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Research Article

Trajectory Planning and Motion Simulation for a Hydraulic Actuated Biped Robot

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Abstract: The purpose of this research is to generate a stable motion for a hydraulic actuated biped robot. Since the application effect of most dynamic biped robot locomotion theories is not very well and the static walk pattern is hard to realize on human-sized hydraulic actuated biped robot because of the small size of foot compared with body height. In this study, we propose a trajectory planning method based on static walking strategy. Firstly, the mechanical structure and kinematics model of the hydraulic biped robot are described. Then, we analyze why biped robot always falls backward during the walking period and propose an improved motion by adding a section of CoG movement during single support phase. The gait planning is realized with cubic spline trajectory. Finally the motion is verified with coordinated simulations based on ADAMS and MATLAB software.

Keywords: Biped robot, coordinated simulation, hydraulic actuated, trajectory planning

INTRODUCTION

When talking about robot, people will firstly think of a mechanical and electronic device with human look, which is actually humanoid robot in narrow sense. Humanoid robot has almost the same appearance as a human and is suitable for moving in an environment which contains stairs, obstacles and so on, where a human lives. Therefore, humanoid robots are suited for the current social infrastructures (Yokoi, 2007).

"The most obvious feature for robot is to walk" (Vukobratovic, 1983). Humanoid robot should have human-like legs and walking capability. The pioneer work about humanoid robot is begun with the research on biped walking structure. Since the first study concerning bipedal robots was carried out in Japan with the world's first active walking biped robot WL-5 developed by Waseda University in 1971 (Kato and Tsuiki, 1972), many research have been done on the development of biped robotics in the following 40 years. Honda's ASIMO (Sakagami *et al*., 2002) and Boston Dynamics' PETMAN are two more famous biped robots. However, it is still difficult to generate human-like walking motion automatically. So far, most of theories applied in biped robot are still based on the concept of ZMP proposed by VuKobratovic and Stepanenbo (1972) and inverted pendulum theories proposed by Hemami *et al*. (1973). But ZMP stability criteria are not essential conditions for stable walk and inverted pendulum is based on the assumption that most weight of the robot is centralized to a point. Both of them have their own limitations.

The application effect of most dynamic biped robot locomotion theories are not very well except for a few biped robots such as ASIMO and PETMAN.

This study generates a stable motion for a hydraulic actuated biped robot. Since the application effect of most dynamic biped robot locomotion theories is not very well and the static walk pattern is hard to realize on human-sized hydraulic actuated biped robot because of the small size of foot compared with body height. In this study, we propose a trajectory planning method based on static walking strategy. Firstly, the mechanical structure and kinematics model of the hydraulic biped robot are described. Then, we analyze why biped robot always falls backward during the walking period and propose an improved motion by adding a section of CoG movement during single support phase. The gait planning is realized with cubic spline trajectory. Finally the motion is verified with coordinated simulations based on ADAMS and MATLAB software.

MECHANISM DESIGN AND KINEMATIC ANALYSIS OF THE HYDRAULIC ACTUATED BIPED ROBOT

So far, most of biped robots are actuated by servo motors. However, servo motors sold in market are mostly with high speed and low torques. To drive the joints of robot, we need to add complicated reduction gears, which are always the weakest and heaviest elements of an electric motor assembly and many moving parts of them prone to wear. Pneumatic systems respond very quickly and easy to sustain, but the compressibility of air means that precise position control of the systems is impossible. Hydraulic actuators have very high power-to-weight ratios, high bandwidth and fast response capability. Hydraulic actuators can be very effective for high power applications (Yibin *et al*., 2011).

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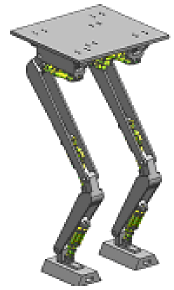
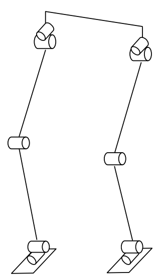


(a)



(b)

Fig. 1: The structure of the hydraulic biped robot: (a) mechanical structure, (b) DOFs distribution

In past years, few robots are actuated by hydraulic actuators because of their low integration and great weight, but all these weaknesses have been overcome with the development of hydraulic techniques, especially the successful cases on Boston Dynamics' BigDog (Raibert *et al*., 2008) and PETMAN and SUCRO's Hanma. The hydraulic drive unit system going to use is the same as "Hanma" and its performance are as follows: the weight is less than 2 kg, the maximum working stroke of the servo actuator is at most 60 mm, the maximum dynamic force is 700 kgf, the maximum working speed is 0.48 m/s and the frequency of the servo actuator is much more than 100 Hz. All actuators are powered by a stationary hydraulic power pack or a portable hydraulic power pack driven by an engine while the biped robot is outside the LAB. The hydraulic actuated biped robot developed is shown in Fig. 1a.

The biped robot is mainly composed of two legs. The anticipated mass of the whole robot is less than 50 kg without payload. The maximum height is 1300 mm and it will be lower to about 1000 mm during walking. Each leg has 5 DOFs (Degrees of Freedom), as shown in Fig. 1b. Among them, both hip articulations and ankle joints have two DOFs: roll and pitch, while the knee only has one pitch DOF. In addition, most DOFs are actuated except two ankle roll joints.

To model the kinematics of the biped robot, we build its coordinate frames shown in Fig. 2 according to D-H rules. $\{O_0\}$ is the base-frame and $\{O_6\}$ is the end-

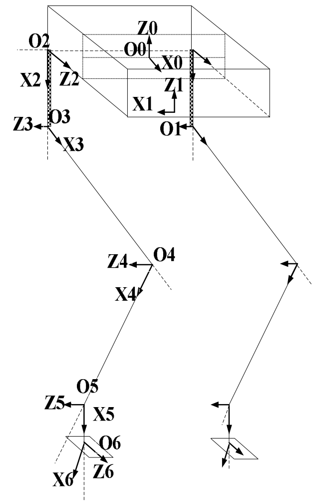


Fig. 2: Local frames linked to the biped robot

Table 1: Geometric parameters of the biped robot

Link i	a_{i-1}	α_{i-1}	d_i	θ_i
1	L_0	0	$d_1<0$	-90°
2	L_1	-90°	$d_2 = -2\ L_0$	θ_2
3	L_2	-90°	0	θ_3
4	L_3	0	0	θ_4
5	L_4	0	0	θ_5
6	L_5	-90°	0	θ_6

effector-frame. Geometric parameters are shown in Table 1.

With this convention, reference frame i can be located relative to reference frame i-1 by executing a rotation through an angle α_i about the x_{i-1} axis, a translation of distance a_i along x_{i-1}, a rotation through an angle θ_i about z_i and a translation of distance along z_i.

The equivalent homogeneous transformation between two adjacent frames is:

$$ {}^{i-1}_{i}T = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i\, c\alpha_{i-1} & c\theta_i\, c\alpha_{i-1} & -s\alpha_{i-1} & -d_i\, s\alpha_{i-1} \\ s\theta_i\, s\alpha_{i-1} & c\theta_i\, s\alpha_{i-1} & c\alpha_{i-1} & d_i\, c\alpha_{i-1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1) $$

where, $c\theta_i$, $s\theta_i$, $c\alpha_{i-1}$ and $s\alpha_{i-1}$ represent $\cos\theta_i$, $\sin\theta_i$, $\cos\alpha_{i-1}$ and $\sin\alpha_{i-1}$, respectively.

Through concatenation of these individual transformations, we get:

$$ {}^{0}_{6}T = {}^{0}_{1}T \cdot {}^{1}_{2}T \cdot {}^{2}_{3}T \cdot {}^{3}_{4}T \cdot {}^{4}_{5}T \cdot {}^{5}_{6}T = \begin{bmatrix} n_x & o_x & a_x & P_x \\ n_y & o_y & a_y & P_y \\ n_z & o_z & a_z & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} \mathbf{R}_{3\times 3} & \mathbf{P} \\ \mathbf{0} & \mathbf{1} \end{bmatrix} \quad (2) $$

where, $R_{3\times3}$ and P represent the rotation transformation matrix and the coordinate vector of foot relative to base-frame respectively and:

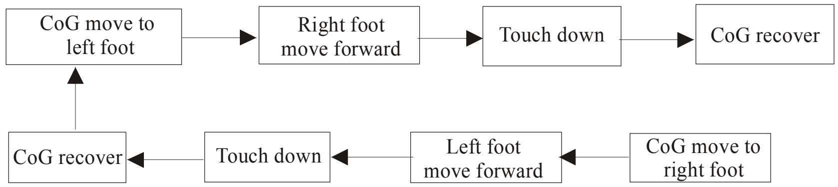


Fig. 3: The process of biped robot's static walk

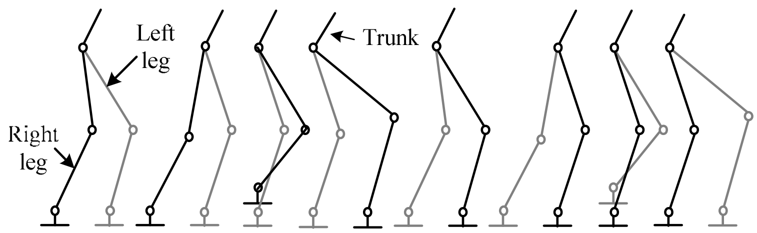


Fig. 4: Motion sequences of the biped robot with static walk

$$\begin{cases} P_x = L_0 + d_2 + L_3 \, s\theta_3 + L_4 \, s\theta_{34} + L_5 \, s\theta_{345} \\ Q = -L_2 - L_3 \, c\theta_3 + L_4 \, c\theta_{34} - L_5 \, c\theta_{345} \\ P_y = -L_1 + Q \, c\theta_2 \\ P_z = d_1 + Q \, s\theta_2 \end{cases} \tag{3}$$

where, $\theta_{34} = \theta_3 + \theta_4$ and $\theta_{345} = \theta_3 + \theta_4 + \theta_5$.

By solving the kinematical Eq. (2) with algebraic method, we can get each joint angle and then compute the length of cylinders with geometrical relationship.

Gait planning: The CoG of the biped robot keeps staying in support convex hull all along while it is walking in static walk pattern. CoG keeps standing still in support convex hull when the robot is in single support phase and moves to new support leg by the action of force moment while entering into double support phase and then enters into next movement cycle. The whole motion process of static walk is shown in Fig. 3. Motion sequences of the biped robot with static walk are shown in Fig. 4.

The change process of CoG's trajectory on ground while in static walk is shown in Fig. 5.

However, the static walk pattern can only be used in small biped robots such as toys at present. On one hand, legs' mass occupies a large proportion to the whole body in biped robot with human size; on the other hand, the foot size is too small compared to the height of robot's trunk, so it is hard to realize static walk on human-sized biped robot, as shown in Fig. 6.

While making trajectory planning, we always treat trunk center as CoG approximately based on the assumption that the leg mass is negligible relative to the trunk weight, the consequence is CoG can't keep standing still in support convex hull when the robot is in single support phase.

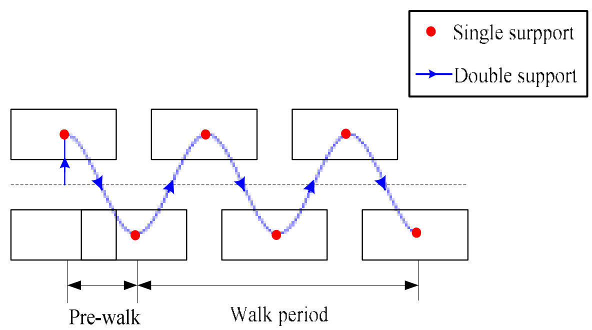


Fig. 5: The trajectory of CoG on ground while in static walk

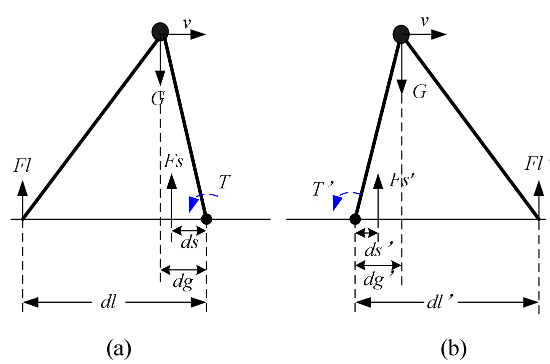


Fig. 6: An analysis about the biped robot while in static walk: (a) from double support phase to single support phase, (b) from single support phase to double support phase

When the biped robot moves from double support phase to single support phase, in the beginning, we can conclude from moment balance theories:

$$F_l \cdot d_l + F_s \cdot d_s = G \cdot d_g \tag{4}$$

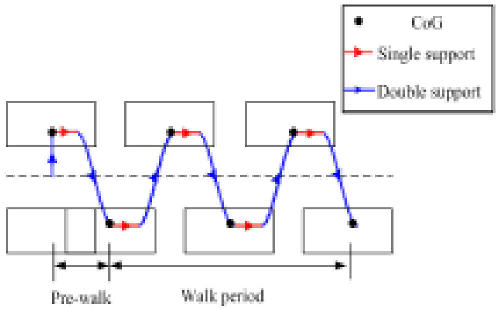


Fig. 7: The trajectory of CoG on ground while walking in the improved pattern

where,

F_l = The support force to the foot which is going to liftoff
F_s = The support force to the support foot
G = The gravity of the robot
d_l, d_s & d_g = The distances of each force to the support point, respectively

Once enter into single support phase, F_l will decrease into zero immediately, but CoG hasn't moved into support convex hull yet and at the moment:

$$F_s \cdot d_s < G \cdot d_g \tag{5}$$

There is a torque T at the support foot ankle which makes the trunk move backward.

When the biped robot moves from single support phase to double support phase, in the beginning, the robot is supported only by one leg, we can conclude from moment balance theories:

$$F_s^{'} \cdot d_s^{'} = G \cdot d_g^{'} \tag{6}$$

where,

$F_s^{'}$ = The force to the supporting foot
d_s = Distance of $F_s^{'}$ to the supporting point
$d_s^{'}$ = The distance of gravity to supporting point

Once enter into single double phase, it will have an impact force immediately, then:

$$F_l^{'} \cdot d_l^{'} + F_s^{'} \cdot d_s^{'} > G \cdot d_g^{'} \tag{7}$$

where,

$F_l^{'}$ = The impact force to the foot which is going to touchdown
$d_l^{'}$ = The distance of the force to supporting point

Similarly, it will have a torque $T^{'}$ which makes the trunk move backward.

In addition, the static walk is introduced based on assumption that the robot moves very slowly, so the effect of inertia force produced by velocity and acceleration can be ignored. If the motion period is a little short or step length is a little long, the robot is easy to loss balance. All these reasons make the static walk easy to fall backward in human-sized biped robot, as shown in Fig. 9a.

Against the above, we propose a trajectory planning method based on the static walk strategy. During the walk cycle, we add a section of CoG movements during single support phase. The trajectory of CoG on ground while walking in improved way is shown in Fig. 7.

In single support phase, when the robot lifts its swing leg, CoG keeps standing still. While swing leg begins to drop, CoG moves forward at the same time. In double support phase, CoG moves to right above next support leg and enters into next locomotion cycle. As to the planning method, we also treat trunk center as CoG

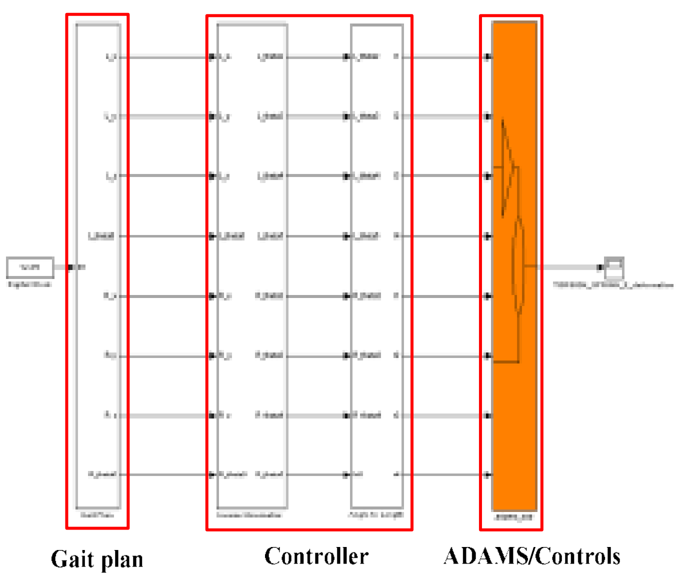
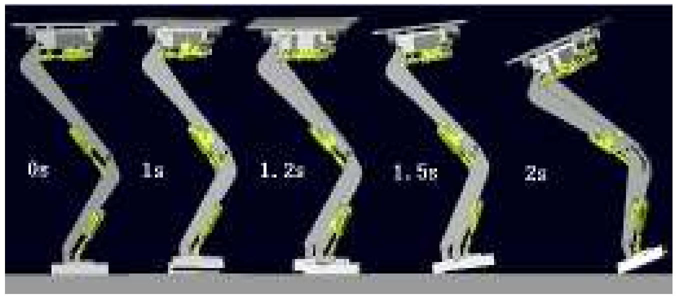
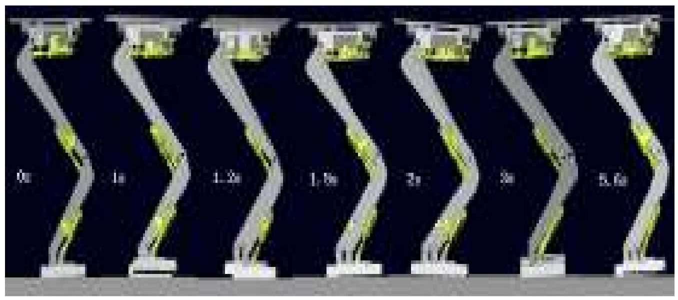


Fig. 8: Coordinated simulation structure with MATALB and ADAMS



(a) The simulation of static walk: cycle time set to 2s, step length set to 80 mm, step height set to 30 mm



(b) The simulation of improved walk: cycle time set to 2s, step length set to 80 mm, step height set to 30 mm

Fig. 9: The biped robot motion simulations with MATALB and ADAMS

and adopt cubic spline way by selecting typical discrete positions of the swing foot and the trunk; the simulation result with our improved walk pattern is shown in Fig. 9b. The result proves that the walk pattern is effective.

COORDINATED SIMULATION

The simulation is conducted with ADAMS and MATLAB. ADAMS provides 3-D model, kinematics and dynamic models for virtual prototype and MTALAB provides trajectory and control algorithms. With the interface of ADAMS/Controls, MATLAB can control the length of cylinder in real time. The whole control system is shown in Fig. 8.

All the gait plan work is done in the left part, which contains foot trajectories of time to base-frame. The controller converts the gait coordinate values to joint angles with inverse kinematics model and then transforms them into the length of each cylinder with geometrical relationship. ADAMS/Controller part is an interface between MATLAB and ADAMS. Through ADAMS, we can monitor the motion state of the biped robot.

The simulation results are shown in Fig. 9. To check the gait plan effect, we adopt the same parameter settings in both simulations. The cycle time of locomotion is 2s, step length is 80 mm and step height is 30 mm. Figure 9a is the simulation result of static walk. We can see that the robot begins to tilt at 1.5s and falls at 2s. Figure 9b is the result of improved walk pattern. We can see that the robot is still walk stably at 5.6s. The simulation result proves that static walk on human-sized biped robot is not stable and the improved walk mode is effective to improve the stability of biped robot.

CONCLUSION

The static walk pattern can only be used in small biped robots such as toys at present because of the small size of foot compared with body height, the difficulty of ignoring the leg mass and the impact of inertia moment. We propose a trajectory planning method based on static walk by adding a section of CoG movement during single support phase. The gait planning is realized by cubic spline method and the application effect is confirmed by the coordinated simulation experiment based on ADAMS and MATLAB. The simulation results show that the gait planning method proposed in this study is effective for improving the stability walking of the hydraulic biped robot.

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