Object Re-identification for Digital Twin Enabled Facility and Workplace Management

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Abstract. Real-time inspection, monitoring, and surveillance are crucial for smarter facility and workplace management in the era of hybrid working. Object identification is a key aspect of digital twin enabled smart workplace management in varisou industrial applications. Despite the adoption of various cutting-edge technologies in facility management, there is limited research on deploying object re-identification (Re-ID) technology effectively. This study aims to fill this gap by conducting a comprehensive review on object Re-ID technology and relevant applications, categorizing challenges in facility and workplace management and summarizing typical tasks and use cases for digital twin enabled solutions. Furthermore, future research and development directions are outlined. This investigation shall contribute to improving the efficiency and reliability of facilities and workplaces by integrating object Re-ID and digital twin technologies.

1. Introduction

Real-time or near real-time inspection, monitoring and surveillance is crucial for smarter facility and workplace management. For example, scientific laboratories uses a variety of sensors and software systems to track and trace the operation status and mobility of key equipment, instruments, lab staff and critical experimental workflows for improving environmental heath, safety and productivity. The monitoring can be as simple as a temperature logging device on a single oven or a refrigerator, a video camera network installed at the egress pathways, a mobile application for recording experiment procedures, or as sophisticated as a fully integrated software system with heterogeneous devices covering all aspects of the lab. Hybrid working that combines remote and in-office working is becoming a *'civilization-level change'* working model in the post-COVID-19 era[1,2]. These changes are disrupting existing facility management practices to (re)shape people-centred workplaces, and render workplace monitoring and surveillance more challenging and important.

Object identification plays a salient role in digital twin enabled smart workplace management. A digital twin is *'a digital representation of a physical object'*; it can encapsulate almost every facet of a physical object or a collection of physical objects [3]. Objects that can be digital twinned include a human, a material, an equipment, a process, a software system, a working environment, or an organization. The required and optional elements of a digital twin include *'model, data, uniqueness, monitor, analytics, control and simulation'*. To accomplish the realistic mapping, two-way communication, simulation, feedback and control between the physical and cyber workplaces, the instances of an object captured across multiple scenes with different sensing devices (e.g., sensors and infrared cameras) have to be identified properly and mapped to the unique twinned object. In computer vision community, the technology for re-identifying an object under different imaging conditions or across non-overlapping cameras is called object re-identification (Object Re-ID) [4]. With the advance in deep neural networks and growing demands for video intelligence and analytics in closed and open environment monitoring, Object Re-ID technology has aroused significant interest from both the academia and industry to tackle the idiosyncratic challenges facing specific applications.

Digitization, automation and intelligence are considered as the future trend to improve the safety, health and productivity of facilities and workplaces.There are several approaches for facility and workplace monitoring. Manual written documentation is the traditional and simplest approach for making operational and maintenance records, detecting trends, reporting service disruptions, and handling safety issues. Other approaches include data loggers, building management systems, lab information management systems, activity and environment monitoring [5]. While the facility management sector has embraced a number of cutting-edge technologies and digital solutions to accomplish digital transformation (e.g., Construction/ Industry 4.0, digital twin, PropTech, augmented reality, deep learning, artificial intelligence, etc.), there is still limited investigation and practical applications on how to deploy Object Re-ID effectively to improve the efficiency and dependability of facilities and workplaces.

To fill the research gap, this investigation aims to: (1) conduct a comprehensive review on the state-of-the-art researches and practices on Object Re-ID technologies and applications; (2) clarify and categorize the challenges facing facility and workplace management when applying Object Re-ID; (3) summarize typical Object Re-ID tasks and use cases for implementing digital twin enabled facility and workplace management solutions; (4) compare the strengths and weaknesses and test the suitability of existing Object Re-ID technology stacks; and (5) present the obtained challenges and position future research and development directions.

2. Literature Review / Related Works

2.1 Challenges Facing Facility and Workplace Management

According to ISO 41011 standard, 'Facility Management (FM)' describes "*an organisational function which integrates people, place and process within the built environment with the purpose of improving the quality of life of people and the productivity of the core business*" [6]. FM is a profession which encompasses multiple disciplines and necessitates effective collaboration of a diverse teams including technical staff, executives, as well as third-party to ensure functionality, comfort, safety and efficiency of the built environment by integrating people, place, process and technology. On the other hand, decisions made throughout the project development and construction process of a building's lifecycle may have considerable influences on FM [7]. Therefore, it is crucial to integrate the vast amount of information and data generated during the building's entire lifespan including the project development, construction and operation and maintenance phases. However, Lucas pointed out that the exchange of information and data throughout the building's lifecycle in the architecture, engineering, and construction (AEC) industry is still fragmented, and the operation and maintenance phase is often considered the least relevant to the other phases [8]. Therefore, it is essential to prioritize effective communication and information management as critical aspects of facilities management.

Nowadays, many stakeholders still use outdated procedures or manual-based approaches for facilities management due to a lack of awareness and technical support in digitalization. Such practices often require large amounts of paper works to manage processes and deliverables such as design drawings and day-to-day management, resulting in an inefficient workforce and a heightened risk of errors and omissions. Furthermore, the FM department relies on a multitude of separate and incompatible systems to monitor asset values, maintain buildings, and perform other jobs, which has also resulted interoperability and 'data silos' issues [9].

Advances in digital technology have revolutionized most knowledge-based businesses, including the construction industry, and profoundly changed conventional FM industry. Despite that the development in CAD and BIM have transformed traditional design processes and information exchange methods, the construction industry has the lowest level of digitalisation and technological innovation compared to other manufacturing industries [9]. There is an urgent need for the construction and FM industries to investigate the methodology and effectiveness of applying a porforlio of emerging technologies (e.g., digital twins, artifical intelligenece, environment sensing and reality capturing technologies, Object Re-ID) and digital transformation practices for improving overall efficiency, health, safety and productivity.

2.2 Object Re-ID in Digital Twin and Computer Vision Enabled Applications

In computer vision enabled applications, a recognized object is identified again after imaging conditions change (e.g., changes of lighting conditions of the environment to which an object is exposed to), which is called object re-identification (Object Re-ID) [10]. Person Re-ID and vechile Re-ID have received extensive attentions in intelligent monitoring, multi-object tracking and smart city management applications [11]. Despite great research and development efforts paid to Object Re-ID in the last a few years in a variety of applications (e.g., autonomous driving, video surveillance, human–computer interactions, robotics, and content-based video retrieval), re-identifying objects in a digital twinned world remains a daunting task due to highly inter-dependency between and among different objects and the significant variations in illumination, poses or viewpoints, or even cluttered backgrounds [12, 13].

Object Re-ID methods are mainly investigated in closed-world and open-world settings. As depicted in Figure 1, there are four major steps when implementing a typical Object Re-ID system including: 1) Acquisition of raw image or video data of target objects; 2) Labelling and annotation of target objects of interests for preparing training and testing datasets; 3) Re-ID model training by feature representation learning, distance metric learning and object descriptor generation; and 4) Retrieving of object-of-interest against a gallery set by calculating query-to-gallery similarity with the Re-ID model learned in previous stage.

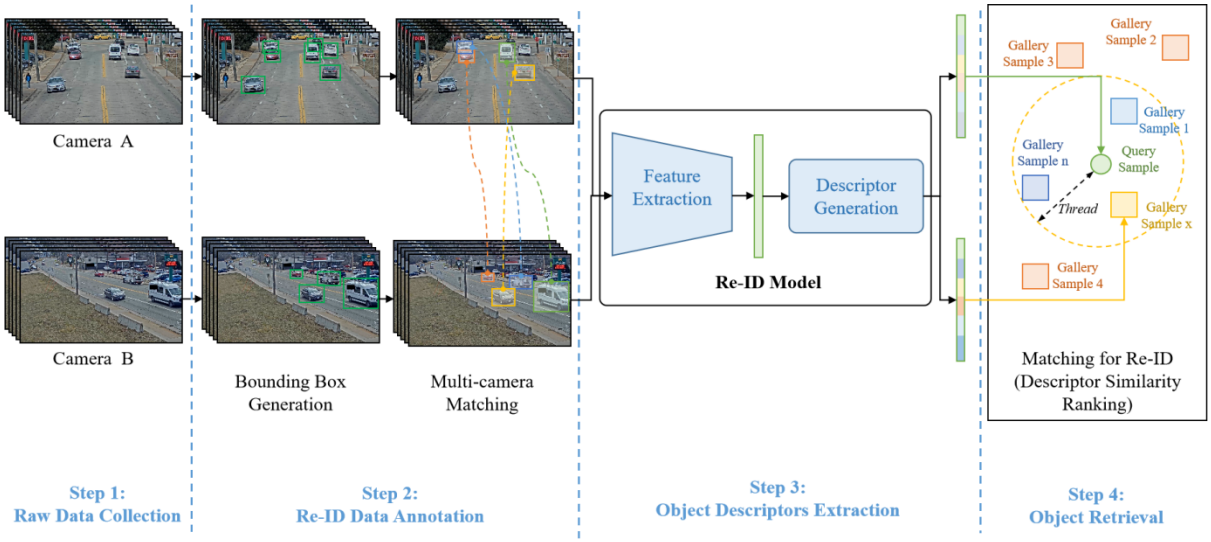

Figure 1: Major Steps for Implementing a Object Re-ID Enabled System

Object Re-ID is closely related to digital twin, internet-of-things (IoTs) and computer vision enabled applications. Real-time analysis and integration of various forms of information and knowledge are necessary for effective workplace and facility management. The design and execution processes of building projects can also be considerably improved by applying these

cutting-edge digital technologies to collect, share and utilize crucial data for efficient management and operations. Digital twin is one of the most promising enablers for smart facility and workplace management. The concept is firstly introduced in 2002s in the manufacutring industry [3, 14]. A digital twin is a virtual representation of a physical system, process, or product. It can be used to simulate, track, and continuously improve performance of physical systems by leveraging the data and insights obtained with sensors and cameras. In manufacturing industry, stakeholders can use 'digital twin' to test and simulate product performance in a virtual environment, identifying potential quality issues, reducing the cost and time of physical prototyping, monitoring the working-in-progress of product lines, diagnosing faults, predicting failures, and conducting prescriptive analytics for improving overall production efficiency.

There are widespread use scenarios for integrating digital twin, computer vision and Object Re-ID in smart city and built environment management. Nowadays, smart cities are evolving from static 3D modeling to digital twins that integrate dynamic digital technologies [15], giving rise to the new concept of digital twin-enabled smart city development. The goal of the digital twin city, which is being implemented at the city level, is to create a vast and intricate network that will enable mutual mapping and two-way communication between the real world and the virtual realm [16]. Digital twin copies benefit smart cities in numerous ways, such as urban planning, resource allocation, policy making, public safety and health, energy management, and transportation system optimization [17–20].

Despite the rapid progress in Object Re-ID research and applications, great challenges remain. One of the key open questions is the performance degradation of Re-ID models, when domain context knowledge lacks, in particularlly when signifiant differences exist between the training data and test data in terms of camera viewpoint, lighting conditions, and background clutter. Other challenges include the occlusion and partial matching problem, which refers to the difficulty of matching objects when they are partially visible or occluded by other entities; and the scalability problem when object Re-ID is applied in large-scale application scenarios, such as smart cities or industrial automation with millions of objects to track and identify. For coming up practical digital twin enabled solutions for smart facility and workplace management and accellerating the digitalization of the whole industry, a systematic investigation is urgently needed on on these challenges.

3. Methodology

3.1 Flowchart of Research Methodology

As illustrated in Figure 2, the following approaches are adopted for achieving the stated research goals.

- A literature review is carried out from two aspects: one from the Object Re-ID and digital twin technology development aspect and the other from the facility and workplace management aspect.
- Challenges of applying Object Re-ID to facility and workplace management is clarified and categorized according to the main steps of cross-industry standard process of machine learning and the lifecycle management process of facility management.
- Field studies to custom inspection facilities and workplaces in Shenzhen, China and a research laboratory on a campus in Hong Kong are made to come up with typical tasks and use cases for applying Object Re-ID to digital twin enabled facility and workplace

management. A network of sensing devices including cameras are installed in those workplaces to inspect the movement of human and materials within the workplaces for ensuring relevant operations comply with the standard specifications.

- Existing public datasets and published deep neural network models for typical objects Re-ID (e.g., person and vehicle Re-ID) are retrieved and downloaded from open source depository for testing their suitability in the above selected use scenarios.
- A small-scale prototype system are developed to compare and test the obtained datasets and models against the target objects and processes of interest. Suitable pre-trained neural networks are selected for deriving the challenges and solutions of applying Object Re-ID in smart facility and workplace management.
- Finally, the research findings are summarized for positioning future research directions.

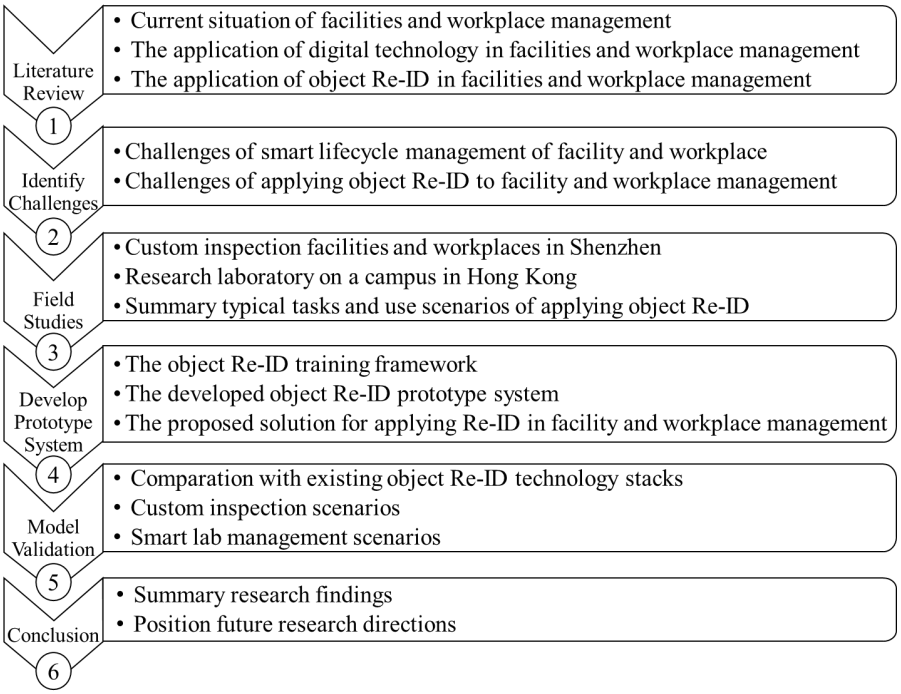

Figure 2: Flowchart of Research Methodology

3.2 Use Cases for Identifying Challenges of Applying Object Re-ID

In this research, two representative use cases are selected for identifying challenges of utilizing Object Re-ID in digital twin enabled facility and workplace management. The analysis focuses on the characteristics of target objects, data collection and annotation methods in corresponding to different environmental conditions.

- Custom inspection scenarios

  Custom inspection and clearance is an offical measure carried out by the custom office. It is an important operation of importing and exporting goods that is executed in customs supervised workplaces and warehouses. Only a large number of customs officers are deployed in various working areas can the freight inspection procedure be completed. In addition, the inspection follows standard operation procedures to guarantee that it is carried out consistently. In China, a real-time monitoring mode is being adopted with the support of a large quantities of cameras. This video mode saves the possible labor cost of the supervision process but is bound to produce a huge amount of monitoring

video data streams. Sifting through the videos to find key incidents generates a heavy workload under numerous working scenes. While the product inspection process only makes up a very small portion of the monitoring video data, the bulk of the remaining content is the freight station in an idle state and other useless segments. Without intelligent video analytics, it is very difficult to complete the product inspection procedure smoothly. This type of goods monitoring and inspection is incredibly ineffective and unable to meet the continually increasing need for goods re-inspection. Therefore, designing and developing a system to analyze the video surveillance of freight inspection procedure, including object Re-ID, has become an urgent task. Nevertheless, the dataset annotation issue under massive surveillance videos and the matching problem of cross-modal data under the low light scenarios are the current challenges in the customs freight inspection scenarios.

- Smart lab management scenarios

  With the rapid advances and applications of various new technologies, such as digital twins, deep learning, and artificial intelligence etc., in industrial and business sectors, intelligenct laboratory management solutions are emering to achieve higher safety, efficiency and productivity of scientific lab workplaces. However, the relevant research and practices in smart and self-driving laboratories are still in its preliminary stage; many problems remains unaddressed comprehensively. For example, safety awareness still needs to be strengthened for lab operators and other stakeholders; irregular operation and untimely equipment maintenance can cause additional laboratory losses and affect the normal operation process. A semi-automated or fully automated monitoring system that detects personnel violations and equipment malfunctions and alerts the appropriate managers can help reduce injuries and fatalities. In addition to monitoring target objects, tracking data can provide useful insights for laboratory management. The solutions also can benefit key informed decisions, such as the optimization of laboratory layouts and operational processes. With the widespread use of cameras, automatic objects tracking enabled by Object Re-ID can be achieved through computer vision. Object Re-ID can identify and monitor people and equipment within the lab, detecting anomalies on time and improving lab health and safety. At the same time, in some key areas where critical equipment is located, object Re-ID can be leveraged to control the access and operation of equipment with authority, further guaranteeing the security and confidentiality of the laboratory.

  However, there are still some challenges in applying Object Re-ID to solve intelligent laboratory management problems. For example, there are many similar objects in the laboratory; the recognition and identification of these objects requires high-precision algorithms and high-efficiency deep learning models. In addition, the laboratory environment is complex, and there are various interference factors, such as lighting and shading, which can affect the accuracy and effect of Object Re-ID. Therefore, applying Object Re-ID to solve laboratory management problems requires comprehensive consideration of various factors and systematic algorithms and models.

3.3 The Proposed Prototype System and Solution

3.3.1 The General Architecture of Object Re-ID and Digital Twin Enabled Solution

For investigating the potentials and issues of applying digital twin and Object Re-ID in smart facility and workplace management, a prototype system is being designed and implemented. The major compoents of the system is shown in Figure 3. By employing advanced computer

vision techniques and deep learning algorithms, this system can recognize and track various objects within a scene in real-time, thus contributing to the efficiency of resource allocation and the effectiveness of security monitoring. With the continuous development of computer vision technologies and deep learning algorithms, this solution shall be deployed extensively and pave a way for more possibilities in intelligent facility and workplace management.

In the solution, the Object Re-ID sub-system can provide accurate object recognition services for IoT devices, facilitating automated energy management, air quality monitoring, and operations and maintenance of equipment, facilties and workplaces. For instance, the system can accurately determine whether a device requires repair or replacement, consequently reducing resource wastage and downtime. Simultaneously, by tracking objects in the scene in real time, the system aids in implementing intelligent lighting, air conditioning, and security monitoring, thereby enhancing the overall efficiency of facility operations.

Furthermore, the Object Re-ID prototype system can assist managers in monitoring employees' locations, behaviors, and activities in real time. For example, by identifying and tracking employees' movement trajectories within the office, more in-depth analysis and optimization of workspace layouts can be achieved. Additionally, the system can be applied to the domain of intelligent security, detecting anomalous behaviors in real time to ensure the safety of employees and corporate assets.

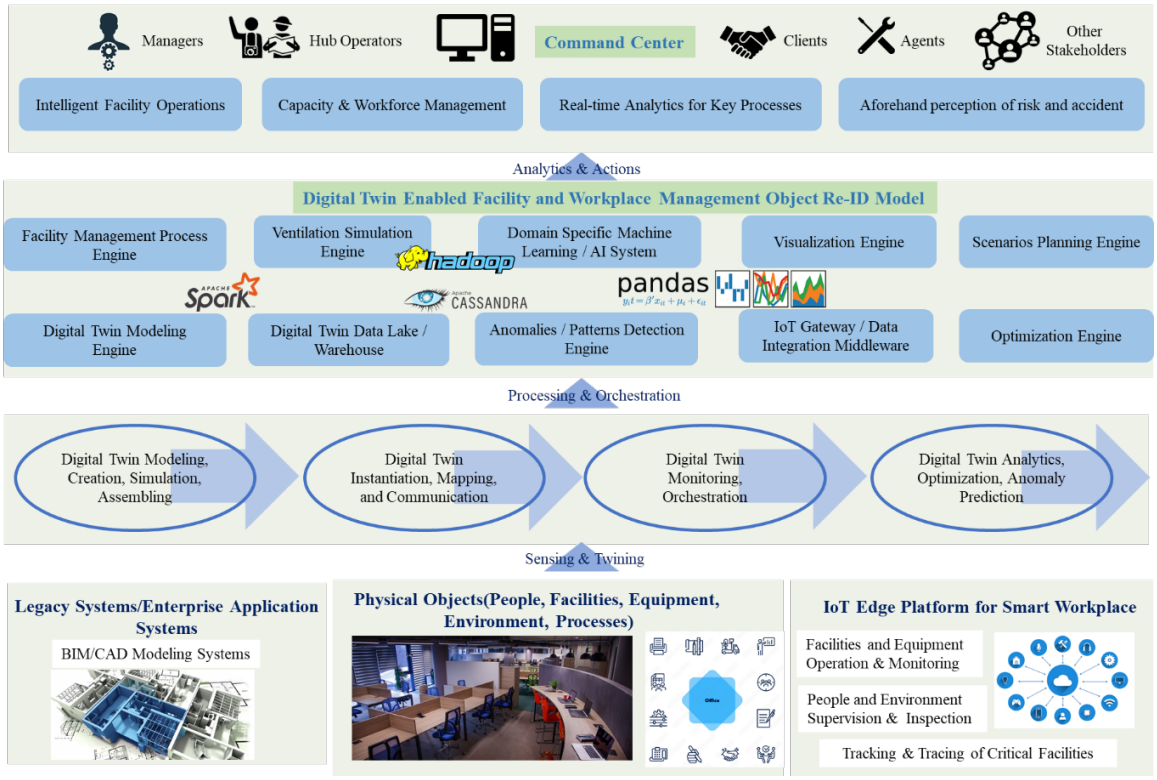

Figure 3: The General Architecutre of Object Re-ID and Digital Twin Enabled FM Solution

3.3.2 The Object Re-ID Subsystem in the Proposed Solution

A Object Re-ID subsystem is cusmtomized to implement the proposed solution for smart facility and workplace management. For tackling the issues of periodic data annotation and fine-tunning the deep learning models, a weakly annotated Object Re-ID training framework is designed to reduce data annotation costs and improve model performance. The framework utilizes weakly annotated information and self-supervised learning techniques for model

training while allowing human intervention to enhance model performance. As demonstrated in Figure 4, for improving the efficiency of data pre-processing the bounding box creation module uses correlated object identification and tracking techniques to extract the target items from the raw data first, then extracts and merge features of target objects to create the unlabeled data pool U.

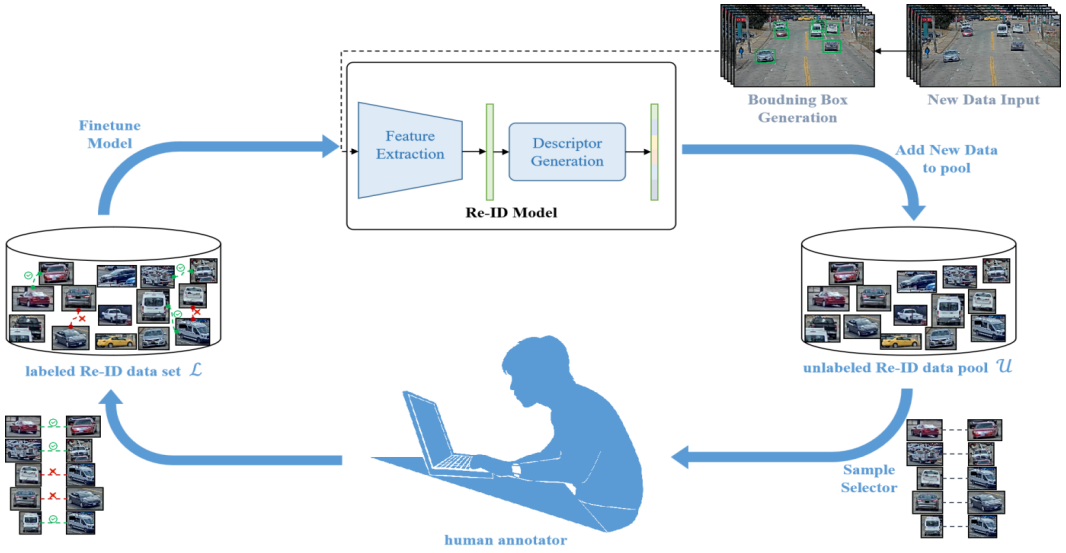

Figure 4: The Object Re-ID Framework for Model Training

In order to enhance the performance of Object Re-ID model, the most useful samples from the unlabeled data pool U are chosen and subjected to manual data annotation. The sample selection process will be repeated for every subsequent model training cycle.The weak annotation of samples is done by annotators and later added to the annotated dataset L. The Object Re-ID model is adjusted using the annotated dataset L.

Figure 5 demonstrates an end-to-end Object Re-ID subsystem that is implemented based on the the proposed Object Re-ID model training framework. The subsystem consists of modules for basic data annotation, sample matching and model training, and model deployment.

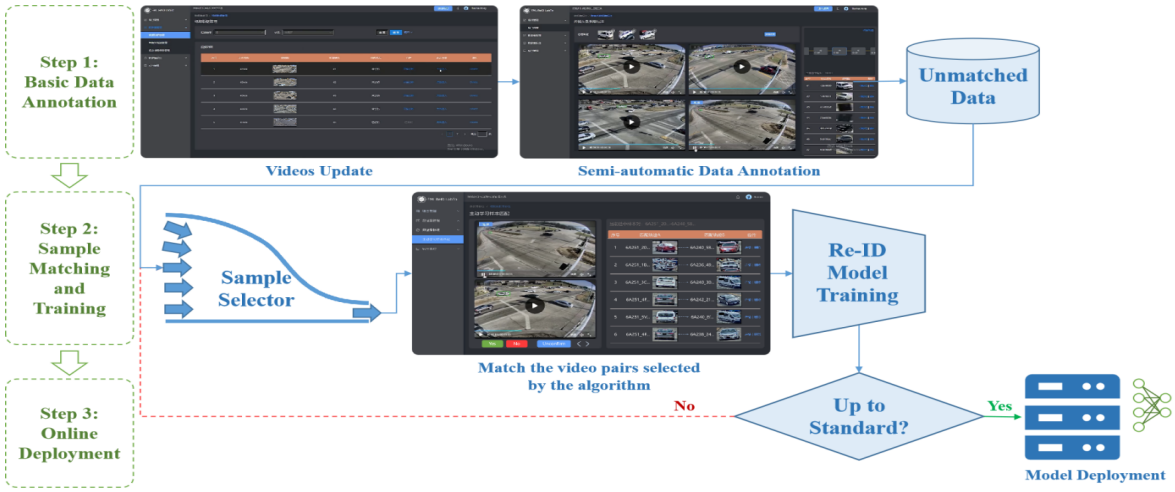

Figure 5: The Developed Object Re-ID Subsystem

In the prototype subsystem, the basic data annotation module (e.g., extracting the bounding box and trajectory) is implemented through relevant computer vision algorithms; the annotated data is stored in the Unmatched Sample database in the backend. For sample matching and model

training, appropriate sample selection algorithms are implemented to extract the best images or videos from the Unmatched Sample database. Then a data list is created to the front-end, where the user can view the selected pair samples and make "Yes" (the selected pair samples are the same),"No" (the selected pair samples are not the same) or "Unconfirm" selections (the selected pair samples can not be intuitively determined). After labeling, the manually labeled results will be submitted to the Re-ID model trainer for model fine-tuning. If the perfomance of trainned models meet the required criteria, they will deployed dynamically into the smart facility and workplace management solution. Otherwise, the system will return to the sample match and model train process.

3.3 Testing and Validation of the Proposed Solution

The proposed Object Re-ID and digital twin enabled facility and workplace management solution is being tested and validated in selected case studies. For custom inspection scenario, the very preliminary results show that the solution can extract useful video clips from the huge amount of original surveillance videos at the customs cargo inspection site and realize the video concentration function, thus saving labor and time cost. The generated condensed video retains the images of key targets and controls the duration to a few percent or even a few thousandths of the original videos. These condensed videos greatly facilitate the review process while ensuring the integrity and accuracy of the surveillance data. For smart lab management scenarios, the solution can be utilized to track the location and tractory of equipment and objects in real-time. The Object Re-ID information can be exploited to streamline facility management procedures, lessen manual intervention, and boost organizational effectiveness. In addition, the system is capable of issuing alerts by monitoring the usage and status of equipment. Abnormal and irregular equipment behavior can be identified, then potential failures and risks be predicted. Administrators can take timely action based on the early warning information to avoid equipment damage or safety incidents.

The Object Re-ID subsystem is also tested and validated. The preliminary findings demonstrate that it can provide a cost-effective solution for data annotation and model training for different applications. The system adopts an end-to-end design that allows users to complete the entire Object Re-ID process on a single platform. This design not only facilitates user operations, but also improves the overall efficiency by avoiding data loss and delays caused by data conversion and transmission between different operations. Moreover, the system adopts a weak annotation method, which can greatly reduce the data annotation cost and effectively reduce the errors caused by manual annotation. Futher, the system can automatically adjust the model and improve the performance of the model through the annotation results fed by users.

The system will be improved further to enhance the efficiency and reliability of supervision and management.

4. Preliminary Results and Research Findings

This research investigates the challenges and solutions of applying the state-of-the-art object Re-ID technologies to digital twin enabled smarter facility and workplace management. In particularly, typical requirements for monitoring objects and processes in a customs inspection workplace and a research laboratory are collected; the corresponding use cases are speculated for developing a small-scale prototype system. In addition, the raw dataset, annotated dataset, feature representation learning models and model evaluation algorithms are customized and fine-tuned to fit the practical application of smart facility and workplace management. This study shall provide relevant stakeholders with fundamental guidance and knowledge to

implement digital twin enabled solutions for achieving higher efficiency, productivity, reliability and safety.

5. Conclusion and Future Works

This paper presents an Object Re-ID and digital twin enabled framework for smart facility and workplace management. An end-to-end prototype subsystem is implemented for object Re-ID and image analytics, which includes the whole lifecycle of dataset collection and pre-processing, effective sample selection, weak annotation of training dataset, model fine-tuning and deployment. The very prelimnary results show that the digital twin enbaled FM solution enhanced with Object Re-ID technology can facilitate accurate asset and person tracking and monitoring; and the Object Re-ID technology is a indispensable compnent for implementing actual digital twin enbabled facility and workplace management solutions.

Future work can be conducted in several directions to optimize the proposed solution. First, more advanced Object Re-ID algorithms are needed to to improve accuracy and efficiency in complex and large-scale environments. Second, integrating the information from other sensors (e.g., environmental, acoustic, etc.) with video data can provide more comprehensive information about the physical facility and workplace environment. Finally, implemening deep learning algorithms for Object Re-ID at the edge can improve the performance of anormaly detection and prediction for proactive and prescriptive opeartion and maintenance of facilities and workplaces.

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