Structural Design and Gait Planning of Hydraulic Humanoid Biped Robots

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Abstract. This paper designs a hydraulic humanoid biped robot with 12 degrees of freedom named Defensor. First of all, this paper chooses the self-designed hydraulic humanoid biped robot as the research object. Then the Defensor's structural design is introduced includes sensors distribution and Defensor's 12-DOF on the structure. Secondly, a linear inverted pendulum model is established to simplify the Defensor's whole model, and a hierarchical control structure is designed to control the movement of Defensor. Thirdly, this paper builds the virtual simulation platform Simscape Multibody and the experiment platform of Defensor. After that, the gait planning of the robot is realized, and the relevant research results are verified. Lastly, this paper realizes the Defensor's continuous and stable walking in the virtual simulation platform. The simulation results show that Defensor's mechanical model is reasonable and the gait planning control method adopted in this paper makes the hydraulic humanoid biped robot stable and feasible.

Keywords: Hydraulic humanoid biped robot · Mechanical structure · Gait planning

1 Introduction

1.1 Research Background

Compared with wheeled and quadruped robot, which has higher requirements for working environments, biped robot can adapt to more terrain environments. Compared with the motor-driven robot with low power density and weak resistance to electromagnetic interference, the hydraulic-driven robot has larger output force and higher productivity. At the same time, humanoid biped robot has similar forms and can better integrate into human society. Therefore, in recent years, more and more biped robot researches have made significant progress.

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Many researchers have successively developed different types of biped robot and designed many gait planning methods based on mechanical models of the robots. Waseda University started to develop humanoid robot with intelligence and mobility from 1986. Since then, a series of biped robots have been developed that can walk statically [1]. Later, the MIT Leg and Foot Robotics Lab [2] developed biped robot that could walk dynamically. Honda's P2 biped robot was introduced to public in 1996, and the Asimo humanoid robot [3] was shown avoiding obstacles and walking steadily on flat ground. In terms of structural design, the LOLA robot was developed by a team in the University of Munich, Germany [4], and this robot contains actively driven toe joints, which has improved the stability of the robot's feet on the ground. Despite the progress achieved in biped robots' researches, there are still some problems. For example, there is a gap between the proportion of most biped robots and the real proportion of human beings, like most robot's feet are relatively large. In terms of gait planning for active walking, researchers have proposed many methods from structural, dynamic and artificial intelligence perspectives: Spring-Loaded Invert Pendulum (SLIP) [5], Hybrid Zero Dynamics (HZD) [6], gait planning algorithm based on machine learning [7], and the 3D linear inverted pendulum (LIP) model [8], they all have been widely used. Boston Dynamics successfully developed hydraulic biped robot ATLAS [9], which has excellent stability and highly dynamic performance. In China, Gan Chunbiao et al. [10] from Zhejiang University designed a hydraulic biped robot. However, there is still a big gap between these Chinese robots designs and their foreign counterparts in overall indexes, even humanoid biped robots show great progress. Compared with Gan Chunbiao' robot, the design of the robot's freedom in this paper is more reasonable in mechanical structure.

1.2 Main Content

In this paper, the structural design of self-designed hydraulic humanoid biped robot Defensor is introduced, including the distribution of robot's 12 DOF, the installation of hydraulic cylinders as active driving elements, and the distribution of sensors. Defensor implements humanoid design on the mechanical structure, with well-distributed hydraulic-drive units and sensors.

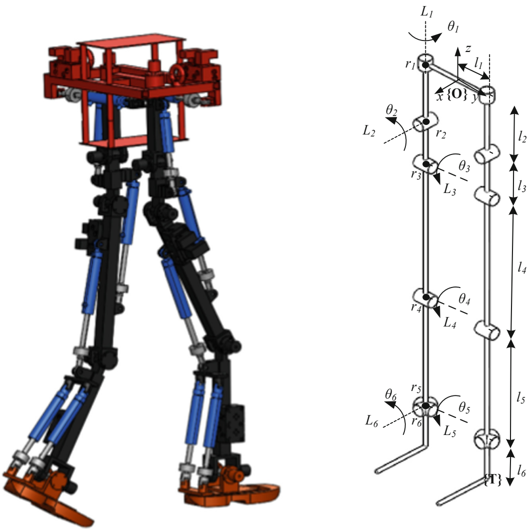
After that, the 3D-LIPM is used to realize the robot's gait planning. A hydraulic-driven layered control method for the robot's gait is built on Defensor, and the motion trajectory of the robot's centroid and feet while walking is obtained.

Based on Simscape Multibody, a virtual prototype of hydraulic biped robot is built to simulate and verify the gait planning algorithm, realize the continuous and stable walking of the robot in the physical engine.

2 Structural Design

This paper independently develops the design of this hydraulic biped robot. Therefore that the Defensor's ankle joint needs to have two basic degrees of freedom: pitch and roll, these two degrees of freedom need to rely on the installation of two hydraulic cylinders to realize their control. Defensor has a new design on active degrees of freedom control of ankle joints.

Defensor has 18 DOF in the whole body (see Fig. 1. (a)), including s6 floating base coordinate system degrees of freedom and 12 active degrees of freedom driven by hydraulic cylinders. Among the active driving degrees of freedom, a single leg is allocated 6 degrees of freedom (see Fig. 1. (b)), they are three degrees of freedom of hip joint, one degree of freedom of knee joint and two degrees of freedom of ankle joint respectively.



(a) (b)

Fig. 1. (a) Structure of Defensor with 12-DOF, (b) Structure simplified model and distribution of 12 degrees of freedom

At present, the structural design of Defender only includes lower limbs, and the structural size is based on the standard of "Chinese Adult body size" [12]. In order to facilitate the layout of the hydraulic cylinder, the three degrees of freedom of the hip joint are arranged in series. The two degrees of freedom of ankle joint are arranged in parallel, which makes the design more humanized.

To facilitate the calculation of the Defender's zero moment point (ZMP), 8 microscopic pressure measuring elements are installed evenly in the sole. In the simulation, they have eight balls with zero radius. To obtain sufficient feedback angles, the angular momentum of rotation in an additional code (EB38K) mounted at both ends of the joint axis is measured. To facilitate the measurement of the output force of the 12 hydraulic drive cylinders, bellows tension pressure sensors (JLBM-2) are installed at the end of the piston rods [11].

3 Method

3.1 3d-Lipm

Many simplified models are proposed to control the motion of the robot. The linear model of inverted pendulum proposed by Kajita [13] in 2001 is a commonly used robot in gait planning research.

In brief, the LIPM approximates the robot as a 3D inverted pendulum model, and concentrates the mass of the robot at the center of mass, which is viewed as the center of mass of the inverted pendulum. The current support leg of the robot is viewed as stretchable massless leg of the inverted pendulum. And the length of this stretchable massless leg is determined by the support force applied to the support leg.

When controlling the robot with 3D-LIPM [14], a constraint plane needs to be added. The model assumes that the vertical acceleration of the robot's centroid is zero.

The motion equation of the robot's centroid is:

$$\begin{cases} m\ddot{x} = \frac{x}{l}f = f_x \\ m\ddot{y} = \frac{y}{l}f = f_y \\ m\ddot{z} = \frac{z}{l}f - mg = f_z - mg \end{cases} \tag{1}$$

In which, l is the length of stretchable massless leg, f is the support force. And x, y, z are respectively the projection lengths of l in three directions of the coordinate axis.

The motion equation of the constraint plane is:

$$z = k_x x + k_y y + z_c \tag{2}$$

where, z_c is the height of the constraint plane.

When the Defensor's centroid moves along the direction of the constraint plane, the acceleration direction of the centroid is orthogonal to the constraint plane:

$$\begin{bmatrix} f_x \, f_y \, f_z - mg \end{bmatrix} \begin{bmatrix} -k_x \\ -k_y \\ 1 \end{bmatrix} = 0 \tag{3}$$

According to Eqs. (1) and (2), can be got:

$$\begin{cases} \ddot{x} = \frac{g}{z_c}x \\ \ddot{y} = \frac{g}{z_c}y \end{cases} \tag{4}$$

According to Eqs. (2) and (3), can be got:

$$f = \frac{mgl}{z_c} \tag{5}$$

3.2 Hierarchical Control Structure

Defensor has many degrees of freedom, and is characterized by strong nonlinear and discontinuous. Using a hierarchical control structure to realize real-time online anti-disturbance gait generation of robot. The management structure is divided into three layers: the simplified model layer, the whole model layer and the prototype layer. The right pathway is the control pathway and the left pathway is the feedback pathway (see Fig. 2).

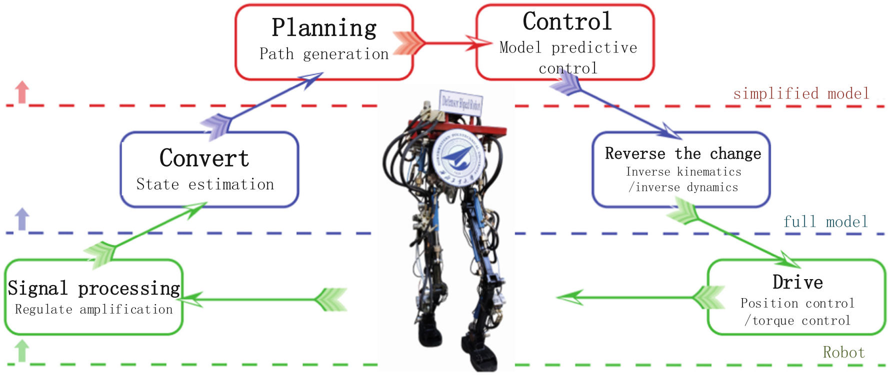


Fig. 2. Hierarchical control structure

3.3 Generate the Trajectory

The main steps to create a 3D-LIPM [15] are as follows: Firstly (see Fig. 3.(a)), in the static state, the robot's centroid height decreases from z_{Robot} to z_{Model}, z_{Model} is the centroid height of the inverted pendulum. Secondly (see Fig. 3.(b)), the robot puts its weight on its right leg and begins to walk. Thirdly (see Fig. 3.(c)), the right foot moves forward half a step according to the initial parameters and the natural dynamics of the pendulum. Finally (see Fig. 3.(d)), the right foot moves half step according to the initial coefficient and the natural dynamics of the swing. After the right foot moves to the next foothold, it becomes the new support point, and is repeated to obtain the trajectory of the robot's centroid and both feet.

Based on the above 3D-LIPM and algorithm analysis, the Defensor's centroid and foot trajectory generated by simulation are shown in Fig. 4.

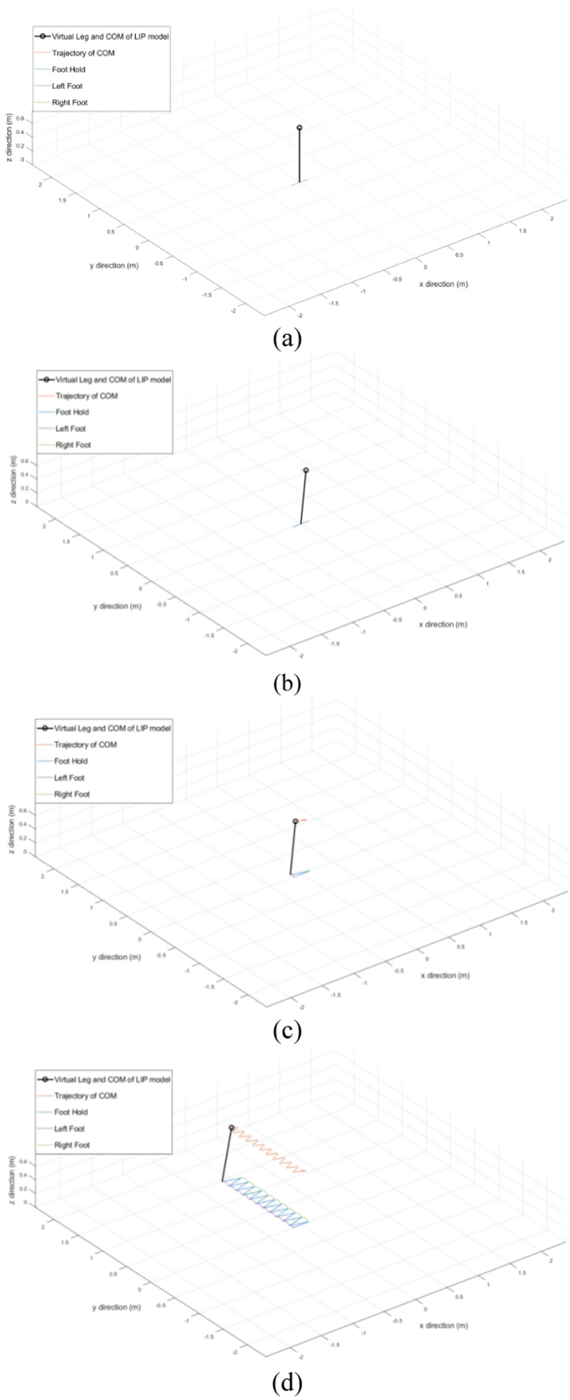


Fig. 3. The 3D-LIPM of robot

Table 1. Algorithm of 3D-LIPM's creating

Algorithm	
1:	**Setup** Set variables and model initial conditions.
	x_{Torso} : The distance from body to foot.
	g : Acceleration of gravity.
	T_s : Sample time.
	z_{Robot} : The height of the robot' centroid in its initial state.
	z_{Model} : The height of the pendulum' centroid.
	swingHeight : Swing height for the feet trajectories
2:	**Set Foot Initial Conditions and Number of Steps**
	Set the initial position of the robot's feet, the inverted pendulum will move forward step by step in the x direction according to its natural dynamics for each footstep.
	Repeat
	Get every left foothold $(p_l(n) \quad -x_{Torso} \quad 0)$ and every right foothold $(p_r(n) \quad x_{Torso} \quad 0)$.
	Set
	Step number = 20.
3:	**Create the 3D-LIPM and save model parameters**
	The LIP model system is actuated in natural dynamics. Hence the input vector $[u_{0x} \quad u_{0y}] = [0 \quad 0]$. And save model parameters after the inverted pendulum moves forward naturally.
4:	**Create the foot trajectory**
	Create a symmetric trajectory and move in a positive x direction, and starting with a positive initial y position y_0 .
	Setup step length, dx_mid (a point where has the minimum x velocity and the maximum energy), and y_0 which is around xTorso.
	Use function findInitialConditions to find suitable parameters to ensure this trajectory is effective.
5:	**Simulation**
	Model is simulated with the given initial condition for single support time ($t_{\text{SingleSupport}}$) to give us the natural trajectory of the LIPM.
	The replacement of the supporting foot in the robot walking process is regarded as an instantaneous action, which simplifies the double supporting stage.

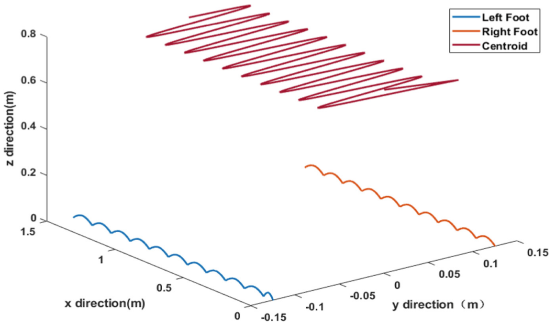
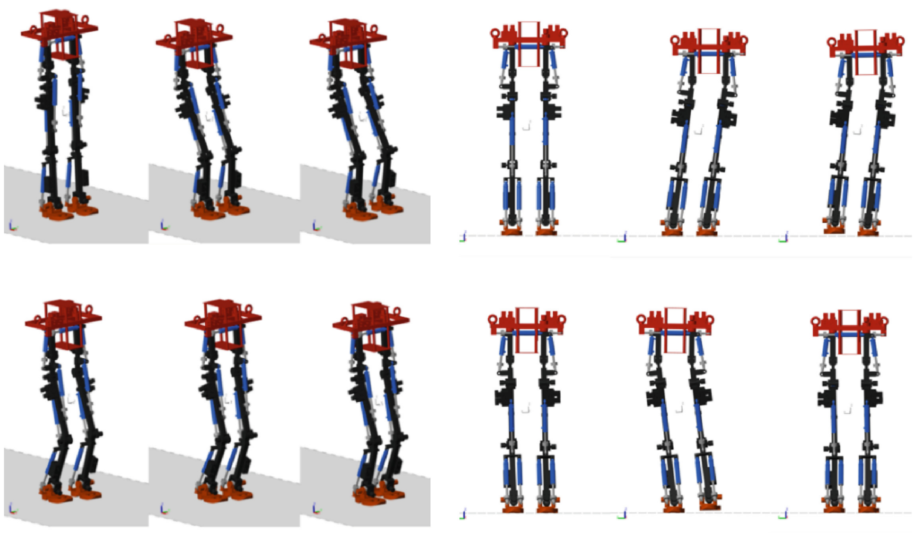


Fig. 4. Trajectories of robot's centroid and feet

4 Simulation Result

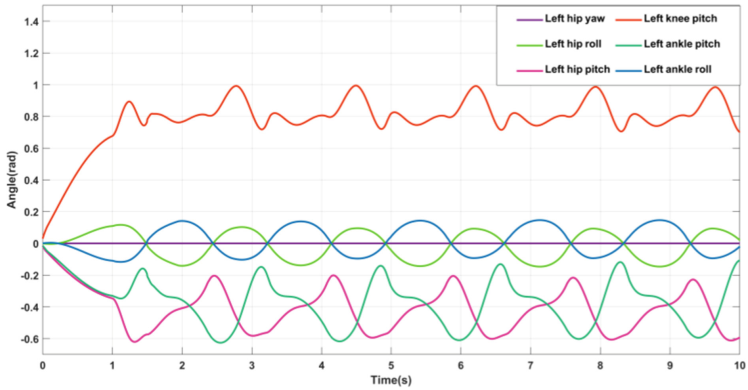
Simulation of Defensor's walking as shown in Fig. 5. The experimental results show that the biped robot can make a smooth and continuous transition on the Earth, which proves the above motion and 3D-LIPM is correct, laying a foundation for the analysis of stability.



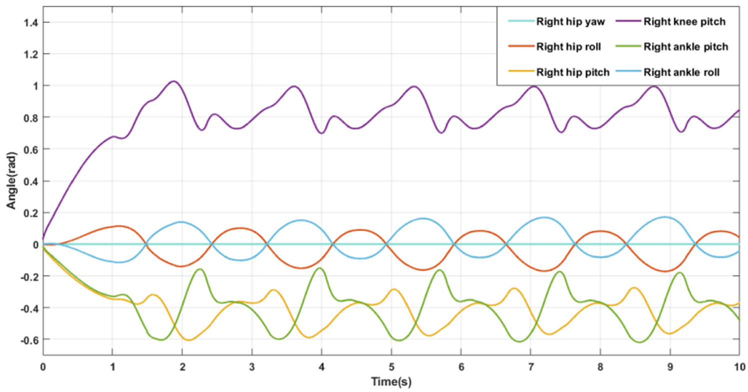
(a) 3D view (b) Rear view

Fig. 5. The snapshots of Defensor's walking

On the basis of the 3D-LIPM and algorithm analysis, The virtual environment of Defensor is a flat ground without obstacles shown in Simscape Mutibody. And the angle changes of each joint while walking are shown in Fig. 6.



(a) Left leg



(b) Right leg

Fig. 6. Each joint's angle of robot

5 Conclusion

In this paper, a novel humanoid biped robot is developed. And the robot's degrees of freedom are simplified to do the main job. Due to the distribution of hydraulic-driven cylinders, especially the parallel structure to the ankle joint, this paper can control feet better, making its gait planning more stable. In addition, sensors are installed to get feedback needed for full implementation. Moreover, the robot algorithm uses 3D-LIPM. This method matches the actual motion of the robot and simplifies the model. Simulation results based on Simscape virtual platform show that the hydraulic biped robot can walk stably, which lays the foundation for further confirmation of the physical model. In the future, in order to plan the gait of the robot better, go on to optimize the mechanical design and actively control the robot will be next work. The mechanical structure of the robot will be cleaner and the force control will be more flexible, thus reducing the influence of external forces on the robot's movement.

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