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Stability Control of Bipedal Walking Robot

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ABSTRACT:

This paper describes the various stability controlling of bipedal robot through mathematical modeling. Basically bipedal robot walks by balancing its whole model through Centre of mass and different moments acting. Here direct kinematics, zero moment point and velocity based stability of bipedal robot are explained. The way how robot walks in polygon region by maintaining the Centre of pressure and zero moment point within the bound is described. It also contains the review of stability margins in bipedal walking robot.

Keywords:

zero moment point, Centre of pressure and direct kinematics.

1. INTRODUCTION:

"How stable is your robot?" is a fundamental yet challenging question to answer, particularly with fast moving legged robots, such as dynamically balanced bipedal walkers. With many traditional control systems, questions of stability and robustness can be answered by eigenvalues, phase margins, loop gain margins, and other stability margins. However, legged robots are nonlinear, under actuated, combine continuous and discrete dynamics, and do not necessarily have periodic motions. These features make applying traditional stability margins difficult. Stability for a biped in terms of whether or not the biped will fall down. However, the concept of falling down is difficult to precisely define. For example, sitting down on the floor and slipping down onto the floor might result in the exact same trajectories and end state but one is considered falling and the other is considered sitting, with the only difference being intent. In this paper we define stability for a biped simply as whether or not the biped will fall down. The focus on velocity-based stability since believe that regulating the velocity of the Center of Mass is the most challenging subtask for human like bipedal walking. Regulating velocity is a challenging subtask due to the extended period during a natural gait that the Center of Mass velocity is under actuated (the actuators cannot produce an arbitrary acceleration on the Center of Mass). For example, once the body has traveled far enough away from the foot, the only course of action that can stabilize the Center of Mass velocity is to take a step. Other requirements such as regulating virtual leg length and body orientation, and swinging the swing leg, can be met through traditional control system techniques since these subtasks are fully actuated during the majority of the gait.

2. DESIRABLE CHARACTERISTICS OF STABILITY MARGINS

An ideal stability margin for a biped would act as a fortune teller. It would tell us when the biped is going to fall down next, what the cause will be, and how it can be prevented. If the biped is not going to fall down, the margin would indicate the closest the biped will be to falling down in the next step or so, at what point during the gait this occurs, and how much extra disturbance it could handle. While such omniscience is infeasible for anything but the simplest systems, some reasonable characteristics may desire for stability margins include:

• If the stability margin is outside an acceptable threshold of values, the robot will fall down.

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• If the stability margin is inside the acceptable threshold of values, the robot will not fall down.

• Two control algorithms should be comparable for stability based on their relative stability margins.

• One should be able to measure the relevant state variables and estimate the stability margin on-line in order to use it for control purposes.

• The stability margin should answer relevant questions as to why the robot fell. It should correlate with the degree of robustness to disturbances, such as noise, terrain irregularities, and external forces or impulses.

The Viability Margin is necessary, sufficient, and allows comparisons. However, its main drawback is that it is very difficult to compute. Various heuristic stability margins, which are much easier to compute, have been used in analyzing and controlling bipeds. In the next section review some of the margins that are commonly used for bipedal walking and discuss how well they achieve these desirable characteristics.

3. REVIEW OF STABILITY MARGINS FOR BIPEDAL WALKING

While there have been many proposed ways to define stability for a bipedal walking robot, we argue that many of these do not adequately address the desired characteristics described above. The review about stability will be explained through direct kinematics, zero moment point (ZMP), foot rotation indicator (FRI) and angular momentum of the robot.

3.1. KINEMATIC MODELING OF LINKS:

The waist link connects the two legs. Each leg has three links: foot link, shank link and thigh link. The joint between the foot link and shank link is the ankle, the joint between shank link and thigh link is the knee while the one between thigh link and waist link is the hip. The bipedal robot has six DOF. The direct kinematics consists of place the robot's final link (position and orientation), with regard to a reference system of coordinates, resolving the values of each link and the geometric parameters of the robot's elements. In other words, from the solution of each link coordinates, the final link localization is deduced (without having control where the final link is going to be). Also it is possible to and the position and the orientation of the robot's final link based only on its geometric relations (by a geometric method) but this is not a systematic method and can be used only in a robot with a few degrees of liberty.

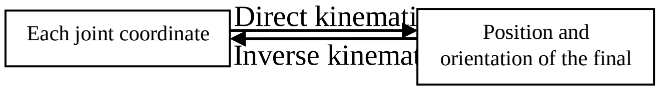

Fig.3.1. pictorial representation of kinematics

Hence through transformation matrices direct kinematics and inverse kinematics will be derived as follows

$$ {}^{n}L_{n+1} = \begin{pmatrix} \cos\theta_{n+1} & -\sin\theta_{n+1}*\cos\alpha_{n+1} & \sin\theta_{n+1}*\sin\alpha_{n+1} & a_{n+1}*\cos\theta_{n+1} \\ \sin\theta_{n+1} & \cos\theta_{n+1}*\cos\alpha_{n+1} & -\cos\theta_{n+1}*\sin\alpha_{n+1} & a_{n+1}*\sin\theta_{n+1} \\ 0 & \sin\alpha_{n+1} & \cos_{\alpha n+1} & d_{n+1} \\ 0 & 0 & 0 & 1 \end{pmatrix} $$

Where θ_{n+1}, d_{n+1}, a_{n+1}, α_{n+1} are the D-H parameters for the i link. Thus, is enough to identify the θ_{n+1}, d_{n+1}, a_{n+1}, α_{n+1} parameters to obtain the ${}^{n}L_{n+1}$ matrices and relate each robot's link.

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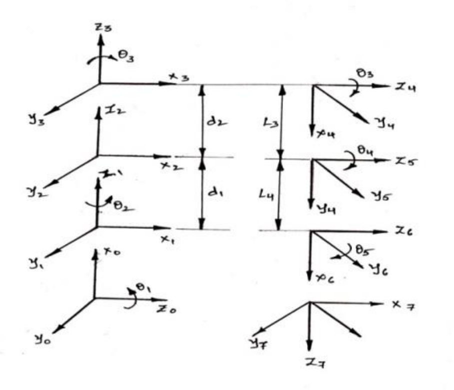

Fig.3.2.FRAME ASSIGNMENT

LINK	a_i	∞_i	d_i	$Ø_i$
1	0	90^0	0	$ø_1$
2	0	0	d_1	$ø_2$
3	0	-90^0	d_2	$ø_3$
4	L_3	90^0	0	0
5	L_5	0	0	$ø_5$
6	0	90^0	0	$ø_6$

Table.3.1.D-H parameters of the bipedal robot

Now substitute the values in the table in ${}^{n}L_{n+1}$ to get the homogenous transformation matrix for each link in the robot. So six matrixes will be obtain because having six links. By the product of six matrixes total homogenous transformation matrix will obtain.

$$\begin{matrix} \cos\theta_1\cos\theta_{2356} & \sin\theta_1 & \cos\theta_1\sin\theta_{2356} & \cos\theta_1(L_4\cos\theta_{235}+L_3\cos\theta_{23})+\sin\theta_1[d_1+d_2] \\ \sin\theta_1\cos\theta_{2356} & \cos\theta_1 & \sin\theta_1\sin\theta_{2356} & \sin\theta_1(L_4\cos\theta_{235}+L_3\cos\theta_{23})-\cos\theta_1[d_1+d_2] \\ \sin\theta_{2356} & 0 & -\cos\theta_{2356} & L_4\sin\theta_{235}+L_3\sin\theta_{23} \\ 0 & 0 & 0 & 1 \end{matrix}$$

$$[{}^{0}L_6] = [{}^{0}L_1] \times [{}^{1}L_2] \times [{}^{2}L_3] \times [{}^{3}L_4] \times [{}^{4}L_5] \times [{}^{5}L_6]$$

$$[{}^{0}L_1] = \begin{pmatrix} \cos\theta_1 & 0 & \sin\theta_1 & 0 \\ \sin\theta_1 & 0 & -\cos\theta_1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$[{}^{1}L_2] = \begin{pmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & 0 \\ \sin\theta_2 & \cos\theta_2 & 0 & 0 \\ 0 & 1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$[{}^{2}L_3] = \begin{pmatrix} \cos\theta_3 & 0 & -\sin\theta_3 & 0 \\ \sin\theta_3 & 0 & \cos\theta_3 & 0 \\ 0 & -1 & 0 & d_2 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$[{}^{3}L_4] = \begin{pmatrix} 1 & 0 & 0 & L_3 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$[{}^{4}L_5] = \begin{pmatrix} \cos\theta_5 & -\sin\theta_5 & 0 & L_4\cos\theta_5 \\ \sin\theta_5 & \cos\theta_5 & 0 & L_4\sin\theta_5 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$[{}^{5}L_6] = \begin{pmatrix} \cos\theta_6 & 0 & \sin\theta_6 & 0 \\ \sin\theta_6 & 0 & -\cos\theta_6 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

The total transformation matrix is product of above all six matrix that is shown below as From the above transformation matrix we can find the link lengths. If transformation matrix is known we can find the angles of the joints and vice-versa. $[{}^{0}L_6]_{4x4}$ =

INVERSE KINEMATICS:

The purpose of solving the inverse kinematics is to find the angle of each joint for a known foot position. The equation provides the solution for the forward kinematics with matrix P being the result. The translation vector $\{P_x, P_y, P_z\}$ gives the position of the foot and the orientation matrix shows the direction of the foot in the space of the motion. Based on the assumption that the values in P are known, the joint angles can be calculated.

The orientation matrix is given as O =

$$\begin{pmatrix} r_{11} & r_{12} & r_{13} & r_{14} \\ r_{21} & r_{22} & r_{23} & r_{24} \\ r_{31} & r_{32} & r_{33} & r_{34} \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

General transformation matrix as T =

$$\begin{pmatrix} n_x & o_x & a_x & d_x \\ n_y & o_y & a_y & d_y \\ n_z & o_z & a_z & d_z \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Hence the orientation and position will be determined by the comparison of above two matrixes with the total transformation matrix $[\ {}^{0}L_6\ ]_{4x4}$. So, the angular position of the hip joint, knee joint and ankle joints are given as below.

$\Theta_1 = \tan^{-1}(\sin\theta_1/\cos\theta_1)$; where $\cos\theta_1 = -(ax/az)$, $\sin\theta_1 = \sqrt{(1-\cos\theta_1^2)}$

$\Theta_2 = \tan^{-1}(r_{31}/r_{32})$,

$\Theta_3 = \tan^{-1}(\sin\theta_3/\cos\theta_3)$; where $\cos\theta_3 = \sqrt{([r_{31}+r_{32}]/2[r_{32}-r_{31}])}$

$\Theta_5 = \tan\text{-}1(\sin\theta_5/\cos\theta_5)$; where $\cos\theta_5 = \{dx^2+dy^2+dz^2+(d1+d2)^2-[L_4^2+L_3^2]\}/2L_4L_3$

$\Theta_6 = \tan^{-1}(\sin\theta_6/\cos\theta_6)$; where $\cos\theta_6 = [r_{11}+1]-\cos\theta_5$

Above angles are defined by considering both legs in bipedal robot. So, this is the kinematic parameters analysis to the bipedal robot. It may vary according to the movement and rotation of the robot.

3.2. ZERO MOMENT POINT (ZMP):

The Zero Moment Point (ZMP) is the location on the ground where the net moment generated from the ground reaction forces has zero moment about two axes that lie in the plane of the ground. The ZMP when used in control algorithm synthesis for bipedal walking robots typically is computed analytically based upon desired trajectories of the robot's joints. As long as the ZMP lies strictly inside the support polygon of the foot, then these desired trajectories are dynamically feasible. If the ZMP lies on the edge of the support polygon, then the trajectories may not be dynamically feasible. During playback of the desired joint trajectories, the actual ZMP is measured from force sensors in the foot or by observing accelerations of all the joints. Then deviations between the precompiled and actual ZMP are typically used to modify the joint trajectories. The ZMP is equivalent to the Center of Pressure (COP) but is commonly used to mean the analytically computed point based on the state and acceleration of the robot whereas the Centre of pressure is commonly used to mean the point measured from ground reaction forces.The resultant force of the inertia and gravity forces acting on a biped robot is expressed by the formula:

$$F^{gi} = mg - ma_G$$

Were, m is the total mass of the robot.

g is the acceleration of gravity.

a_G is the acceleration of COM.

The moment in any point X can be defined as

$$M^{gi}_x = XG \times mg - XG \times m\, a_G - H_G$$

Were H_G is the rate of angular momentum at the Centre of mass.

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Bipedal robot is dynamically balanced if the contact forces and the inertia and gravity forces are strictly opposite. So zero moment point can define by

$$PZ = M^{gi}_{x} \; / \; F^{gi} .$$

Were P is the point of contact with surface.

3.3. FOOT ROTATIONAL INDICATOR (FRI):

1. The Foot Rotation Indicator (FRI) point is the point on the ground where the net ground reaction force would have to act to keep the foot stationary given the state of the biped and the accelerations of its joints.

2. If the foot is stationary, then the FRI, the ZMP, and the COP are all the same point.

3. If the foot is experiencing rotational acceleration, then the ZMP and COP are on an edge of the support polygon, and the FRI is outside the support polygon.

4. Therefore the FRI is a more general form of the ZMP and provides both a positive and negative margin when used for control and analysis purposes.

3.4. ANGULAR MOMENTUM:

1. Humans appear to regulate angular momentum about the Center of Mass when standing, walking, and running.

2. Researchers have suggested that angular momentum about the Center of Mass (referred to as spin angular momentum) of a biped should be minimized throughout a motion.

3. On reverse of angular momentum and a couple leads to net angular momentum of biped around COP is only modified by gravity.

4. The angular momentum dynamics about the Center of Pressure can therefore be written as

$$H_{tot} = mgl\sin\theta_1$$

The total momentum about the Center of Pressure consists of the angular momentum of the Center of Mass rotating about the Center of Pressure, plus the spin angular momentum about the Center of Mass:

$$H_{tot} = H_0 + H_{cm} = ml^2 \dot{\theta}_1 + H_{cm}$$

Differentiating, we get

$$\dot{H}_{tot} = mgl\sin\theta_1 = ml^2\ddot{\theta}_1 + 2ml\dot{l}\dot{\theta}_1 + \dot{H}_{cm}.$$

1. The first term, $ml^2\ddot{\theta}_1$ is the acceleration of the Center of Mass around the Center of Pressure.

2. The second term, $2ml\dot{l}\dot{\theta}_1$ encodes the coupling of distance to Center of Mass and rotational velocity.

4. IMPORTANT STEPS TO STABILISE THE BIPEDAL ROBOT.

1. Maintain body orientation within a reasonable bound.

2. Maintain virtual leg length within a reasonable bound.

3. Swing the swing leg.

4. Transfer support from one support leg to the other.

5. Regulate Center of Mass velocity.

5. DISCUSSION AND FUTURE WORK:

In this paper, have defined stability assuming a deterministic system. However, bipeds should be considered nondeterministic, since ground variations, sensor noise, and external disturbances are impossible to precisely model. Most stability margins handle non determinism by relating to the tolerance to a particular unknown disturbance. This is the case for phase margins and gain margins in traditional linear control and is the case for many margins for bipedal walking, such as the static stability margin and the margins introduced in this paper. These margins typically give comparative indications of robustness to terrain, noise, and disturbances (the larger the margin, the greater the disturbance that can be tolerated). They sometimes are an indication of the magnitude of the largest single disturbance that can be tolerated. However, they usually do not indicate the probability of instability given a particular disturbance distribution. In a companion paper, explore stochastic stability margins for legged locomotion.

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