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Train inspection robots virtual teaching system based on Isaac Sim and ROS

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***Abstract*—In response to the inspection demands in the complex environment of train bottom, this paper proposes a virtual teaching system based on digital twin technology to improve deployment efficiency and safety of train inspection robots. The virtual teaching system utilizes a five-dimension (5D) digital twin system to seamlessly integrate the virtual and physical domains of the train inspection robot via the Isaac Sim and the Robot Operating System (ROS). It features two test modes, Software-in-the-loop (SIL) and Hardware-in-the-loop (HIL), enabling path planning and motion control to be tested in a photo-realistic environment, with optimized teach-in data deployed to the physical robot. The system can effectively optimize the inspection process, improve automation, and reduce risks and costs during deployment.**

Keywords- Digital Twin, Isaac Sim, ROS, Train Inspection Robot, Virtual Teaching

I. INTRODUCTION

Train inspection robots have become a crucial infrastructure for the automation of rail vehicle maintenance. With the development of digital twin technology, its integration with train inspection robot systems offers a new perspective for addressing challenges such as operation and deployment. At the same time, digital twin technology provides support for virtual teaching for efficient robot control and operational optimization.

The international standard ISO 23247-1-4 [1][2][3][4] provides general principles and a reference architecture for the development and application of digital twin technology in manufacturing. In [5][6], digital twin-based simulation modelling techniques and real-time data-driven virtual reality synchronization for industrial robots are proposed. The virtual system corresponding to a physical robot entity is constructed by Unity 3D, in which algorithms are validated, and data is transmitted in real time to drive the motion and to remotely observe the motion of the physical entity. In industrial robot programming for teaching system, digital twin mechanisms are often combined with virtual reality technology [7] or augmented reality technology [8][9] to provide a workspace that simulates a robotic manipulator and its operations to perform a range of physical tasks. These applications are used to record human actions in virtual environments, which are then reproduced by real robots.

Although digital twin technology has demonstrated significant potential across various industrial sectors, particularly for creating virtual replicas for predictive maintenance, performance optimization, and decision-making [10], its application in train inspection robots remains in its early stage and requires further investigation. Manual teaching methods are commonly used for fixed-point image acquisition in train inspection robots, where the end-effector is manually guided to the target position, and pre-defined trajectories are followed [11]. The contribution of this paper is the development of a virtual teaching system for train inspection robots using digital twin technology. Isaac Sim, a simulation platform developed by NVIDIA, provides a highly realistic photo-realistic environment for testing and developing robotic applications. By integrating the Isaac Sim and Robot Operating System (ROS) and constructing a five-dimensional (5D) digital twin system, the virtual teaching system enables the testing and validation of control algorithms and inspection strategies. This system identifies and optimizes potential problems before actual deployment, minimizing the time and costs associated with field implementation.

II. SYSTEM ARCHITECTURE DESIGN

Based on the digital twin reference model outlined in the international standard ISO 23247-2 [2], this paper proposes a 5D digital twin system for train inspection robots. As shown in Fig. 1, the framework consists of the following components: observable manufacturing elements, device communication entity, digital twin entity, user entity, and cross-system entity.

A. *Observable Manufacturing Elements*

Observable manufacturing elements refer to those aspects of the manufacturing process that can be directly observed, including the equipment used and the surrounding environment. In the specific context of under-train inspection, the main inspection target is the train bogie and the equipment is a train inspection robot, which consists of an Autonomous Mobile Robot (AMR) and a collaborative robotic arm.

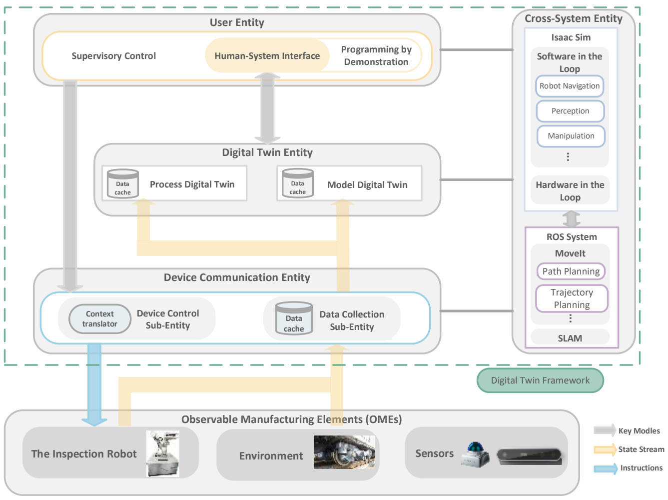

Figure 1. 5D digital twin framework

B. *Device Communication Entity*

The device communication entity serves as a critical interface for enabling seamless data exchange between the observable manufacturing elements and their corresponding digital virtual entity within the framework. It comprises two principle sub-entities: the data collection sub-entity, which is responsible for acquiring real-time data from the observable robot elements, and the device control sub-entity, which manages the control of the train inspection robot.

C. *Digital Twin Entity*

The digital twin entity digitally represents the observable manufacturing elements, which is divided into two categories: model digital twin and process digital twin.

1) *Model Digital Twin*

The creation of a model digital twin in Isaac Sim involves integrating both static environment and the train inspection robot. The static environment is typically designed using Computer Aided Design (CAD) software like SolidWorks. The train inspection robot is modeled using the Unified Robot Description Format (URDF). Upon importation into Isaac Sim via the CAD and URDF importer, a Universal Scene Description (USD) file representing assets is generated. These assets are configured with relevant physical properties, including mass, inertia, collision meshes, and material settings in Isaac Sim. Furthermore, the train inspection robot has to be added joint drives and corresponding sensors, such as camera and radar. By integrating these physical properties, the virtual train inspection robot realistically simulates forces, constraints, and dynamic behaviors, ensuring that it can perform tasks and move in a manner that closely mirrors real-world robotic behavior. The mapping of the model digital twin is shown in Fig. 2.

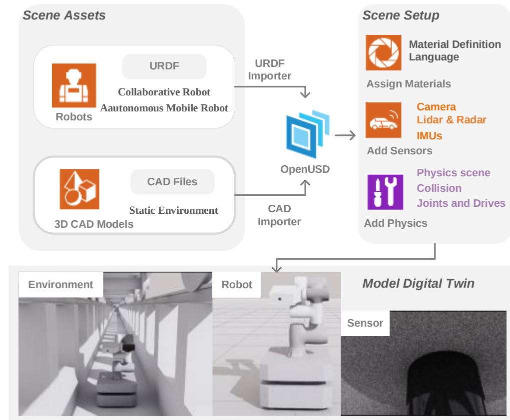

Figure 2. Mapping of the model digital twin

2) *Process Digital Twin*

The process digital twin is used to simulate and optimize the inspection deployment process. Based on the ISO 23247-4[4], an implementation mapping of the process digital twin has been devised, as illustrated in Fig. 3. This mapping illustrates the functional entity architecture of the process digital twin, where these entities work together to support status updates, visualization, simulation, data analysis, and report generation during the inspection deployment process. Each functional entity is standardized according to the ISO 23247-2 [2], as detailed in Table I, ensuring the consistency and scalability of the digital twin in practical applications.

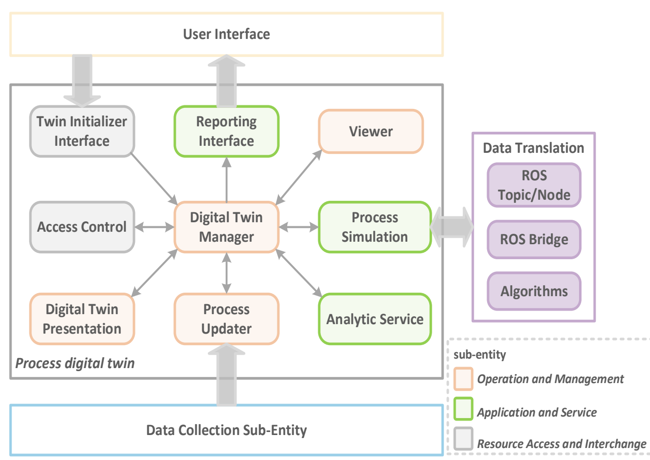

Figure 3. Implementation mapping of the process digital twin

D. *User Entity*

The user entity serves as the interface between the user and the model digital twin, enabling control, monitoring, and adjustment of the system. The system utilizes extensions as the core workflow, with modules designed to interact with the stage. The extension supports hot reloading and adaptive physical steps, enabling real-time simulation. As an independent application, the extension can be installed into the

Extensions Manager and used across different NVIDIA Omniverse applications.

TABLE I. MAPPING OF PROCESS DIGITAL TWIN TO FUNCTIONAL ENTITY

Role in digital twin entity	Functional Entity (FE)	ISO 23247-2 reference	Comment
Process updater	Synchronization FE	ISO 23247-2: 2021,6.3.1.1	Updates the digital train inspection robot of the inspection process.
Digital twin representation	Digital representation FE	ISO 23247-2: 2021,6.3.1.3	Represents the physical characteristics and status of the digital model.
Digital twin manager	Maintenance FE	ISO 23247-2: 2021,6.3.1.4	Manages updating and sharing of digital twin representation.
Viewer	Presentation FE	ISO 23247-2: 2021,6.3.1.2	Displays the inspection process.
Process simulation	Simulation FE	ISO 23247-2: 2021,6.3.2.1	Simulates motion generation, including path and trajectory planning and motion control.
Analytic service	Analytic service FE	ISO 23247-2: 2021,6.3.2.2	Manages and analyses data collected from the result of simulations.
Reporting interface	Reporting FE	ISO 23247-2: 2021,6.3.2.4	Interface to the user entity is used to generate reports about the inspection process.
Access control	Access control FE	ISO 23247-2: 2021,6.3.3	A security mechanism for managing permissions and access rights for digital twin entity.
Twin initializer interface	User interface FE	ISO 23247-2: 2021,6.4	Interface to the user entity is used to retrieve the initial and planned states of the digital train inspection robot.

E. Cross-system entity

The cross-system entity is designed to ensure interoperability and collaborative operation between different systems. It facilitates efficient integration across diverse platforms by providing essential services such as data transmission, protocol conversion, data integrity assurance, and security support.

III. VIRTUAL TEACHING SYSTEM

The digital twin system provides an essential platform for virtual teaching, ensuring comprehensive testing and validation of the robot control system in a photo-realistic environment and facilitating a smooth transition to the physical train inspection robot. The virtual teaching system integrates two key components, Software in the Loop (SIL) and Hardware in the Loop (HIL).

In SIL mode, the digital train inspection robot allows the tuning of various software components such as navigation and manipulation, enabling a more seamless and accurate transition to the physical train inspection robot. Once the software stacks have been verified, the HIL mode is used to integrate the virtual simulation with the actual hardware. The target deployment device receives data from both the digital train inspection robot and sensors, with ROS acting as the middleware to efficiently transfer data between the digital twin system and the physical device. The virtual teaching process is shown in Fig. 4.

In the Human-System Interface based on Isaac Sim, the process begins with environment modeling via Simultaneous Localization and Mapping (SLAM), then the navigation system guides the AMR to the first parking spot. Next, the virtual end-effector of the collaborative robotic arm is dragged to locate the target observation point, and upon clicking Execute, the path planning algorithm is triggered to autonomously plan the trajectory towards the observation point. During SIL testing, the motion of the virtual train inspection robot is observed to ensure that the path is collision-free and the trajectory is safe, with real-time collision detection and physical simulation provided by NVIDIA PhysX SDK. During this phase, the pose of the AMR and the trajectory of the collaborative robotic arm are recorded. Subsequently, the HIL model is used to transfer the data to a physical train inspection robot and guide it to execute the same task in the real world, ensuring high task execution accuracy and expected performance.

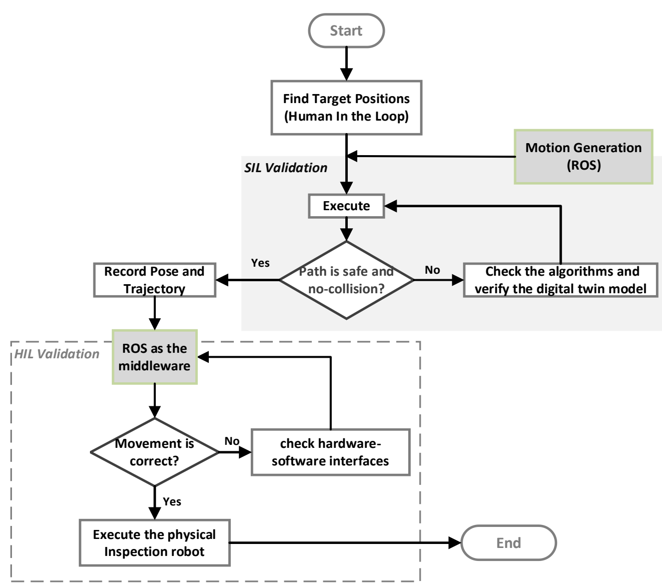

Figure 4. Flowchart of the virtual teaching

IV. EXPRIMENTS AND RESULTS

The train inspection robot system comprises several key components described as follows: AMR is equipped with LIVOX MID-360 LiDAR laser scanner, using differential drive, with a maximum driving speed of 0.5 m/s. The AMR can navigate autonomously in the environment and perform path planning tasks. The CR5 is a 6-axis collaborative robotic arm designed by Dobot, known for its high precision and flexibility in automation tasks. The CR5 is equipped with RealsenseD415 depth camera, responsible for executing path planning tasks from the initial position to the specified observation point and returning. The CR5 supports high-precision motion control to accurately reach the target point.

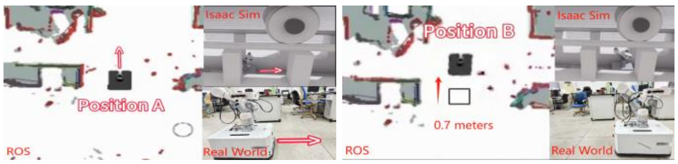

Figure 5. Movement of the AMR in the Isaac Sim and real world

The experiment first starts the AMR and moves along the set path from the initial position A to the preset parking point B, advancing 0.7 meters. The physical AMR moves along the path obtained from digital AMR as shown in Fig. 5.

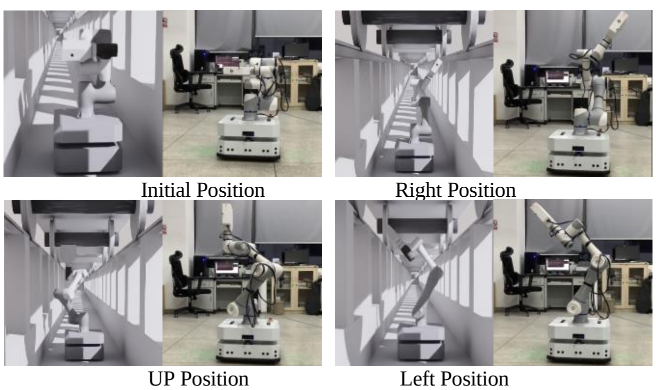

Figure 6. Target positions in the Isaac Sim and real world

The trajectory of the CR5 is recorded in real time from the initial point to the right, up and left in sequence, shown as Fig. 6. These data are transferred from the digital twin system to the physical CR5 via ROS as a middleware. Fig. 7 shows the simulated joint trajectory angles of the CR5 compared to the actual trajectory angles. Table II lists the Mean Absolute Error (MAE) between the simulated and real trajectories for the six joints.

From Fig. 7 and Table II, it can be observed that the discrepancy between the simulated and actual joint trajectories is minimal, with all the MAE values below 0.0250. The results indicate that the trajectories generated through virtual teaching meet the accuracy requirements for real-world operations, ensuring high precision and reliability in practical tasks.

TABLE II. MAE BETWEEN SIMULATED AND REAL TRAJECTORIES

Joint	***Joint1***	***Joint2***	***Joint3***	***Joint4***	***Joint5***	***Joint6***
MAE *(radian)*	0.0075	0.0023	0.0090	0.0220	0.0118	0.0146

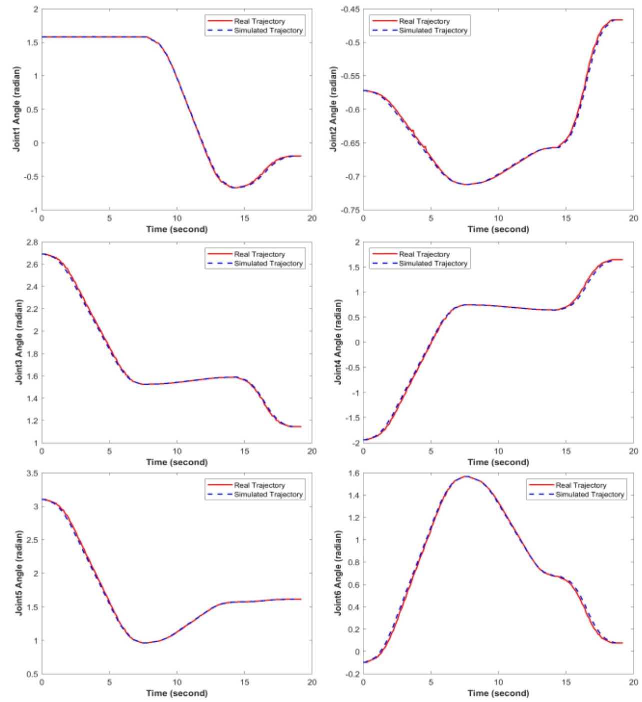

Figure 7. Simulated and Real Trajectory Angles of the CR5

V. CONCLUSIONS

This paper proposed the virtual teaching system, utilizing 5D digital twin system to facilitate the testing and validation of train inspection robots. By integrating SIL and HIL modes, the system provides an effective platform for verifying control algorithms and optimizing the performance of train inspection robots before deployment. This methodology was applied to simulations of both the AMR and the CR5, where path planning, trajectory planning, and motion control were successfully implemented. Experimental results indicate that the AMR can move from position A to position B with the real distance close to 0.7meters, and the trajectory tracking error of the CR5 is minimal, which proves that the digital twin system can accurately simulate the behavior of the actual robot and maintain high accuracy in practical applications. Future research will focus on combining the digital twin with big data technology to deeply mine and analyze experimental data in order to create optimization and feedback mechanisms for smarter maintenance tasks.

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