Dynamics and simulation analysis of table tennis robot based on independent joint control

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Abstract. The purpose of this paper is to prove the accuracy and flexibility of the speed of the table tennis robot when it strikes. The method is to analyze table tennis mechanical simulation based on the control strategy of robot independent joint. Independent control strategy is adopted at first, and PID control principle is also used to design and analyze the control system of table tennis robot and mechanical-control co-simulation system. In addition, the virtual scene is simulated when two robots are playing. Finally, performance index of robots is evaluated and optimized to confirm proper parameter of sample robot design and provide theory instructions for the developing and producing of table tennis robot. According to control demands of servo motor, the three loop control system of table tennis is established. The experimental results show that the co-simulation and control system of table tennis prove its correctness. Based on the above finding, it is concluded that the mechanical parameters of hybrid robot can be optimized. Meanwhile, simulation and analyses in the study of table tennis robot based on the control system of independent joint control strategy play an important part in developing and producing hybrid robot 3 robot programming system (RPS) + robot programming (RP).

Key words. Table tennis robot, PID control system, mechanical simulation, control strategy of independent joint.

1. Introduction

1.1. Description of the problem

Robot is one of the important inventions in the 20 century. Table tennis robot is of wide interest and also a universal technology platform combining machinery, vision, control and other disciplines [1]. In terms of technology, crucial technology in table tennis can directly radiate to all kinds of related fields; in terms of teaching, to develop robots which can play table tennis with people or play with each other is useful for activating students' passion and enthusiasm for exploring scientific knowledge; In terms of recreation and sports, table tennis robot can be used in such fields

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as entertainment, exercise, partner training, competition, which can enrich people's free time and help them build body health [2–3]. Thus, the research of table tennis is important in the filed of intelligent robot research.

1.2. State of the art

Scholars both at home and abroad have made many researches about table tennis robot. Table tennis robot shows rapid development in advanced countries, while China began to do researches about it in a relatively late time. Some scholars make deep researches on vision prediction and servo control system of table tennis [4]. There are some studies on visual tracking, trajectory prediction and control technology. Studies on the trajectory prediction of table tennis are carried out [5].

A great deal of mechanical simulations are made at home and abroad. Some simulation researches on decomposition control of arm accelerating speed of table tennis robot are analyzed [6]. Experts make researches on robust control of operation arm of table tennis with anti flexible joint [7]. In the robot industry in the 21 century, there is trend that product design is completed with the help of computer simulation [8]. As lots of practical experiments are carried out after the bases of a series of virtual simulation experiments, which improve the efficiency and reduce risks and costs, thus design defects of the product are dealt with in time before the shaping of physical objects [9–10]. It also goes to the mechanical simulation of table tennis simulation. The study on mechanical simulation offer important instructions for the developing and producing of real simple machine. For reasons above, table tennis robot is chosen as the experiment platform in the study for simulation and analyses to design and simulate the mechanical system and control system of table tennis robot.

2. Materials and methods

Dynamics of table tennis robot is analyzed and dynamic model for hybrid robot 3-RPS+RP and 6R serial robot is established before the research, and the trajectory of its striking ball is programmed; next, the dynamic model is proven accurate by theory calculation and mutual simulation, which lay a foundation for the simulation in the environment of striking balls of table tennis and its control system.

2.1. The control system of table tennis robot

Hybrid robot 3-RPS+RP is the study is controlled by PID control with single joint, whose body is connected by parallel mechanism and serial branches. Robot control is realized by driving joint of the motor, and the AC servo motor control model is used to drive the joints of table tennis robot. Compared with DC servo motor, there are many advantages of AC servo motor: it has no brush and commutator which ensures reliable operation and low demands for maintenance; the heat dissipation of the stator winding is more convenient; it has small inertia, which is easier to improve the speed of the system; it has relatively small volume and weight in the

same power [11]. The servo motor adopts the traditional PID controller, which is of good stability, simple procedure for parameter setting and excellent robustness. PID control principle [12] is a reasonable algorithm based on imprecise model and system information estimation. The principle of PID control system is shown in Fig. 1.
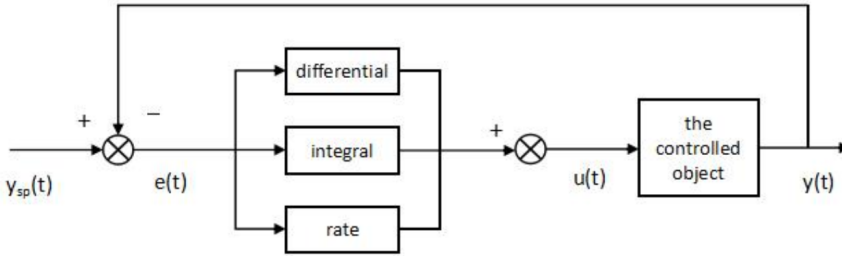

Fig. 1. Principle of PID control system

System shown in Figure 1 mainly consists of PID controller and the controlled device. It composes control deviations according theoretical preset value and actual output value, and make up correspondent control portfolio u(t) with deviations composed in different combination forms of PID.

AC servo control system of joint control of the robot often uses frequency converter as the driver of the motor, and it is composed of three closed loop control system, namely, position loop, speed loop and current loop [13]. The function of current loop is to adjust current to maintain constant output of torque, refrain current deviation and improve the performance of the system by enhancing the stability of current; the function of speed loop is to refrain load disturbance and velocity perturbation and effectively overcome dynamic errors and shorten adjustment time; the function of position loop is to ensure the system can position and follow in a correct way. The control principal and structure model of AC servo motor with three closed loops is shown in Fig. 2.
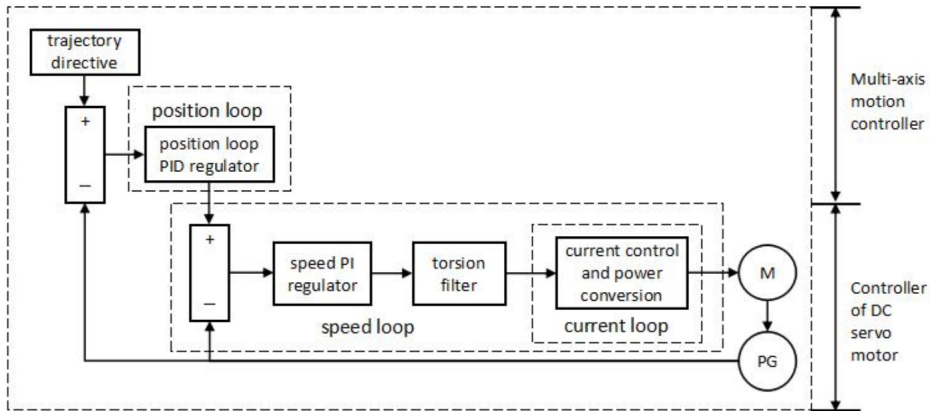

Fig. 2. Control model of AC servo motor with three closed loops

2.2. *Mechanical-control co-simulation system of table tennis*

As far as the mechanical-control co-simulation system of table tennis is concerned, the position and speed control co-simulation based on kinematics and control co-simulation with dynamics as the basic force are introduced in the study. The principle of he position and speed control co-simulation based on kinematics is to develop robot kinematics inverse solution and obtain joint potion and information about speed, and to transform position information into information about joint driving torque through control system so as to drive the robot [14]. Information about force or torque between motor shaft, moving and rotating shaft is transferred by connecting ball screw, coupling and the robot. At this time, input and output of robot co-simulation system reflects robot kinematics relation. Its model is shown in Figs. 3 and 4.
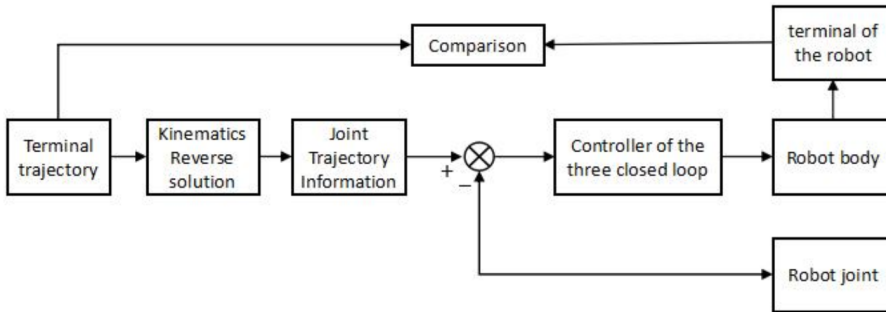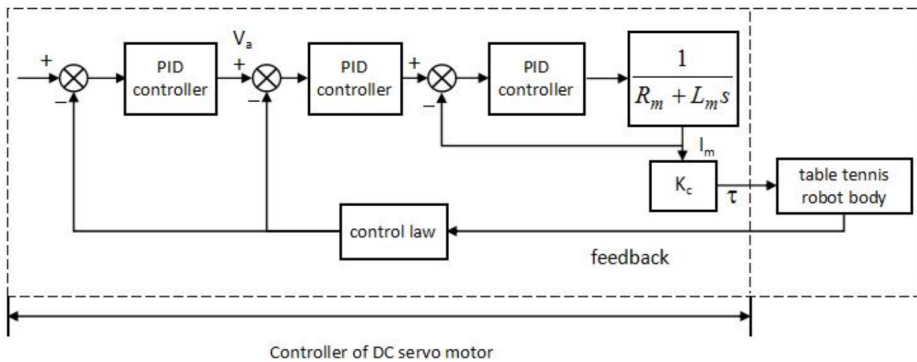
Fig. 3. Model of co-simulation system

Fig. 4. Driving model of AC servo motor

The principle of control and co-simulation system based on kinematics. The principle of the control co-simulation with dynamics as the basic force is to develop inverse resolution through terminal position information by using robot dynamics so as to get information about joint force and torque, and then to connect each joint of

the robot through joint driving force and torque parameters after the output of the control system so as to drive the robot. At this time, co-simulation system of input and output robot reflects its dynamic relation. Its principle of the control system is shown in Fig. 5.
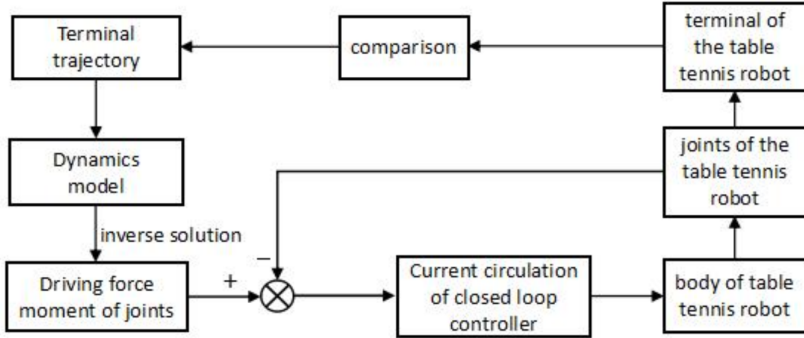

Fig. 5. Principle of dynamic control co-simulation system

What is shown in Fig. 5 is the co-simulation model of robot with semi-closed loop. The features of table tennis robot are combined in the study. Terminal trajectory of the robot is received after developing inverse resolution to obtain joint information and controlling the robot through control principal of joint closed loop based on the tracking what has been programmed. Comparative analyses are made, in the following, between the terminal trajectory and programmed trajectory so as to commend on motion characteristics of the robot.

3. Experimental results and discussion

3.1. Virtual simulation environment when two table tennis robots are playing

The virtual simulation environment mainly concludes robot body, serial 6R robot and hybrid robot 3-RPS+RP; the environment of two robots are playing with each other includes striking balls trajectory of robots, motion and collision model of table tennis; virtual control system of the robot, Paul three-loop servo control system, is set. Focus on the study is scenes simulation which requires bodies of the playing table tennis robot, sticking ball environment for the playing robots and its controller.

Virtual scene where two robots are playing can be established. The environment for double play is closely related with the motion model of the robot and table tennis. The stress state of the table tennis may affect the speed and accuracy of the robot's striking on balls. Terminal position of the mechanical arm is developed to joints by inverse resolution to simulate robots playing. Effects on the robot made by elements in striking ball environment are [15]: pat speed, pat position, direction the pat surface faces when it touch the ball and different trajectories of striking ball. In a word, the motion of the table tennis robot decides the motion of the ball,

and moving features of the ball affects the motion of table tennis robot. Mechanic-control co-simulation model of table tennis robot is shown in Fig. 6, and results of simulation model is shown in Fig. 6 and 7.
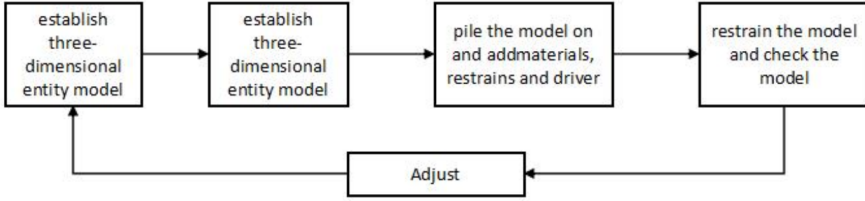

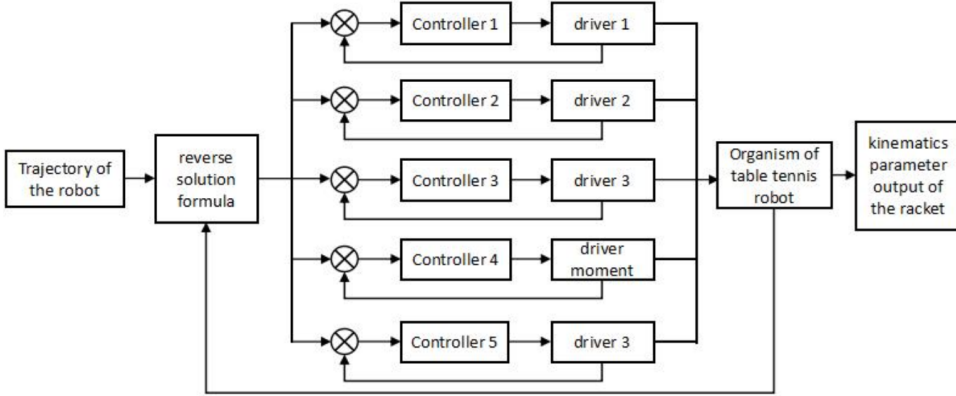Fig. 6. Flow chart of the establishment of mechanical model

Fig. 7. Simulation system model

3.2. Evaluation and optimization of performance of the table tennis robot

Mechanical performance index is the important element to evaluate robot. Different indexes serve for evaluating robots with different tasks, which reflect the performance of robots. Table tennis robot with the task to striking on balls is evaluated from the perspective of spatial coincidence degree, speed response characteristics and speed stability. Spatial coincidence degree stands for the coincidence rate of working space the robot needs in practice and the design requires for, namely, volume percentage. The design demand for space when hybrid robot works and realizing parameters are shown in Table 1.

When there is no pose motion at the end of the robot, the working space is a cylinder, but the actual working space is bigger than a cylinder. It is concluded through calculation that space coincidence rate of table tennis robot is far over 1, meeting the working space requirement.

Velocity response characteristic stands for the speed of striking balls at the end of

the robot and acceleration characteristic when the robot is striking balls. The speed parameters the robot strikes the ball are shown in Table 2. The characteristic is that the results of accelerate speed of terminal of the robot show its overall non-smooth skipping and the skipping range of the second half is particularly large, thus it needs to be optimized.

Table 1. Test results of insulated resistance value (kΩ)

Design area	Up and down working field (mm)	Horizontal working area (mm)	Longitudinal work area (mm)
Estimated parameters	±250	1600	450
Realization method	Telescopic rod rotation	Telescopic rod circle rotation	Telescopic rod moving

Table 2. Speed parameters of striking balls

Environmental parameters	Full speed (m/s)	Rotation speed (r/s)	Maximum deformation (%)
Ball	0∼27	0∼172	27
Ball pat	5∼12	/	seldom

ADA MS/Vibration vibration analysis module is adopted to analyze vibration in the study. When the response of the shock excitation is close to $2.5\,$Hz, the result of frequency response shows that the frequency where there is maximum acceleration response is near $2.7\,$Hz to $32.9\,$Hz and resonance can be avoided.

Works about the optimization of the table tennis robot are carried about from two aspects, namely, control and machinery. In terms of the control, parameters of the controller is regulated, control performance is improved and control evaluation index is stepped up, thus enhancing speed response characteristics of the robot; As for machinery, from the aspect of decreasing inertia, light materials meeting striking ball tasks are chosen to reduce inertia of mechanical system; linear motor driver is selected which means inertia of ball screw is ignored, and dynamics equation is simplified, thus making the robot more flexible. The diagram of optimization process is shown in Fig. 8.

Tests are carried out on the optimized robot. It can be found that its speed steps up, the acceleration stability is better than before and its stability improves too. And meanwhile, the impact force in the experiment produced by the ball and ball pat in the striking ball scene is $80.7493\,$N, which is about $102\,$N in practice coinciding with the actual impacting environment. Finally, some relatively ideal mechanical data about the robot is shown in Table 3.
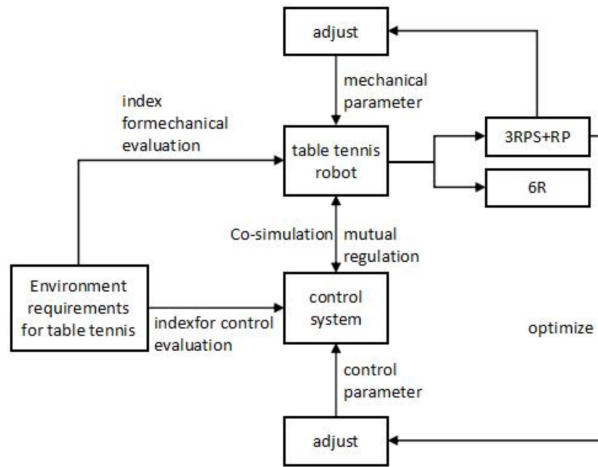
Fig. 8. Diagram of optimization process

Table 3. Parameters of mechanical system

Component name	Size (mm)	Component name	Size (mm)
Rectangular base	510×357×102 (L×D×H)	Elbow	Diameter: 62, Turning diameter: 306
Cylinder base support	Length:620, diameter:62	Double racket	Diameter: 153, thickness: 10
Fixed platform	Diameter: 410	Racket	Length: 367
Moving platform	Diameter: 305	Swigging are of the serial branch	46×46×470
Upper branch	Diameter: 34, length:494	Screw of the paralleling branch	Lead: Ph=15, Nominal diameter: $d0 = 15$, the distance is 400
Lower branch	Diameter: 56, length: 530	Swinging arm screw shaft of the serial branch	Lead: $Ph = 12$, Nominal diameter: $d0 = 8$, the distance is 400

4. Conclusion

The control system and mechanical-control co-simulation system of table tennis robot are studied. The performance of it when two robots are playing in the virtual simulation environment is evaluated and optimized. It is concluded, finally, that, three-loop control system of the robot is established according to the control demand of servo motor, and that co-simulation model of hybrid robot is created, which mean

mechanical-control simulation system is realized and it is feasible; simulation environment of double play between robots is created, methodologies for the evaluation and optimization for the whole system is put forward. In addition, hybrid robot with five degrees of freedom is optimized and relatively ideal parameters for the system are known, which lay a good theoretical foundation for the control system of the table tennis and its producing.

However, there are some limitations in the study due to limited experiment time and equipment. The further research will be carried out from the following two aspects: the mechanical-control co-simulation for the robot can be made in the way of adopting the driving combining linear motor and rotating servo motor. Furthermore, comparative analyses will be made between it and response from the robot driven by rotating servo motor. Through appropriately simplifying its dynamic equation, real-time control system with feedback closed loop is realized after the mechanical-control co-simulation.

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