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Development of a Digital Twin System for Snake Endoscope Manipulator in Fusion Reactors

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Highlights

- Construct the snake endoscope manipulator digital twin system architecture
- Design of the Motion Control Algorithm for the snake endoscope manipulator
- Develope the snake endoscope manipulator Algorithm Integration and Verification Platform
- The design of the snake endoscope digital twin system is verified by simulation and experiment

***Abstract*—Tokamak fusion is one of the solutions to the energy crisis. The environment of the vacuum chamber as a reaction site is extreme, so it needs to be observed during the operation period. This paper has developed a digital twin system for the snake endoscope manipulator (SEM) system, designed to observe of the fusion reactor vacuum chamber. The system includes a five-dimensional model of the SEM digital twin and a three-category architecture encompassing perception, data, and interaction. Additionally, a visualization and interaction system based on ROS-Unity has been developed to depict the working conditions of the SEM accurately. A terminal traction-based trajectory tracking control algorithm has been designed, enabling the SEM to maneuver flexibly within the confined space of the vacuum chamber to avoid collisions and prevent additional damage to the vacuum chamber. The system has integrated a Python-ROS-Unity-based algorithm for joint simulation channel development, which has been used for the virtual simulation experiments of SEM to validate the algorithms and collect data. Furthermore, a prototype has been constructed for virtual-to-real mapping experiments. Experiments show the digital twin system is feasible, with low latency, high sync, and stable operation, which verifies the feasibility of the system.**

Keywords—Snake endoscope manipulator; Digital twin; Trajectory tracking; Fusion reactor

1. Introduction

Clean and renewable energy is a strategic focus for countries worldwide, and controllable nuclear fusion technology is one of the most effective measures to solve the energy crisis [1]. The tokamak, an innovative design originating from the Soviet Union, achieves controllable nuclear fusion through magnetic confinement and plasma heating [2]. China Fusion Engineering Test Reactor (CFETR) [3] is an independently developed international collaborative project by China, aimed at overcoming the challenges of nuclear fusion and contributing to sustainable energy.

As the reaction site of a fusion device, the vacuum chamber creates an extreme environment with high thermal loads, strong electromagnetic fields, dust, and neutron irradiation during operation[4], making manual maintenance difficult. Teleoperation maintenance thus becomes critical, allowing operators to perform equipment maintenance from a safe distance through remote control technology, which is of great significance for ensuring the stable operation of the experimental reactor [5]. Currently, multiple global projects, including JET [6], Tore Supra [7], ITER [8], EAST [9], and CFETR [10], are all developing specialized teleoperation maintenance technologies and are proposing the need for intelligent control systems. The Institute of Plasma Physics of the Chinese Academy of Sciences has designed a Snake Endoscope Manipulator (SEM) System as shown in Fig. 1, to meet the inspection needs during the operational intervals of CFETR [11].

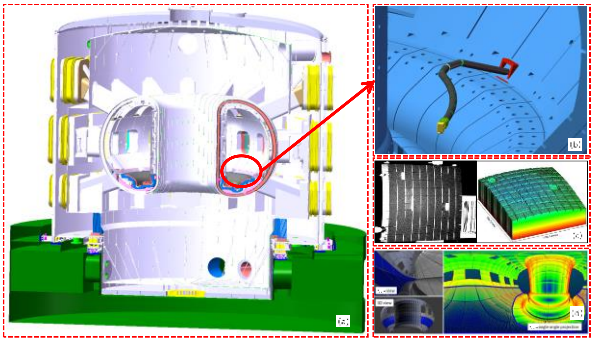


Fig. 1. Installation and Observation Process of the SEM System

The SEM system is designed to be installed in the diameter of the fusion reactor through the transport system, After the fusion reactor reaction ends, it enters the vacuum chamber to observe the damage to the first wall components and the blanket to determine if they meet the requirements for the following reaction. The rest of the time, it is on standby within the diameter, isolated from the vacuum chamber through the shielding door. The system mainly consists of six parts: a serpentine robot, an end effector, a feed mechanism, a reel, a supporting system, and a neutron shielding shroud. The serpentine robot is designed based on the principles of an ultra-redundant degree-of-freedom robot and wire rope traction. Structurally, the joint units are driven by wire rope traction, which belongs to a purely mechanical structure with high reliability. The movement control is achieved by the ball screw module driven by multiple servo motors installed in the end drive box, which pulls the wire rope. During operation, the mechanical arm carries the observation equipment into the vacuum chamber to complete the inspection task, At the same time, the drive box does not enter the vacuum chamber, to the maximum extent to ensure that the drive motors and other components are not affected by extreme environmental conditions. Due to the limited installation space reserved in the fusion reactor, a targeted design is required, and its main parameters are shown in Table. 1.

Table. 1 SEM design parameters.

Parameter types	Values
Diameter of the joint unit	90 mm
Number of joint units	10
Single joint unit length	246 mm
Whole arm length	3000 mm
Maximum end load	≥ 5 kg
Maximum position error	≤ 1 mm
Number of drive motors	24+1
Drive box diameter	230 mm
The maximum rotation angle of a single joint	≤ 25°
Inner hole diameter	40 mm
Cooling method	Inert gas cooling
Storage pipe diameter	250 mm
Camera observation accuracy	± 1 mm
Maximum observation distance	≤ 4500 mm
Coverage Area	Vacuum chamber ±45°

Considering that after the SEM system is installed in the pipe diameter, the operator can not directly monitor its running status, whether in the inspection or in the standby state, building a set of efficient visualization platforms is essential. With the help of sensors and other devices, the platform records core data such as the speed, voltage, current, temperature of the motor, the angle of each joint of the robot arm, and the tension borne by the wire rope, etc. It synchronizes the critical data of the SEM system with the dynamic attitude in real time to present it to the operator intuitively and clearly. This way, the operator can quickly grasp first-hand information, carry out precise control, or take crisis response measures. Therefore, a higher standard is proposed for the comprehensive display ability of the visualization platform, while traditional monitoring has obvious shortcomings in this aspect [12] . To optimize remote operation and maintenance, we built a productized full life cycle operation and maintenance system. In designing the SEM intelligent control system, according to the mature process from simple to complex, we created an "L0-L1-L2" three-level digital twin system, realized comprehensive and accurate digital modeling, and accurately copied the physical form and operation state of SEM in virtual space. This system can not only simulate and evaluate a variety of operation and maintenance schemes in the virtual environment to anticipate and solve potential problems but also carry out real-time monitoring and analysis of the actual working conditions of the SEM, providing detailed data support and accurate guidance for remote operation and maintenance, which greatly improves the efficiency and safety of the operation and maintenance.

2. The Development of Digital Twins

Digital twin refers to the comprehensive utilization of physical models and data collected by sensors to integrate multidisciplinary, multi-physical simulations of various probabilities and scales, thereby achieving a mapping of the physical world's entities in the virtual space and reflecting the lifecycle processes of the physical entities [13].

Research on digital twins can be traced back to Professor Michael Grieves at the University of Michigan in 2003, during a product lifecycle management executive course, when he proposed the concept of a virtual, digital counterpart equivalent to a physical product, which was the embryonic form of the digital twin concept [14]. In 2010, the term "Digital Twin" appeared in NASA's integrated technology roadmap [15], which was used to reflect the life cycle status of spacecraft, and research on Digital Twins began to emerge in large numbers. In 2015, further exploration was undertaken to establish digital twins that could simulate astronaut health degradation and mortality caused by space radiation, and to improve the execution of missions in near-Earth orbit and deep space [16]. The potential of digital twins in human health and simulation modeling was also affirmed and emphasized [17].

In recent years, research on digital twins has seen an explosive growth rate, with the research area expanding into various fields such as aerospace, maritime shipping, machinery, medical, and more. Heo and others [18] have achieved synchronization of the load on the CNC machine tool spindle and the CNC data through the use of digital twins, thereby optimizing the machining process of the machine tool; Wang [19] proposed a fault diagnosis digital twin model for rotating machinery based on rotor dynamics and finite element analysis, which diminishes the differences in dynamic response between the physical rotor and its digital counterpart; Guivarch and others [20] proposed the development of a digital twin for helicopter dynamic systems using multibody simulation and performed a significant simplification of the tilting rotor assembly; Farah et al. [21] have established a digital twin entity for ball bearings based on the discrete element method, enabling the simulation of the movement characteristics of ball bearings under elastohydrodynamic lubrication conditions; Based on the three-dimensional digital twin model proposed by Grieves, Tao and others [22] have added the dimensions of data and services, expanding it to five dimensions, making the digital twin applicable to more fields.

The real-time dynamic characteristics of digital twins have attracted the attention of the scientific and industrial communities, with a flood of research papers and digital twin platforms coming into people's view, witnessing the great potential of this technology in simulating complex systems and providing forward-looking solutions. The China Academy of Information and Communications Technology proposed in 2018 that digital twins are an important facility for achieving industrial intelligence, leading to a qualitative change in informatization. It has been promoting the concept of digital twins, extending the application of digital twins from small-scale industrial equipment to large-scale complex scenarios, and transforming into a new integrated digital infrastructure.

3. Digital Twin Architecture Design and Simulation Integration

3.1 Construction of SEM Digital Twin System

To accurately portray and describe the state and performance of SEM under extremely complex working conditions, and to further integrate SEM path planning, precise control algorithms, and other features, further research is needed on the SEM "information-physical" integration and visual interactive control issues. This involves establishing a visual and intelligent motion control system architecture to prepare for SEM prototype experiments. This paper constructs a five-dimensional model of the SEM digital twin body as shown in Fig. 2, In which the physical entity is the basis for the digital twin's five-dimensional model, mainly comprising subsystems, sensor acquisition devices, and environmental data; the virtual entity includes the geometric, physical, rule, and behavior models that provide a comprehensive mapping of the physical entity; the service encapsulates various kinds of data, models, and results for different fields, users, and businesses, and offers human-computer interaction in the form of specific applications; the digital twin data is the core, integrating virtual and physical data to provide more accurate and comprehensive data support; the connections ensure real-time interaction among the data generated by the physical entity, the virtual entity, and services, and enable the twin model to run completely.

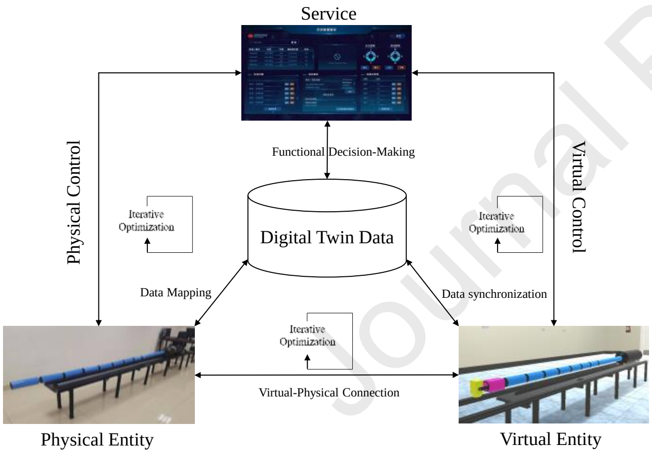


Fig. 2. SEM Digital Twin Five-Dimensional Model

Furthermore, to achieve the application of digital twin technology in SEM, this paper constructs a three-category, five-layer digital twin architecture, as shown in Fig. 3. This architecture starts from the perception and control layer, which collects and processes data from the physical world in real-time for the upper data layer, model layer, function layer, and application layer, providing a solid data foundation. The data layer is responsible for storing and managing a large amount of data from the perception and control layer, providing inputs to the model layer. The model layer constructs an accurate model of the physical entity, including geometric shape, physical properties, and behavioral rules, to simulate and predict the behavior of SEM. The function layer implements model-based analysis and decision-making, supporting the application layer. Finally, the application layer provides users with an intuitive operational interface and decision-making services, allowing users to interact seamlessly between the real world and the digital world.

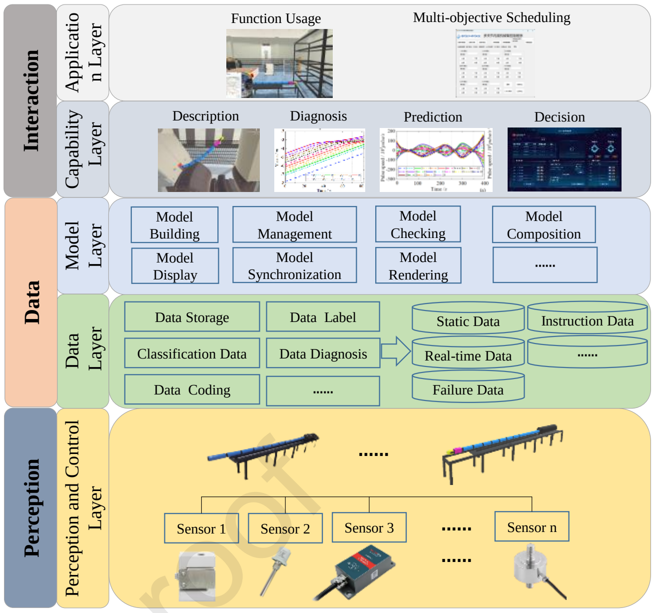


Fig. 3. The Three-category and Five-layer Architecture of SEM Digital Twin

3.2 SEM System Based on a Terminal Dragging Trajectory Tracking Control Algorithm

SEM is composed of several basic joint units connected in series. To avoid collisions between the joints and components inside the vacuum chamber during motion, which could cause additional damage, a terminal dragging trajectory tracking control algorithm is proposed to ensure that each joint moves strictly along the given trajectory curve.

The principle of the terminal dragging algorithm is shown in Fig. 4, and its core is that each joint unit of the robot is updated in position according to a certain method. Using any two robot links, l_{AB}, l_{BC}, as an example, an analysis of the terminal dragging trajectory tracking algorithm is conducted. At time t_i, the position of the robot's end point C is updated along the target trajectory by a step length of d_i. The displacement of the base point A moving on the moving platform in the positive x-axis direction is h. Depending on the actual working condition of the robot, the path curve can be calculated in real-time or generated offline. Regardless of whether the path curve is generated online or offline, the path from the current moment to the next sampling moment is known. Based on the position information of each joint at time t_i, the equation of the line on which any joint unit is located can be derived (taking the link l_{AB} as an example):

$$\frac{x - x_A}{x_B - x_A} = \frac{y - y_A}{y_B - y_A} = \frac{z - z_A}{z_B - z_A} = k_1 \tag{1}$$

At the next moment (time t_{i+1}), the robot's endpoint is updated along the target path to point C_{i+1}. The remaining joint points are sequentially updated along the direction of the link. Scanning the space is performed with end point C_{i+1} as the center and joint unit l_{BC} as the radius. Based on the distance formula between any two joint points, determine the unknown area of joint point B_{i+1}:

$$|C_{i+1}C_i| \leq l_{BC} \leq |C_{i+1}B_i| \tag{2}$$

When the iterative step size d_i satisfies Eq. (2), the spatial positional information of joint point B_{i+1} on the straight line equation of l_{BC} is calculated through the rod length condition and Eq. (1). When the iterative step size d_i does not satisfy Eq. (1), the iterative step size is reduced and the calculation is performed again. By iterating and calculating in sequence, the positional information of each joint can be obtained. By combining the positional information of all joint points with the SAM kinematics equations, the inverse kinematics solution for the position update at time t_{i+1}, $[\boldsymbol{\alpha}, \boldsymbol{\beta}]$, and the feed displacement h of the platform can be obtained.

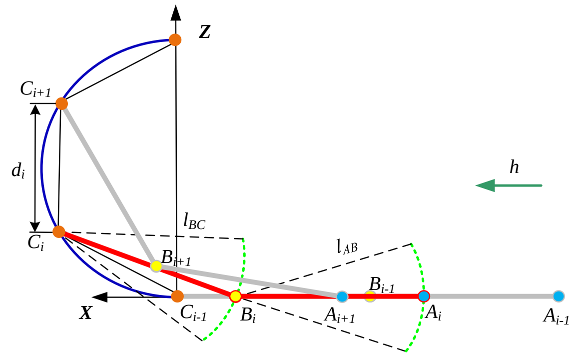


Fig. 4. The Principle of Terminal Dragging Trajectory Tracking Algorithm

3.3 SEM Digital Twin System Integrated Verification Platform Construction

To meet the motion control and real-time online monitoring needs of the SEM maintenance system, it is essential to focus on the research and design of the control algorithm itself, and to compensate for the deficiencies of the ROS development environment. This thesis proposes a communication development and implementation based on the combined simulation of Python-ROS-Unity, as shown in Fig. 5.

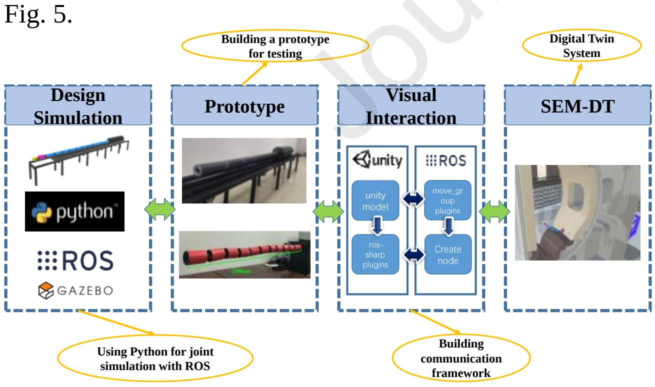


Fig. 5. Python-ROS-Unity Algorithm Integration and Joint Simulation Channel

In the construction of an integrated SEM algorithm and Joint Simulation Communication Channel , we have begun by employing Python to design and simulate the motion control algorithms for SEM. The primary goal is to craft more efficient and precise control strategies, ensuring that the developed algorithms can maintain peak performance under various dynamic conditions. Upon this premise, we seamlessly integrate these algorithms into the SEM module of ROS, either as data packages or dynamic link libraries. Utilizing ROS's superior code generation capabilities, we guarantee that the designed algorithms can be transformed into control packages for robots, further optimizing and expanding the functionality of the core Moveit move_group plugin, enhancing its intelligence and adaptability. Moreover, to bridge the gap between the physical and digital realms, we have established a robust communication link between ROS and Unity. This connection facilitates real-time "virtual-physical" interactions and 3D visualization, laying the groundwork for a wider array of augmented reality (AR) and virtual reality (VR) experiences. By offering interfaces for interaction with devices such as smart helmets and haptic feedback controllers, users can execute direct control of the robot and receive immediate feedback, establishing a comprehensive closed-loop control system. Ultimately, this integration significantly enhances the user experience, granting operators more intuitive and natural engagement with the robotic system and substantially improving control precision and responsiveness.

Further design the specific scenarios and the communication requirements for the control method of the digital twin, as shown in Fig. 6.

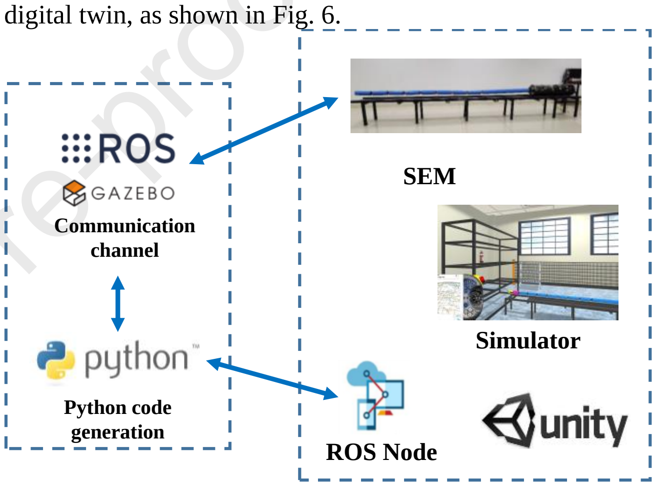


Fig. 6. SEM Digital Twin Communication Architecture

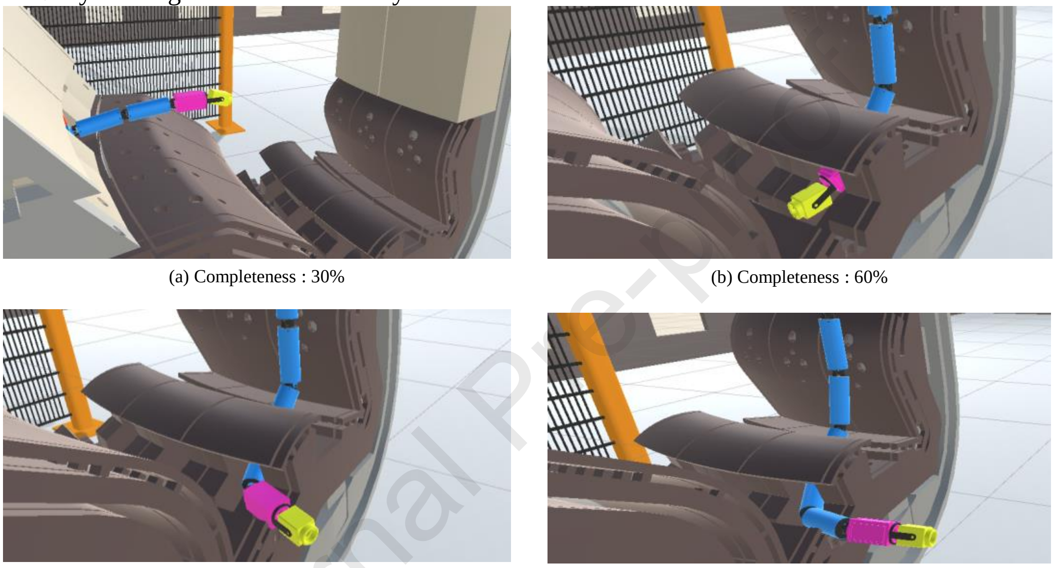
By establishing a communication protocol between Python and ROS, with Python serving as the computational backend, we expedite the integration and validation of self-designed algorithms. This not only enhances the system's computational efficiency but also simplifies the development processes and bolsters system stability. Secondly, following the schematic diagram of communication, we can integrate Python into the ROS communication network for the design and development of SEM autonomic systems. By connecting to the existing ROS network, we can explore the topics, services, and operations available for SEM, facilitating the sending of commands to and receiving data from ROS network simulators, hardware, or software nodes. This framework also manages common sensor data types such as laser scans and 3D point clouds, and if using recorded data from ROS files, it supports reading these files for post-processing or playback of simulation input.Thirdly, the Python-ROS communication framework that we've established provides a platform for designing and implementing algorithmic components for the control, perception, logic, and decision-making of SEM. By connecting to simulators and hardware that support ROS, we can test algorithmic components in a desktop prototype setup.In the fourth phase, once the algorithms are tested and refined, we can automatically generate C++-based executable ROS nodes from our design. These nodes, upon integration with the ROS construction system, can run independently on the target system, and are no longer reliant on Python.Lastly, once the algorithmic components are deployed as part of a distributed system, Python can maintain a connection with the ROS network to perform interactive design tasks such as data visualization and parameter adjustment. This makes the entire system integration process more agile and efficient.

4. Experiment Verification

4.1 Virtual Simulation Experiment

Digital twin technology provides a superior rehearsal stage for SEM , where its motions are precisely simulated through virtual emulation. By writing control code in Python and encapsulating it into a dynamic link library (DLL), it is available for invocation by the digital twin system. This approach allows for comprehensive simulation of SEM operations and maintenance without the need to engage with actual hardware. It enables detailed simulation and evaluation of various motion control and maintenance strategies in a virtual environment from the early stages of design, identifying and resolving potential issues beforehand, and thus lays a solid foundation for design optimization.

In this paper, the digital twin system first conducted verification tests in a simulated environment for complex spaces, such as the openings of divertor filters. With a fixed posture set, we tested the movement of the snake arm in these confined spaces to ascertain the observational capabilities of SEM. These tests provided data support for the development of motion control algorithms, with the results shown in Fig. 7.



(a) Completeness : 30%

(b) Completeness : 60%

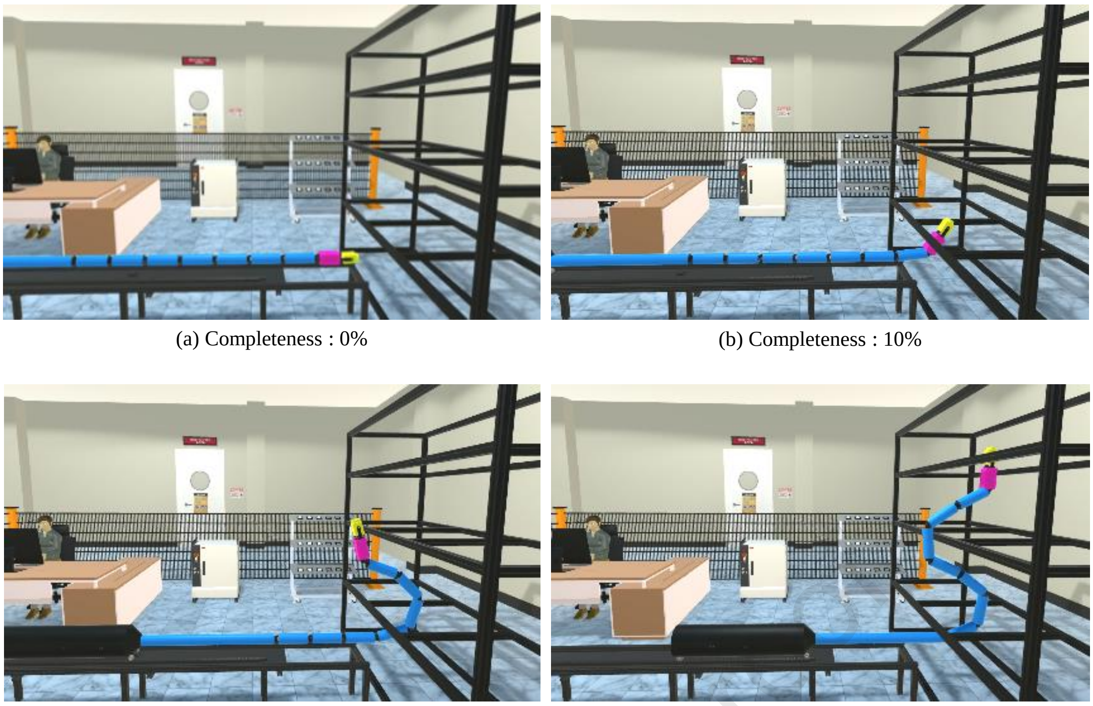
(c) Completeness : 80%

(d) Completeness : 100%

Fig. 7. SEM Narrow Space Motion Test

After completing preliminary tests, we commenced the development of motion control algorithms for SEM and carried out simulation tests in a virtual environment, primarily to verify the accuracy of the algorithms and the operational limits of the joints. To this end, we constructed a framework that allows SEM to perform two-dimensional obstacle avoidance movement along an S-shaped path, with the test results illustrated in Fig. 8.

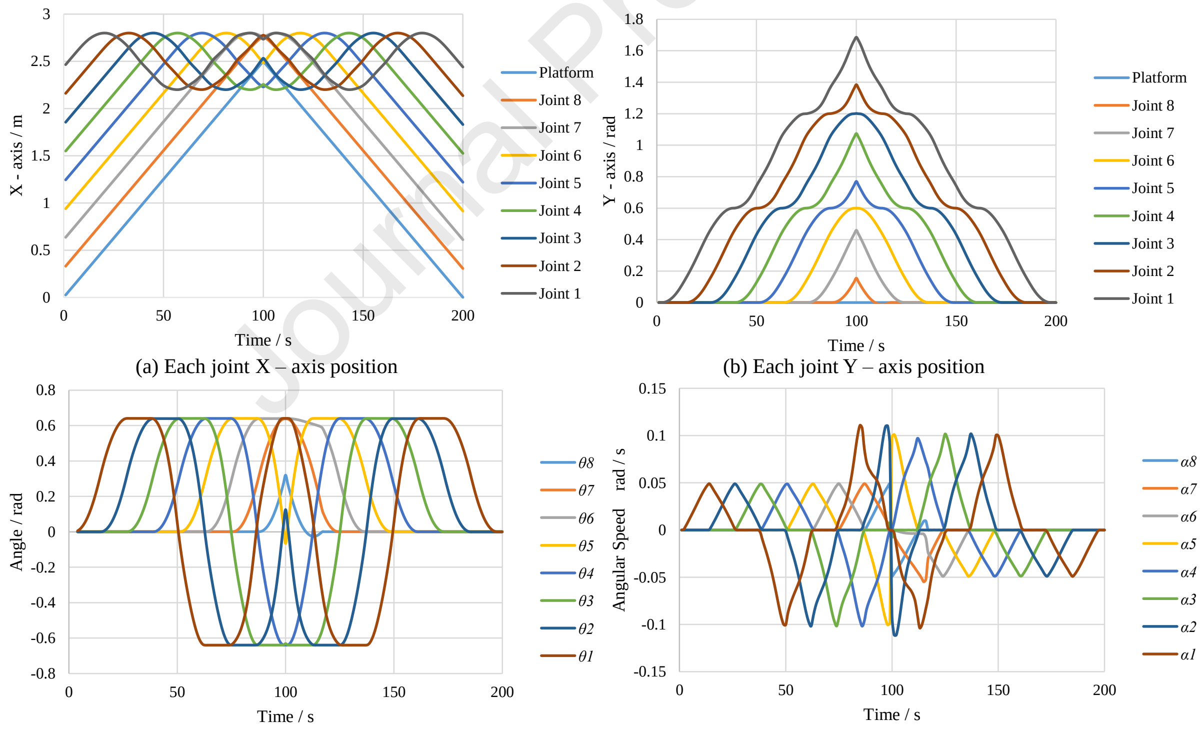
Furthermore, Fig. 9 details the key data collected during the simulation experiment. Figures (a) and (b) display the displacement changes of SEM's joint units and the moving platform along the X-axis and Y-axis, respectively. These data provide an accurate description of SEM's motion trajectory. Figure (c) highlights the changes in the joint angles, and from the data, we can see that the maximum angular displacement of all joints is below the designed limit of 35 degrees, thus validating the correctness of the algorithm design. Figure (d) reveals the angular velocity changes of SEM's joints, showing a moderate variation and ensuring that the movements are within the safety range. With these detailed tests and data, we are confident that the entire algorithm design is rational. It not only endows SEM with the ability to evade obstacles but also confirms the robustness of its joint design.



(a) Completeness : 0% (b) Completeness : 10%

(c) Completeness : 50% (d) Completeness : 100%

Fig. 8. SEM Motion Algorithm Simulation



(a) Each joint X – axis position (b) Each joint Y – axis position

(c) Rotation angle curve of each joint (d) Angular velocity of each joint

Fig. 9. SEM Motion Algorithm Simulation Data

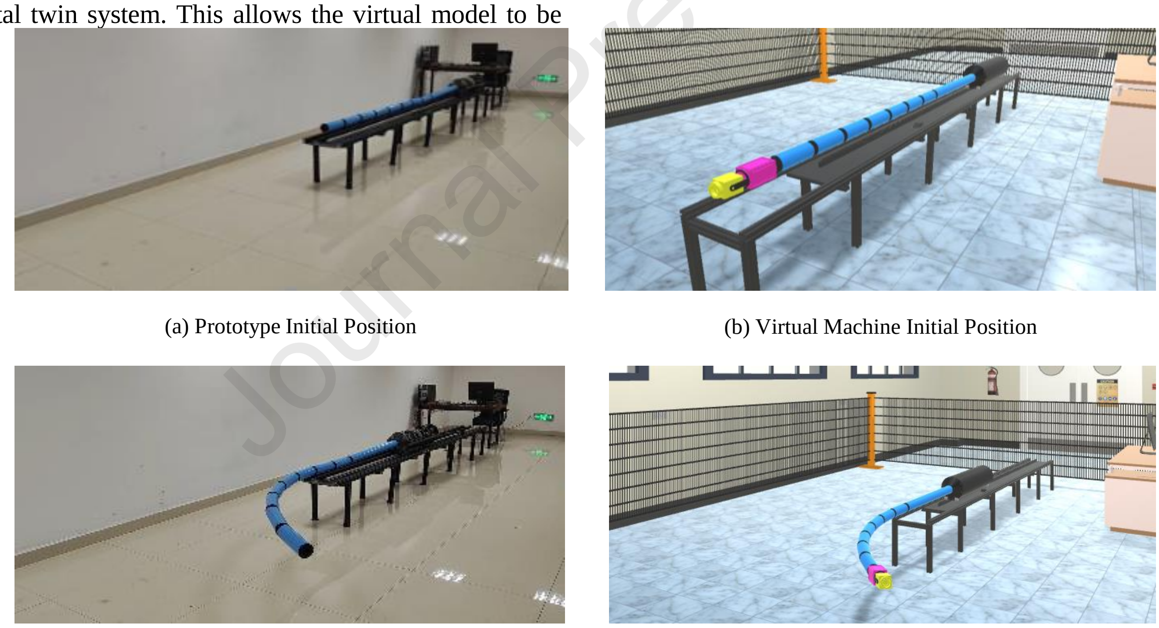
4.2 Synchronous Mapping Experiment

Following the completion of the virtual simulation and verification of the SEM motion control algorithm, the next mechanical step is to achieve synchronous mapping between the SEM prototype and the digital twin system, aiming for real-world and virtual integration. This process is a crucial step in unlocking the potential of the digital twin system and ensuring that its value is fully realized. To this end, we have specially constructed an SEM prototype to participate in the synchronous mapping experiments.

With the SEM digital twin system constructed in this paper, we have successfully carried out a simulation experiment for the SEM motion trajectory. As shown in Fig. 10, the motion trajectory is designed as a simple two-dimensional arc, which aims to verify the feasibility of the synchronous mapping technique and to record the motion data generated during the experimental process in detail, as shown in Fig. 11. Figures (a) and (b) depict the displacement variations of the joints and the moving platform of the SEM on the X and Y axes, respectively, accurately capturing the SEM's motion. Thanks to the simplicity of the trajectory design, the changes in joint angles and angular velocities shown in figures (c) and (d) are all within a safe and controllable range. The prototype has demonstrated excellent smoothness and continuity in the motion of all joints throughout the process, with minimal deviation from the predetermined path. Each joint action can precisely follow the target trajectory, meeting the observation accuracy requirements of the SEM. The digital twin mapping error is low, with high synchronization, indicating that our digital twin system has high precision and ease of operation.

During the experimental preparation phase, our first task is to ensure that the sensors and actuators of the snake robotic arm can achieve real-time data acquisition and transmission to the digital twin system. This allows the virtual model to be dynamically updated and adjusted based on feedback from the real world. The implementation of this process is dependent on efficient and stable communication links and data processing technology to ensure a high degree of fidelity and responsiveness in virtual simulation. With the real-time monitoring of the system, the digital twin system can accurately simulate the robotic arm's performance under various working conditions and complex environments. Such synchronous mapping techniques not only help validate the performance and reliability of the robotic arm but also can monitor its health status over the long-term operation and predict and prevent possible equipment failures.

Furthermore, the technology of synchronous mapping between virtual and real-world scenarios gives us the capability to apply insights gained from virtual simulation to guide our decision-making in real operations. For example, if after a system upgrade, we find that the performance of the snake robotic arm under a specific load does not meet the expected targets, we can quickly identify the root cause by deeply analyzing the data mapped back from the twin. We can then try out different solutions within the digital twin system to find and implement effective improvement measures. This method not only improves the efficiency of problem-solving but also deepens our understanding of robotic arm operations, leading to more precise and intelligent equipment management.



(a) Prototype Initial Position (b) Virtual Machine Initial Position

(c) Prototype Planned Position (d) Virtual Machine Planned Position

Fig. 10. SEM Synchronous Mapping Experiment

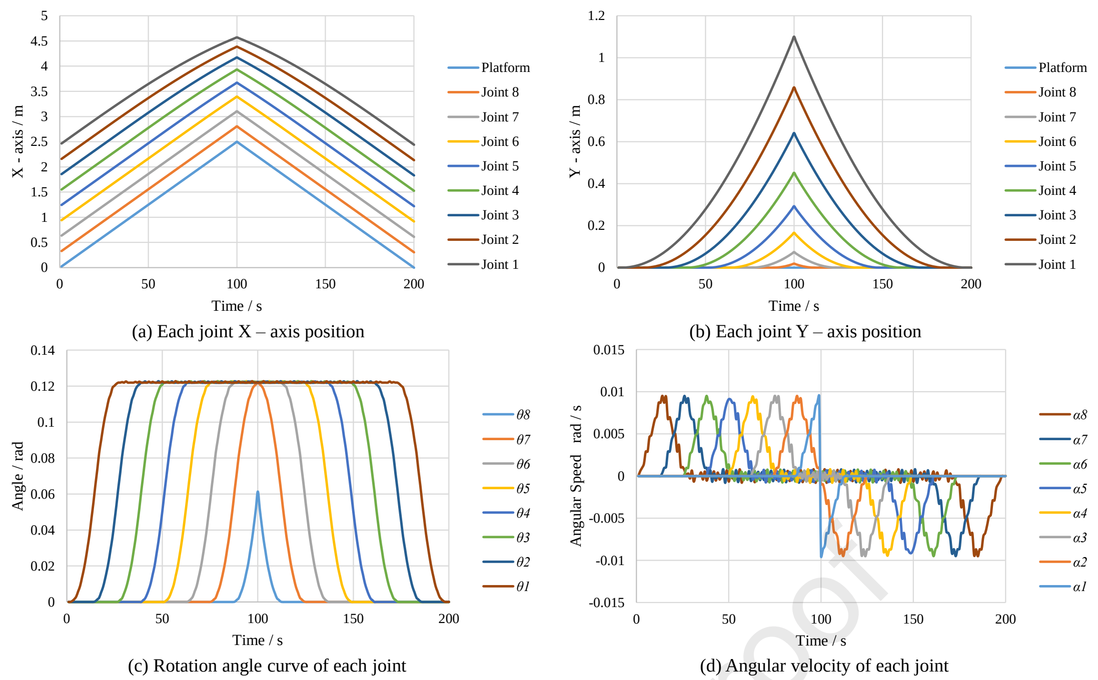


Fig. 11. SEM Synchronous Mapping Experiment Data

5. Discussion

When performing observation tasks in a vacuum chamber, the SEM has demonstrated unique advantages, especially in scenarios that require flexibility and operation in confined spaces. The SEM can conduct observations without disrupting the vacuum and high-temperature conditions within the chamber, thus maintaining a stable operating environment for the apparatus. A similar design, such as the EAST-AIA [23] system jointly developed by Chinese and French researchers, has also proven its basic functionality through experiments in both non-vacuum and vacuum states [24]. However, such designs also bring challenges: the features of long cantilevers, large slenderness ratio structures, and characteristics like multi-joints and super-redundant degrees of freedom, are the main factors affecting control precision. These characteristics make real-time motion calculations relatively tricky, such as the redundant degrees of freedom and continuous bending joints, which are easily strongly influenced by structural coupling, leading to an increased cumulative error in the end effectors. Additionally, it is necessary to be mindful of issues such as avoiding the physical joint limits of the manipulator, surrounding obstacles, and kinematic singularities, as well as the increased difficulty of inverse kinematics calculations and path planning due to the redundancy of degrees of freedom. These demands necessitate the continuous refinement of design and algorithms, as well as the integration of precision compensation algorithms for error compensation, allowing the SEM to perform its tasks more effectively.

Additionally, the application prospects of reinforcement learning algorithms cannot be overlooked. In a physical engine environment, these algorithms can automatically learn and optimize the path planning and control parameter settings for the SEM. By leveraging reinforcement learning, the SEM can learn from its interactions with the environment, gradually developing efficient and adaptable operational strategies. To address the deformation issues in the SEM caused by structural coupling effects, we will use sensing technology and computational models to monitor and reconstruct the structural deformation of the SEM in real-time. This is helpful for better understanding and predicting the behavior of the SEM and provides essential information for maintenance and repair work.

6. Conclusion

In response to the need for observation of the first wall within the vacuum chamber after the termination of the fusion reactor reaction, as well as the challenge of operators' inability to directly monitor the operational status of the installed SEM system, this study has successfully proposed an innovative SEM operation and maintenance (O&M) solution. This solution is based on digital twin technology, which integrates the display of the SEM's key operational data and real-time posture, greatly enhancing the operators' intuitive understanding of the SEM's operational status and providing strong support for subsequent operations and emergency response. Furthermore, this solution significantly improves the efficiency of the first wall observation work while minimizing interference with the vacuum chamber environment.

The solution also creates a highly realistic testing environment for the SEM system, allowing for the pre-testing and evaluation of various O&M strategies in the virtual world. This method can identify potential issues in advance and develop countermeasures, significantly reducing the risk of the equipment during actual operations. This not only accelerates the progress of related work but also enhances the system's overall reliability.

Looking ahead, we will continue to explore the application of digital twin technology in SEM and related fields. This includes but is not limited to further optimizing precision compensation algorithms, developing more complex reinforcement learning strategies, and utilizing digital twin technology for long-term equipment health management and performance improvement. Through these efforts, we hope to promote SEM technology development and support a wider range of industrial applications.

7. Credit authorship contribution statement

Shijie Liu, Guodong Qin: Formal analysis, Investigation, Writing–original draft, Writing–review & editing. Hongtao Pan, Congju Zuo: Conceptualization, Formal analysis, Writing–review & editing, Kun Lu, Yong Cheng: Conceptualization, Investigation, Writing–review & editing, Funding acquisition.

8. Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

9. Acknowledgements

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☒The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, " Development of a Digital Twin System for Snake Endoscope Manipulator in Fusion Reactors".