Research on sports planning and stability control of humanoid robot table tennis

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Abstract
The humanoid robot has the human shape and has great advantages in assisting human life and work. The ability to work, especially in a dynamic, unstructured environment, is an important prerequisite for humanoid robots to assist humans in their mission. Table tennis hitting involves a variety of key technologies such as visual inspection, trajectory planning, and artificial intelligence. It is an important research example that can reflect the ability of humanoid robots. First, according to the requirements of humanoid robots in the human living environment and the requirements of coordinating table tennis batting movements throughout the body, a method of establishing a humanoid robot model was analyzed, and a control system was designed to meet the needs of rapid table tennis batting. Second, a motion model construction and optimization algorithm based on intelligent learning training is proposed. Based on the parameter knowledge base established by the multiple trajectories of table tennis, a kind of electromagnetic mechanism and D-optimality regularized orthogonal minima are introduced. Design a two-pass method (regularized orthogonal least squares method + D-optimality) to learn the two-level learning method, which is used to learn the key parameters of the table tennis model. Third, for human-like robotic table tennis fast-moving, it is necessary to satisfy both the task and the stability requirements and to propose a stability-optimized whole-system coordinated trajectory planning method. The effectiveness of the proposed humanoid robot table tennis hitting motion planning and stability control method is verified by experiments.

Keywords
Humanoid robot, table tennis hitting, trajectory planning, stability control

Date received: 02 December 2019; accepted: 17 January 2020

Introduction
The humanoid robot has human contour features such as limbs, head, and torso and has basic functions similar to those of human appearance. This special shape characteristic determines its adaptability to human life and working environment and can better serve human beings. One of the most important goals of humanoid robot research is to study a humanoid robot that can live in harmony with people. It can work in the human real environment and use the tools people use. In addition, humanoid robots involve a variety of technologies and disciplines such as mechanics, electronics, computers, automatic control, artificial intelligence, and sensing. They are an ideal experimental platform for researching new theories and methods, and their research and development level is it reflects the high-tech

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comprehensive strength and equipment manufacturing level of a country.

The motion control of the humanoid robot is the first problem that the researcher tries to solve after completing the basic shape design of the humanoid robot. Generally speaking, the realization of the movement of the humanoid robot in space can be considered from two aspects. One is to study how the humanoid robot realizes the transfer of position in the empty view and the other is to study the humanoid robot. The movement of complex limbs is based on the own structural features. Nowadays, many well-known world-famous humanoid robots have begun to have certain macroscopic positional mobility. The basic method of positional movement of these robots in three-dimensional space is according to the physical design features of humanoid robots. Off-line training of an action library can be actually executed by the robot, while requiring these actions to be guaranteed in the stability of the robot, and to consider the skilled switching of various actions, in a specific environment, when the command robot is completed. When a position is transferred, the system calls some mature search algorithms, finds the most reasonable set of solutions in the action library and then controls the robot to perform these actions. This method has been implemented on humanoid robots such as ASIMO and HRP and has shown good practical results. However, the biggest problem with this method is that when the action library is designed to be richer, the time required for the intelligent search algorithm to search for the optimal solution tends to be large. Many studies are considering how to improve on the basis of the original method to meet better time performance, such as further reducing the dimension of the action description, but at the same time, it may also cause the action that is not very rich to change. It is more singular and cannot reflect the characteristics of flexible movement ability under the complex structure of humanoid robot. The humanoid robot has a small support area and is easy to fall and lose stability when performing a quick-hitting task. The dynamic filtering method of the reference acceleration of the trunk is corrected to ensure that the zero moment point (ZMP) is in the support area, the minimum acceleration in the synchronization period is generated by the bang-bang solution, the corrected motion is synchronized to the reference motion, and the upper body work task of different speeds is adopted on the ASIMO model. The proposed method was validated. This method corrects the desired torso trajectory without the integration of the upper body inverse kinematics compensation, which easily leads to operational task errors. The research on the operation of the operating arm was carried out, the common problems such as motion constraint and singularity were discussed and a unified method of manipulating arm motion and force control was proposed. On this basis, according to the characteristics of humanoid robots, the tasks such as task, constraint, and attitude optimization are classified, and a hierarchical control framework based on whole-body behavior units is proposed. The study does not discuss the specific job types. Problems such as trajectory planning and stability control. The ping-pong hitting movement requires a humanoid robot to coordinate the individual body’s respective degrees and, at the same time, meet the task requirements, kinematic and dynamic constraints, stability constraints, and so on. There are two main problems in previous research. First, most robotic work research such as table tennis hits mainly discusses tasks such as task target recognition and task arm trajectory planning. It does not involve the full-body trajectory planning and stability control of humanoid robots. Such methods can easily lead good stability cannot be guaranteed in a fast-hitting ball. Second, a few studies have discussed the stability maintenance of humanoid robots, but such methods often cannot guarantee the originally expected task requirements and cannot be applied well to table tennis. Therefore, studying the whole-body trajectory planning and stability control of humanoid robots in table tennis is a very important and effective way to improve the humanoid robot’s operating ability.

This article studies the trajectory planning and balance of the whole-body coordination in the table tennis hitting movement of humanoid robots and the problem of stable control of sliding prevention. First, the human simplified model and humanoid robot model are introduced, and the basic kinematics and inverse kinematic formulas based on the humanoid robot model are given. The humanoid robot control system and control structure designed to realize the table tennis batting motion are introduced in general. Second, a new two-layer network construction model is proposed. Based on this algorithm, the model is optimized and the prediction accuracy is further improved. Third, an overall trajectory planning method for humanoid table tennis batting motion is proposed, which can meet the task requirements and has the best stability. According to the task requirements, determine the position and speed of the redundant working arm joints of the humanoid robot and the torso position of the robot’s center of mass in the support area of the specified position, so that the humanoid robot has better time to operate when fast. Finally, to solve the problem that humanoid robots can easily lose stability during the fast stroke of table tennis, a method of controlling the double-constrained stability of the feet’s contact with the ground is proposed. Experiments prove the effectiveness of the proposed stability control method.

**Humanoid robot model and control system**

**Humanoid robot model**

The simplified model of the human body is still very complicated when applied to the humanoid robot. Therefore,
according to different application backgrounds, the simplified model of the human body needs to be further simplified. In general, when discussing the mobility problem of the humanoid robot, the influence of the upper limb can be neglected, which greatly simplifies the model complexity. This simplification is more common in the study of robotic motion dominated by lower limbs such as walking, running, and jumping. Figure 1 is a simplified model of several common humanoid robot walks.

As shown in Figure 1, the inverted pendulum model is commonly used in motion planning and control such as walking and running of a humanoid robot. It is equivalent to the mass of the robot as a concentrated mass, that is, the centroid. Converting kinematic or dynamic solution is to joint space motion by moving the center of mass. To obtain an analytical solution, the inverted pendulum model can be further simplified into a linear inverted pendulum model by assuming that the centroid has no vertical motion. The two-link and three-link models mainly add some joints in the leg, such as the ankle or knee joint, in an effort to make the model more precise. The seven-link model models the robot as the torso, thigh, calf, and foot. The seven-bar linkage model considers the important role of the robot’s torso in movement, has good integrity, and can accurately represent the dynamics of the robot. It is a model that is currently used more.

**Humanoid robot kinematics and inverse kinematics**

A connecting rod can be described by two parameters: the length of the connecting rod and the angle of the connecting rod. These two parameters respectively correspond to the distance and the angle between the two axes of the connecting rod space. The distance between the two axes of the space is the length of the vertical perpendicular of the two axes of the connecting rod. For example, \( \alpha_{i-1} \) is the distance between the axis \( i - 1 \) of the connecting rod \( i - 1 \) and the axis \( i \), and \( \alpha_i \) is the axis \( i \) and the axis \( i + 1 \) of the connecting rod \( i \). The angle between the two axes of the space can be defined such that in the plane perpendicular to the vertical perpendicular \( \alpha_{i-1} \), the projection of the axis \( i - 1 \) follows the angle of the right-hand rule about the axis \( \alpha_i \) to the axis \( i \), that is, \( \alpha_{i-1} \) in the figure.

Two parameters, the link offset and the joint angle, are needed between two adjacent links to determine the connection between the links. The link offset is the distance of adjacent links along the common axis. As shown in Figure 2, the distance from the intersection of the male perpendicular \( \alpha_{i-1} \) and the axis \( i \) to the intersection of the male perpendicular \( \alpha_i \) and the axis \( i \) is the link offset \( d_i \). The vertical line of the \( \alpha_{i-1} \) is rotated about the axis \( i \) to the vertical line. The angle of the \( \alpha_i \) is the joint angle \( \theta_i \).

When the rod and rod connections can be described by the above method, the coordinate system can then be established on the rod. Establishing the rod coordinate system is a key step in robot kinematics and inverse kinematics solution. The Denavit–Hartenberg parameters of the upper limbs can be represented by Table 1.

After the coordinate system is established, according to the limitations of the actual robot application, the kinematic constraints and the defined zero states are first given. Then, the transformation matrix of the end coordinate system to the previous coordinate system and the transformation matrix \( T_{tool} \) of the tool.

![Figure 1. Humanoid robot walking model. (a) Inverted pendulum model, (b) two-link model, (c) three-link model, and (d) seven-link model.](image-url)
coordinate system in the end coordinate system are expressed as follows:

\[
\begin{align*}
    \begin{bmatrix}
        c_T & -s_T & 0 & 0 \\
        0 & 0 & 1 & 0 \\
        -s_T & c_T & 0 & 0 \\
        0 & 0 & 0 & 1
    \end{bmatrix}
    & \times \\
    \begin{bmatrix}
        1 & 0 & 0 & 0 \\
        0 & 1 & 0 & t_e \\
        0 & 0 & 1 & 0 \\
        0 & 0 & 0 & 1
    \end{bmatrix}
\end{align*}
\]

Then the new robot end pose matrix \( T_e \) can be simplified as follows:

\[
T_e = \begin{bmatrix}
    N_1, O_1, A_1, P_z \\
    N_2, O_2, A_2, P_y \\
    N_3, O_3, A_3, P_z \\
    0, 0, 0, 1
\end{bmatrix}
\begin{bmatrix}
    c_T, -s_T, 0, 0 \\
    0, 0, -1, 0 \\
    s_T, c_T, 0, 0 \\
    0, 0, 0, 1
\end{bmatrix}
\]

**Table 1. Upper limb D-H parameters.**

| \( i \) | \( \alpha_{i-1} \) | \( \alpha_i \) | \( d_i \) | \( \theta_i \) |
|---|---|---|---|---|
| 1 | 0 | 0 | \( l_e \) | \( \theta_1 \) |
| 2 | \( \pi/2 \) | 0 | 0 | \( \theta_2 \) |
| 3 | \( \pi/2 \) | 0 | \( -h_{a2} \) | \( \theta_3 \) |
| 4 | \( \pi/2 \) | 0 | 0 | \( \theta_4 \) |
| 5 | \( \pi/2 \) | 0 | \( -h_{ct} \) | \( \theta_5 \) |
| 6 | \( \pi/2 \) | 0 | 0 | \( \theta_6 \) |
| 7 | \( \pi/2 \) | 0 | 0 | \( \theta_7 \) |

D-H: Denavit–Hartenberg.

**Whole-body trajectory planning and stability control of humanoid robot table tennis**

Taking the table tennis quick-hitting movement as an example, a control system that satisfies real-time, easy scalability, and interactivity is realized. The control system is constructed as shown in Figure 3.

As shown in Figure 3, taking the table tennis hitting motion as an example, the humanoid robot visually detects the ball information. If the incoming ball exceeds the hittable space, the robot abandons the hitting task and feeds the information back to the robotic operator via the interactive device. If the incoming ball is within the slam dunk space, the human–machine interaction command is captured. If the human–machine interaction command is not captured, the control system generates the hitting task requirement (the racket hitting posture, speed, etc.) according to the default command (predetermined return ball landing point), thereby performing trajectory planning and stability control, and finally the ball. Hit back to the scheduled landing point. If a human–computer interaction command is captured, the control system generates a hitting task request according to the received command (the newly designated return point) and completes the hitting operation.

**Motion planning parameter learning model**

The kinematics inverse of the continuous model parameters is the position and velocity information obtained from the visual input. After analysis, the motion equation parameters corresponding to the trajectory are obtained. Here, the continuous model parameters are obtained by the state equation, which is then transformed into discrete model parameters. For table tennis flying that is only subjected to first-order resistance, there is a state equation as follows. Here, \( k \) is the drag coefficient, and \( g \) is the input in the vertical direction.
Here, the position state is introduced to find the $g$ value.

\[ \begin{align*}
V_x(t) &= V_{x0} e^{-\frac{t}{C_0}} \\
V_y(t) &= V_{y0} e^{-\frac{t}{C_0}} \\
V_z(t) &= \left(V_{z0} + \frac{g}{k}\right) e^{-\frac{t}{C_0}} - \frac{g}{k}
\end{align*} \]  \hspace{1cm} (3)

The algorithm proposed in this section combines an electromagnetic-like mechanism (EM) and a D-optimality (D-opt) regularized orthogonal least squares method (ROLS X-D-opt) to design a two-level self-optimizing radial tomb (radial basis function (RBF)) network. The learning method is used to learn the key parameters of the table tennis flight and collision model. This article proposes a new two-level learning machine model; this algorithm combines EM algorithm with the ROLS + D-opt algorithm to form a complete RBF network establishment algorithm based on the swarm optimization intelligent algorithm. In the upper layer, an EM algorithm is used to optimize the RBF tomb width parameter; the regularization coefficient of the ROLS algorithm and the parameter combination of the D-opt optimization parameters are used to construct a simple self-establishment mechanism of the RBF model. The algorithm is based on a two-level learning mode, which can break through the limitations of the original manual adjustment in the application of the project. The selection of relevant parameters can search for the optimal value to make it reasonable. In practical applications, the processing of massive data is practical. The feasible function and the established network have a corresponding guarantee for the reliability of the actual project application because of its simple structure, generalization, and good robustness.

The model uses the ROLS algorithm learning RBF network as the basic algorithm of parameter learning, combined with D-opt algorithm to enhance the robustness of the network and establish a machine learning method that can efficiently and accurately learn the parameter model. Correlation modelling of the relevant influencing factors; by appropriately eliminating the model error of the sample training, the model’s generalization ability is maximized; and learning is continuously updated during the accumulation of table tennis trajectory data.

As shown in Figure 4, the EM algorithm generates $P$ candidate solutions in the solution space (i.e. charged particles in the EM algorithm), and each candidate solution calculates its value $f_i$ through the defined adaptation function and then optimizes according to the EM algorithm. After updating each particle and after multiple iterations, the best particle in the population is finally obtained.

**Stability-optimized whole-body coordinated trajectory planning**

In the trunk trajectory planning, the influence of the arm trajectory on stability will be comprehensively

![Diagram](image-url)
To ensure the real-time stability control, the dynamics of the robot is modeled by the inverted pendulum flywheel model. Taking the longitudinal plane as an example, the motion model in the lateral plane is similar. The model is shown in formula (5), where $j$ and $m$ are the rotational inertia and mass, $P_C = (x_C, z_C), P_Z = (x_Z, z_Z)$ is the COG and ZMP position, $l$ is the distance between COG and ZMP, and the angle between the line and the vertical direction of $\theta_a$, $T_c$ is the torque required to accelerate the rotation of the flywheel, and $f_x, f_z$ is the force required to obtain the centroid acceleration. The humanoid robot’s foot is designed as a rectangular foot plate, and the axis of symmetry supporting the foot when standing is parallel to the coordinate system. Performing force and moment analysis at COG and applying Newton’s second law, we can get the following equation:

$$
mx_C = f_x \\
mz_C = f_z - mg \\
T_c = J\theta_a
$$

(6)

Considering the relationship between force and torque between COG and ZMP, the following equation can be obtained as follows:

$$
F_x = f_x \\
F_z = f_z \\
T_c + f_z l \cos \theta_a = f_z \sin \theta_a \\
l^2 = (x_C - x_Z)^2 + (z_C - z_Z)^2 \\
\tan \theta_a = (x_C - x_Z)/(z_C - z_Z)
$$

(7)

The vertical direction is $\theta_a$, $F$ is the relationship between force and torque between COG and ZMP, $T_c$ is the torque required to accelerate the rotation of the flywheel, and $f_x, f_z$ is the force required to obtain the centroid acceleration.

If the trajectory of the robot does not cause the slip to occur, the constraint needs to be satisfied. For practical convenience, this article proposes a real-time sliding indicator.

$$
\mu_{ost} = \frac{\frac{x_C}{z_C + g}}{\frac{-x_C - x_Z - \frac{J \theta_a}{m(z_C + g)}}{z_C - z_Z}}
$$

(8)

Using the real-time slip indicator factor $\mu_{ost}$ to estimate whether the robot is slipping on the one hand can be applied to a robot with no force/torque sensor or a position-based robot and on the other hand can quantitatively explain the horizontal, vertical centroid motion, and the rotational motion at the centroid in the robot the effect of sliding.

Considering that after the stability control, the acceleration adjustment may lead to the accumulation of speed and position, and the recovery motion strategy adopted is to decelerate and then recover. First, since the large velocity accumulation easily causes the position to approach the boundary constraint, to eliminate the speed accumulation...
in the stability control, the acceleration adjustment amount in the recovery motion is given as follows:

\[ V_{\theta C} = \begin{cases} -k_{\theta \theta} \theta_C \\ -\theta_C \end{cases} \]  

(9)

Among them, \( k_{\theta \theta} \) is the adjustable coefficient, and \( \theta_C \) is the adjustable speed threshold. The location item can then be restored to the reference state given in the task request. In this phase, the speed accumulation caused by the stability control has been eliminated and can be achieved by polynomial interpolation. The initial value of the polynomial interpolation is set to the current state value of the robot, and the end value is set to the reference value given by the task.

**Verification analysis**

**Experimental data and motion planning verification**

In this experiment, three speed gears were selected for each of the low, medium, and high elevation angles of the ball (see Table 2). The distribution selected 28 trajectories, 13 trajectories, 15 trajectories, and 26 trajectories for verification.

**Table 2.** Experimental data.

| Speed gear | Low exit angle | Out of the ball | High elevation angle |
|------------|----------------|-----------------|---------------------|
| Speed gear 1 | 28 tracks | 13 tracks |
| Speed gear 2 | 15 tracks | 26 tracks |
| Speed gear 3 | 26 tracks | 28 tracks |

In terms of application results, run the neural network established by the system. In the physical model section, the most important parameters of the table tennis model are gravity, the vertical additional force input of buoyancy, and the air resistance generated by the speed of flight. The parameters corresponding to these two elements in the continuous model are defined as \( g \) and \( k \), respectively.

Figure 5 is the convergence line of the EM optimization algorithm in the application of the longitudinal additional force parameter. The horizontal axis is the number of iterations, and the vertical axis is the return size for establishing the optimal neural network adaptation function. It can be seen that the convergence of the algorithm in this reference is fast, and a satisfactory result can be achieved after 20 generations.

Figure 6 shows the convergence of the EM optimization algorithm in the application of motion tamper resistance as a parameter. The horizontal axis is the number of iterations, and the \( y \)-axis is the return size for establishing the optimal neural network adaptation function. Similarly, the convergence speed of the algorithm in the application has reached a satisfactory result after the first 20 generations.

It can be seen from the test results in Table 3 that the proposed network parameter model correction method has better prediction accuracy and stability than the linear trimming correction method. To be precise, you can get the following:

1. For the prediction of the drop time, the network parameter model correction method is better than the linear trimming correction method.
2. For the prediction of the location of the drop point, the deviation of the network parameter model correction method is larger than the linear correction method, and the mean square error is much better than the linear correction method, which is also reasonable. Since the linear fine-tuning correction method can be manually set for the trajectory of a
specific state, the error is almost eliminated. However, for different ball paths, it is very sensitive to the change of the attitude and speed of the table tennis flight, which is a key factor for the dependence of the whole system on the stability of the ball prediction accuracy.

3. Network parameter search is related to the collection of data. It can be automatically acquired in large quantities and is feasible in the application of actual projects. This method improves efficiency and is highly portable.

The above verification shows that the optimized RBF network can be designed in a global scope by using the two-level learning method. It is not only simple in structure but also has superior generalization performance. It is an effective method for designing RBF networks. By updating the setting matrix in the online prediction program by learning the obtained network feature quantity, a well-corrected neural network for online application can be obtained.

### Stability-optimized systemic coordination trajectory and stability verification

When the camera detects the arrival of the ball information (flying to the ping-pong position and speed of the robot) to hit the ball back to the predetermined landing point, the end of the robot needs to meet the given task requirements, that is, the end needs to meet a certain position, posture, and speed. Claim. To ensure the stability of the hitting operation time, the trunk needs to generate a certain displacement, so that the projection of the center of mass of the robot in the support area is as far as possible at a specified position (such as the center of the support area). The following table shows the ball information, end position, velocity, attitude requirements detected by the vision system in the five quick shots recorded, and the optimized torso displacement results under these conditions.

As can be seen in Table 4, there are repeated values of the trunk displacement, such as \(-0.0 S 125 \text{ m}, -0.05875 \text{ m}, -0.06625 \text{ m}\), and the like. The reason for this phenomenon is that the dichotomy method is used to obtain the optimized torso displacement, and the number of solutions in the dichotomy is \(N_k = 5\). The number of solves can be adjusted in a specific application. When the \(N_k\) is large enough, a higher precision torso displacement value can be obtained. In addition, in this experiment, to prevent the optimized trunk displacement from approaching the edge of the support area, this article limits the range of the trunk displacement to \([-0.07 \text{ m}, 0.05 \text{ m}]\). This value range can be adjusted according to the support area.

To verify the effectiveness of the proposed acceleration stability control method in maintaining balance and preventing slip, the required acceleration in the longitudinal

### Table 3. Comparison of test data results.

|                        | RBF network parameter model correction method | Linear trimming correction method |
|------------------------|---------------------------------------------|----------------------------------|
| Average value of the absolute value of the predicted deviation of the \(p\) term at the falling point position | 0.0277, 0.0042, 0.0001 | 0.0242, 0.0043, 0.0001 |
| Falling point \(P\) prediction deviation mean square error | 0.2828, 0.0292 | 0.3508, 0.0304 |
| Fall time \(T\) | 0.0018 | 0.0022 |
| Absolute value average | 4.58E-06 | 7.58E-06 |

RBF: radial basis function.

### Table 4. Torso displacement optimization results.

| Information about the ball, the unit is: (m, m, m) (m/s, m/s, m/s) | End position, speed, in units of: (m, m, m) (m/s, m/s, m/s) | End posture, the unit is: (rad, rad, rad) | Torso displacement in units of: (m) |
|-------------------------------------------------------------------|---------------------------------------------------------------|------------------------------------------|----------------------------------|
| (2.29, 0.71, 0.33) | (-0.41, -0.38, 0.22) | (1.39, 0.08, -1.57) | -0.06625 |
| (2.39, 0.27, -0.08) | (0.29, -1.27, 0.18) | (1.48, 0.04, -1.39) | -0.06625 |
| (2.31, 0.63, 0.30) | (-0.44, -0.38, 0.14) | (1.51, 0.07, -1.47) | -0.05875 |
| (2.93, 0.34, 0.68) | (0.11, -1.25, 0.06) | (1.49, 0.05, -1.27) | -0.05875 |
| (2.31, 0.68, 0.33) | (-0.44, -0.37, 0.19) | (1.51, 0.07, -1.47) | -0.05875 |
| (2.82, 0.35, 0.95) | (0.08, -1.45, 0.16) | (1.58, 0.14, -1.92) | -0.05125 |
| (2.35, 0.80, 0.27) | (-0.46, -0.31, 0.30) | (1.51, 0.07, -1.47) | -0.05875 |
| (2.82, 0.59, 1.44) | (0.03, -1.31, 0.17) | (1.51, 0.07, -1.47) | -0.05875 |
| (2.43, 0.84, 0.23) | (-0.56, -0.21, 0.34) | (1.58, 0.14, -1.92) | -0.05125 |
| (3.19, 0.65, 2.05) | (0.03, -1.22, 0.17) | (1.58, 0.14, -1.92) | -0.05125 |
plane is used to generate the required acceleration to track the expected ZMP. In the simulation, the stability control uses three accelerations. Producing methods to prevent slip and obtain the desired ZMP can better illustrate the advantages of the proposed acceleration control method. Method I limits the horizontal ground reaction by adjusting the horizontal acceleration. Method 2 adjusts the vertical ground reaction by adjusting the vertical acceleration. Method III, also proposed in this article, applies all forms of motion associated with sliding in the longitudinal plane, including horizontal centroid motion, vertical centroid motion, and rotational motion at the centroid to prevent slippage and produce the desired ZMP. The definitions of these three methods also apply to the experimental part.

When using three methods, Method I, Method II, and Method III to generate acceleration, the real-time sliding indicator factor $\mu_{\text{ast}}$ can be obtained by definition. According to the results shown in Figure 7, several features can be found. The different factors obtained by the different factors are different from the $\mu_{\text{ast}}$ and the friction coefficient $\mu_0$, which also indicates different sliding trends. From the smallest distance between $\mu_{\text{ast}}$ and $\mu_0$, the sliding trend is the strongest. From the maximum distance between $\mu_{\text{ast}}$ and $\mu_0$, the sliding trend is the weakest. For example, the $\mu_{\text{ast}}$ generated by Method III in the figure has the largest distance from $\mu_0$, so Method III has the strongest ability to prevent slip while producing the desired ZMP.

From the perspective of the entire time zone, the root mean square (RMS value) of the $\mu_{\text{ast}}$ value can be used to evaluate the effectiveness of the three methods in the stability control in preventing slippage. The RMS values are listed in Table 5.

If the RMS value is large, it means that the $\mu_{\text{ast}}$ has a large amplitude over the entire time zone, that is to say, the sliding tendency is strong. As can be seen from Table 5, 3.5–5.5 s is the time period for the entire push action and stability control and 4.0–5.5 s is the time period during which stable control is performed. The RMS value over the 4.0–5.5 s period is a better estimate of the effectiveness of each method in preventing slippage. The results in the above table show that the Acceleration Control Method (Method III) proposed in this chapter can better limit the amplitude of the real-time sliding indicator factor, thus reducing the sliding tendency.

**Conclusion**

In this article, the humanoid robot table tennis hitting movement is taken as an example, and research is carried out in the aspects of the task requirements acquisition, the whole body trajectory planning of the hitting movement, and the stability maintenance. A new motion model construction and optimization algorithm based on intelligent learning training is proposed as a mechanism model for the introduction of table tennis in the parameter learning optimization module of the motion model. This article studies the problem of how the motion planning in the table tennis fast-hitting movement meets the requirements of the task and stability at the same time and proposes a stability-optimized humanoid trajectory planning method. The problem of stability control of humanoid robots in balancing or preventing slippage during fast hitting of table tennis is studied. Taking the longitudinal plane as an example, a stable control method considering horizontal, vertical, and rotational motion in the plane is proposed. On the basis of analyzing the influence of horizontal, vertical, and rotational motion on ZMP and real-time sliding indicating factor, by generating acceleration adjustment amount, controlling ZMP and real-time sliding indicating factor does not exceed the expected range, thus preventing humanoid robot from being fast in table tennis. Lose balance or slip in the hitting movement. The proposed task requirements adjustment method, trajectory planning method, and stability control method are experimentally verified on the humanoid robot platform.

In the overall planning method, the problem of planning and control of the swinging legs of the robot is not considered in detail. The problem of planning and control of the supporting leg is the core of this article, and other issues such as the impact of the robot’s other swing leg on the robot during its swing process and the possible collision with the environment during the swing process have not been discussed in detail.
been considered. To this end, we can consider how to combine the swing analysis of the swing leg in the model.

**Declaration of conflicting interests**

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

**Funding**

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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