**Proceedings of ECTC 2008**
**2008 ASME Early Career Technical Conference**
**October 3-4, 2008, Miami, Florida, USA**

# INVERSE STABILITY ANALYSIS OF A BIPED ROBOT

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## ABSTRACT

*This paper addresses the design and programming of a biped robot. Simple kinematics will be employed to carry out an analysis of biped stability and control. Center of mass and angular position are key components of successful motion. These variables are monitored throughout each process gait. The motion is simulated using COSMOSMotion. Different software packages found in the market are analyzed to show their capabilities to facilitate learning.*

## MOTIVATION

Understanding stability control for successful biped motion is a key component of robot design. Undergraduate programs in Mechanical Engineering emphasize the need to obtain continuous motion of the robot's limbs. The analysis of dynamic motion of a biped robot is an arduous task usually expected from graduate students. Simple static analysis of the biped motion can be achieved by employing center of mass and force balance. The following paper is intended to assist future work in the University's effort to improve its undergraduate robotics program as well as to facilitate future learning.

## BACKGROUND

Perhaps one of the major discoveries in the 20th century has been robot locomotion. From automated production lines to simple daily use of electronics, robotics has helped revolutionize our daily lives. Recent attention has been diverted towards creating smart motion of smart human-like robots such as the robot THBIP-2, the second-generation biped of Tsinghua University [1]. Human-like robots are better known as humanoids. The bottom section of a humanoid, the biped, is one of the key components in achieving successful human-like motion.

The fast advance in computer technology over the past decade has facilitated the development of biped robots. Different methods are used to design motion and stability of a biped. The two main areas of analysis are dynamic analysis and static analysis. Dynamic analysis employs the use of advanced system dynamic techniques; the Lagrange method could be considered a dynamic analysis [2]. Static analysis employs easier mathematics, mainly derived from geometrical and static relations. The use of dynamic models as well as static models has been enhanced by the increase in computational speed.

Static analysis of biped stability is more practical for beginners in the area of robot design. One of the key challenges in using the method of static analysis is maintaining stability throughout the progress of each gait.

## BIPED DESCRIPTION

Biped BRAT (Bipedal Robotic Articulating Transport) which is used in the project is a six Hitec HS-422 servo biped walker featuring three degrees of freedom (DOF) per leg. The biped is made from brushed aluminum servo brackets and includes an electronics carrier made from ultra-tough laser-cut Lexan. The robot is powered by a 6.0vdc Ni-MH 1600mAh battery pack.

## KINEMATIC ANALYSIS

Optimal mass distribution is achieved by understanding the location of the center of mass [3]. According to the results presented, a cluster region of solutions is found when the function of $(c, r_{gyr})$ approaches (l,0). The value c represents the distance of the center of mass measured from the floor. We can expect the system to reach a more balance position when this distance approaches the "l" length of the biped leg. We must also consider that the radius of gyration must also approach zero to obtain these desired conditions.

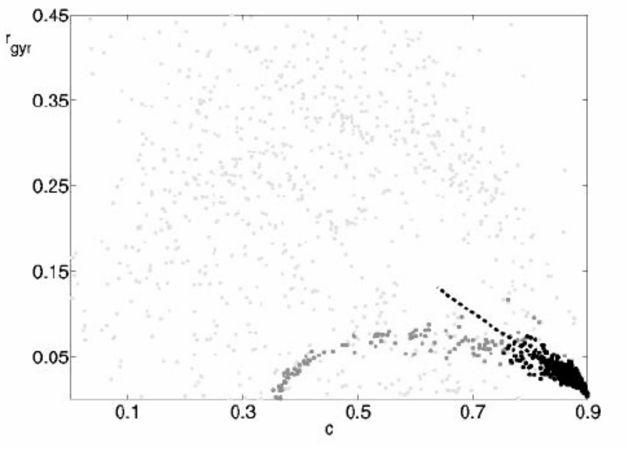


Figure 1. Region of solutions [1]

The ratio of biped weight to height is also an important factor that contributes the dynamics of movement.[2]The distance between the two ankle centers is crucial in maintaining stability. If too large, the distance between the offset between projection of COG and the supporting center will increase. This will decrease the Zero Moment Point stability margin.

The kinematics analysis is based on the basic equations of link motion where the position of the end effector point is described by the position ($X_H$,$Y_H$).

$$X_H = L_N \cos\theta_N + L_{N-1}\cos\theta_{N-1} + ...L_0 \cos\theta_0 \tag{1}$$

$$Y_H = L_N \sin\theta_N + L_{N-1}\sin\theta_{N-1} + ...L_0 \sin\theta_0 \tag{2}$$

The biped assembly closely resembles the link equation above.

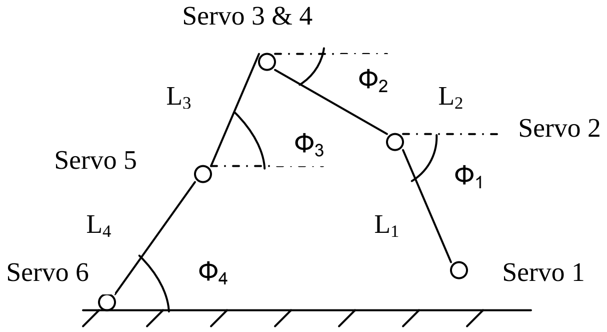


Figure.2 Biped motion-Sideview

Each joint also experiences a mass force due to the weight of the servo. Applying equations (1) and (2) relation (3) below can be obtained for the position of the end-effector.

$$\begin{pmatrix} \sin\phi_4 & \sin\phi_3 & \sin\phi_2 & \sin\phi_1 \\ \cos\phi_4 & \cos\phi_3 & \cos\phi_2 & \cos\phi_1 \end{pmatrix} \begin{pmatrix} L_4 \\ L_3 \\ L_2 \\ L_1 \end{pmatrix} = \begin{pmatrix} X_H \\ Y_H \end{pmatrix} \tag{3}$$

The center of mass (C) is another important factor that must be considered. As previously mentioned, the center of mass is a key component in maintaining stability during biped motion. Equation (4) will be used to simulate the motion of the center of mass as the biped attempts each phase.

$$\frac{1}{\sum_{i=1}^{N} m_i} \begin{pmatrix} \sin\phi_4 & \sin\phi_3 & \sin\phi_2 & \sin\phi_1 \\ \cos\phi_4 & \cos\phi_3 & \cos\phi_2 & \cos\phi_1 \end{pmatrix} \begin{pmatrix} \sum_{i=1}^{N-1} m_i \\ \sum_{i=1}^{N-2} m_i \\ \sum_{i=1}^{N-4} m_i \\ \sum_{i=1}^{N-5} m_i \end{pmatrix} = \begin{pmatrix} C_x \\ C_y \end{pmatrix} \tag{4}$$

The center of mass in the z-direction is a totally independent function. Theta represents the ankle degree angles. Servo #6 serves provides the turn in theta 1, while servo #1 provides the turn in theta 2.

$$C_z = \frac{\left( L_4 \sum_{i=1}^{N-1} m_i + L_3 \sum_{i=1}^{N-2} m_i - L_2 \sum_{i=1}^{N-4} m_i - m_1 L_1 \right) \cos\theta_1 - \left( L_z \sum_{i=1}^{N-3} m_i \right)_1 \sin\theta_1}{\sum_{i=1}^{N} m_i} \tag{5}$$

Both ankles must be synchronized in order to keep the foot from striking the ground at an angle. This type of synchronization must be achieved by continuous feedback from both ankle servos.

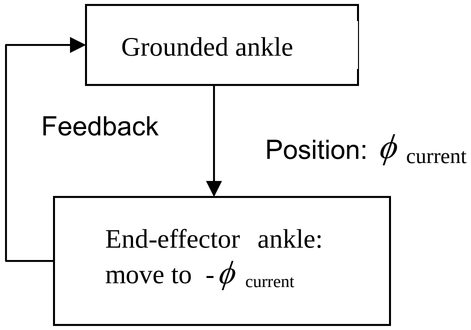


Figure. 3 Control loop.

Servo motion is not exactly reflected by the motion angles. The maximum motion that can be achieved by these servos is $90^o$. Keeping this in mind, all servos must have the same initial point position and their real displacement must be in accordance with the following table:

| Servo # | Gate | Initial position | Displacement | Direction |
|---|---|---|---|---|
| 2 | Step 1 | $90^o$ | $\phi_1 - \phi_2$ | CCW |
| 3 | Step 1 | $90^o$ | $\phi_2 - 90$ | CCW |
| 4 | Step 1 | $90^o$ | $90 - \phi_3$ | CW |
| 5 | Step 1 | $90^o$ | $\phi_4 - \phi_3$ | CW |

Table. 1 Displacement control

The end-effector location is known by specifying the path trajectory. The path would be an elliptical shape with In order to maintain stability we would need to have the smallest possible distance between end-effector and the ground. Figure.3 below illustrates the swing phase of the elliptical path.

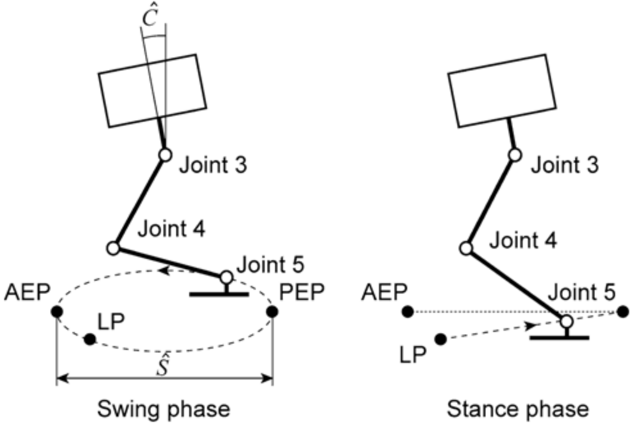


Figure.4 Nominal foot trajectory [3]

The kinematics analysis was conducted by using $\phi_3$ and $\phi_4$ as the input for the motion and stability equations.

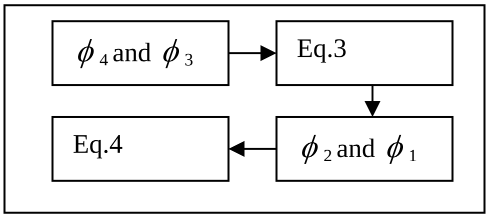


Figure 5. Mathematical sequency layout

The following results were obtained using angular displacement of $\phi_3$ at twice the rate as $\phi_4$. These results are obtained with the purpose of understanding the kinematics behavior of the biped motion.

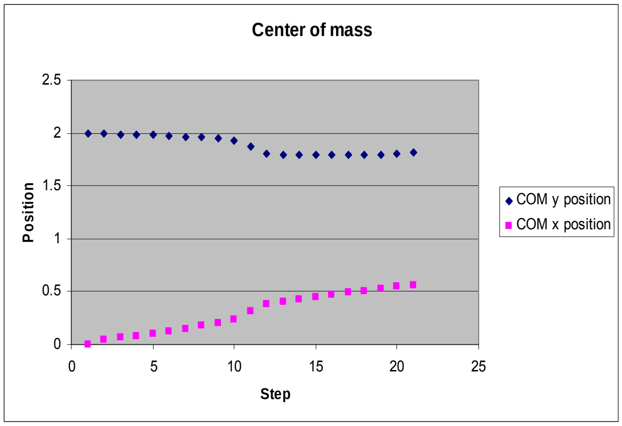


Figure 6. Center of mass position relative to grounded foot.

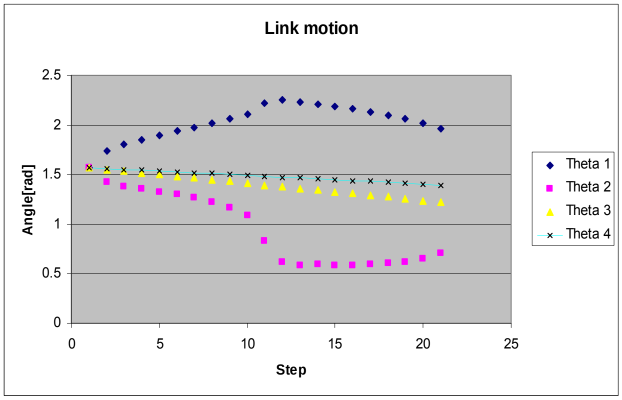


Figure 7. Link angular position.

Once the results for angular position have been obtained the servo displacements must be synchronized. Simply assuming that the angular position will result in successful motion is an invalid assumption. The individual servo displacement is a direct function of each link's position. Table.1 shows the synchronization of the servos.

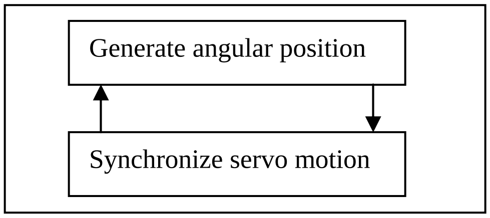


Figure. 7b. Synchronization logic

## SOFTWARE DEVELOPMENT

The controller language used was Lynxmotion Visual Sequencer v1.16 (figure 8). This Windows program allows controlling whatever thing built containing up to 32 servos using the SSC-32. That’s the case for biped BRAT (figure 9) used in the project.

The software also includes a main screen where servo control boxes can be added, and positioned on a grid. Such capability greatly facilities the positioning of servos in each sequence. In addition, Visual Sequencer generates Basic Atom and Basic Stamp 2 codes.

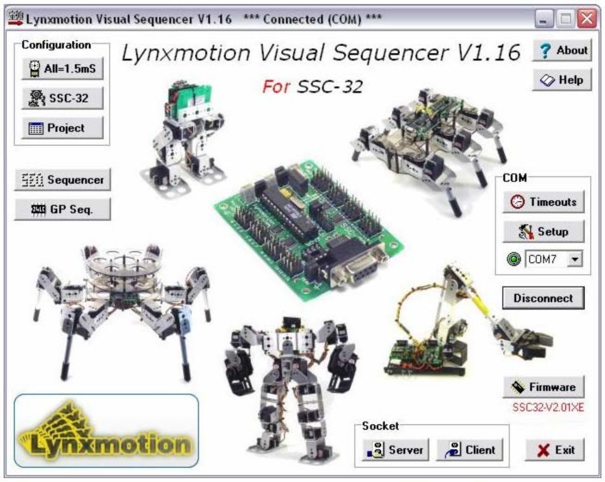


Figure 8. Lynxmotion Visual Sequencer v1.16

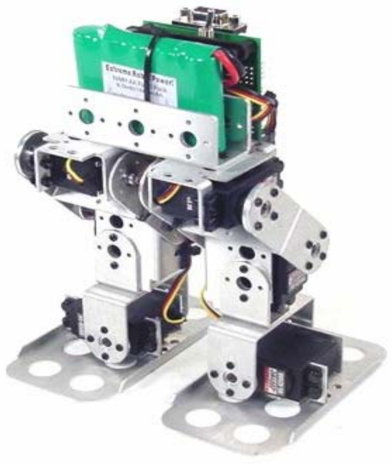
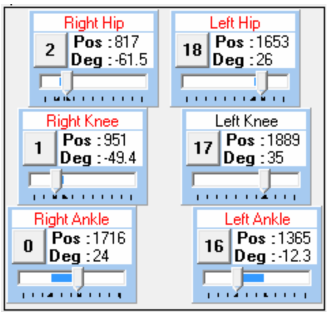


Figure 9. Biped BRAT

The project presents three programs built using Visual Sequencer; all corresponding to different activities performed by BRAT. First of all, BRAT performs a simple walking forward with a salute for the audience, secondly, it climbs up stairs, and finally, BRAT concludes its perform with a dance for the audience.

*Walking-salute*

The walking-salute activity was built basically in fifteen steps. These are: three sets of shifting weight of the biped to its right, stepping forward, shifting weight of the biped to its left, and stepping forward, followed by standing straight, tilting forward to salute and finishing with a standing straight position. The last two steps, within the first three sets, are mirror images of previous two. A sample of the walking-salute action, viewed in Visual Sequencer and Basic Stamp 2 code, is shown next.

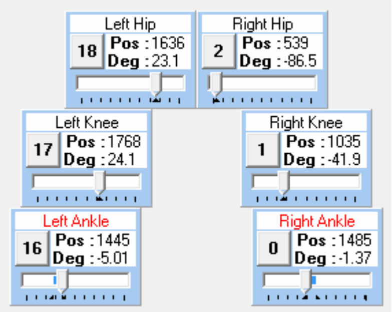


Right Hip 2 Pos :817 Deg :-61.5
Left Hip 18 Pos :1653 Deg :26
Right Knee 1 Pos :951 Deg :-49.4
Left Knee 17 Pos :1889 Deg :35
Right Ankle 0 Pos :1716 Deg :24
Left Ankle 16 Pos :1365 Deg :-12.3

Figure 10. Visual Sequencer

*Climbing Up Stairs*

The climbing up stairs program contains eleven steps. These are: first standing straight, second tilting to the left & raising backward right leg, third keeping left leg in position & raising right leg to the front, fourth stepping right foot on stairs step, fifth stepping right foot on stairs step, sixth raising left leg & moving left foot to the back, seventh moving left foot to the front, eighth stepping left foot on stairs step, ninth balancing both ankles, tenth raising hips & straightening knees, and finally standing straight. Samples of the first four steps viewed in Basic Stamp 2 code and of fourth step in Visual Sequencer, are presented below.

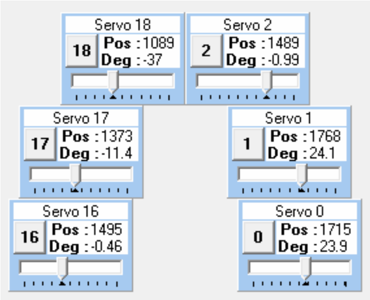


Left Hip 18 Pos :1636 Deg :23.1
Right Hip 2 Pos :539 Deg :-86.5
Left Knee 17 Pos :1768 Deg :24.1
Right Knee 1 Pos :1035 Deg :-41.9
Left Ankle 16 Pos :1445 Deg :-5.01
Right Ankle 0 Pos :1485 Deg :-1.37

Figure 11. Visual Sequencer

*Dancing*

BRAT dancing activity is executed with the help of a nineteen steps program. Mentioning all of them in order, beginning with the very first one, they are: Bending both knees in opposite direction, from step 2 till 6 are mirror images of step 1, the seventh is bending knees having ankles tilted, from step 8 to 10 are mirror images of seventh, then, from step 11 till 17 are alternation of standing straight and tilting both ankles, the eighteenth is tilting forward and the last one is standing straight. Samples of the first nine steps, viewed in Basic Stamp 2 code and the seventh step in Visual Sequencer, are shown below.



Servo 18: 18 Pos :1089 Deg :-37
Servo 2: 2 Pos :1489 Deg :-0.99
Servo 17: 17 Pos :1373 Deg :-11.4
Servo 1: 1 Pos :1768 Deg :24.1
Servo 16: 16 Pos :1495 Deg :-0.46
Servo 0: 0 Pos :1715 Deg :23.9

Figure 12. Visual Sequencer

## EXPERIMENTS AND RESULTS

Experiments related to BRAT dancing and walking-salute required less working hours to be developed than BRAT climbing up stairs. Since their algorithm was in essence a combination of basic motions, all tests were successful along the entire experiment. On the other hand, BRAT climbing up stairs was a real challenge due to the uniqueness of each motion that configured the algorithm. Trying to accomplish the activity with six degrees of freedom biped and servos of 180 maximum rotation angle complicated a bit more the situation, going through many failures before finally achieving the climbing goal. Sequences corresponding to each three activities are presented in the following pictures.

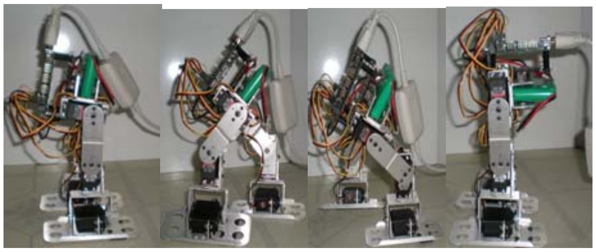


Figure 13. Walking-salute

Figure 14. Climbing up stairs.

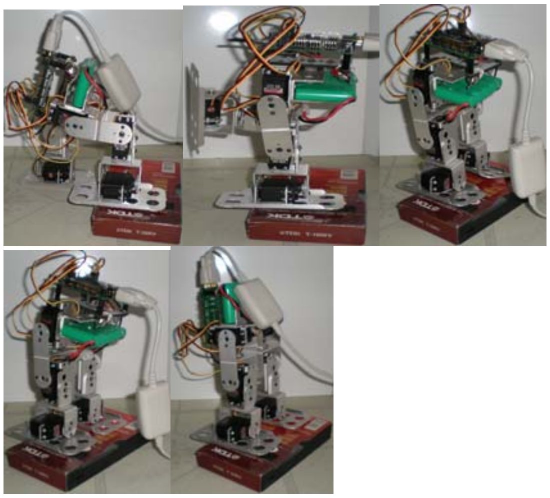


Figure 14b. Climbing up stairs.

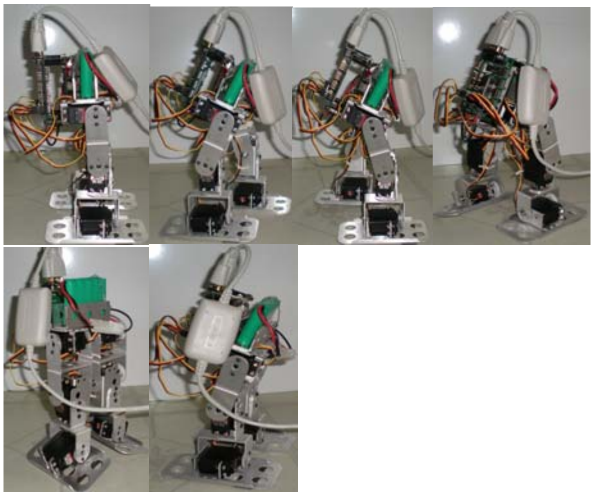


Figure 15. Dancing

## CONCLUSIONS

The paper discusses the use of simple kinematics techniques used towards the design of bipeds. It also explores a variety of commercial software intended to facilitate learning. It has been shown that different gaits can be developed using the LynxMotion Visual Sequencer.

Research on humanoid robotics is still in the primary period and has high potential for further development. The final goal is that robots substitute humans in a wide variety of tasks. To accomplish such aspiration, future robots are expected to have a human-like mechanism and function to coexist with human beings. Especially, a two-legged system, like BRAT, will be effective as a locomotion system in human living spaces (homes, offices and so on).

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