot back in contact with the ground. Therefore in complete walking gait, the lifted foot follows the pulse waveform in Sagittal plane. While actuation, the care is also taken for smooth actuation i.e. zero initial and final speed. Fig. (3) depicts the actuation sequence of each joint versus time.

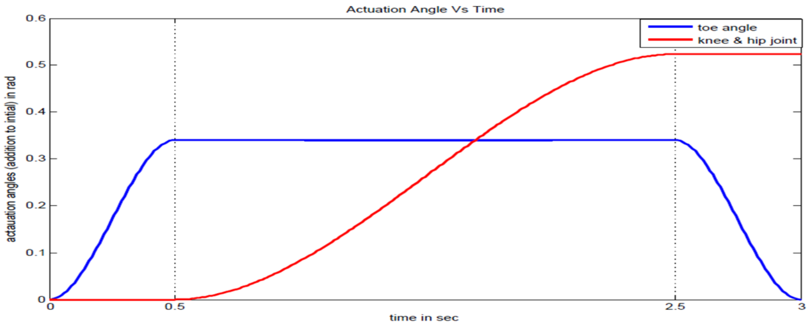


Figure 3:Graph of Actuators angle versus time

From Fig. (3), it is visible that the first and last sequence are performed in 0 to 0.5 and 2.5 to 3 sec respectively, while the second sequence is performed during the 0.5 to 2.5 sec. The actuation angle and time were decided based on the stability of robot. The actual movement of each link corresponding to the above actuation angle is visible in Fig. (4).

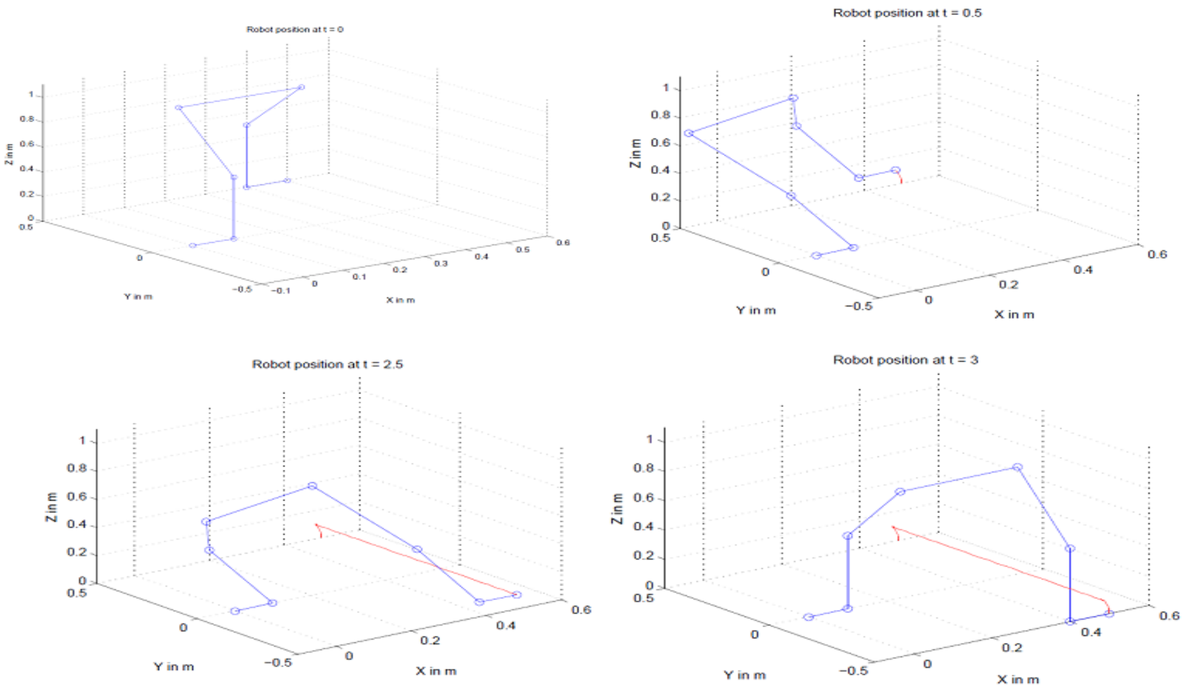
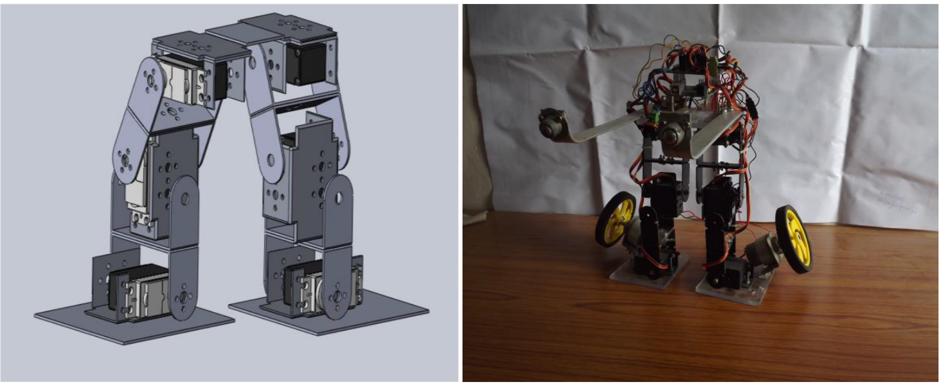


Figure 4: Robot link position for different time interval

2.3 Design of Biped Robot

2.3.1 Design without leaf springs at foot:

This design consists of 6 servo motors for biped mode and 2 DC motors for wheeled mode as shown in Fig. (5). In this case, there are no leaf springs at the foot. The foot is a single part body and rigidly connected to the motor brackets. The advantage of this design is higher static stability. However, overcoming obstacles during walking is not efficient. This is because the impulse caused by the obstacle is transferred to the complete leg due to absence of any compliant part. Fig. 5(a) shows the CAD model for the walking part of the design. The wheels and DC motors used during wheeled mode were added in the prototype as shown in Fig 5(b). The prototype developed for this design was tested on even and uneven surfaces. Wheeled mode was highly efficient for mobility on even terrain. However, walking mode showed that adding compliance to the foot would help in walking over the obstacles on rough terrain.



(a) CAD model of the robot (b) prototype developed

Figure 5: Design of the biped robot without springs at foot

2.3.2 Design with leaf springs at foot:

Design with springs on foot also consisted of 6 servo motors for biped mode and 2 DC motors for wheeled mode. In addition there were 2 leaf springs on each foot. Each foot was divided into two parts such that there is a hinge connecting them. Any obstacle encountered in front part of the foot will result in rotation of front part, thereby compressing the leaf spring in front. As a result, the impulse will be damped before reaching the complete body. Although stability is compromised in using compliance but overcoming obstacles becomes a smooth process. Fig. (6) shows CAD models for the design with springs on foot. Two black colored curved cantilever beams are attached on each foot which act as leaf springs between ankle and the two parts of the foot. The wheels and DC motors are also shown in the CAD model. Prototype for this design is yet to be developed.

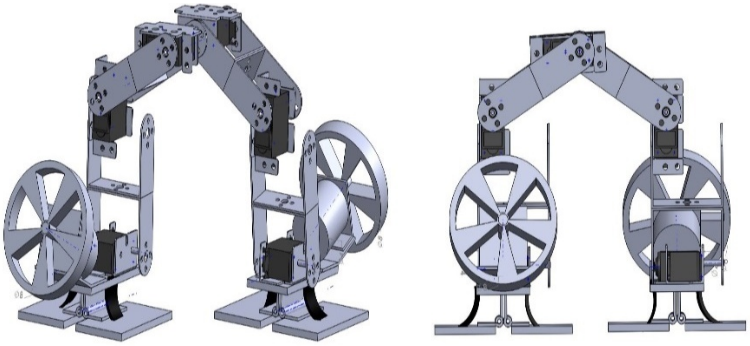
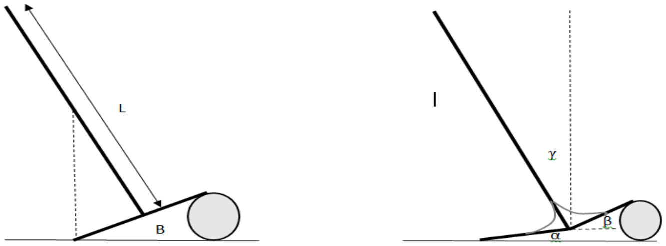


Figure 6: Design of the biped robot without springs at foot

2.3.3 Comparison of the two designs

In the design proposed, two springs were attached on each foot. One spring connects the ankle to the front part of the foot and the other spring connects the ankle to the rear part of the foot. For comparing this design to that without springs, simplified models were considered as shown in Fig. 7(a) and Fig. 7(b).



(a) Design without leaf springs at foot

(b) Design with leaf springs at foot

Figure 7: Simplified models for comparing rigid and compliant designs

Fig.7(a) shows the simplified model for the rigid case. The ankle is rigidly mounted on the foot and the angle between them is fixed. It is assumed that the weight of foot is very small compared to the weight of entire leg. As such, center of mass of the system lies at the center of the link forming the leg. The figure shows the boundary case of stability. If an obstacle of greater height is encountered, then the center of mass will exit the support polygon of the foot and the robot will fall. Considering the length of foot to be 12cm and length of leg to be 30cm, the obstacle height for boundary case was found to be 4.45cm. The entire robot is tilted by an angle of 21.8 degrees. Fig. 7(b) shows the simplified model for the design having leaf springs attached at foot. Now, if the same obstacle height is encountered by the leg with springs at its foot, the behavior is different. Instead of entire robot getting tilted by the same angle, there will be three different angles. The rear part of the foot is tilted by angle ‘α’ and the front part by angle ‘β’ from the horizontal. The leg is tilted by an angle ‘γ’ from vertical. To find the three different angles α, β and γ, potential energy of the system was minimized. A function P was considered to measure the shift in center of mass when the obstacle is encountered.

$P = (B/2)*\cos(\alpha) - (L/2)*\sin(\gamma)$

For an obstacle height of 4.45cm, P is zero for rigid case. Now, if P is greater than zero then the stability is better than rigid case because center of mass is further inside the support polygon of the foot. If P is less than zero then the stability is worse than rigid case as the center of mass is exiting the support polygon of the foot. To find the effect of adding springs on stability, change in function P was analyzed with varying spring stiffness whose result is shown in Fig. (8)

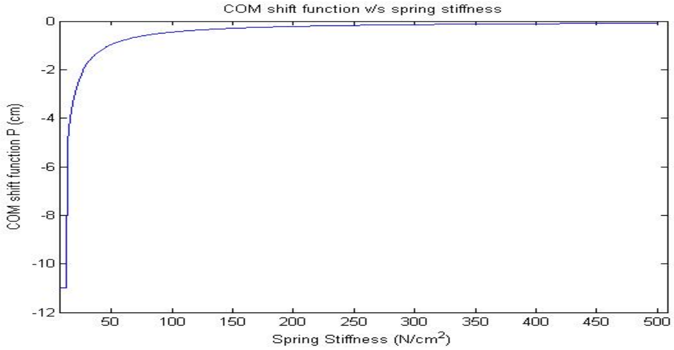
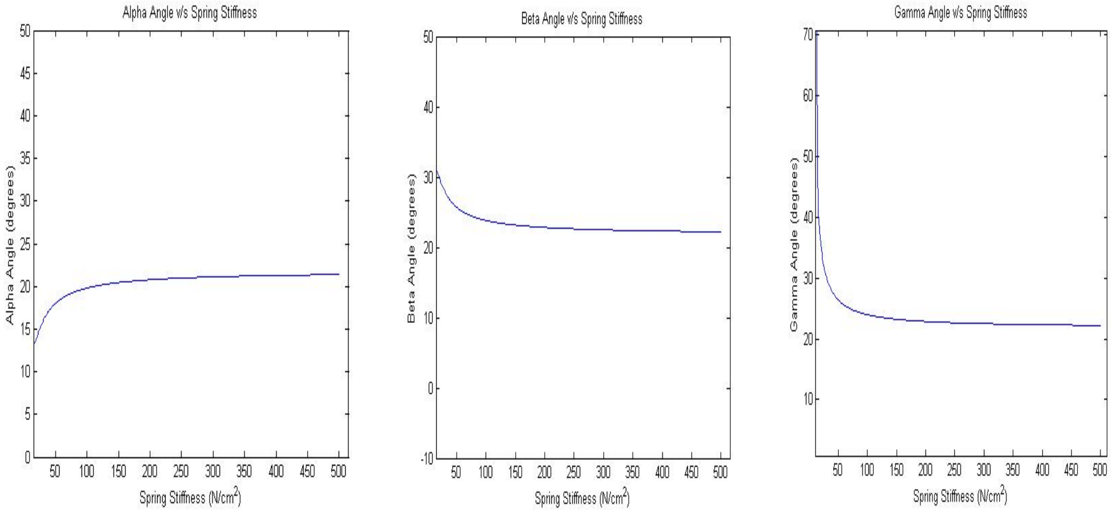


Figure 8: COM shift function P v/s Spring Stiffness

From Fig. (8), it can be seen that the function P decreases with decrease in spring stiffness. The maximum possible value for the function ‘P’ is zero, which is obtained when the spring stiffness is infinity. This result shows that the maximum possible stability is achieved when the spring is of infinite stiffness. This case is analogous to the design in which there are no springs on the foot. Hence, addition of springs compromises with stability during walking. Further, variation in angles α, β and γ with spring stiffness was also studied whose results are shown in Fig.(9).



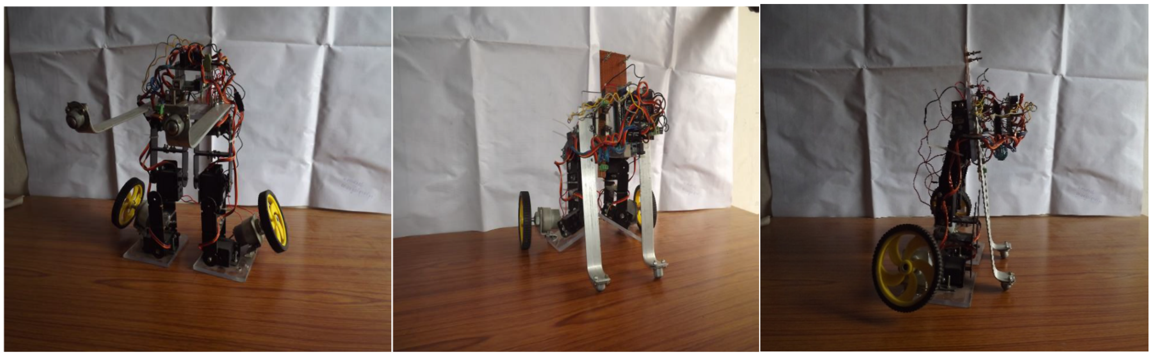
(a) Alpha angles v/s spring stiffness (b) Beta angle v/s spring stiffness (c) Gamma angle v/s spring
stiffness

Figure 9: Variation of the three angles with spring stiffness

From Fig. (9), it can be seen that for a small spring stiffness, angle γ is high but the angle α is low. This means that when an obstacle is encountered, the effect on rear part of the foot is very less compared to the leg. Since the leg is of much higher mass and it is tilting with a greater angle than rear part of the foot, the center of mass exits the support polygon of the foot more easily. As the spring stiffness is increased, angle α increases and angle γ decreases. Further, the three angles α, β and γ approach the case with no springs, i.e., all the three angles approach towards the value of 21.8 degrees. From Fig. (8), it was clear that addition of springs at the foot results in a decrease in stability. However, when an obstacle is encountered during walking, the springs will absorb the shock and result in smooth walking. In case of rigid design, the shock will be carried to the entire body and the might result in falling down of the robot. Moreover, if a compromise is made in stability then both the advantages of stability and smooth overcoming of obstacles can be accessed. From Fig. (8), it can be seen that the COM shift function increases rapidly in the beginning. It reaches very close to zero with less increase in stiffness of the spring. So, it is the lower range of spring stiffness which is the concern for decreased stability. Spring stiffness higher than 50 N/cm^2 results in stability close to that of rigid case. Moreover, the difference in stability that still exists can be taken into account while considering the obstacle height. Calculations were done to find the spring stiffness for the case in which stability is 90% of rigid case. It was found that a spring with stiffness 53 N/cm^2 would provide 90% stability. Further, the COM shift function P in this case is -0.9 cm. The angle α was found to be 18.2 degrees, β was 25.48 degrees and γ was 26.11 degrees.

3 Transformation Mechanism

Biped legged robots have the advantage of locomotion over uneven train whereas wheeled robots provide the advantage of fast and stable locomotion over even terrain. Incorporating the advantages of both these modes, a transformation mechanism was designed which can transform the robot from legged mode to wheeled mode and vice versa whose positions at different stages is shown in Fig. (10). The prototype was developed for the design without springs on foot. As such, transformation mechanism was applied on that design. However, it can be easily applied to the design with springs on foot also.



(a) During walking mode (b) During wheeled mode (c) During Transformation

Figure 10: Orientation of the robot during different stages of transformation

Fig, 10(a) shows the robot in walking mode and Fig. 10(b) shows the robot in wheeled mode. As described earlier in the design of the robot, to transform the robot from walking mode to the wheeled mode, two castor wheels were attached on two horizontal (when the bot is upright) arms on the top and two motors were attached on the foot at an angle. The transformation process starts with the actuation of motors at the knee and the hip. Both the knee motors are actuated simultaneously to an angle of 30^o with the vertical and both the hip motors are actuated by an angle of 60^o each such that arms on which the castor wheels are attached are now vertical. As shown in Fig (10), a dc motor is mounted on the foot at an angle of 30 degrees. While walking, the wheel is at an elevation above the ground. When the robot is to be transformed to wheeled mode, both the servo motors at the foot are actuated in opposite directions such that the wheels come in contact to the ground and become vertical. It is also ensured that the foot is no longer in contact with the ground.

4 Wheeled Mode

Once the robot has transformed to the wheeled mode, it can move as a 4 wheeled mobile robot. The two rear wheels are active having a diameter of 9mm each and are actuated by two separate motors. The motors used for rear wheels are 200RPM DC motors weighing 117 grams each. There are two castor wheels in the front which are passive. The links connecting these castor wheels to the body are Aluminum strips of length 21 cm.

The robot can be transformed to the wheeled mode when the surface is even and fast mobility is required. Also, as it is a 4 wheeled locomotion it provides much more stability compared to the biped walking mode. Another important feature of wheeled mode is that height of the robot can be changed by actuating the servo motors at the hip. Normally, these motors are actuated by an angle of 60 degrees. When the height of the robot has to be increased further, the angle can be made more which will pull the castor wheels inside, thereby raising the robot. When the height has to be decreased, the angle can be made less than 60 which will push the castors outside. To ensure that the foot still has no contact with the ground, the servo motors at the foot can be actuated accordingly.

5 Conclusion

A robot capable of exhibiting walking as well as wheeled modes of mobility has been designed. The walking mode consisted of a biped robot. Different walking gaits were studied and gaits suitable for the designed robot were applied. In the forward kinematics of the robot, the position and orientation of the end-effector was obtained from the configuration of the active joints of the robot. DH parameters were assigned and visualization was done using RoboAnlyzer tool. Two designs were proposed for the walking mode, one with springs at the foot and the other completely rigid. Comparison of the two designs were made based on aspects like stability and smooth overcoming of obstacles. Prototype was developed for the rigid design and experiments were done. The robot was designed to have a transformation mechanism to convert the robot from one mode to the other. Wheeled mode consisted of a 4 wheeled mechanism wherein the two front castor wheels were passive.

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