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Research on Humanoid Robot Slope Gait Planning

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Abstract: This paper is based on the robot model NCEPU-I. With this model, we proposed a robot slope walking gait method based on improved algorithm of inverse kinematics. With the bar linkage model, the humanoid robot slope gait could be planned by hips and swing leg ankle trajectory planning and then the slope gait planning can be achieved. This method can achieve and apply to different angles with high efficiency. Finally, after mathematical modeling and simulating by MATLAB and ADAMS, the simulation results verify the correctness and applicability of gait planning.

Keywords: Humanoid robot, inverse kinematics, slope gait planning, ZMP (zero moment point).

1. INTRODUCTION

Humanoid robot is one of the important research directions in Robotics. Compared with other robots (wheeled, crawler etc.), the humanoid robot has the following characteristics: Discrete supporting foot, alternately touching the ground, walking stability under different circumstances, increased flexibility, more suitable to replace human work in harsh environments; Walking humanoid robot is a high level, strong coupling, nonlinear multi-degree of freedom system and a typical study in control theory and control engineering fields [1]; Walking humanoid robots have anthropomorphic mobile features and better affinities. They are more suitable for the task together with human; Research on walking gait of humanoid robot can promote the development of kinetic prosthetic and rehabilitation medicine; Research on walking humanoid robot could also promote the development of artificial intelligence, bionics, sensors, communications, computers and other related disciplines [2].

With the rapid development of robot technology, humanoid robot has been widely used. However, the walking environment of humanoid robot is not always flat road but undulating. In order to adapt to this situation which must be adapted to different gait slope, the planning for humanoid robot gait slopes is required, by creating parametric model, this paper is to solve the problem of the humanoid robot's gait planning in different slope.

Humanoid robot gait planning can be broadly divided into several categories:

1.1. Gait Planning Based on Bionic Kinematics

The initial studies of gait studies are based on bionics. Humanoid robot designed to mimic human walking characteristics, so its gait planning can draw on bionic human gait. Using the human walking motion capture data (HMCD), complex and diverse actions can be planned, such as Honda's ASIMO research team generated gait by analyzing the law of mutual inhibition and coordinated in human lower limb joints when it's walking [3-4]. Since the reference action produce by the human body, this approach of gait planning becomes simpler than others; however, due to the large private walking data is needed to plan this gait, it does not have the versatility.

1.2. Model-Based Gait Planning

The inverted pendulum model and table-mobile models, etc. [5]. They are mainly based on the link model. These gait planning methods are based on a simplified ideal model, they mainly through the cubic spline interpolation method, polynomial interpolation method and the method of elementary functions to plan the gait. This gait planning method has the advantages of intuitive and clear physical meaning, and there is no need to consider the problem of the dynamics. Meanwhile, the link quality, centroid location, moment of inertia and other parameters are needed in the planning process, so it is complex and has a large amount of calculation. since the coupling between the radial movement and lateral movement has been ignored when the gait planned, so that when the planned gait applies to the actual prototype, inevitably there is an error, what's more, some questions just like, the interference between the forward motion and the lateral movement, the gait switching is not continuous, the swing leg is not parallel with the ground, etc. may occur.

In addition, all these gaits are offline planning under ideal conditions, so the adaptability to the actual walking environment and robustness to interference of the robot is poor.

1.3. Gait Planning Method Based on Energy Optimization

This method is able to give full play to the humanoid robot performance and reduce energy consumption during walking, but the optimal planning need a large amount of calculations and it is not real-time calculations yet; currently,

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energy optimal planning method is only used in the simplified model of the robot and using numerical methods.

R. Kurazume *et al*. [6] compared the traditional knee biped robot walking gait, proposed straight leg walking, introduced degree of knee extension parameters, introduced a ZMP knee plane when comparing the knee drive torque, simplified the calculation of joint torques, pointed out the natural straight leg walking gait improved the knee energy consumption and used this method in the gait experiments of biped robot HOAP 1.

Miomir Vukobrastovic [7] analyzed gait problems from the view of energy earliest and came to a conclusion: The smoother the walking posture, the less power the walking system consumed. Jiang Shan *et al.* fitted the trajectories of the robot hips and ankles with cubic polynomial. Using genetic algorithms to optimize the polynomial coefficients, they obtained optimal energy walking gait based on the optimal energy targets.

1.4. Intelligence Technology Based Gait Planning

Intelligence technology such as neural networks, fuzzy logic, genetic algorithms, etc. so that the robot has a powerful self-learning, adaptive and fault tolerance. This approach has attracted many domestic and foreign scholars in the field of robotics research attempts to apply it to the humanoid machines.

J.G Juang [8] trained the multilayer feedforward networks and neurofuzzy networks with back time learning algorithm, performed gait synthesis based on a given reference trajectory.

M. Cao *et al.* [9] optimized the neural oscillator network to the 8 degrees of freedom joint trajectory generation. Network connection permissions value is determined by the balance method and the genetic algorithm. J. Yamaguchi *et al*. [10] determined the motion of each joint from the ideal ZMP trajectory using FFT and achieved a stable dynamic walking with humanoid robot WABIAN.R. This method took advantage of the cyclical nature of the walking motion and would be more suitable to approximate solutions. K. Nagasaka *et al.* [11] generated pedestrian mode based on Optimal Gradient Method and achieved a stable dynamic walking with humanoid robot H5.

Based on the full analysis of the robotic lower limb institutions degree of freedom and the drive way, this paper used d-h method for robot structure modeling of lower limb institutions, obtained the inverse kinematics solution by combining analytic method and numerical algorithm, and improved the operation efficiency and accuracy. By setting the initial parameters, planned the ankle joint trajectory, and proposed a hip trajectory planning method based on polynomial interpolation, which can adjust the scale factor of single leg support phase and two legs support phase to adjust the proportion coefficient of the walking gait of the robot.

This paper used the combining of model-based gait planning, analytical method and numerical algorithms to solve the inverse kinematics of link model, achieved a different slope gait planning and gait planning feasibility and applicability of verification.

2 HUMANOID ROBOT KINEMATICS MODELING AND ANALYSIS

2.1. NCEPU-I Robot

NCEPU-I Robot's legs have 12 degrees of freedom(DOF), That is, each leg includes three DOFs for a hip, one DOF for a knee and two DOFs for a ankle. 12 DOFs of the humanoid robot composed of rotating joints.

Simplified model of the robot, according to D-H rule to establish linkage coordinate system shown in Fig. (**2**).

Fig. (1). NCEPU-I robot.

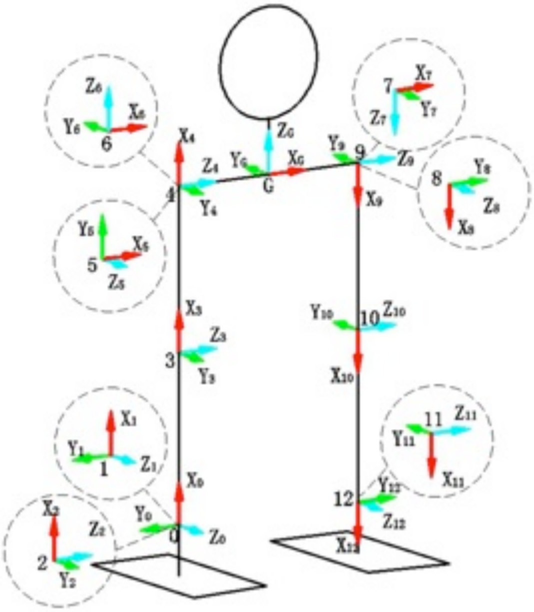

Fig. (2). Simplified model and coordinate system.

Defined the center of the robot's right ankle joint coordinate system is $\{0\}$ for the world coordinate system, when the robot start walking, the right foot is the support leg, left leg is swinging leg.

2.2. Improved Algorithm of Inverse Kinematics

Compared with chain by matrix calculation for forward kinematics, solving the inverse kinematics is much more complex.

With simple and straightforward solving process, analytical geometry, through geometric relationships, can solve the joint variables, which is mainly used for solving inverse kinematics problem with fewer links and specific structures of the operating arms.

Complex as the process of the numerical method for solving the inverse kinematics problem, a large number of matrix operations and computing capacity are needed. Furthermore, the error in the solution obtained after solving process will be relatively larger because the solving process exist serious error accumulation phenomenon resulted from an intermediate variable operation [12].

This paper uses this two solutions for integration, namely analytical and numerical algorithms combined method. Using this method can avoid the intermediate variables and the problems of multiple solutions.

By analyzing the structure of the robot leg in Fig. (**3**), when the variable of knee joint angle is not zero, it can be found that no matter how the robot's leg movement, A, B, C (respectively, the center of hip, knee and ankle) has three points to form a triangle. As the triangle sides l_a and l_c are robot leg and thigh, their length is known, just need to obtain l_b length that can be used for joint angle geometry respectively $\theta_1 \sim \theta_3$ to solve it.

l_b is the distance between the intersection of the hip joint axis and the intersection of two axes at the ankle. Fig. (**3**) shows that $l_b = \sqrt{P_{x1}^2 + P_{y1}^2 + P_{z1}^2}$, knee angle variable θ_3 can be calculated according to the law of cosines, by θ_3 , θ_1 , θ_2 can be obtained according to a simple sine theorem.

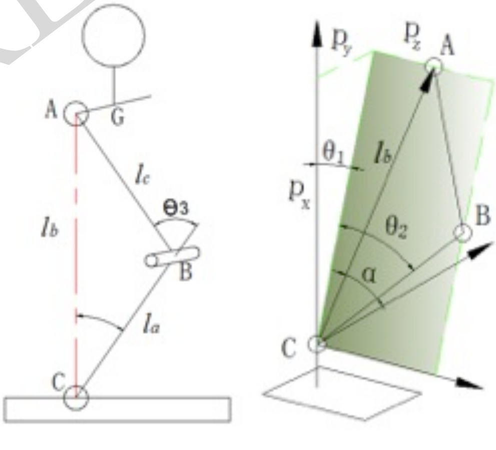

Fig. (3). Structure of the robot leg.

Then, according to the traditional numerical methods, we can solve the value of the other three angles.

Using this method for solving robot inverse kinematics problem only need once matrix multiplication operations, compared with numerical solution, it will not only save a lot of calculations, but also reduces the number of variables in the middle of the solution process. To take a direct solution, it can avoid the accumulation of errors in the calculation process; improve the efficiency and precision [13-15].

2.3. Slope Walking Method Based on Inverse Kinematics

What the new inverse kinematics solution indicates is that we need to get hip and ankle angle in real time if we want each angle of the joint. Through the ankle and hip trajectory planning and solving the ankle joint coordinates $(x_1(t), 0, z_1(t))$ and hip coordinates $(x_2(t), y_2(t), z_2(t))$ can be obtained. So that you can use inverse kinematics equations, solving the movement of each joint angle curve. Therefore, to complete the slopes walking based on inverse kinematics humanoid robot needs to take ankle and hip joint trajectory planning.

2.4. Planning Methods

This paper uses parallel gait, when the humanoid robot is walking, its' two feet are parallel [16]. In the process of walking, the feet always stay parallel to the ground; the motion can be divided into three stages:

1) Beginning phase: Humanoid robot starts move from upright stationary state, first, the center of gravity fall to suitable height for walking. At the same time by the hip joint's lateral movement, the center of gravity will offset from the middle to the supporting foot.
2) Normal walking phase: Humanoid robot's leg alternately move forward, the upper body stays upright and projection of center of gravity on the ground moving between two feet, in this process, ZMP should always keep in stable support domain.
3) Ending phase: robot's swinging leg stamp half step forward, and then it will be placed in the position of flush with support foot, the center of gravity offset from support foot to middle of two legs. At last raise the robot center of gravity to the initial upright position.

The parameters are described in Fig. (**4**):

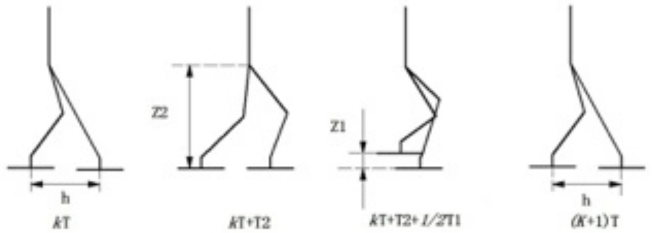

Fig. (4). Robot's walking parameters.

When the robot's walking motion is planned, its walking trajectory will be planned, in this paper, we ignore the coupling between forward motion and lateral motion and carry out resolution on movements, in their own plane to plan the trajectory of hip and ankle, Use polynomial interpolation method to solve the trajectory, then with the knowledge of robot inverse kinematics, the joint angle during walking can be obtained [17].

3. STABILITY CRITERION

We use the ZMP (zero moment point) principle proposed by the Yugoslav scholars, Vukobratovic and Stepanenko to judge the walking stability. It represents force projection point on the ground of humanoid robot suffered force of gravity and inertia force during movement, at this point the force moment is zero. When walking on the horizontal ground, ZMP point must always in the projection of convex area consist by support feet on the ground, which is stable support domain. In the process of walking, the minimum distance between ZMP point and stable support area boundary is defined as stability margin, greater stability margin is, that is closer ZMP is to the center of the support polygon, humanoid robot will more stable [18, 19]. ZMP formula:

$$Y_{zmp}=\frac{\sum_{i=1}^{n} f_i Y_i}{\sum_{i=1}^{n} f_i}=\frac{\sum_{i=1}^{n} m_i\left(\ddot{x}_i+g\right)y_i-\sum_{i=1}^{n} m_i \ddot{y}_i x_i}{\sum_{i=1}^{n} m_i\left(\ddot{x}_i+g\right)} \tag{1}$$

$$Z_{zmp}=\frac{\sum_{i=1}^{n} f_i Z_i}{\sum_{i=1}^{n} f_i}=\frac{\sum_{i=1}^{n} m_i\left(\ddot{x}_i+g\right)z_i-\sum_{i=1}^{n} m_i \ddot{z}_i x_i}{\sum_{i=1}^{n} m_i\left(\ddot{x}_i+g\right)} \tag{2}$$

According to above method for programming in MATLAB and draw the ZMP curve of a walk cycle, this is shown in Fig. (**5**).

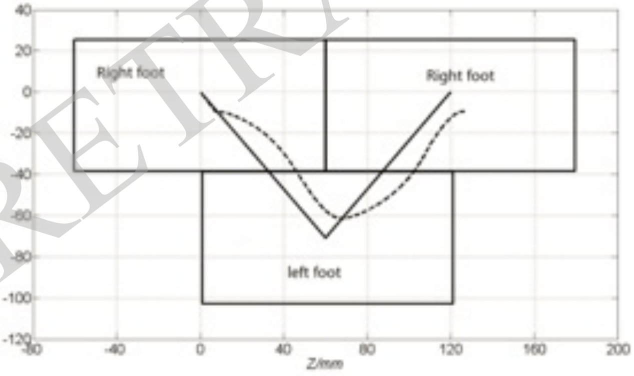

Fig. (5). Actual ZMP curve and center line of support domain.

The right foot is the staring origin, move left foot supported by right foot forward, and then the center of gravity is moved to left foot, next left foot support right foot to take a step. In Fig. (**5**), The biggest convex area is stable support domain, which is composed of the point between supporting foot and ground, the solid line is the center line of stable support domain, the dotted line is actual ZMP curve calculated by above parameters, the distance between two lines is defined S, it is the reference to judge the walking stability. Smaller the S value is, higher the contact ratio of actual ZMP curve and center line of support region is, greater stability margin is, more stable when robot is walking, S is calculated as shown in Equation.

$$S=\sum_{K=1}^{N}\sqrt{(z_{zmp}(k)-z_{dzmp}(k))^2+(y_{zmp}(k)-y_{dzmp}(k))^2} \tag{3}$$

Among them, K is the sampling points, (Z_{zmp}, Y_{zmp}) is the point on the center line of support domain, (Z_{zmp}, Y_{zmp}) is the point on actual ZMP line.

4. HUMANOID ROBOT SLOPES GAIT PLANNING

4.1. Humanoid Robot Slopes Motion Planning

It's shown in Fig. (**6**), the slope angle is α. The whole process of humanoid robot gait can be divided into three stages: initial stage, start to walk. In the initial stage, starting with the upright standing posture, the robot bends its knees and squats while the center of gravity is shifted to the right side. Then the robot takes a step with its left leg, starting to embark on slopes. Normal walking stage, the center of gravity moves with the movement of the hip joint which moves around cyclically and two legs take a step alternately. Multiply the circles and slope walking in actualized. Stop phase, the left and right feet get together, straighten the knees, restore upright posture and the walk is over.

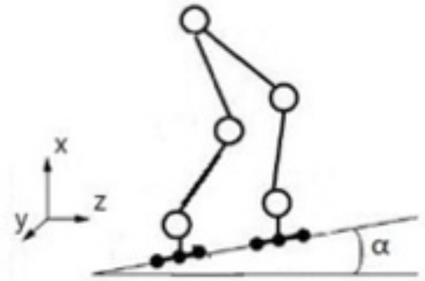

Fig. (6). Humanoid robot slopes gait planning.

It should be noted that, when the robot starts to move, it stands on the ground, however, when the first step finished, it sets foot on the ramp. Consequently, it requires joint trajectory planning in the initial stage to pay attention to the height direction displacement because of the terrain conversion. The whole slopes walking process is shown in Fig. (**7**).

4.2. Ankle Trajectory Planning

It's different with the gait planning on the ground, the ankle trajectory planning when the robot on the slope needs to add geometric constraints for tiptoe stance to avoid foot collision of the slope during its swing. Meanwhile, the displacement in the height direction of ankle joint is not zero when the robot is walking; therefore, we need to take trajectory planning separately for ankle in the X direction.

Planning ankle trajectory by polynomial interpolation method, design swing ankle trajectory is:

$$\begin{cases} x_1(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5 \\ z_1(t) = b_0 + b_1 t + b_2 t^2 + b_3 t^3 + b_4 t^4 + b_5 t^5 + b_6 t^6 \end{cases} \tag{4}$$

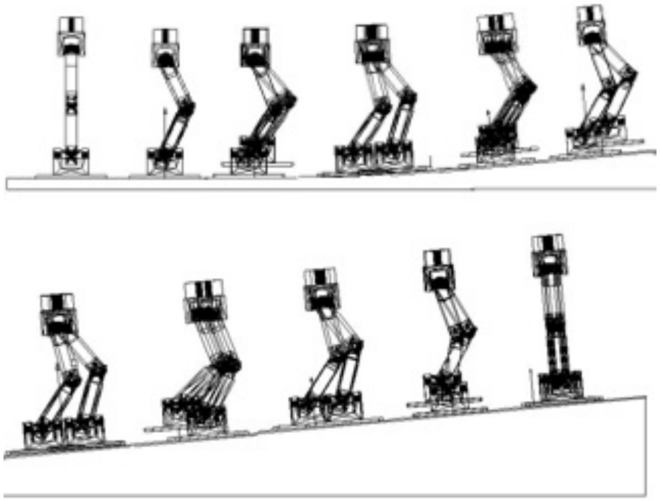

Fig. (7). Humanoid robot slopes walking process.

In formula (4), $x_1(t)$ represents the ankle trajectory in the X direction of the swing leg in a leg swing stage, $z_1(t)$ represents the ankle trajectory in the Z direction of the swing leg in the stage. t is the time variable, where, a_0, $a_1 \cdots a_5$, b_0, $b_1 \cdots b_6$, are undetermined coefficients.

By adding a known location on tiptoe stance posture and geometric constraints as boundary conditions into the formula, we can get the coefficients. Ankle trajectory can be obtained after coefficient determined.

Let leg's walking cycle is 0.5s, step length is 100mm, the maximum height of the heels 30mm, as shown in Fig. (**6**) is the swinging leg's ankle space trajectory.

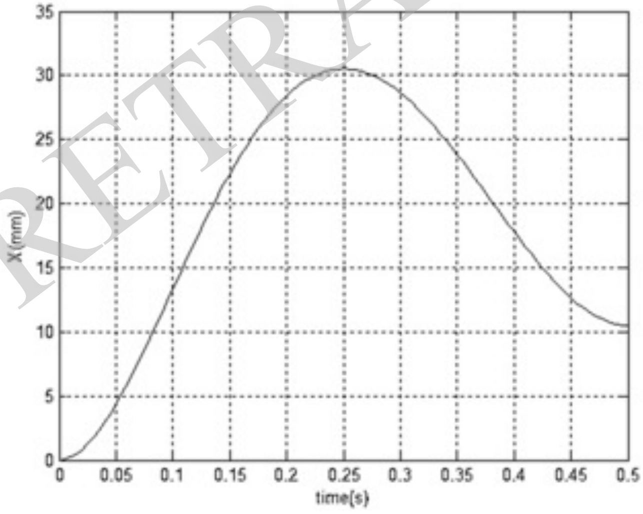

Fig. (8). Swinging leg's ankle trajectory.

Tangent slope of the curves in the Fig. (**8**) react the changes of ankle joint's velocity in the space in the start-up and step down phase, the slope of the tangent in this phase is small, which is indicating slower; intermediate stage, the larger the slope of the tangent, indicating faster, which basically comply with the characteristics of human walking. With the robot set foot on the ramp, displacement produced in the height direction of ankle, the displacement is exactly equal to the tangent of the slope Multiplied by the angle, which can be to some extent reflects the ankle gait planning is reasonable.

4.3. Hip Trajectory Planning

When the gait planning is on the ground, it's general to set the height of the hip joint to constant values. It's different when the robot is on the ramp which requires hip trajectory planning on the height direction.

Planning hip trajectory by polynomial interpolation method, design the trajectory is:

$$x_2(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5 \tag{5}$$

According to the geometrical relationship and while the hip walking in a straight line can be considered as a constant height h, the track X can be simplified after the track Z is solved:

$$z_2(t) = b_0 + b_1 t + b_2 t^2 + b_3 t^3 + b_4 t^4 + b_5 t^5 + b_6 t^6 \tag{6}$$

$$x_2(t) = z_2(t)\tan\theta + h \tag{7}$$

Each walk cycle T, the hip joint in the y direction complete a round trip between two extreme positions, to achieve stable walking the curve of back and forth movement should be consistent, Therefore, we can choose a half cycle specific point in time as the boundary condition for solving the trajectory y direction.

Design of the hip joint path in the direction of motion is:

$$y_2(t) = c_0 + c_1 t + c_2 t^2 + c_3 t^3 + c_4 t^4 \tag{8}$$

In formula (5)(6)(8):

a_0, $a_1 \cdots a_5$, b_0, $b_1 \cdots b_6$, c_0, $c_1 \cdots c_4$, are undetermined coefficients.

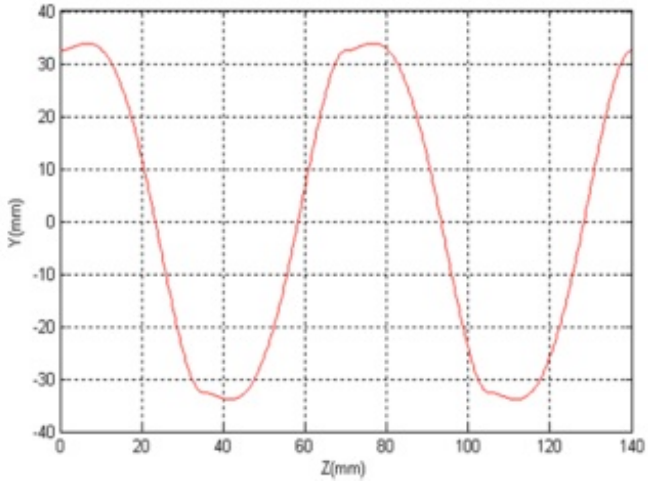

Fig. (9). Hip trajectory.

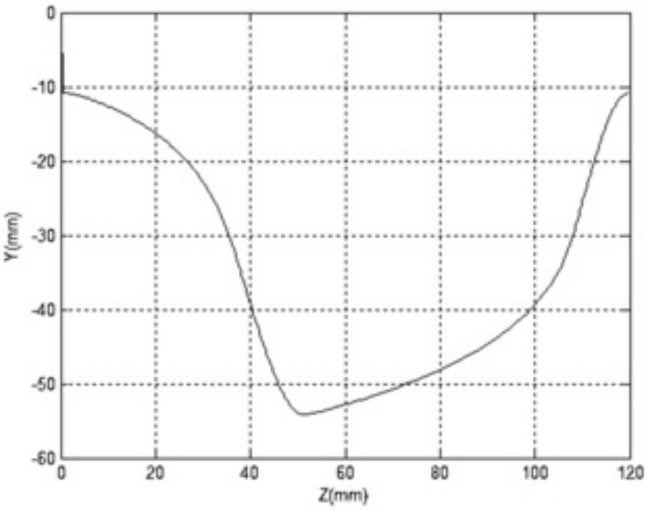

Fig. (10). ZMP trajectory curve.

5. SIMULATION AND RESULT ANALYSIS

5.1. Verify the Feasibility

Currently, ZMP criterion is widely accepted walking robot stability criterion [20]. The closer ZMP the center of the support region, the better the stability of the robot. The validation tests are also mainly based primarily on ZMP criterion, taking the results of ADAMS simulation as a secondary verification. Create mathematical models to get the corresponding ZMP trajectory by MATALAB, if the ZMP trajectory is in the support polygon, we can say the walking gait stability conditions are met.

Humanoid robot created by using ADAMS virtual prototype, take slope angle α is 5, step length is 100mm and heels height is 30mm. Import the velocity change function of each join into ADAMS virtual prototype model, the gait of robot model can be simulated.

Simulation shows that the gait of robot model moves coherently and walks stably consistent with the plan.

5.2. Applicability

To study this slope gait planning available how much slope angle would up to, we conducted applicability validation, verification process shown in Fig. (**12**).

Specific steps are as follows:

1) Input the fixed parameter, the length of each step is 120mm, the heels height is 60mm, and the time of a cycle of walking is 1.5s

2) Input ramp angle α, set the initial value α = 1, α ≤ 90;

3) According to the value of α, obtained corresponding ZMP trajectory by the previous method;

4) If the ZMP trajectory is in the support polygon, we put the date of α into ADAMS simulation verification, and then α=α+0.01, use the new value of α enter the next cycle. On the contrary, which means the ZMP trajectory beyond the support polygon; it is time to output the value of α.

5) Multiple cycles until the ZMP trajectory beyond the support polygon. At this point α value is evaluated and the experiment is end.

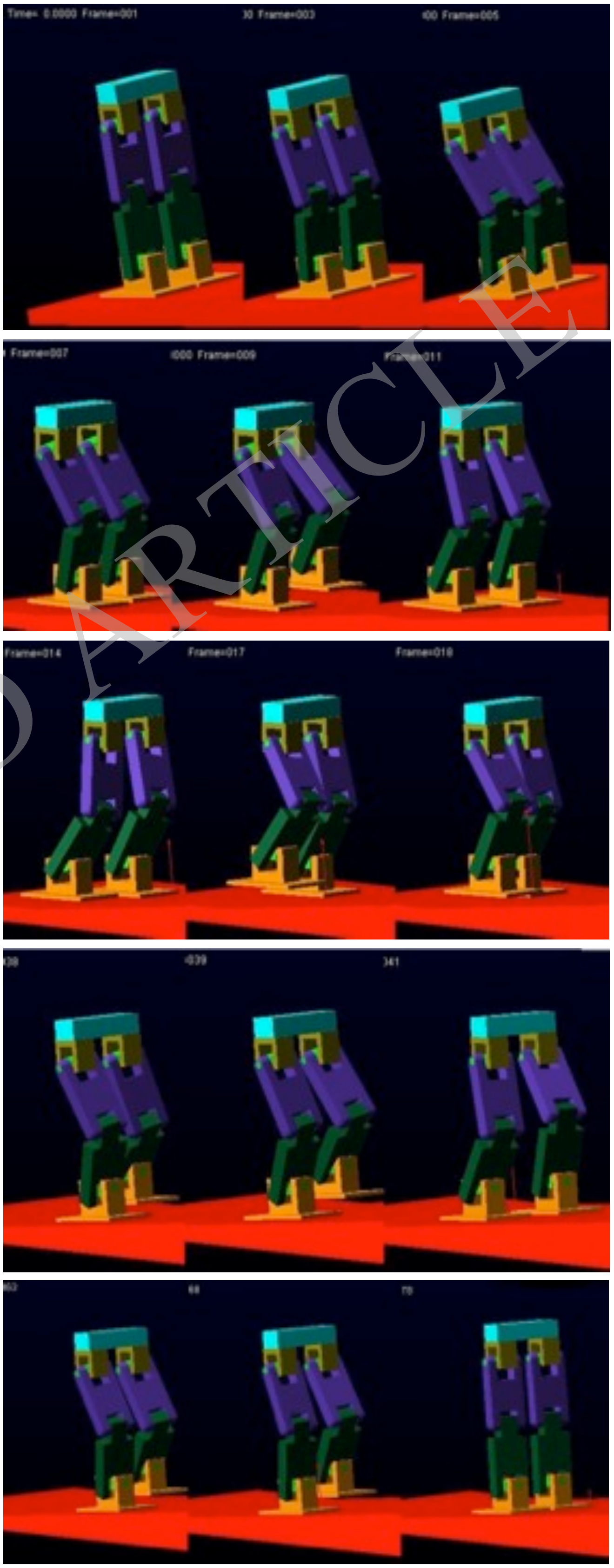

Fig. (11). ADAMS simulation.

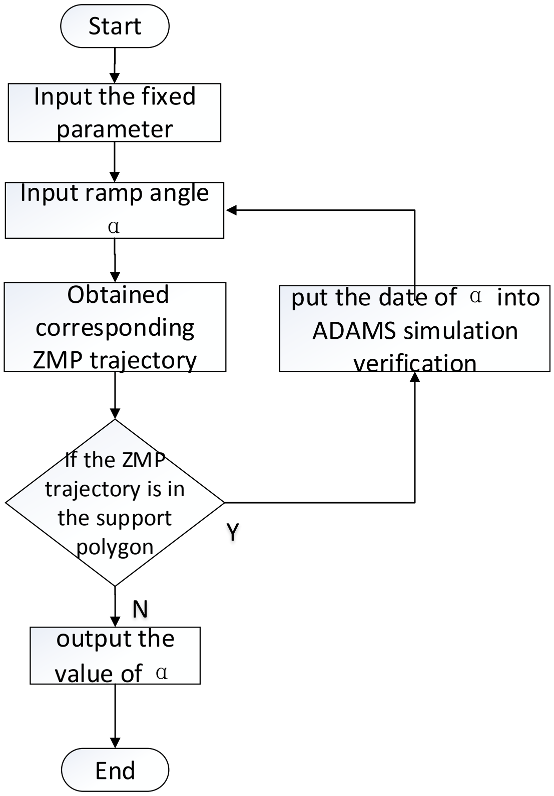

Fig. (12). Validation process.

The need to meet certain gait stability margin requirements can be achieved by reducing the support polygon. This section the long side of the support polygon decreases inwardly 20mm, the broadside side of decreases inwardly of 12.5mm, shown in Fig. (**11**). After calculation, the ranges of the slope angle α with a stable gait can be obtained. By experiment the maximum value is 28.84.

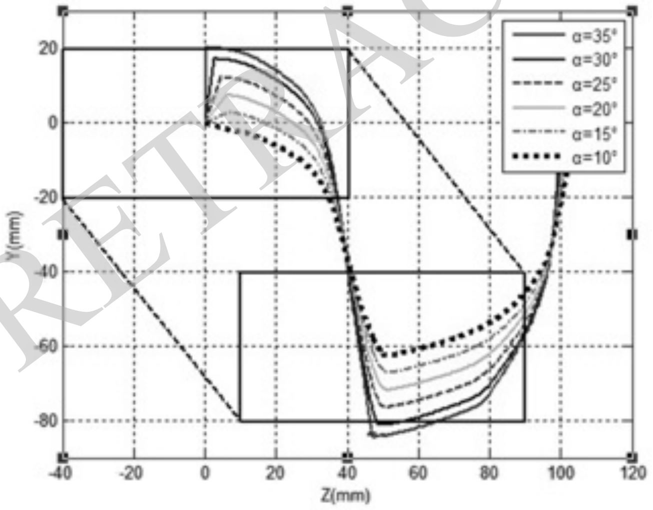

Fig. (13). ZMP curve and the support polygon.

From this paper, in order to meet the stability margin and limit the foot friction, the humanoid robot, by adjusting the value of α from 1 ° to 28.84 °, can achieve the adjustments for different angles of slopes gait and keep step and the time in single foot support phase constant.

6. SUMMARY

Aiming at the gain planning of humanoid robot NCEPU-I, a slope walking method based on the improved algorithm of inverse kinematics had been designed. The trajectories of the hip and the ankles had been planned based on the bar linkage model to achieve the slope walking patter. MATLAB and ADAMS simulation results verified the effectiveness of this gait planning and applicability.

CONFLICT OF INTEREST

The author confirms that this article content has no conflict of interest.

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