A Study of Digital Twin and Its Communication Protocol in Factory Automation Cell

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SUMMARY As for a growing population, factories need to be more productive and efficient. It is unarguable that machine-to-machine robot communication contributes to the improvement of data exchange between robots. Robots will be able to perform tasks that require higher precision, like robot-robot collaboration. Aside from the communication between robots themselves, it is necessary for humans to be able to communicate with them. Human supervisors need to be able to monitor the whole robotics system through a digital twin using real-time data acquisition from every robot. The objective of this study is to focus on the implementation of machine-to-machine robot communication and real-time data acquisition, especially in real and scalable industry use cases. First, implementing communication protocols is applied for communication between robots. Second, set up edge computing to help robots with motion planning after an interruption occurs. Then, retrieve all the robot data to perform localization and mapping of all robots in the workspace. Finally, the system was simulated and monitored real time in a digital twin.
keywords: *Digital Twin; Communication Architecture; Robotics; Cyber-Physical System*

1. Introduction

Today, there are many different technologies involved in the development of smart manufacturing factories using wireless networks and digital twins for communication and data analysis. These developments would lead to the possibility of intelligent automation, collaborative robot systems, and multi-scale dynamic modelling.

Machine-to-machine networks have become a crucial part of the next generation of factory automation because all the information is used in the production process. A smart manufacturing factory contains many autonomous robots working together with computers and digital information called multiple-robot systems (MRS) [1]. A decentralized system has no central controller but instead uses machine-to-machine interactions between robots. None of the robots have authority over their teammates, so they are unaffected by the failure of individual robots [2].

Over the past few years, many experiments have been conducted related to the machine-to-machine network. One of which uses the four application-layer protocols which are TCP, UDP, UDP Broadcast and UDP Customized Broadcast [3]. The experiment shows that each of the four application-layer protocols can be implemented into a machine-to machine communication protocol as an auction-based framework for mobile robots forming a factory wireless network [3].

Localization and mapping of robotic systems are also important concepts in smart manufacturing. One of the localization and mapping technologies, the visual positioning system, is an interesting method. It is small, low-cost, and has a simple hardware setup. For example, the camera or position sensors such as the odometer or IMU [4]. The data gathered by Lidar will be correlative to points on the 3D map. A map is built from multiple Lidar measurements or Lidar embedded on a mobile robot [5].

Digital twin is another technology that has been implemented in many industries. A digital twin is referred to as a virtual duplicate or real-time visualization of a physical system with the use of smart sensors, the Internet of Things (IoT), edge computing, machine learning, and artificial intelligence (AI) [6]. The digital twin's main function is to reproduce the physical object (properties, behaviors, and rules) to operate the models through simulation. It allows users to remotely monitor, predict problems, and validate the performance of physical objects. Performing the following tasks requires a connection between physical-physical space, virtual-virtual space, and physical-virtual space [7].

The digital twin reference model has been presented by pointing out the four main layers [8]. The first layer is the physical space consisting of physical industry resources. The second layer is the communication systems, which can be sensors, transducers, or any device that can send out data. The third layer, the digital twin, is where prediction, control, execution, or simulation takes place. All data is then stored on the platform and sent to the last layer, the user space. User space is where people can easily access all the warnings, data, and status. There are currently many enabling technologies that can support the four layers [9].

Literature studies described above have pointed out an enabling technology for the development of smart manufacturing and digital twin. However, the above reviews provide just a general framework but do not really focus on the implementation of the technology. Here, we are pointing out the use case of both the digital twin and our selected communication protocol. Section 2 will briefly explain our scope overview, communication protocol, and robot localization and mapping. Section 3 shows our experiments on real factory automation cells. Section 4 includes our conclusion.

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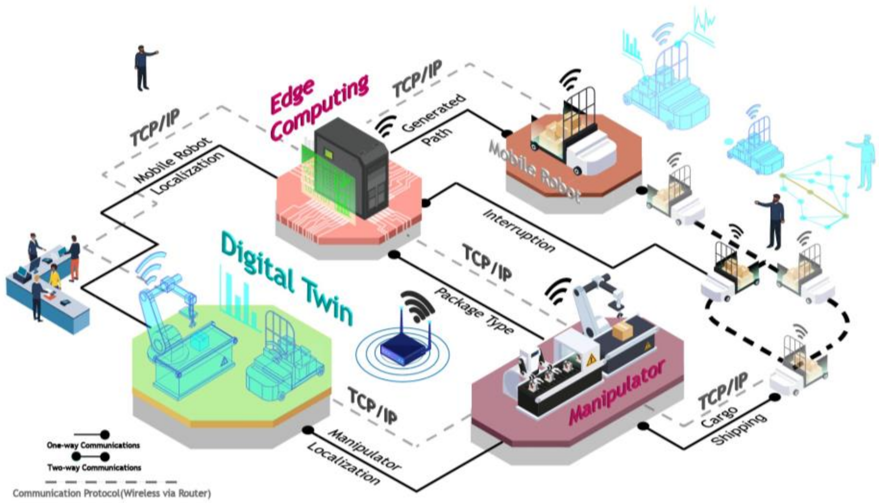

Fig. 1. An overview diagram of our scenario automation cell.

2. Methodology

2.1 Scope Overview

For an overview, an automation cell operates wirelessly via a Wi-Fi (OFDMA: 802.11ax) router for scalable massive machine type communication, with a combination of devices interacting with each other in a physical space and their data processing in a digital space, called a digital twin. The purpose of the digital twin is to monitor, predict, and control the working process and behavior of devices in a physical environment with soft computing [10].

In our research scenario, Fig. 1, a cargo is sent to a mobile robot by a manipulator in physical space, delivered to three different warehouses classified by its type. This mobile robot travels along the path that edge computing has generated. It is flexible due to its sensor that interrupts the movement when something obstructs its path. Thus, edge computing will compute and send a new route for the mobile robot to avoid that obstacle. Meanwhile, the manipulator is doing some own tasks until the mobile robot gets close enough. Then the manipulator breaks its working loop, preparing and sending a package to the mobile robot. The manipulator will send the cargo type to edge computing to assign the route to the kind of warehouse for the mobile robot. Moreover, the digital twin can collect real-time data from the devices and monitor them running parallel to their process. In our case, we use the localization method to get position data to display the real-time movement of the manipulator and the mobile robot.

For the virtual warehouse system, all the devices will simulate on a 3D map. The map consists of 5 main parts: Unloaded Station (A, B, C), Loading Station, and Charging Station. Normally, the mobile robot is at the Charging Station. It will move to pick up the cargo at the Loading Station to deliver the cargo to the Unloaded Station (A, B, C). When the delivery is complete, it will return to wait at the Charging Station.

Usually, the movement of the mobile robot is a fixed path, which is the fastest way and optimized routes to receive and deliver goods, except there is an interrupt, which will exist in two cases. First is when the mobile robot has delivered the goods and is moving back to the charging station but is called from the manipulator that changes the route from charging station to loading station. Another case is when the mobile robot detected an obstacle. It will follow a new path of movement that can still reach the target position.

2.2 Communication Protocols

In an automation cell, several devices are limited to only some communication protocol. For example, a manipulator can be developed and programmed by using G-code and UR-script programming. However, it does not support MQTT (Message Queuing Telemetry Transport) wireless protocol. Thus, as shown in Fig. 2, Raspberry Pi4 boards, programmed with Python, are brought to connect with them as a wireless receiver. For the digital twin, we used edge computing to calculate paths and display the simulation of the system with MATLAB wirelessly. Now, we can use TCP/IP and MQTT protocol as our standard communication protocol for the automation cell.

During an operation, the digital twin collects the Dynamic IP Address of the manipulator and mobile robot via their topics (MQTT) and puts them into the Routing table. Thus, the digital twin can connect to them and exchange information via TCP/IP protocol. When the manipulator gets a cargo from a conveyor, it sends the package's type to edge computing to identify which warehouses to deliver. The digital twins search for the mobile robot, which is free from the duty in this area. Then, it will send this mobile robot's IP Address to the manipulator by MQTT Protocol. Thus, the connection between the manipulator and the mobile robot creates.

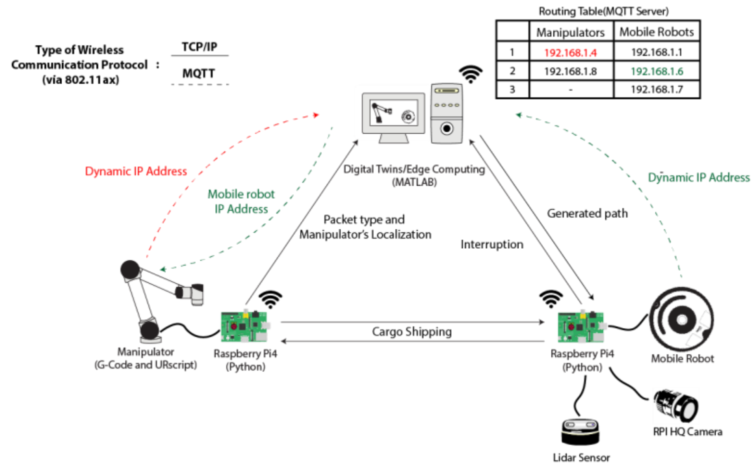

Fig. 2. The proposed system architecture.

2.3 Robot Localization and Mapping

For localization and mapping of robotics system, cameras and lidar scanners are applied. The lidar is used with the mobile robot to initialize its position by scanning and sending an absolute position to the edge computing in order to perform cargo shipping tasks, while a camera installed on the mobile robot is used for obstacle avoidance tasks. Each manipulator is equipped with a camera used for its workspace mapping. We used Robotic System Toolbox in MATLAB to visualize the localization and mapping of the robotics system. This toolbox generates paths for the iRobot so the robot can travel along the route. Each devices' localization data will be brought and displayed the same 3-D coordinate creating a virtual simulation of the devices running parallel to the real-world operation.

3. Experimental Results

3.1 Localization and Mapping of Manipulator

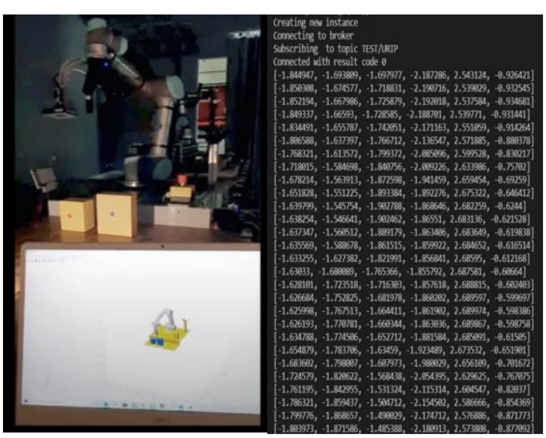

Fig. 3. Physical space and virtual space of manipulator with raw data of its joint positions.

The localization and mapping of the robot manipulator can be seen in the physical space and virtual space as in Fig. 3. Wireless data transmission was used to retrieve the robot joint position of the robot arm. Both the IPs of the digital twin and robot manipulator were registered via MQTT, while the protocol used to send the manipulator joint angle position was TCP/IP. Data were collected and transmitted through python programming and then sent to MATLAB for simulation as shown in Fig. 3.

The camera was used to create workspace mapping. We started by using Color Thresholder to crop the front of each box by choosing the right color that matches the box color. Next, we identified each box using Bounding Box which was used to find different edge points. Then we extracted the center point, length, and width of the image in pixel unit. To identify box location, we mapped the depth of the camera by measuring pixel coverage per unit length in each depth using linear regression. See full operation from Supplementary Material [S1].

3.2 Localization and Mapping of Mobile Robot

The mobile robot, iRobot Create, operated with the odometry method and SLAM (Simultaneous Localization and Mapping). In detail, the lidar scanner detected the mobile robot initial position before starting the task, the onboard processor then controlled the robot trajectory using the waypoint estimated by odometry, the processed data was sent from the robot to digital twin via wireless communication to update an accurate physical map in the digital twin. As shown in Fig. 4, the mobile robot performed a task in physical space while collaborating with the digital twin showing the updated status, waypoint, and trajectory of the mobile robot in digital space which could be applied in terms of trajectory estimation and path planning.

In this experiment, the mobile robot delivered cargo to the unloading station B. The mobile robot used a camera,

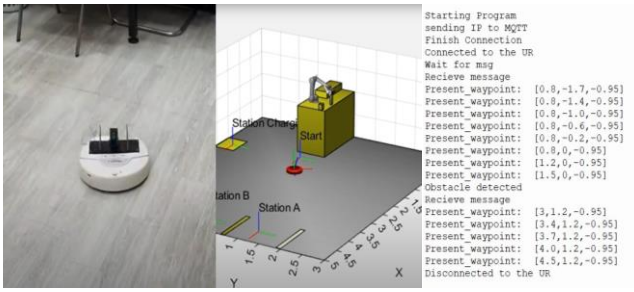

Fig. 4. Physical space and virtual space of mobile robot with raw data of its waypoints.

attached to the front of the robot, to inspect the obstacle in the running direction. When an obstacle was found, there will be a display in the digital twin of the system and a box showing that the robot would not be able to pass through that coordinate. When an interruption occurs, the edge computing was required to recalculate the route using PRM (Probabilistic RoadMap). New paths on a given map are found using random selecting empty coordinates, also known as nodes. This result in a new path, moving from its starting point to the end point without going off the map or hitting any obstacle. See full operation from Supplementary Material [S2].

3.3 Robot interaction in digital twin

In this experimental scenario, the mobile robot and robot manipulator could operate their task in the physical space and virtual space. Digital twin was the main system that collect and store the most reliable mobile robot and manipulator performance data for massive computation features and time-dependent missions.

When the cargo was ready for shipping, the manipulator requested a mobile robot from the digital twin with the cargo type. Since the digital twin knew the status of every mobile robot in the system, it assigned a mobile robot to the manipulator. The manipulator received the mobile robot IP address that was assigned and made a TCP/IP communication to successfully deliver cargo to the mobile robot. After the successful connection between robots, they disconnect from input from digital twin, communicating on their own resulting in lower latency between the robots.

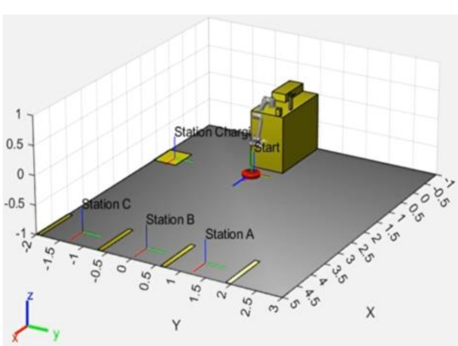

Fig. 5. Mobile robot-manipulator interaction

With machine-to-machine communication, manipulator would directly be triggered by the mobile robot to perform the cargo shipping tasks when the mobile robot enters the manipulator's workspace. After the mobile robot received the package, as seen from Fig. 5, it would disconnect communication with the manipulator.

4. Conclusion

We successfully localized and mapped the robotics system integrating machine-to-machine communication in factory automation cell showcase. Machine-to-machine communication and digital twin offer many benefits as they support machines to work together and supervisors to monitor the systems effectively. As a result, our study provides some prospects for next-generation technology. The digital twin plays an important role not only in industry 4.0 but also in new technology products. It gives accurate information about the device monitoring in real-time. Thus, it can predict and optimize the maximum performance through all stages of the product life cycle.

Acknowledgments

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