Kinematic and dynamic simulation of biped robot locomotion on multi-terrain surfaces

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Abstract. Locomotion of Bipedal Robot has been the major topic of research in recent years. Still, the stability and control of locomotion of these robots on various terrains have not fully uncovered. The aim of the current work is to design a force feedback controller, which takes account of contact forces between foot and ground while the robot is in locomotion. This paper will focus on the variation of the contact forces on different terrains and effects of friction over these contact forces while the robot is in locomotion. The kinematic and dynamic constraints that are formulated are simulated using MATLAB (SimMechanics).

1. Introduction
When the mobility of robot is considered, biped robots have superiority over conventional wheeled robots, particularly over the rough terrains, stairs or path with more obstacles [1][2]. On the contrary, biped robots are less stable in comparison with the wheeled, four-legged or six-legged robots [3],[4].

Over decades of research, many successful robots have been developed, such as Honda’s ASIMO [5], Humanoid Robotics Project-4(HRP-4) [6], NAO [7], WABIAN [8]. Many studies have been focused on the generation of walking patterns over which some studies investigate the walking pattern of robot referring to the kinematic data of human [9], while some other describes a walking pattern using the passive interaction of inertia and gravity [10].

Accounting for the stability of the biped robot, many methods have been proposed[11]-[14], which includes static and dynamic stability. B.Borovac et al[15] have proposed a walking method based on Zero-Moment Point(ZMP). ZMP is defined as a point on the ground over which the moment over the plane of the ground is zero. If the ZMP of the robot lies within the stable region then the robot will be able to attain stability and can locomote. The stability margin obtained by this method is high.

But when moving over a physical terrain, a robot will face different ground conditions[16]. To cope up with these conditions it is safe to design foot trajectory and hip trajectory first and then obtain ZMP. To generate foot trajectories over different parameters, it requires higher order polynomial, which requires hectic calculations. Quang Hang et al[17] have proposed an algorithm which uses a cubic-spline interpolation method to generate the smooth and continuous trajectories.

Though when encountered with the physical environments, the ground conditions will affect the locomotion of the robot. The friction over the contact surfaces and the contact forces play a major role in locomotion of the robot. Research has been done using contact force distribution over a variety of the robots such as quadruped robots, chained manipulators [18]-[21]. But the same method is not utilized on the biped locomotion control.
The advantage of this contact force distribution is that the contact forces over certain terrain and surface of a particular robot will be collected. During the locomotion of the robot, if the contact forces at that instant differ, the error amount of force can be wrench to make the locomotion stable. This project focuses on the design of the controller which gives feedback on the amount of force that is differed from the collected data and then rectifies it.

This paper focuses on the generation of data on the variation of contact forces over different terrains and surfaces. The data of contact forces are obtained by simulating kinematic and dynamic constraints of an open-source humanoid robot [22] over different terrains and surfaces. The simulation results that are presented here were obtained using MATLAB(SIMMECHANICS).

2. Kinematic modeling

2.1. Humanoid robot-The POPPY

Poppy is a humanoid robot which weighs about 3.5kg and of 0.84m height. It consists of 25 joints each with one Degree of Freedom (DOF) summing up to 25 DOF. These joints are motorized using Robots Dynamixel servomotors (MX-28 and AX-12). The material that is used to 3-D print the whole mechanical structure is polyamide which has a mass density of 960kg/m3, the yield strength of 49Mpa, young modulus of 1.65Gpa [23].

Each Leg of Poppy robot consists of 5 joints (i.e. 5 DOF) 3 at hip, 1 knee, 1 foot. Five DOF articulated Torso and 4 DOF on each hand and 2 DOF in the head. Since it is an open-source project, the simulations performed on the CAD model of the poppy robot which is shown in figure 1.

![Poppy Humanoid Robot CAD model](image)

Figure 1: Poppy Humanoid Robot CAD model

2.2. Forward kinematics

Forward Kinematics of a robot can be stated as a calculation to obtain the position and orientation of the certain link of a given robot structure using joint parameters. This forward kinematics can be used to determine the center of mass of robot and also to detect collisions while in locomotion. Forward Kinematics of a link is calculated using the chain rule of the homogeneous transformation as shown in equation (1).

\[ wT_j = wT_b bT_1 T_2 \ldots j^{-1} T_j \] (1)
Where \( wT_j \) is the transformation of \( j^{th} \) link with respect to the world coordinates. Similarly \( \bar{b}T_1 \) are transformations from base link to the world and first link to the base respectively. The homogeneous transformation is a 4x4 matrix which is made of a 3x3 rotation matrix and 1x3 position matrix as shown in equation (2).

\[
\begin{bmatrix}
    R_j & p_j \\
    0 & 1
\end{bmatrix}
\]

(2)

The rotation matrix shown in equation (2) can be obtained with the help of Rodrigues rotation formula [24]. \( \bar{p}_j \) is the position of \( j^{th} \) link with respect to the \( \bar{b} \) link of the robot. Forward kinematics uses joint angles to determine the position and orientation of a link. But in the physical environment, often the link position and attitude will be known and joint parameters must be determined. This can be obtained by inverse kinematics. In this paper jacobian method is used to obtain the inverse kinematics of the robot.

2.3. Jacobian

Jacobian is a matrix which gives the relationship between the variation of joint movements and spatial motion. Jacobian can also be used to determine the relationship between torque and force of joints. Jacobian also gives the relationship between linear and angular velocities of manipulators with respect to the rate of change of joint parameters as shown in equation (3).

\[
\dot{E} = J\dot{q}
\]

(3)

Where \( \dot{E} \) is the velocities of end-effector, \( \dot{q} \) is the rate of change of joint parameters and \( J \) is the jacobian matrix. The jacobian matrix described by the position vectors as well as unit angular rotation vector (\( r \)) is shown in the Appendix A. In humanoid robot locomotion, the robot while under locomotion come across with many singularity situations and redundancies, to overcome these the inverse of the above mentioned jacobian is modified as per the equation (4).

\[
J_{DLS} = (J^TJ + \alpha I)^{-1}J^T
\]

(4)

Where \( J_{DLS} \) is known as damped least-square (DLS) inverse [25], \( \alpha \) is a definite positive variable and \( I \) is an identity matrix of order of number of joint variables. Jacobian Inverse \( J_{DLS} \) forms a key player in solving inverse kinematics of the robot.

2.4. Inverse kinematics

Inverse kinematics is often required in the locomotion of the robot as in physical environment the end-effector positions are known rather than joint angles, which is quite inverse of what the forward kinematics will offer. This paper uses Inverse Kinematic Algorithm [26] to obtain the joint parameters at respective foot positions.

The \( J_{DLS} \) of equation (4) is used in this algorithm to obtain results that are not affected with singular situations and also the boundary conditions in the neighbourhood of singular positions where there will be a steep rise of velocities will be taken care by the Inverse Kinematic Algorithm.

3. Trajectories

Biped robot walking consists of two phases: a single-support phase and a double-support phase. Single-support phase is when one foot is stationary and other is swinging. Double-support phase is that both feet are in contact with the ground. Many studies treated double-supported phase as instantaneous which results in high acceleration during switching between phases. Reference [27] stated that double-support phase in a human locomotion is about 20% of walking cycle, this value is used in further calculations.
For locomotion of biped robot on multi-terrain, it is necessary to develop patterns that can suite on multi-terrain by changing a small number of variables. To design those patterns [18] suggested a method where the foot trajectories are designed with variables which can account for multi-terrain. After the foot trajectory is obtained hip trajectory is determined. By getting the hip and foot trajectories, joint trajectories are obtained using the inverse kinematics mention in the previous section.

But to account for the dynamic stability, a stability margin is calculated using ZMP of the robot and the trajectory which has higher stability margin is taken and used in the simulation. Other than turning, mostly the locomotion of hip and foot will be in a sagittal plane.

3.1. Foot trajectory

Foot trajectory over a sagittal plane can be described with a vector \( T_f = [X_f, Z_f, \theta] \) where \((X_f, Z_f)\) is the position of foot ankle in the sagittal plane and \(\theta\) is the angle of the foot with respect to the time. Below are the equations for each parameter of the vector \( T_f \). For a complete one step the period required is denoted as \( T_f \), \( T_d \) period required for double support, \( n \) defines step number.

\[
\theta_f(t) = \begin{cases} 
\theta_{gs} & t = n T_f \\
\theta_b & t = n T_f + T_d \\
\theta_f & t = n T_f + T_t \\
\theta_{ge} & t = (n + 1) T_f + T_d 
\end{cases}
\]  

(5)

Where \( \theta(t) \) is the foot angle, \( \theta_{gs}, \theta_{ge} \) are ground angles at start and end respectively and for flat ground, these two will become zero. The \( \theta_b, \theta_f \) are angles of the foot at start and end of step respectively. Figure 2a shows the variation of foot angle.

\[
X_f(t) = \begin{cases} 
'nL_s & t=nT_f \\
nL_s + \ l_f(1 - \cos \theta_b) + \ l_h \sin \theta_b & t=nT_f + T_d \\
'nL_s + \ l_h & t=nT_f + T_m \\
(n+1)'L_s - \ l_f(1 - \cos \theta_f) - \ l_h \sin \theta_f & t=(n+1)T_f + T_d \\
(n+1)'L_s & t=(n+1)T_f + T_d 
\end{cases}
\]  

(6)

Equation (6) defines the position of the foot along the x-axis with respect to time. \( L_s \) is the step length, \( l_f \) is the length of the foot from joint to the front toe along the x-axis, \( l_h \) is the length of the foot from joint to the back heel along the x-axis, \( l_h \) is the height of joint from the base of the foot along the z-axis. Figure 2b shows the movement of the foot along the x-axis.

\[
Z_f(t) = \begin{cases} 
'h_{gs}(n) + l_h & t=nT_f \\
h_{gs}(n) + l_h \cos \theta_b + l_h \sin \theta_b & t=nT_f + T_d \\
h_{gs}(n) + l_h \cos \theta_f + l_h \sin \theta_f & t=nT_f + T_m \\
h_{gs}(n) + l_h & t=(n+1)T_f + T_d 
\end{cases}
\]  

(7)

Variation of the foot over z-axis is given by equation (7), where \( h_{gs}(n), h_{ge}(n) \) are heights of the ground at start and end of step respectively and for a flat ground these two will be same. \((x_h,z_h)\) defines the position of the foot at its maximum height. Figure 2c shows the variation of the foot over Z-axis.
3.2. Hip trajectory

Similar to the foot trajectory, hip trajectory also can be described over a vector $T_{hip} = [X_{hip}, Z_{hip}]$. There is no angle parameter as mostly the hip angle remains constant. Though there will be no much variation in the z-axis of the hip of the robot, it is assumed that hip moves in a small range of $[Z_{hip}(min), Z_{hip}(max)]$

$$
Z_{hip}(t) = \begin{cases} 
Z_{hip(min)} & t=nT_t + 0.5T_d \\
Z_{hip(max)} & t=nT_t + 0.5(T_t + T_d) \\
Z_{hip(min)} & t=(n+1)T_t + 0.5T_d 
\end{cases}
$$  \hfill (8)

$$
X_{hip}(t) = \begin{cases} 
nL_s + X_{hs} & t=nT_t \\
(n+1)L_s - X_{hs} & t=nT_t + T_d \\
(n+1)L_s + X_{he} & t=nT_t + T_t 
\end{cases}
$$  \hfill (9)

$$
\begin{cases} 
0.0 < X_{hs} < 0.5L_s \\
0.5L_s < X_{he} < L_s 
\end{cases}
$$  \hfill (10)

Where $X_{hs}$, $X_{he}$ are the distances along the x-axis from hip to ankle of the stationary foot at the start and end of step respectively in single-support phase. By varying these two values in the range of the equation (10), various trajectories can be obtained using iterative method and ZMP and stability margin is verified. The hip trajectory which has major stability margin is selected.

Figure 3 shows the variation of hip along the x-axis along with the both foot trajectories. As both the foot and hip trajectories are obtained using inverse kinematics all the joint angles are determined.
4. Contact forces
The main forces that account for contact forces are a normal force and friction force.

4.1. Normal force
Normal force between feet and ground is generally determined with the help of linear spring damper law. This linear spring-damper law uses stiffness coefficient, damping coefficient, and penetration depth.

\[ N_f = K\dot{\beta} + D\ddot{\beta} \]  

Where \( N_f \) is normal reaction force from the ground, \( K \) and \( D \) are spring stiffness and damping coefficient and \( \beta \) is penetration depth.

4.2. Friction force
Friction force required is computed using stick-slip continuous friction law [28], where the coefficient of kinetic friction, the coefficient of dynamic friction and threshold velocity are parameters that make the friction vary along with the normal force generated.

5. Simulation
The simulation is carried out in MATLAB. The URDF file of the poppy robot is defined and the environment is designed with the help of the contact forces. These contact forces are determined by the multibody contact force library that is compatible with the MATLAB. The results obtained are presented below. Figure 4 shows the walking of the robot of two steps in time 0.64s.
5.1. Variation of joint parameters of leg while walking

Figure 5 shows the variation of the angles of joints in both legs while walking. The walking parameters that are considered to obtain the locomotion are step length 0.1m and speed of robot as 0.5m/s. The variation of angles has recorded for 0.84s.

Figure 5a shows the variation of angles of three hip joints on the left side of robot placed in three axes, similarly figure 5b shows hip joints angle variation of the right leg. Figures 5c, 5d shows the angle variation of the knees of the robot. Figures 5e, 5f shows the ankles variation.

As figure 5 shows angle variation of joints of both legs, figure 6 shows the rate of change of the angles of the joints in similar manner as that of the figure 5. Figures 6a, 6b shows rate of change of angles of hip joints on both sides, figures 6c, 6d shows rate of change of angles of knees and figures 6e, 6f shows rate of change of angles of ankles.
5.2. Variation of friction and normal forces

The contact forces such as friction and normal forces has been recorded while the robot is in locomotion. Figure 7 shows the friction and normal reaction forces over both feet while the left feet of the robot takes one step from still position. The graphs of figure 7 are obtained by using the parameters such as kinetic friction co-efficient as 0.5, static friction coefficient as 0.7, velocity threshold as 0.001m/s, contact damping as 100N-s/m and contact stiffness as 1000N/m.

Figures 7a, 7b shows the variation of friction while the robot moves its left leg from a still position to make a step and figures 7c, 7d shows the variation of normal reaction force over the feet for the same movement of robot.
6. Conclusion
To make a biped robot walk on multi-terrain surfaces, it is necessary to check with the stability and control of the robot. Which forms the topic of research and to address those tasks, it is decided to design a force feedback controller to compensate the physical environment unaccounted errors. In this paper, the data that is required for the force feedback controller has obtained i.e. the contact forces of the robot while walking on different surfaces to check the variability of contact forces with a change of surface friction.

The results shown above are well within the limits of the specifications and stresses of the materials. The dynamic simulation shows promising results. From the simulation, it was observed that with the increase in the coefficient of friction and contact stiffness the Normal force and frictional forces will increase, which results in increase in torque for the same movement. Further, the data that is obtained from these will be useful to develop and train a force feedback controller.

Appendix A. Jacobian matrix
Jacobian matrix J shown in A.1 is obtained with the unit rotation vector of the link in world frame $w_{r_j}$ as well as the position vector of the link in world frame $w_{p_j}$ where $j$ is link number. $w_{r_N}, w_{p_N}$ are rotation vector and position vector of end-effector in the world frame respectively. $\times$ represents cross-product of vectors.

$$J = \begin{bmatrix}
  \frac{w_{r_1}}{1} \times (\frac{w_{p_{N-1}}}{1} \frac{w_{p_{N}}}{1}) & \ldots & \frac{w_{r_N}}{1} \times (\frac{w_{p_{N-1}}}{1} \frac{w_{p_{N}}}{1}) & 0
\end{bmatrix}
$$

(A.1)

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