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Development of Rail-guided Smart Patrol System for Surveillance and Monitoring of Facilities Safety

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Abstract— **This paper describes the design and implementation of a rail-guided mobile robot-based monitoring system that can be used for autonomous monitoring of the facilities and rapid response to the on-site event. It is necessary to improve the safety and efficiency of the monitoring system when applying a robot system, and the implementation of intelligent functions can increase the level of automation to facilitate operation. In order to increase driving safety and lower the level of control, a two-track rail structure of circular pipes, U-shaped wheels, and a differential gear are used to develop a driving system that enables rotational path driving even with forward and backward movement. For the proper monitoring of facility conditions, high-temperature occurrence, and environmental quality, cameras (RGB and thermal imaging) and air quality sensors are chosen by considering the range of the monitoring site and target subjects. Data communication between the robot and the remote control room(a remote server) is built up to patrol in a planned schedule and deliver acquired video streams and environmental sensor data. Emergency alarms about high temperatures and the abnormality of air conditions can be generated by processing the transferred data. Additionally, deep network-based detection services on video data are implemented on the server for the detection of emergency situations; fall downs. Integrating the developed driving system, image/sensor data communication, and alarm function through data analysis in an operating framework reduces management work through automatic patrol and enables efficient on-site response when an alarm occurs. The validity of the proposed system is demonstrated by building and operating the system in the existing multi-use facility. The automatic patrol function and the manual operation function are performed through a test operation similar to the facility monitoring task of a human operator. The operator can control the robot to move to a desired position along the path, and by manipulating the camera module, the operator can check the on-site situation via a video stream The environmental sensor data is also transferred to the server and stored during operation, and the robot normally completes the automatic patrol task and returns to the charging station. In a simulation experiment to verify the detection alarm service, the test shows that a human falling down is detected even in the field.**

I. INTRODUCTION

There has been an increase in the demand for intelligent systems that perform monitoring and surveillance of multi-use facilities such as wholesale markets, exhibition halls, and terminals. These kinds of facilities often require continuous monitoring as with many repetitive, routine tasks. The current approach is to install a large number of CCTV, sensors, and alarms. While the fixed monitoring devices can be simply installed and operated, they are limited to providing multi-angle information and reacting to the suspect site.

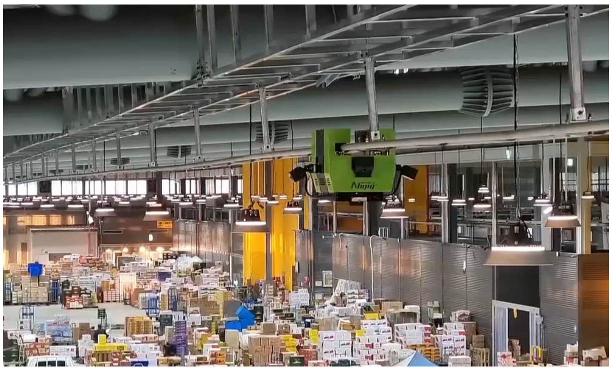

Fig. 1. Rail-guided smart patrol robot on an agricultural wholesale market

During the last decade, many researchers have shown an increased interest in the use of the robotic system for scalable and flexible solutions for automation and fine operation over large facility monitoring with safety and efficiency. Rail-guided systems are one of the most promising solutions in the facility monitoring field, as they have several advantages over other mobile systems' complexities such as; high localization precision, simply achieved by restricting the robot on the rail structure [1] [2] [3] [4]. Rails can be installed on walls or ceilings to provide a safe separated robot operational region from visitors, workers, or ground machinery. It also enables the robot to scan the facility in a scheduled routine at the designed position efficiently and accurately. In an emergency, the robot can rapidly move to the emergency site without any obstacles. There have been similar studies on facility management with rail-guided robot systems [5] [6] [7].

This research aims to develop an intelligent patrol system(see Fig.1) with an integrated autonomous driving system and multiple sensors for prevention and reaction to conflagration, accidents, and dangerous situations by patrolling and scanning the whole area of the facility. To realize this, the design and development of a rail-guided autonomous patrol robot are considered to provide safe and efficient operation for facility monitoring and initial reaction. The detection functions based on image processing and deep learning-

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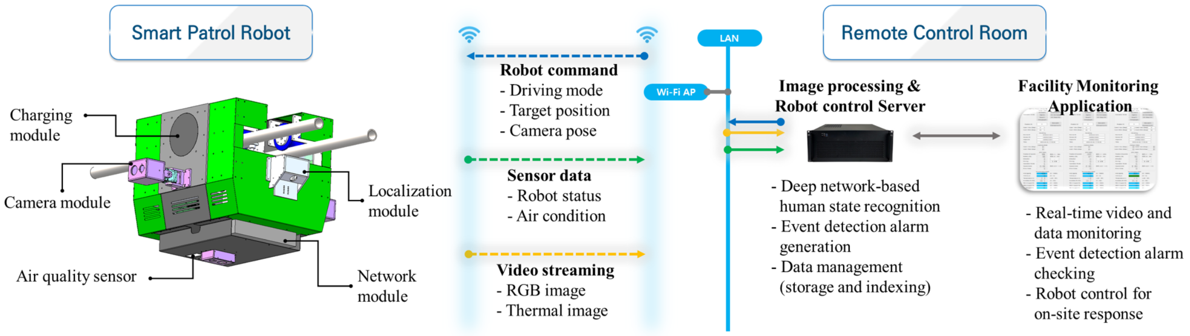

Fig. 2. System overview: configuration of Smart patrol robot, the definition of data, and services of Remote control room

based detection techniques can provide useful information to reduce the monitoring effort of the human operator and prevent disaster from happening.

II. SMART PARTOL ROBOT-BASED FACILITY MONITORING SYSTEM

Figure 2 shows detailed configurations of the proposed rail-guided robot-based facility monitoring system. To accomplish the development of the target system, the automated patrol robot and the data processing server in the remote control room are required to embed the next five functions.

24-hour mobile patrol: The smart patrol robot automatically drives according to the plan to check the status of the facility, and it is possible to return to the charging station after completion. Considering the monitoring viewing angle and distance, the robot is required to place within $\pm 0.2m$ position error. The docking range of the wireless charging station is within $\pm 0.05m$. Through precise position control using the BLDC motor, the driving unit is possible to achieve with $\pm 0.01m$ error by the encoder pulse computation. Additionally, the absolute position is collected using the barcode reader of the localization module by reading the barcode attached to every $1m$ of the rail path. To prevent collisions while driving, ultrasonic sensors are installed in the front and rear to perform emergency stop operations to facilitate automatic driving.

Active camera motion: The camera module attached to the side includes a pan-tilt actuator to move the direction of the cameras up, down, left, and right, so the operator can check the situation in the facility where detailed observation is required. A full-HD RGB camera with 60° Field Of View(FOV) and a thermal camera with a 320x240 pixels sensor, 60° FOV are selected to cover a cell of stores horizontally and floor to top of the store vertically. Real-Time Streaming Protocol(RTSP) servers are created for each camera to stream videos over a connection from the server.

Environmental monitoring: The environmental condition in the facility is monitored by measuring the air quality at each location during patrol. The air quality sensor is selected to measure the following 7 types of air quality; temperature, humidity, CO_2, Volatile Organic Compounds(VOC), Particulate Matter(PM1.0, PM2.5, PM10). The measured data is converted into a message form and transmitted to the server every 1 second.

Fire detection and response: All data acquired while the robot is patrolling in the facility is collected and stored in the server of the remote control room in real time. The video streams of the camera module are transferred to the server by connecting to the RTSP server running on the robot. The maximum temperature in the thermal image is detected and classified into a state of interest/caution/alert/danger according to the temperature level. The RGB image confirms whether a fall accident has occurred through human detection and posture recognition. To collect data, the server creates a Message Queuing Telemetry Transport (MQTT) message broker to collect and manage all data transmitted by the robot. Changes in air quality data are monitored and an environmental anomaly detection alarm is generated.

Dissemination of on-site situation and countermeasures: In addition to the MQTT message broker for sensor data, an MQTT message broker for robot driving system control and camera posture control is also created to convert commands from the dashboard into messages. The message stored in the broker is checked in real time by the robot, and the robot operates according to the command. Therefore, the operator can check the data collected from the server and the generated alarm information, and remotely control the robot for further confirmation and action on the on-site situation.

III. DRIVING SYSTEM OF SMART PATROL ROBOT

Figure 3 shows detailed mechanical configurations of the driving system of the developed smart patrol robot. The proposed patrol robot is designed to run on a 2-track rail structure with 4 wheels. The rail structure is supported by square frames installed on the ceiling. The robot is driven by controlling the BLDC motor placed in the robot body. The motor shaft is connected to the differential gear and the gear output shaft is connected to the left and the right pulley and belt respectively. After the pulley and belt components, the driving wheels are connected. The circular pipe is gripped with a U-shaped wheel, and a damper pushes the pipe to

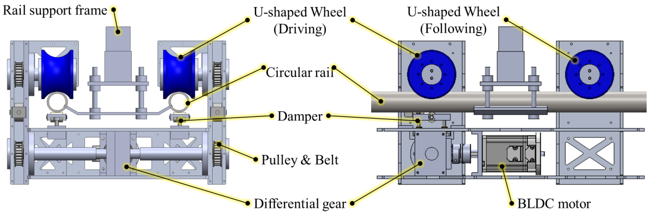

Fig. 3. Configuration of driving system

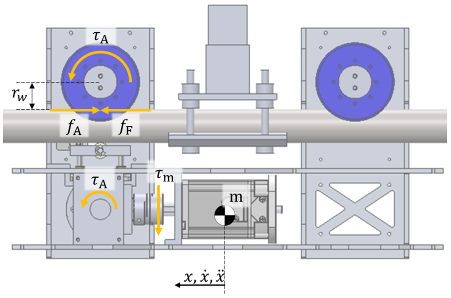

Fig. 4. Dynamic model of the smart patrol robot

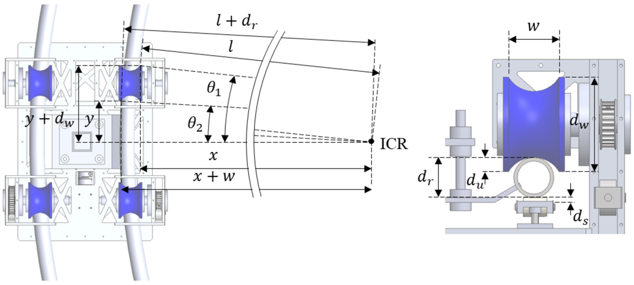

Fig. 5. Kinematical descriptions of the rail structure and the smart patrol robot

maintain the contact condition between the robot and the rail.

Figure 4 shows the relationship between the robot motion, x,$\dot{x}$,$\ddot{x}$ and the output torque of the motor,τ_m, and it can be defined as follows:

$$m\ddot{x} + b\dot{x} + f_F = f_A \tag{1}$$

where, x is the position of the robot according to the rail path. m is the total mass of the robot, and b is the damping coefficient at the wheel. the driving force,f_A can be driven with the driving torque, τ_A, and the radius of the wheel, r_w. The driving torque, τ_A is driven with the motor torque, τ_m, and the gear ratio, n.

$$f_A = \tau_A / r_w \tag{2}$$

$$\tau_A = n\tau_m \tag{3}$$

The following equation is the model of the friction force.

$$f_F = \mu mg \ sign(\dot{x}) \tag{4}$$

where, μ and g are the friction coefficient of the contact surface and the gravity acceleration respectively. The signum function is used to define the direction of the friction force. Using the above dynamic model, the motor selection and damper internal spring can be selected according to the target performance of the driving system. In this research, a $200W$ BLDC motor with $3000rpm$ speed and $0.635Nm$ rated torque is selected to achieve $1.8m/s$ of the peak speed.

Figure 5 shows the state of the minimum radius of rotation that does not deviate from the groove of the wheel. The robot can be driven by constraining it to a circular rail pipe using a U-shaped wheel and damper when the maximum stroke of the damper, d_s is shorter than the depth of the groove of the wheel, d_u. Therefore, the radius of rotation of the rail is limited according to the design parameters of the robot. The equation expresses the distances from the ICR to the inner contact point and the outer contact point of the wheel and the rail.

$$l\sin(\theta_1) = y + d_w \tag{5}$$

$$l\cos(\theta_1) = x \tag{6}$$

$$(l + d_r)\sin(\theta_2) = y \tag{7}$$

$$(l + d_r)\cos(\theta_2) = x + w \tag{8}$$

where, the radius of the rotational path, l, and the distance between ICR and wheel, x, can be found by determining the design parameters of the robot and the rail; the distance between the front wheels and the rear wheels, y, the wheel diameter, d_w, the rail diameter, d_r, the groove width of the wheel, w. Using trigonometric functions and rearranging the equation, the expression for l can be obtained as follows:

$$l = \sqrt{(y + d_w)^2 + x^2} \tag{9}$$

where,

$$x = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \tag{10}$$

$$a = \left(\frac{w}{d_r}\right)^2 - 1 \tag{11}$$

$$b = \frac{w(y^2 + w^2 - (y + d_w)^2 - d_r^2)}{d_r^2} \tag{12}$$

$$c = \left(\frac{y^2 + w^2 - (y + d_w)^2 - d_r^2}{2d_r}\right)^2 - (y + d_w)^2 \tag{13}$$

Figure 6 is a reference model of the speed controller used for position control of the robot. The acceleration time and deceleration time are experimentally decided in the range where vibration does not occur during acceleration and deceleration. When the target distance and constant velocity are determined, the position of the robot can be controlled with constant movement time. Also, it is possible to correct errors that occur due to the acceleration/deceleration of the robot and the slip of the wheels.

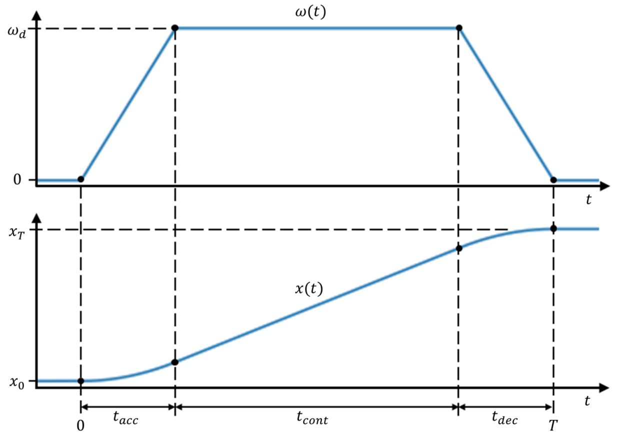

Fig. 6. Speed reference model for driving control

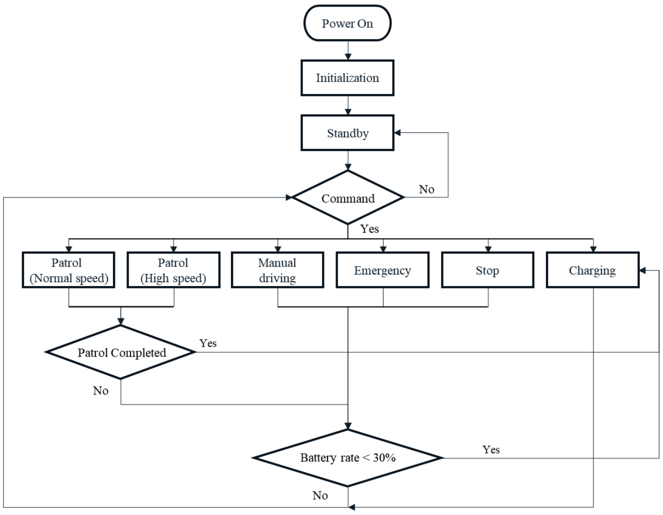

Fig. 7. Flow chart of smart patrol robot operation

IV. OPERATION FRAMEWORK FOR SMART PATROL SYSTEM

To manage the facility with the configured robot-server system, it is necessary to classify the necessary tasks and define the appropriate operation commands. The tasks are largely divided into a task that collaborates with the operator and a planned task without the operator's intervention, and the actions are defined as the task for movement and the task for data acquisition.

Normal-speed patrol: In order to monitor the status of the facility without the intervention of an operator, the robot carries out the patrol task according to a planned schedule, acquires environmental data, and performs video streaming. In a situation where the facility is in a normal state, it is driven at a low speed($0.6m/s$) to periodically check changes in the environmental condition to acquire as much data as possible about the facility. The angles of the camera module are fixed in advance while performing patrol operations. The alarm information is generated from the detection function and provided to the operator. This operation can reduce the workload by acting on behalf of operators on repetitive and tedious tasks.

High-speed patrol: At the request of the manager, it moves at a faster speed than normal speed patrols to quickly monitor the general management area of the facility remotely. both environmental data acquisition and video streaming are performed in the same way as normal speed patrols. The angles of the camera module are fixed in advance while performing patrol operations. The maximum speed $(1.2m/s)$ is determined as within the range where video streaming is possible. When driving at high speed, it is difficult to obtain enough image data for the detection function, so the alarm information cannot be provided. This operation can increase work efficiency by assisting operators with repetitive and tedious tasks faster.

Manual driving: This operation mode is for the operator to remotely monitor a specific location of the facility from the control room. The operator's decision is the first prior and allows a high degree of freedom. The robot receives the location input from the operator and moves at high speed $(1.0m/s)$. While driving, the operator can manually control the camera angle remotely. However, the detection function is not supported until arriving at the target point. This operation can increase work performance by extending the operators' task area.

Emergency: When an emergency alarm is received from the linked external system, the robot operation task can be immediately confirmed with this operation command. The robot moves at the maximum speed $(1.5m/s)$ according to the received emergency information and performs the detection and monitoring functions after arriving at the site. This operation provides the highest level of automation, however, it is important to link it with highly reliable information.

Figure 7 is a flowchart for the transition of operation mode for task execution. In addition to operation modes, there are actions required to initialize the system or switch to another mode after stopping or completing each operation mode. Stop mode is a command to pause all work, and it is possible to resume or change work after grasping the situation. In charging mode, the battery status is checked to recharge the consumed power after performing all tasks and returns to the charger when the battery is low. Robot control commands are transmitted to the robot in the form of messages through the server's MQTT broker.

The facility monitoring application can monitor all information about the robot status, environment state, and detection alarm by subscribing to three message brokers; robot data, sensor data, and alarm data. And robot control is also possible by publishing a robot command message to the robot command MQTT broker.

V. FALL-DOWN DETECTION SERVICE

A fall-down detecting service is implemented to respond to a fall accident occurring to a visitor or worker. Figure 8 is a flowchart of the fall detection algorithm. This algorithm is implemented on the server and processes the robot's video stream. From the transmitted video stream, a person is detected. The detected person is tracked and his pos is continuously estimated until accumulated enough. The person's action is recognized based on the accumulated data and determined if the action is a fall. The detailed implementation of each step is as follows.

Human detection: YOLOv3 is used as a deep learning network to detect people in video stream[8]. In the result of the algorithm, the detected person is bounded with a box. YOLOv3 has the advantage of fast operation. Therefore, it is suitable for use in fall detection algorithms for real-time processing.

Pose estimation: AlphaPose[9] is used as a deep learning network for estimating the posture of a person recognized through YOLOv3. AlphaPose is a posture estimation network that uses a Top-Down approach, showing high accuracy and maintaining a processing speed of 15 FPS.

Object tracking: Continuous spatial and temporal information about a person's posture is required over several frames in an image to recognize a person's behavior. In order to secure real-time performance, a tracking method based on the minimum cost bipartite matching is implemented and applied. The Hungarian matching algorithm [10] is used to obtain the bipartite matching in this research.

Action recognition deep-network: The ST-GCN (Spatial Temporal Graph Convolution Network) deep learning network is used to recognize human behavior using stored posture information [11]. ST-GCN uses temporal and spatial graphs as inputs to recognize human behavior. AlphaPose extracts a total of 17 joint points. A person's posture is defined as a graph structure by using the human joint point as a vertex and the connection between each joint point as an edge. Then, according to the object tracking method, the stored human posture is used as a temporal movement to recognize human behavior.

The implemented detection algorithm is preliminarily evaluated with UP-Fall Data set [12] and UCF101 Data set [13]. Table I is the result of the implemented algorithm. As a result of the experiment, this algorithm's fall detection accuracy rate is up to 97.66%, and the processing speed is up to 10.87 FPS, so it is expected that the robot will be able to detect falls in real-time. The detection alarm message is published to the server alarm MQTT broker when the fall-down detection occurs.

TABLE I

RESULT OF PRELIMINARY TEST

HAR-UP Data set	Accuracy	97.66%
	Precision	99.15%
	Recall	92.8%
	Speed	10.87 FPS
UCF101 Data set	Accuracy	86.25%
	Precision	96%
	Recall	70.59%
	Speed	9.01FPS

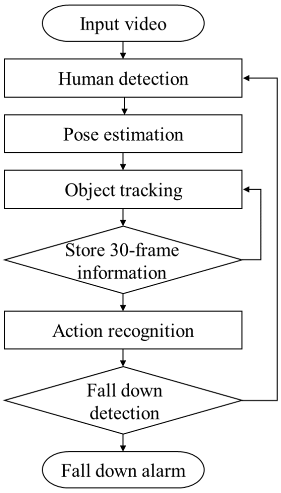

Fig. 8. Flow chart of fall down detection algorithm

VI. EXPERIMENTAL SETUP AND RESULT

The developed smart patrol system is implemented in an agricultural wholesale market. Figure 9 shows the floor plan of the rail structure. The path is designed to be a circular path to monitor stores and passageways together. The total distance of the path for 1 cycle is $220m$. Data transferring and video streaming from the robot while driving is tested. The robot state data and environmental sensor data are saved through the server, and the result is shown in the figure. Looking at the first robot position result graph, the robot initially operates in a low-speed general patrol mode, followed by the command, and moved to the charging station to complete the docking. In addition, environmental sensor data is also transmitted to the server and stored. To test the operation of the video streaming and detection service, a fall accident is simulated while the video is being streamed, and it is confirmed that it is detected by the server. Figure 11 (a) is an image of the result of the detection of a fall in the field, and (b), (c), and (d) of the figure are images of fire detection, intrusion detection, and violation detection using the implemented YOLO algorithm. It is confirmed that the system construction is carried out smoothly through the empirical experiment.

VII. CONCLUSIONS

In this paper, a rail-guided smart patrol system is developed for facility monitoring. The goal of the proposed system is to enable the system to autonomously monitor the facilities and rapid response to the on-site event. To move safely within the facility, a rail-guided driving system is developed for stable driving. The robot is equipped with a camera module and air quality sensor to measure the situation in the field. A message transmission function is implemented for the measured sensor data and robot control commands The high-temperature detection function and the fall detection function are implemented to use the sensor data and images for facility management. The effectiveness of the proposed system is

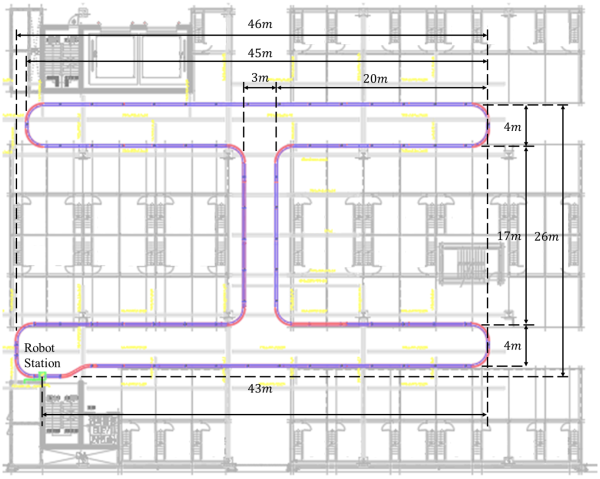

Fig. 9. Design of rail path: straight section (blue) and round section (red)

demonstrated by implementing and operating the system in the existing agricultural market. In future work, extensive experiments and analysis will be performed implementing and evaluating detection algorithms. This system can be further improved by employing various data processing and machine learning techniques for facility management functions.

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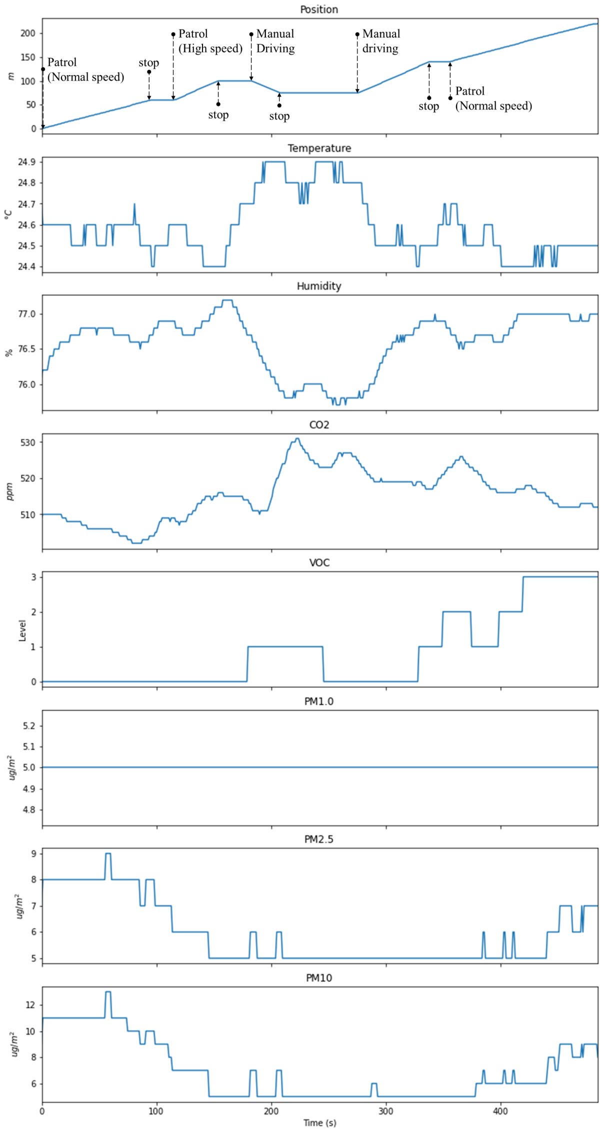

Fig. 10. Result of system operation: Robot position, Temperature, Humidity, CO2, VOC, PM1.0, PM2.5, PM10

(a) (b)

(c) (d)

Fig. 11. Result of detection service