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Development of Multi-function Underwater Inspection Robot Digital Twin System for Nuclear Power Plant

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Abstract

Multi-functional underwater inspection robots in nuclear power plants face challenges such as high radiation doses, deep water refraction, and complex unstructured environments when performing missions in nuclear reactor pools. These factors lead to inaccurate pose observation and poor probe position sensing ability during the working process of the robot. To solve the above problems, the digital twin system of the multifunctional underwater detection robot for nuclear power station is developed through the digital twin technology architecture. The system can not only realize the conventional control operation of the robot, but also twin the robot body. Through establishing the data twin correspondence between the physical entity of the robot and the virtual model, the accurate control of the motion position and pose state of the robot mechanical arm is realized, and the motion position and pose state of the robot mechanical arm are also visualized, so that the operator can directly observe the real-time position and pose of the robot mechanical arm on the computer screen, and the robot can safely and reliably carry out the foreign matter search and recovery and NDT tasks in the pool and core environment of the nuclear reactor, so as to ensure the safe and smooth operation of the nuclear power plant.

Keywords

Digital Twin; Inspection Robot; Mechanical Control.

1. Introduction

In recent years, the development of advanced manufacturing industry has become the general direction of global manufacturing development, and the development direction of advanced manufacturing industry is moving towards digitalization and intelligence [1]. With the development of advanced manufacturing industry, digital twin technology [2,3] has become a general technology of advanced manufacturing industry, and it is also an important technology to promote the intelligence and digitalization of advanced manufacturing industry. In view of the fact that the multifunction underwater inspection robot of nuclear power plant is affected by the complex unstructured environment such as deep-water refraction in the nuclear reactor pool. There are some problems in the work of robot, such as poor real-time pose determination and pose accuracy, uncertainty of real-time motion state parameters of robot and poor position perception ability of inspection probe. Digital twin technology can realize virtual reality mutual control, virtual reality synchronization and accurate mapping to observe the working state of objects in real time, which assist the robot to better complete the task.

Digital twins create virtual models of physical entities in the information space through digitalization, and use data to simulate the behavior of physical entities in the real environment [4]. Through information fusion and data interaction between virtual models and physical entities, which provide more optimized decisions and risk estimates for physical entities [5]. The digital twin model is a five-dimensional structure model [6] and composed of five parts: physical entity, virtual model, twin data,

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service system and mutual connection. In this paper, through the study of the digital twin standard system, and combined with the working environment and its own structural and functional characteristics of the multifunctional underwater inspection robot. A research scheme is proposed. The proposal of this research scheme can realize the multifunctional underwater inspection robot elements in the twin space to complete the foreign body location, search and salvage and non-destructive testing operations in real time.

Building the system architecture of digital twin inspection robot [7,8], carry out virtual entity modeling, information fusion between virtual entities and physical entities. Finally, the digital twin control system is developed [9]. It provides virtual physics for tasks such as foreign object search, salvage and nondestructive testing of multifunctional underwater inspection robot and constructs the relationship between physical entities and virtual models. Thus, completing the application and expression process of digital twins. The entity inspection robot can complete a series of operation instructions in full real-time and information process underwater, which makes the digital twin control system optimize the entity function of the multifunctional underwater inspection robot to a large extent.

2. Architecture of Digital Twin Robot Development System

The nuclear power plant multifunction underwater inspection robot (hereinafter referred to as robot) can be divided into three parts: control system hardware, control system software and robot physical entities. The hardware part of the control system mainly includes the hardware integration of the information system subsystems such as the upper computer, nondestructive testing (NDT) system, data acquisition system, control command interaction system, video acquisition system, etc. The hardware part of the control system is the physical entity part included in the digital twin, and is the key component of the twin robot in the process of realizing digital twin, It provides a precondition for the twin robot to obtain data sources and transmit data. The nuclear power plant multifunction underwater inspection robot (hereinafter referred to as robot) can be divided into three parts: control system hardware, control system software and robot physical entities.

The hardware part of the control system mainly includes the hardware integration of the information system subsystems such as the upper computer, NDT system, data acquisition system, control command interaction system, video acquisition system, etc. The hardware part of the control system is the physical entity part included in the digital twin, and is the key component of the twin robot in the process of realizing digital twin. It provides a precondition for the twin robot to obtain data sources and transmit data. The control system software includes ordinary control system and digital twin system. With the help of Visual C #, Unity3D, SolidWorks, 3d Max and other software tools, the development and application of control system software are realized. Visual C # and Unity3D software are respectively responsible for compiling background scripts and realizing the performance and functions of digital twins. SolidWorks and 3d Max software have respectively completed the physical modeling and preliminary rendering of digital twins.

The functions of the two types of hardware and software systems are combined through connection and integration to complete the integration of the hardware and software parts of the digital twins, and further realize the storage, processing and application of the twin data. The physical entity of the robot, including the externally visible main camera, auxiliary camera, wheeled mobile platform, manipulator and NDT probe not clamped at the end of the manipulator, as well as DC servo motor, reducer, encoder, DC motor driver, lighting and other components which are not involved but in the waterproof device. Digital twin virtual entities include twin models of all connected physical entities. Twin data mainly includes data storage, data mining, data cleaning, data computing, etc. The service system mainly includes operation decision-making, planning and dispatching, command and control, equipment operation and maintenance, environmental monitoring, etc. In this paper, the architecture of digital twin robot is designed for the virtual digital twin related functions that the robot needs to realize [10]. As shown in Figure 1.

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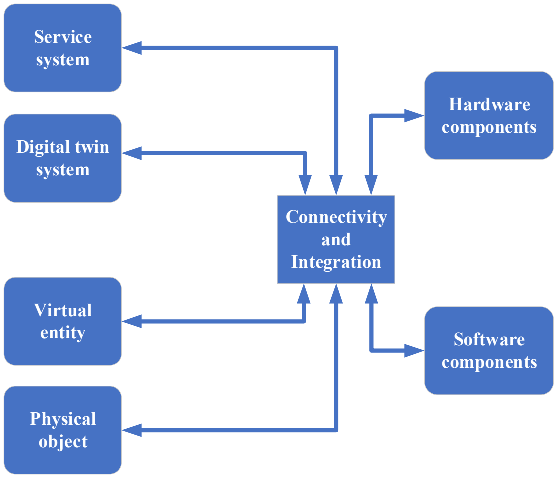

Figure 1. Architecture of digital twin robot

3. Construction of Digital Twin Robot System

3.1 Construction of Virtual Model

The virtual physical entity elements of the digital twin robot mainly include a four-DOF manipulator, a wheeled mobile platform, a main camera, an auxiliary camera, and a bottom box structure supporting the waterproof design. According to the digital twin standard model, virtual entity function settings should include: geometric function settings, physical function settings, behavior function settings, capability descriptions, etc. Geometric function is the real mapping between virtual entity and physical entity of digital twin robot, which is the most direct embodiment of physical entity; All types of models shall first ensure their three-dimensional space size, and the three-dimensional physical structure of each subsystem shall be highly consistent with the physical entity. And it is expected that the digital twin model has the characteristics of high fidelity, high reliability and high precision, and can truly depict the physical world.

The physical functional model describes the physical characteristics of physical entities, such as object morphology (external physical characteristics of twins such as four-DOF manipulator and wheeled mobile platform), and physical characteristics of specific forms, such as motion sensitivity, water resistance, vibration and stability of the overall structure. This is the mechanism modeling of physical entities. The behavioral functional model describes the specific functional behavior of physical entities, including: the behavior of objects evolving with time, the dynamic functional behavior of objects, and the functional fading behavior of objects. For example, in the pool and core environment of nuclear reactor, the behavior of the robot moving and wearing itself for a long time, and the behavior of the machine body being corroded by liquid in the pool for a long time, etc. Capability description is a general description of the above three behavioral characteristics of physical entities, facilitating the management and use of models.

According to the external physical characteristics of the overall structure of the robot, the 3D modeling tool SolidWorks is used to design and construct the model. The entities such as the four-DOF manipulator, the wheeled mobile platform, the main camera, the auxiliary camera, and the bottom box structure supporting the waterproof design are mainly modeled, as shown in Figure 2. Since the external structure of the robot is relatively specific, the modeling effort is not large. In order to balance the project quality and development schedule, during the solid geometric dimension mapping, the actual mapping and the combination of each solid component design drawings, overall structure assembly drawings, installation layout drawings and other methods are used to model. The physical properties are rendered in three dimensions through material and property display.

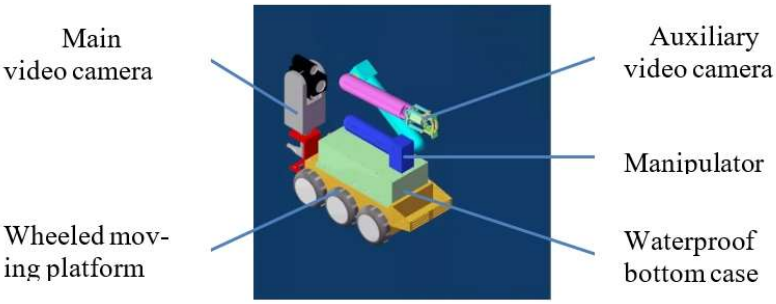

Figure 2. Structure diagram of digital twin robot

3.2 Access to Physical Entities

The physical entity is the object and data source of the digital twin robot, which is mainly divided into three functions: perception access, decision execution, and edge computing [11]. The perception access achieves the effect of foreign body search, salvage and nondestructive testing according to a series of action instructions that the entity needs to complete. At present, the robot has been equipped with hardware information systems such as non-destructive testing system, data instruction interactive system, control instruction interactive system and video acquisition system. At present, the robot has been equipped with hardware information systems such as nondestructive testing system, data command interaction system, control command interaction system and video acquisition system. The hardware parts involved in the subsystems of these hardware information systems are almost all integrated in the control cabinet. The control cabinet system is shown in Figure 3. Therefore, robot entity access is realized in digital twin connection and integration. By integrating with the robot control cabinet system, the basic state perception of robot entities can be realized, such as running state, angle conversion, moving speed, grasping posture and other information.

The multifunctional inspection robot will generate a lot of data in the process of operation. These data come from multiple modules of the robot. After integrating these data, the robot can perform edge computing and decision-making in real time, and accurately transmit them to the virtual monitoring platform to achieve the effect of the robot's real-time and accurate foreign object search and salvage and nondestructive inspection. The accuracy of physical entity access is the basis for the complete and correct mapping between the real world and the virtual world. The real-time property of data mapping is an important indicator of the monitoring system and the basis for ensuring the stable operation of the monitoring system.

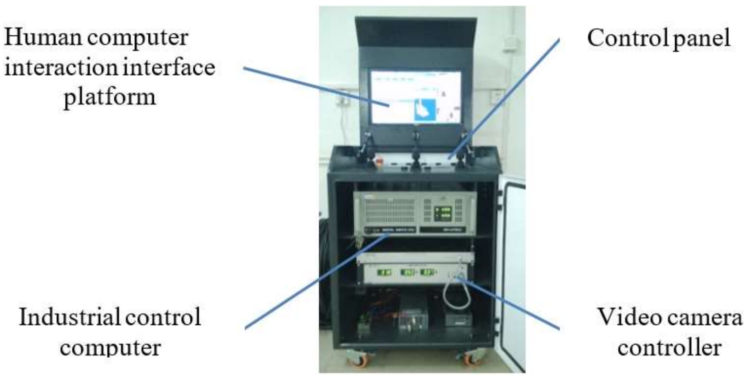

Figure 3. Control cabinet system of multifunctional inspection robot

3.3 3D Visualization Platform

The 3D visualization platform is the user UI part of the digital twin robot and the platform for providing services for users. The UI interface of the digital twin robot is shown in Figure 4. It has formed many system functions, such as multi scene management, system configuration, user management, etc., which facilitate the daily maintenance and management of the twin system by operators. ring system.

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Figure 4. UI interface of digital twin multifunctional inspection robot

The biggest feature of the system is that it completely stands on the user's point of view and designs the interaction mode according to the user's usage habits. For example, the rotation angle and movement speed of the elbow joint and wrist joint of the digital twin robot manipulator can be set, and the end of the arm can clamp and place the NDT probe; The control of the forward vector of the twin robot's left and right wheels, and the real-time monitoring of the whole search and salvage and NDT process by the main and auxiliary cameras. The above series of operations can be carried out on the 3D visualization platform through the mouse to complete the foreign object search, salvage and NDT operations and present them in the virtual scene. After adapting to the virtual environment, the goal of search, salvage and NDT operation is realized through the 3D visualization platform with the robot twin.

4. System Development and Application

In order to better realize the design goal of underwater foreign body search and nondestructive testing of digital twin robot, based on the system architecture of digital twin robot, it is necessary to further design and explain its specific development and application. In view of the model construction, through the actual design and measurement of the overall model of the structural components of the relevant dimensions, further application of SolidWorks 3D modeling tools for virtual entity 1:1 modeling related dimensions; After the modeling is completed, the external rendering and format conversion of the model are carried out by 3d Max software. After completing the model modeling and rendering, the model was imported into Unity3D to realize the preliminary construction of the virtual model.

Under the hardware support of the host computer, non-destructive testing system, data acquisition system, control instruction interaction system, video acquisition system and other information systems, Visual C# software is also needed to encode the C# language background script and apply it to the virtual model preliminarily constructed in Unity3D software. Through the connection and concentration of the hardware part and the software part, the digital twin function of the multifunction inspection robot is realized by giving the twin specific functions and characteristics. At the same time, in order to facilitate the daily maintenance and management of the twin system, the C# language is used to create a 3D visualization platform controlled by the twin system based on the Visual C# software platform, as shown in Figure 5.

Figure 5. 3D visualization platform

5. Conclusion

This paper studies the digital twin development process of the robot. Combined with the problems that the robot cannot accurately observe the pose and the detection probe has poor sensing ability, the digital twin system development architecture of the robot is designed, and the key design and development application details of the system are described in detail in the physical entity, virtual entity, twin data, service, connection and integration. Through the development of the digital twin system of the robot, the information sensing ability of the robot to the underwater work site is further improved, and at the same time, the operation function and working performance of the robot are also upgraded, the efficiency and accuracy of the robot in foreign matter searching and recycling and non-destructive testing are improved, and the pool environment of the nuclear reactor is clean and free of foreign matter, and the reactor core environment is timely and safely inspected, which provides a good guarantee for the smooth operation of the nuclear power plant.

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