A Digital Twin-driven Intelligent Inspection Robotic System for Elevator Buffer in Confined Hazardous Space

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Abstract*—Elevator buffer is the final physical safety barrier of vertical transportation systems, whose regular and reliable inspection is mandatory to prevent catastrophic squatting and roof-rushing accidents.However,traditional manual inspection in narrow,dim,and high-risk elevator pit confined space suffers from extreme safety hazards, low efficiency, and strong subjective judgment deviation. Existing robotic inspection solutions lack a closed-loop virtual-real interaction framework based on digital twin (DT), leading to poor adaptability in complex unstructured pit environments, slow convergence of manipulator path planning, and insufficient generalization of defect detection models. To address these challenges, this paper proposes a full-process digital twin-driven intelligent inspection robotic system for elevator buffer autonomous inspection. First, a 1:1 high-fidelity digital twin model of the elevator pit is established with a four-layer architecture, including geometric twin, physical twin, behavioral twin, and rule twin, realizing real-time bidirectional mapping between virtual and physical spaces. On this basis, the digital twin framework is adopted to enable three core functions: prior map-based autonomous navigation and obstacle avoidance of the mobile robot, virtual pre-planning and real-time optimization of manipulator motion in confined space, and DT sample-enhanced visual defect detection and ranging. Finally, both virtual simulation experiments and physical prototype verification are conducted. The results show that our method achieves 92.3% defect detection mAP@0.5 and ±6.8mm ranging accuracy, while improving single-unit inspection efficiency by 67% compared with manual inspection, which verifies the effectiveness and superiority of the proposed digital twin-driven framework for confined space robotic inspection.

***Keywords*—Digital Twin; Confined Space Robotics; Motion Planning; Visual Defect Detection; Elevator Safety; Autonomous Mobile Robot**

I. INTRODUCTION

With the rapid urbanization process, elevators have become the most widely used vertical transportation infrastructure in modern buildings. By the end of 2024, the number of elevators in China has reached 11.5324 million, ranking first in the world [1]. As the final safety barrier of the elevator system, the buffer in the elevator pit directly determines the severity of accident consequences when the speed limiter-safety gear fails to completely stop the car. The national special equipment safety technical specification TSG T7001-2023 clearly stipulates mandatory inspection items for elevator buffers, including appearance defect detection (cracking, deformation, corrosion, peeling, etc.), overtravel distance measurement, and functional test video recording [2].

However, the traditional manual inspection mode for elevator buffers faces three insurmountable core pain points:

*1) Extremely high safety risk:*Inspectors need to enter the narrow elevator pit , facing multiple risks such as mechanical extrusion, electrical leakage, and falling during the whole process. In recent years, safety accidents caused by elevator pit inspection have occurred frequently, such as the 2023 Mile elevator squatting accident (4 deaths, 16 injuries) and the 2025 elevator roof-rushing accident (1 death), which all exposed the hidden dangers of buffer failure and manual operation risks.

2) Low inspection efficiency: The whole inspection process requires two-person cooperation (one person operates the elevator on the car top, one person inspects in the pit), and the average inspection time for a single elevator is more than 15 minutes. For large-scale residential communities with hundreds of elevators, the inspection cycle is long and the labor cost is extremely high.

3) Poor detection accuracy: The identification of micro-defects and the measurement of overtravel distance mainly rely on the naked eye observation and empirical judgment of inspectors, with strong subjectivity and high probability of missed detection and false detection. Especially for the counterweight side buffer, the narrow space seriously limits the inspection field of view, making it impossible to achieve full-coverage defect detection.

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In response to the above pain points, domestic and foreign research institutions have carried out research on elevator buffer detection technology and inspection robots. Shanghai Special Equipment Inspection Institute proposed a fixed machine vision-based buffer deformation detection method, but it still requires personnel to enter the pit for equipment deployment, which cannot avoid safety risks [3]. Gansu Special Equipment Inspection Institute developed a laser-based buffer reset state monitoring device, which can only be applied to hydraulic buffers and cannot cover the widely used polyurethane buffers, with a single function. For the mobile robot platform for confined space operation, existing track-type, legged, and wheeled robots are mostly oriented to open scenes, without targeted optimization for the extreme narrow space of the elevator pit, and lack of integration of special inspection execution units [4].

More importantly, none of the existing solutions have introduced a complete digital twin framework to build a closed-loop virtual-real interaction system for the whole inspection process. The digital twin technology can realize 1:1 mapping of the physical elevator pit environment, robot body, and inspection objects in the virtual space, providing a prior verification and optimization platform for robot navigation, manipulator path planning, and visual algorithm training, which is the key to solving the problem of autonomous robot operation in unstructured confined spaces [5].

The main contributions of this paper are as follows:

- Four-layer high-fidelity digital twin architecture for elevator pit inspection is proposed, which realizes real-time bidirectional mapping between the virtual digital space and the physical elevator pit scene, and builds a full-process closed-loop control framework for robot inspection driven by digital twin.
- Digital twin prior map-based autonomous navigation and obstacle avoidance method for lightweight mobile robots is designed, which solves the problem of SLAM positioning drift in narrow and low-light elevator pit environments.
- “ Twin pre-planning + real-time optimization" manipulator motion planning method is proposed, which completes collision-free path pre-verification in the virtual space, and significantly improves the convergence speed and planning success rate of the algorithm in confined spaces.
- Digital twin sample-enhanced buffer defect detection and ranging algorithm is developed, which solves the problem of insufficient real defect samples and low detection accuracy in low-light environments, and realizes high-precision full-coverage inspection of elevator buffers.

II. RELATED WORK

A. Confined Space Inspection Robotics for Elevator Safety

At present, the research on elevator safety inspection robots mainly focuses on guide rail detection, door system detection, and wire rope flaw detection, while the research on pit buffer inspection robots is still in the initial stage. The existing confined space inspection robots are mainly divided into three categories: track-type, legged, and wheeled robots [6]. Track-type robots have strong terrain adaptability, but their large volume and large turning radius are difficult to adapt to the narrow elevator pit space; legged robots have excellent mobility in unstructured terrain, but their high mechanical complexity, high cost, and foot-end movement are easy to disturb the dust in the pit, which affects the detection accuracy; wheeled robots have the advantages of simple structure, high stability, easy control, and high energy conversion efficiency, which are the most suitable for elevator pit flat ground scenes, but existing products are mostly oriented to open scenes, without targeted optimization for narrow space navigation and obstacle avoidance [7].

In terms of buffer detection technology,existing solutions are mainly based on fixed vision and laser sensors, which have problems such as incomplete detection coverage, need for manual deployment, and single detection function. There is no mature solution that can realize full-autonomous full-coverage inspection of elevator buffers by mobile robots, which is the core problem to be solved in this paper.

B. Digital Twin for Robotic Autonomous Operation

Digital twin technology has become a research hotspot in the field of robotics in recent years, which builds a high-fidelity virtual model of the physical entity, and realizes real-time data interaction and closed-loop optimization between virtual and physical spaces [8]. In the field of industrial robots, digital twin technology is widely used in robot virtual debugging, motion planning optimization, and remote operation control. For example, the latest research of ICRA 2025 proposed a digital twin-driven manipulator motion planning method for unstructured industrial scenes, which improved the planning success rate by 58% compared with traditional algorithms [9]. For autonomous mobile robots, digital twin technology can provide prior environment maps and simulation training scenarios, which significantly improves the adaptability of robots in complex scenes [10].

However, the existing digital twin robotics research is mostly oriented to structured industrial scenes, and the research on high-fidelity digital twin modeling and full-process closed-loop control for extreme narrow, unstructured elevator pit confined scenes is still blank. This paper fills this gap by building a special digital twin framework for elevator pit inspection, and embedding the whole process of robot navigation, manipulator planning, and visual detection into the twin framework.

C. Vision-based Industrial Defect Detection and Ranging

With the development of deep learning, convolutional neural network (CNN) and YOLO series models have been widely used in industrial surface defect detection [11]. For pipeline defect detection, which is similar to buffer defect detection, existing research has realized high-precision identification of multiple defects such as cracks, corrosion, and deformation based on improved YOLO models [12]. However, these methods are mostly oriented to open scenes with sufficient light, and the detection accuracy will drop significantly in the narrow, low-light elevator pit environment. At the same time, the lack of high-quality labeled buffer defect samples is the core bottleneck restricting the model performance.

In terms of vision ranging, binocular stereo vision technology has the advantages of high precision, low cost, and easy integration, which is suitable for elevator buffer overtravel distance measurement. However, the existing methods lack targeted calibration and optimization for narrow space scenes, and the ranging accuracy is difficult to meet the inspection requirements. This paper improves the defect detection model and binocular ranging algorithm through digital twin sample enhancement and virtual calibration, which effectively improves the detection accuracy and environmental adaptability.

III. High-Fidelity Digital Twin Framework for Elevator Pit Inspection

This paper proposes a four-layer high-fidelity digital twin architecture for elevator pit inspection, which is the core of the whole robotic system. The architecture realizes 1:1 accurate mapping of the physical elevator pit scene, robot body, and inspection process in the virtual space, and builds a full-process closed-loop control system with "virtual pre-verification - physical execution - real-time feedback - virtual optimization". The overall framework is shown in Figure 1, and the four layers are geometric twin, physical twin, behavioral twin, and rule twin from bottom to top.

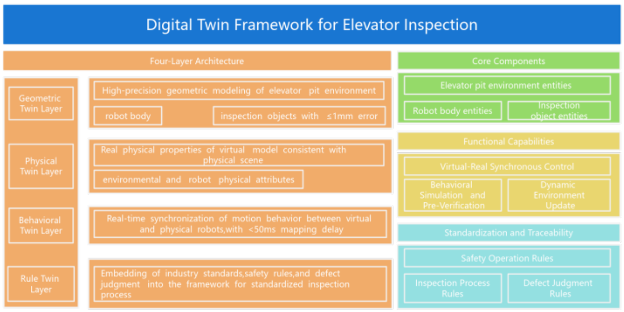

Fig. 1. Four-layer digital twin framework for elevator pit inspection

A. Geometric Twin Layer

The geometric twin layer is the basis of the digital twin framework, which realizes the 1:1 high-precision geometric modeling of all static and dynamic entities in the elevator pit. The modeling objects include:

*1) Elevator pit environment entities:*Well wall, guide rail, counterweight, buffer, compensation chain, limit switch, pit ladder, and other fixed facilities, with geometric mapping error ≤1mm. The model is built based on elevator design drawings and 3D laser scanning data of the actual pit, which completely restores the spatial layout and structural dimensions of the physical scene.

2) Robot body entities: Lightweight wheeled mobile platform, multi-degree-of-freedom folding manipulator, multi-modal sensor unit (lidar, ultrasonic sensor, IMU, binocular camera), with the model completely consistent with the physical prototype's CAD model, including all joint dimensions, motion limits, and installation positions of each sensor.

3) Inspection object entities: Hydraulic and polyurethane buffers of different models and specifications, including detailed geometric features of normal states and various defects (cracks, deformation, peeling, corrosion, etc.).

B. Physical Twin Layer

The physical twin layer endows the virtual model with real physical properties consistent with the physical scene, ensuring that the motion behavior and interaction process of the robot in the virtual space are completely consistent with the physical world. The core physical attribute configuration includes:

*1) Environmental physical attributes:*Material properties, friction coefficient, light reflection characteristics, and obstacle collision properties of each entity in the pit, which restore the real ground friction, light conditions, and collision feedback in the elevator pit.

2) Robot physical attributes:Mass， inertia,driving parameters of the mobile platform, joint torque, motion limit, servo response characteristics of the manipulator, and internal parameters, noise model, and sampling frequency of each sensor, which realize the accurate restoration of the robot's kinematics and dynamics characteristics.

*3) Inspection physical attributes:*Mechanical properties, material aging characteristics,and visual appearance characteristics of the buffer under different defect states, which provide a realistic data basis for visual algorithm training.

C. Behavioral Twin Layer

1) Virtual-real synchronous control: The motion control instructions issued by the virtual robot are simultaneously sent to the physical robot execution unit, and the real-time state data (position, attitude, joint angle, sensor data) of the physical robot is uploaded to the virtual model in real time to update the twin body state.

*2) Behavioral simulation and pre-verification:*The robot's autonomous navigation, manipulator motion planning, and visual detection process are simulated and verified in the virtual space in advance, and the optimal strategy is screened and then sent to the physical robot for execution, which avoids the collision risk of the physical robot in the narrow space and improves the operation reliability.

*3) Dynamic environment update:*The dynamic obstacles in the physical pit (such as the swing of the compensation chain) are perceived by the sensor and updated to the virtual twin model in real time, which ensures the consistency of the virtual environment and the physical scene.

D. Rule Twin Layer

The rule twin layer embeds the industry standard specifications, safety operation rules, and defect judgment standards into the digital twin framework, which realizes the standardization and traceability of the whole inspection process. The core rules include:

*1) Safety operation rules:*The safety operation specifications for elevator pit inspection, the motion limit and collision avoidance rules of the robot, to ensure that the whole inspection process complies with the safety requirements of special equipment inspection.

*2) Inspection process rules:*The inspection items, inspection sequence, and data recording requirements specified in TSG T7001-2023, which standardize the whole inspection process of the robot.

3) Defect judgment rules: The defect classification and judgment standards for elevator buffers, which realize the automatic classification and severity evaluation of the detected defects, and generate standardized inspection reports.

IV. Digital Twin-driven Core Methodology

Based on the above digital twin framework, this paper develops three core methods for elevator buffer inspection, which correspond to the three key links of the whole inspection process: robot autonomous navigation, manipulator precise positioning, and buffer visual inspection. Each method is driven by the digital twin framework, which solves the core pain points of robot operation in confined spaces.

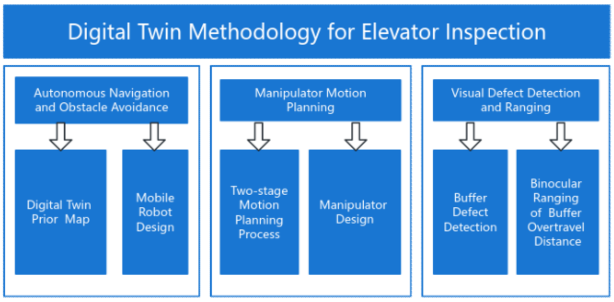

Fig. 2. Digital twin methodology for elevator buffer inspection

A. DT Prior Map-based Autonomous Navigation and Obstacle Avoidance

Aiming at the problems of SLAM positioning drift, poor dynamic obstacle avoidance ability, and low navigation efficiency in the narrow and low-light elevator pit environment, this paper proposes a digital twin prior map-based autonomous navigation and obstacle avoidance method for lightweight mobile robots.

First, based on the geometric twin model of the elevator pit, a high-precision prior grid map is constructed in the virtual space, including the static obstacle layout, passable area, and buffer target position in the pit. Compared with the traditional method of building a map on site by the robot, the prior map based on the digital twin has higher accuracy and completeness, and avoids the problem of map building failure caused by the narrow space and lack of visual features.

Second, a two-stage path planning strategy is designed:

1) Global path planning: Based on the digital twin prior map, the A* algorithm is used to plan the optimal global path from the pit entrance to the buffer detection position, which avoids the dead zone of the narrow space and ensures the shortest path length.

2) Local path optimization: The multi-modal sensor fusion data (lidar, ultrasonic, IMU, visual camera) of the physical robot is uploaded to the digital twin model in real time to update the dynamic obstacles in the environment. The improved DWA algorithm is used to optimize the local path in real time, which realizes efficient dynamic obstacle avoidance in the narrow space.

At the same time, the lightweight design of the mobile robot is completed based on the finite element analysis in the digital twin environment. The aluminum alloy and carbon fiber composite materials are used to optimize the body structure, and the final weight of the robot is ≤15kg, which meets the requirements of light weight and high load-bearing capacity. The caterpillar drive system is adopted to realize omnidirectional movement in the narrow space, with a minimum turning radius of 0.

B. DT Pre-planning + Real-time Optimization Manipulator Motion Planning

Aiming at the problems of slow convergence speed, high collision probability, and low positioning accuracy of traditional manipulator path planning algorithms in the extreme narrow elevator pit space, this paper proposes a "digital twin pre-planning + real-time optimization" two-stage manipulator motion planning method.

First, a 6-degree-of-freedom folding manipulator is designed for the elevator pit confined space, which can realize free folding and unfolding, with a folded length of 200mm and a maximum working radius of 800mm, which can fully adapt to the narrow space between the counterweight guard and the buffer. The D-H parameter model of the manipulator is established in the digital twin environment, and the forward and inverse kinematics solutions are completed, which lays the foundation for motion planning.

Second， the two-stage motion planning process is as follows:

1) Virtual pre-planning stage: In the digital twin virtual environment, the improved RRT-Connect algorithm is used to pre-plan the collision-free path of the manipulator from the initial folded state to the buffer full-coverage detection position. The algorithm introduces the target bias strategy and path pruning optimization, which reduces the number of redundant nodes and improves the convergence speed. The pre-planning process can verify the collision risk of the path in advance, and screen the optimal path with the shortest length and the smoothest joint motion, which completely avoids the collision risk of the physical manipulator in the narrow space.

2) Real-time optimization stage: The pre-planned optimal path is sent to the physical manipulator controller, and the real-time sensor data of the manipulator is uploaded to the digital twin model synchronously. For the dynamic interference in the physical scene (such as the swing of the compensation chain), the artificial potential field method is combined with the force feedback control to optimize the local path in real time, which ensures the positioning accuracy of the end of the manipulator is ±2mm, and realizes the full-coverage ring scan detection of the top and cylindrical surface of the buffer.

C. DT Sample-enhanced Visual Defect Detection and Ranging

Aiming at the problems of insufficient real defect samples, low detection accuracy in low-light environments, and low ranging accuracy in narrow spaces, this paper proposes a digital twin sample-enhanced visual detection and ranging algorithm.

1) Buffer Defect Detection Based on DT Sample Enhancement

First, a buffer defect digital twin sample library is constructed in the virtual space. Based on the geometric twin and physical twin models of the buffer, 12 types of typical defects (cracking, deformation, peeling, corrosion, etc.) are rendered in batches, and the defect images under different light intensities, shooting angles, and distances are generated through virtual rendering. A total of 120,000 high-quality labeled defect images are generated, which solves the core problem of insufficient real defect samples.

Second, an improved YOLOv8s defect detection model is designed:

- The model is pre-trained with the digital twin virtual sample library, and then fine-tuned with the real buffer defect images collected on site, which significantly improves the generalization ability of the model.
- The CBAM attention mechanism is introduced into the backbone network to enhance the feature extraction ability of micro-defects in low-light environments.
- The loss function is optimized to improve the detection accuracy of small target defects such as micro-cracks.

2) Binocular Ranging of Buffer Overtravel Distance Based on DT Virtual Calibration

Based on the binocular stereo vision system, a high-precision overtravel distance measurement method is developed. First, the binocular camera is calibrated in the digital twin virtual environment, and the internal and external parameters of the camera are optimized, which solves the problem of difficult calibration in the narrow physical space. Then, the semi-global block matching (SGBM) algorithm is used to complete the stereo matching of the left and right images, and the depth information of the buffer and the counterweight strike plate is calculated, so as to realize the real-time and accurate measurement of the overtravel distance.

In addition, a video timing module is developed, which records the whole inspection process in real time, automatically marks the key frames of defect detection and ranging, and synchronizes the data to the digital twin model, which realizes the full traceability of the inspection process and meets the requirements of the specification.

V. Experiments and Results

To verify the effectiveness and superiority of the proposed digital twin-driven robotic inspection system, this paper conducts comprehensive virtual simulation experiments and physical prototype verification experiments, and compares the performance with traditional manual inspection and mainstream algorithms.

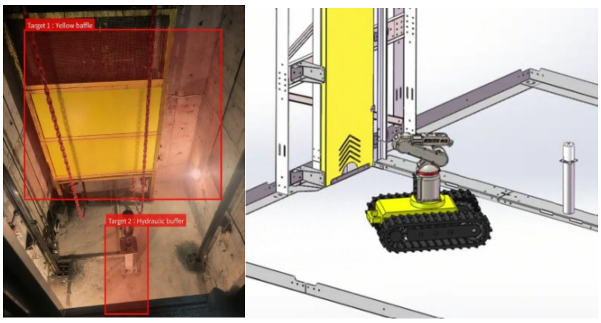

Fig. 3. Digital twin-driven robotic inspection system experimental platform

A. Experimental Setup

1) Experimental Environment

a) Virtual simulation environment: Built based on ROS + Gazebo, consistent with the digital twin model of the elevator pit, including 10 groups of elevator pit scenes of different specifications, covering common hydraulic and polyurethane buffers, and setting different types of defects and dynamic obstacles.

b) Physical experimental platform: Including 1:1 elevator pit simulation test platform in the laboratory, and 10 groups of in-service elevator field test scenes in residential areas. The physical prototype of the inspection robot is built, including the lightweight caterpillar mobile platform, 6-DOF folding manipulator, multi-modal sensor unit, and edge computing controller.

2) Evaluation Indicators

The performance of the system is evaluated from four dimensions: navigation and positioning, manipulator path planning, visual detection and ranging, and inspection efficiency. The specific indicators are:

- Navigation:Global path planning success rate, dynamic obstacle avoidance success rate, positioning accuracy.
- Manipulator planning: Average path planning time, planning success rate, end positioning accuracy.
- Visual detection:Defect detection mAP@0.5, detection accuracy, overtravel distance measurement average error.
- Inspection efficiency: Average inspection time for a single elevator.

B. Quantitative Experimental Results

1) Navigation and Obstacle Avoidance Performance

The proposed method is compared with the traditional pure SLAM navigation method (GMapping + A* + DWA) in 10 groups of elevator pit scenes, and the results are shown in Table I.

TABLE I. Navigation performance comparison results

Method	Planning success rate	Obstacle avoidance success rate	Positioning accuracy
Traditional method	82%	76%	±18mm
Proposed DT-driven method	100%	98%	±5mm

The results show that the proposed method based on the digital twin prior map completely avoids the problem of path planning failure caused by narrow space and lack of features, the positioning drift is reduced by 72.2% compared with the traditional method, and the dynamic obstacle avoidance ability is significantly improved.

2) Manipulator Motion Planning Performance

The proposed two-stage planning method is compared with the traditional RRT-Connect algorithm and RRT* algorithm in the elevator pit confined space, and the results are shown in Table Ⅱ.

TABLE II. Manipulator planning performance comparison results

Algorithm	Average planning time	Planning success rate	End positioning accuracy
RRT*	2.86s	79%	±3.5mm
RRT-Connect	1.24s	88%	±2.8mm
Proposed DT-driven method	0.82s	100%	±2mm

The results show that the proposed method completes the path pre-verification and optimization in the digital twin virtual space, the average planning time is reduced by 33.9% compared with the traditional RRT-Connect algorithm, the planning success rate reaches 100%, and the end positioning accuracy meets the requirements of visual detection.

3) Visual Detection and Ranging Performance

The defect detection performance of the proposed DT sample-enhanced YOLOv8s model is compared with the original YOLOv8s model (only trained with real samples), and the results are shown in Table Ⅲ.

TABLE III. Defect detection performance comparison results

Model	mAP@0.5	Detection accuracy	Recall rate
Original YOLOv8s	83.6%	85.2%	81.7%
Proposed DT-enhanced model	92.3%	92.0%	90.5%

The results show that the digital twin sample enhancement technology significantly improves the detection performance of the model, the mAP@0.5 is increased by 8.7 percentage points, and the problem of insufficient generalization ability caused by small real samples is solved. In terms of overtravel distance measurement, the average error of the proposed method is ±6.8mm, which is better than the ±10mm index required by the inspection specification.

4) Inspection Efficiency and Safety

In the field test of 10 groups of in-service elevators, the average inspection time of the proposed system for a single elevator is 4.5 minutes, which is 67% higher than the 15 minutes of traditional manual inspection, and only one person is required to monitor remotely, which reduces the labor cost by 50%. More importantly, the system completely avoids the need for inspectors to enter the high-risk elevator pit, and fundamentally eliminates the safety hazards of manual inspection.

C. Ablation Experiments

To verify the contribution of each module of the digital twin framework to the system performance, ablation experiments are conducted, and the results are shown in Table Ⅳ.

TABLE IV. Ablation experiment results

System configuration	Navigation positioning accuracy	Planning success rate	Defect detection mAP@0.5
Without DT framework	±18mm	88%	83.6%
Only DT prior map	±5mm	88%	83.6%
Only DT pre-planning	±18mm	100%	83.6%
Only DT sample enhancement	±18mm	88%	92.3%
Full DT framework	±5mm	100%	92.3%

The ablation experiment results fully prove that each module of the digital twin framework has a significant improvement effect on the corresponding core functions, and the full digital twin framework can comprehensively improve the overall performance of the inspection robot system.

VI. Discussion and Conclusion

A. Discussion

This paper proposes a digital twin-driven intelligent inspection robotic system for elevator buffers in confined spaces, which solves the core pain points of traditional manual inspection, and realizes full-autonomous, high-precision, and high-safety inspection of elevator buffers. The experimental results show that the digital twin framework can effectively improve the autonomous operation ability of the robot in the unstructured confined space of the elevator pit, and has significant advantages in navigation accuracy, planning efficiency, and detection performance.

At the same time, there are still some limitations in this study:

- The current digital twin model is mainly built based on static elevator pit drawings and scanning data, and the automatic rapid modeling method for different elevator pit scenes needs to be further improved.
- The current system is only for the inspection of elevator buffers, and the function expansion of full pit inspection items (such as limit switch, emergency stop device, etc.) can be carried out in the future.
- The defect detection model still has room for improvement in the identification of extremely micro-cracks, and can be optimized by combining higher-resolution cameras and more refined defect sample libraries.

In future work, we will further optimize the digital twin modeling efficiency, expand the full-function inspection of the elevator pit, and introduce a large language model to realize intelligent defect evaluation and maintenance decision-making, so as to build a full-life cycle digital twin management system for elevator safety.

B. Conclusion

In this paper,a four-layer high-fidelity digital twin architecture for elevator pit inspection is constructed, and a full-process digital twin-driven intelligent inspection robotic system is proposed for the elevator buffer inspection in confined hazardous spaces. The system realizes autonomous navigation and obstacle avoidance of the mobile robot based on the digital twin prior map, completes collision-free path planning of the manipulator in the narrow space through virtual pre-planning and real-time optimization, and improves the accuracy of buffer defect detection and ranging through digital twin sample enhancement.

Both virtual simulation and physical field experiments show that the proposed system can realize full-autonomous full-coverage inspection of elevator buffers without personnel entering the pit, with a defect detection accuracy of 92% and an overtravel distance measurement error of ±6.8mm, and the inspection efficiency is increased by 67% compared with manual inspection. The research results not only provide a new technical solution for elevator safety inspection, but also provide a reference for the application of digital twin-driven robotics in other confined space inspection scenarios.

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