Industrial Robot Digital Twin System Motion Simulation and Collision Detection

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***Abstract*—The research on the motion simulation and collision detection technology of industrial robot is of great significance to the application of robot. Based on the fusion of physical entity and virtual system of digital twin technology, this paper studies the robot motion simulation, and realizes an industrial robot virtual motion simulation system with high openness, good visualization effect and high collision detection accuracy.The main work and contribution of this paper is to propose a four-dimensional architecture of industrial robot digital twin system, and constructs a virtual system corresponding to a physical robot entity by using Unity3D. Based on the research of motion simulation technology and investigation on collision detection technology in virtual environment, an improved hybrid hierarchical bounding box collision detection algorithm is proposed, which improves the accuracy of collision detection. Finally,an industrial robot prototype system is developed to verify the feasibility and effectiveness of the proposed system.**

***Index Terms*—industrial robot, digital twin, four-dimensional architecture, motion simulation, collision detection**

I. INTRODUCTION

Industrial robot is a very representative equipment in the field of intelligent manufacturing. It is of great significance to study the robot motion simulation technology.On the one hand, the robot's teaching and trajectory planning are completed in the simulation system, and the planned trajectory is run for trial to check the correctness and safety of the trajectory, so as to avoid collision in the actual operation, reduce losses, and save manpower, material resources and costs. On the other hand, it provides an open platform for scientific research and teaching staff, which can promote the design of robot control methods and daily teaching and training.At present, the commercial robot simulation platform has the problems of low degree of openness and strong restrictions. The high price also limits the use and promotion of the simulation platform. However, some other simulation platforms have problems such as low visualization, low accuracy of collision detection and low reliability. Therefore, it is necessary to study the robot simulation technology.

The development of digital twin technology provides a new idea for robot motion simulation.Digital twin,as a technology of integrating multi-physics,multi-scale and multidisciplinary attributes,characterized by real-time synchronization,faithful mapping and high fidelity,could realize interaction and integration between physical space and virtual world [1].In recent years, the concept of digital twin has been gradually integrated into the manufacturing industry [2]. By constructing digital twin, the faithful mapping to the physical world can be realized in the virtual environment, so as to realize virtual debugging, operation monitoring and intelligent decision-making of the physical world.

Schluse and Rossmann proposed a simulation method using digital twin for virtual debugging [3], which integrates different simulation systems in the Versatile Simulation Database (VSD) for virtual debugging.This method is called experimentable digital twin.Grinshpun et al proposed an algorithm to guide the robot to insert the peg into the hole [4], which could fit the peg and hole with a very small clearances, and constructed the digital twin. The simulation in the virtual environment verified the effectiveness of the algorithm, and applied the algorithm to the physical Kuka LWR4 manipulator.Slavkovic et al. used digital twin technology to compensate the robot trajectory [5], developed a virtual robot machining model, and simulated the trajectory compensation algorithm in the virtual model to improve the machining accuracy of the robot in the actual working process.

Digital twin is also applied to the simulation of human-robot collaborative scenarios.Bilberg and Malik built a digital twin of the flexible assembly cell [6], which realized the simulation of the human-robot collaborative assembly process, and assigned tasks and balanced workload according to the

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difficulty of tasks.Brem et al. proposed a digital twin model for human-robot collaborative production system [7].During the commissioning phase, potential errors can be detected through virtual commissioning or hardware-in-the-loop simulation to reduce development time.

In this paper, combined with digital twin, the motion simulation technology of industrial robot is studied, aiming to develop a motion simulation system, and propose an improved hybrid hierarchical bounding box collision detection algorithm, which has the advantages of high openness, good visualization effect, high collision detection accuracy, and monitoring function.

The remainder of the paper is organized as follows: the second section elaborates the architecture of digital twin system and constructs the virtual space corresponding to the physical space. In the third section, the framework of motion simulation system of industrial robot based on digital twin is discussed. The fourth section introduces the experimental test. The fifth section summarizes the whole paper and looks forward to the future work.

II. Design of Digital Twin System

A. Four-dimensional architecture of digital twin system

Referring to the digital twin model proposed by Tao Fei et al. [8], the architecture of the digital twin simulation system proposed in this paper is shown in Fig. 1,which includes four parts: physical entity, virtual system, connection and application service.

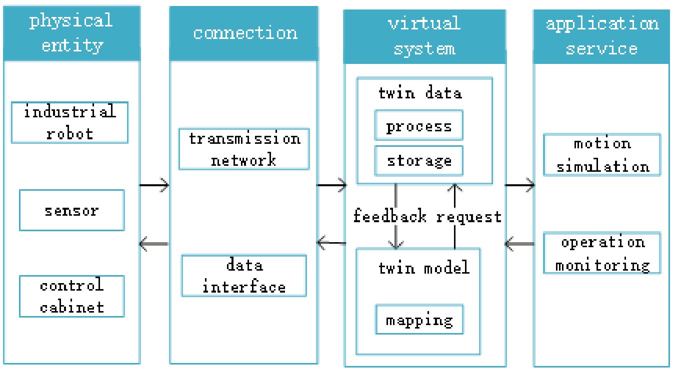


Fig. 1. Four-dimensional architecture of digital twin system.

1)Physical entity.Physical entity refers to the environment of the production site, including a variety of equipment, such as industrial robot body, control cabinet and sensors, etc., through their cooperation to achieve production activities. Physical entity is the basis of digital twin systems.

2)Virtual System.Virtual system is a faithful mapping of physical entity. The virtual system is divided into twin data and twin model. Twin model is a true portrayal of the characteristics of physical entity, including location, geometric size, material, color and so on, as well as the subordination and kinematic characteristics of entity. Twin data comes from physical entity, which is processed and stored as data sources to drive twin model.

3)Connection.Connection is the bridge between the physical entity and the virtual system, that is, through the transmission network and the definition of data interface, to realize the two-way data transfer between the physical entity and the virtual system, so that the data flow between each other.

4)Application service.Application service refers to the functions provided by the digital twin system, including motion simulation and operation monitoring.The motion simulation function allows users to complete the teaching and path planning in the virtual environment, simulate the path, and use the collision detection algorithm to find the collision points in the path in advance. The planning results are output to the robot controller, and then the robot entity is controlled to move according to the planned path. The operation monitoring function realizes the omni-directional and multi-data monitoring of the running state of the robot.

B. Composition of physical entity

Physical entity is an important part of digital twin system, which is the foundation of virtual system. The physical entity in this paper includes mechanical system, electronic control system and man-machine interaction system.

1)Mechanical system.Mechanical system refers to the mechanical body. The robot used in this paper is EFORT ER20C-C10 robot, including six rotating joints.

2)Electronic control system.The electronic control system includes servo driver, control system, communication cable and sensor.

3)Man-machine interaction system. The man-machine interaction system includes the teaching device and the upper computer interface.

C. The design of virtual system

The design of the virtual system follows the following three principles:

1) Hierarchical consistency.The physical entity is complex and has a certain level, so attention should be paid to the subordinate relationship between the components. As a characteristic of the physical entity, it should be described in the virtual environment to realize the faithful mapping of the physical entity.

2) Behavioral consistency.The motion of the industrial robot model should be consistent with that of the robot entity, such as the axis of rotation, direction of rotation, angle of rotation, etc., and the law of motion should be followed. Behavioral consistency is an important part of implementing loyalty mapping.

3) Performance balance.model rendering will take up a lot of computer memory space, which may affect the smooth operation of the system. Therefore, the system performance should be considered in a balanced way, and the model should be lightweight to ensure the smooth operation of the system without affecting the user's visual experience.

According to the above three design principles, Unity3D is selected as the development platform of the virtual system to build the virtual environment.The 3D environment is shown in Fig. 2.

Fig. 2. The 3D environment.

III. Realization of Motion Simulation Function

The virtual environment constructed by digital twin system is used to study the motion simulation of industrial robot, realize the motion simulation function, and design a collision detection algorithm to detect the collision in the simulation process.

A. Path planning

The trajectory planning process of robot involves solving forward and inverse kinematics. First, the D-H model of the robot was established to obtain the D-H parameters. The homogeneous transformation matrix of joint i of the robot relative to joint i -1 is:

$$T=\begin{pmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -s\alpha_{i-1}d_i \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & c\alpha_{i-1}d_i \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{1}$$

According to equation (1) and D-H parameters, the homogeneous transformation matrix of adjacent links can be obtained successively. Then the transformation matrix of the robot terminal relative to the base coordinate system is:

$$T=\begin{pmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{2}$$

Solve the forward kinematics of the robot according to equation (2) . The last three axes of the robot in this paper intersect. According to Piper criterion, the inverse kinematics problem can be solved.

Based on the forward and inverse kinematics, the trajectory planning algorithm is completed. The simulation system proposed in this paper can realize joint space trajectory planning, linear planning and circular planning.

B. Collision detection in virtual system

Unity3D has some collision detection functions based on bounding boxes, which can detect the collision between models.However, the built-in colliders are all implemented with a single bounding box, which does not have the structure of hierarchical tree and can not detect objects more accurately at the level of triangular primitives.

Therefore, based on Unity3D's own collider, this paper proposes an improved hybrid hierarchical bounding box collision detection algorithm, which combines Unity3D's built-in collider and AABB's hierarchical bounding box. The algorithm flow is shown in Fig. 3. Firstly, the Unity3D built-in Box Collider is used for preliminary detection. For the model with collision detection, AABB hierarchical bounding box tree is established for further detection. Traverse the tree structure to determine whether the root node and the leaf node intersect. If they intersect, enter the accurate detection stage, and detect the intersection of the leaf node at the triangle level. The proposed algorithm makes up for the lack of hierarchical tree structure of Unity3D built-in collider, realizes triangle level collision detection, and improves the accuracy to a certain extent.

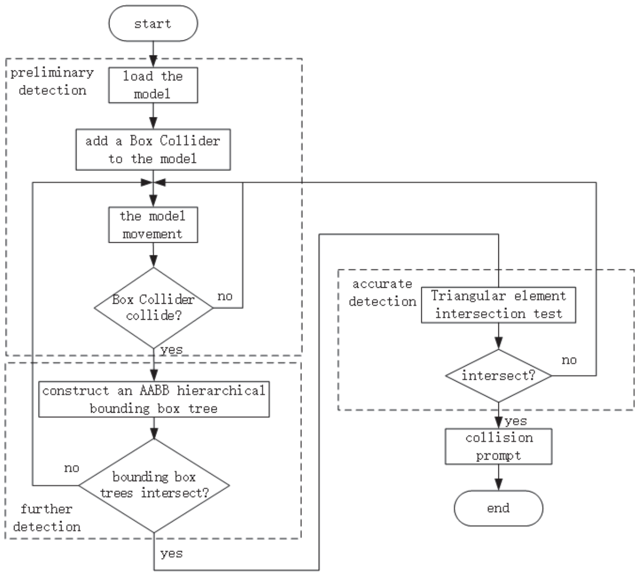


Fig. 3. Algorithm flow chart.

IV. Real Time Monitoring Function Based on Simulation Environment

In the previous paper, in order to realize the function of motion simulation, the robot virtual model and virtual environment are constructed. Based on the virtual model, the state data of the robot is transmitted to the virtual model, and the robot entity is monitored by three-dimensional visualization. The system block diagram is shown in Fig. 4.

The perception layer is used for data acquisition and transmission. The data layer parses and processes the data from the perception layer. The logic layer realizes the interaction between the data layer and the application layer. The application layer is the monitoring interface that the user sees.

V. Experiment

The motion simulation function and collision detection function are tested.Trajectory planning methods include joint space planning, linear planning, circular planning and combination planning. The trajectory planning effect is shown in Fig. 5. It can be seen that the system can correctly call the trajectory planning algorithm and visually display the motion trajectory.

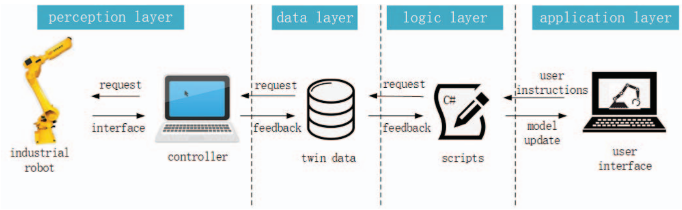
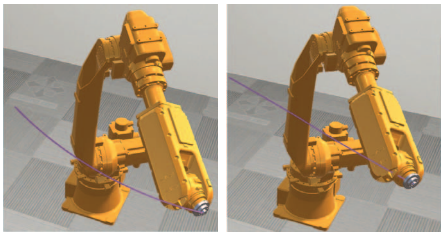
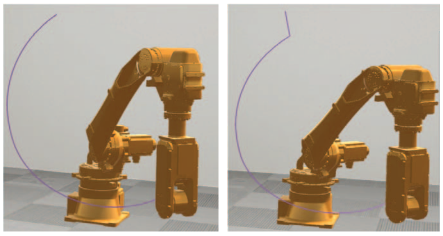


Fig. 4. Block diagram of monitoring system.



(a) Joint space planning (b) Linear planning

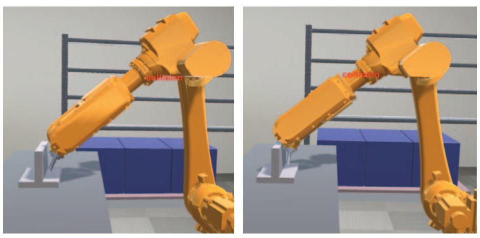


(c) Circular planning (d) Combination planning

Fig. 5. Trajectory planning results.

The collision detection function in the virtual environment is tested, and the detection results are shown in Fig. 6. The results show that compared with the built-in Box Collider of Unity3D, the improved hybrid hierarchical bounding box collision detection algorithm can detect collision more accurately.

The virtual model of the digital twin system is used to simulate the movement of the robot entity. The simulation results are used to check the correctness and safety of the path in advance. The simulation results can be used for the actual operation of the robot.



(a) Box Collider in Unity3D (b) The algorithm in this paper

Fig. 6. Collision detection

VI. Conclusion

In this paper, a digital twin system is built to simulate the behavior of physical entity by creating a virtual model of physical entity. The main contributions of this paper are as follows :(1) The four-dimensional architecture of digital twin system is proposed and the digital twin system is built. According to the existing physical entity in the laboratory, the structure, behavior and attributes of the entity unit are abstracted, and the digital twin is established by using Unity3D. (2) The kinematics modeling and trajectory planning analysis of EFORT industrial robot are carried out. The kinematics algorithm is developed separately from the virtual system, which improves the expansibility of the system. Aiming at the limitation of the lack of hierarchical tree structure of Unity3D built-in collider, an improved hybrid hierarchical bounding box collision detection algorithm is proposed to improve the accuracy of collision detection and reduce the false detection.On this basis, we will further study the deep fusion technology of physical entity and virtual system, and carry out data analysis and mining, in order to realize more intelligent functions such as online optimization and fault prediction of robot.

Acknowledgment

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