Development of Tele-Operated Mobile Robots for COVID-19 Field Hospitals

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***Abstract*—In this article, a mobile robot for item delivery with tele-operation capability is developed and used in the field hospital. The user is able to control the robot and communicate with the patients via an web-app on a cloud server. The robots are deployed and tested on-site in a large size field hospital, while the workload of the robot is studied and planned by using simulation approach. However, the difficulties on actual implementation have arise due to the working condition and risk of infection. These take into account in the development and deployment phases of the system.**

Keywords – Autonomous Mobile Robot, Service Robot, Tele-operation, Field Hospital.

I. INTRODUCTION

In 2020, Coronavirus spread heavily and became a critical issue globally. Various robotic technologies were developed in order to support healthcare systems. Mobile service robots are used in many activities to help reducing the risk of infection of the health workers in hospitals, especially in the COVID-19 patient's wards. The main activities consist of item delivery, disinfection tele-medicine and etc. [1]. Autonomous Mobile Robot (AMR) is a main technology that has been adopted and applied to conduct these activities. "CARVER-AMR" is an AMR platform developed by the authors for logistic management in hospitals [2]. It can automatically navigate in patient wards, in this case, to deliver food and medicine to individual patients. The system was successfully implemented in many hospitals. However, the installation process is necessary to perform the effective auto-navigation.

In Thailand, the situation was under controlled in the last quarter of 2020. Unfortunately, the pandemic was out of control again in the second half of 2021. The pandemic situation went critical, especially when the number of infected increased dramatically. The patients outnumbered the capacity of normal hospitals. As a result, more than 500 field hospitals were established nationwide to serve the patients with mild-to-moderate symptom to expand the capacity of healthcare system. Generally, field hospitals were setup instantly within few days and quickly admitted the patients. Consequently, the installation of AMR system is challenging and risky since the infected patients were already on-site. This issue became a critical constraints of this AMR project leading to the problem statement: *"How can we deploy the robots without entering the hospital while the health workers can use the system effectively?"*.

According to the constraints and functions required, a tele-operated mobile robot seems the most appropriate solution so far. The system is designed to be "worried-free" for the user and extra installation is not required. Recently, this system has been successfully implemented and used in many hospitals. The process from development to deployment of the system will be revealed in this article.

This article is organized as follows: AMR and tele-operation robots are reviewed in *Section II*. Methodology for system development is described in *Section III*. Detailed implementation is explained in *Section IV*. Experiment and simulation results are in *Section V*. Conclusion and discussion are in *Section VI*

II. LITERATURE REVIEW

A. *CARVER-AMR Platform*

"CARVER-AMR" is designed based on safety protocol for service robots which cab be operated safely in the same area with people. The robot is equipped with industrial grade Lidar sensors in order to perform free-navigation throughout the predefined area. The Internet-of-Things (IoT) module allows the users to control and monitor the robot remotely via a web-app [3]. The platform is adapted for various applications, for example CARVER-Cab, a robot for food and medicine delivery with patient self-verification [4]. In this research, the robot is adapted based on this CARVER-AMR platform (see Fig. 1)

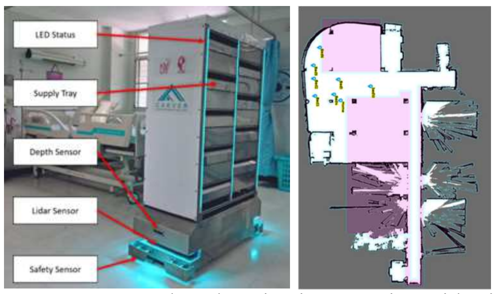

Fig. 1 CARVER-Cab and navigation mapping with Lidar

B. Tele-operation robot

Real-time response is one of the most important capability for the tele-operation robot. A delayed response increases the possibility of damage on the system due to the crash accident. Therefore, considering reduction of time delay is important for improving performance of the tele-operation robot. In addition to the time delay issue, tele-operation is developed in many approaches for increase performance and user experience.

[5] proposed a solution to tele-operate a humanoid robot easier. In general, the preset postures with one by one operation, which is time-consuming and cannot be real-time, is used. In this research, the system was able to achieve complicated operation by the finger-tip motion using glove type interface via Zigbee protocols in local network. [6] this paper proposed strategy of Internet of Things (IoT)-based human-robot collaborative control in robot-assisted minimally invasive surgery (RA-MIS) with HTC VIVE PRO controllers. Collision detection and visual force are applied to the robot for human-robot interaction. The experimental results showed that the performance in terms of the accuracy of the remote center of motion (RCM) constraints and surgical tip was improved. [7] proposed a new interaction mechanism for tele-operating a mobile robot by exploring the notion of tele-presence and physical embodiment. A Kinect sensor and Open-NI library are used to track the body posture that defines the 3D configuration of a skeleton-like model. The modules are communicated as a master-slave via wireless TCP/IP based connections in local network. For the commercial products, Temi [8] robots have been one of the most popular tele-present robots in recent years. Users can remotely control the robot to target positions both manually and automatically via the tablet. But the limitation is that the robot can carry only small payload.

Most of the tele-operation applications developed the communication system over Wi-Fi in which the time delay can be reduced. However, little research was focused on investigation of the tele-operation over the internet which needs to be implemented in our system.

III. Methodology

A. Requirements and constraints

The main goal of this system is to support health workers who work in the field hospitals by physically distancing between the health workers and the patients. However, the robot is required to perform various activities those are generally conducted by nurses. In addition, according to the limited accessibility to the hospital wards with full patients admitted, the mission has become extremely challenging. Therefore, the robot system and execution plan need to be strategically designed. The requirements, constraints, and solutions are described as follows:

- Performing food and medicine delivery for patients in spacious cohort ward at specific time, 3 meals for food and maximum 7 rounds for medicine each day.
- Nurses and doctors are able to communicate visually and verbally with patients for explanation, screening, and diagnosis purpose.
- The robots are able to operate in large patient area, e.g. 30,000 sqm. with approxim. 1,000 patients admitted in a field hospital.
- The users able to control the robot remotely from the command center. The remote control using radio frequency is technically infeasible due to the long distance and physical obstacle.
- Internet coverage via Wi-Fi in the patient area may be unreliable due to high data traffic from many users.
- The robot operation must be aligned with the current workflow, including pharmaceutical activities, nurse activities, food serving, and etc.
- Training for the users, in this case, nurses. It needs to be concerned that nurses are generally not robot users. Therefore, the usage must be intuitive and easy to use. The training is required. However, it should not be done on-site due to the risk of infection.
- Cost constraint and producibility of the system for serving many field hospital nationwide.

From the these requirements and constraints, the proposed solution is a mobile robot with the following functions

- The tele-operated robot that is controlled by the user which is a nurse. The robot will be navigated to specific locations to deliver items and the nurse can communicate with patients via a video call.
- The system must be easy to use by non-technical users. From the user's study, physical or virtual joystick is preferred for controlling robot movement.
- The auto-navigation function is inapplicable due to the environment conditions of the field hospital. Installation of additional equipment, e.g. markers or reflector, is unavoidable for accurate localization. In practice, the patient area in the field hospital consists of a large number of beds and partitions placed in a repetitive pattern (see Fig. 2), so that the AMR with lidar solely will not be able to localize accurately.
- The robot communicates over 4G cellular network. The signal bandwidth can be maintained therefore the time delay of the robot control can be determined. This is more appropriate than using Wi-Fi network due to complicated configuration and devices on-site installation are required.

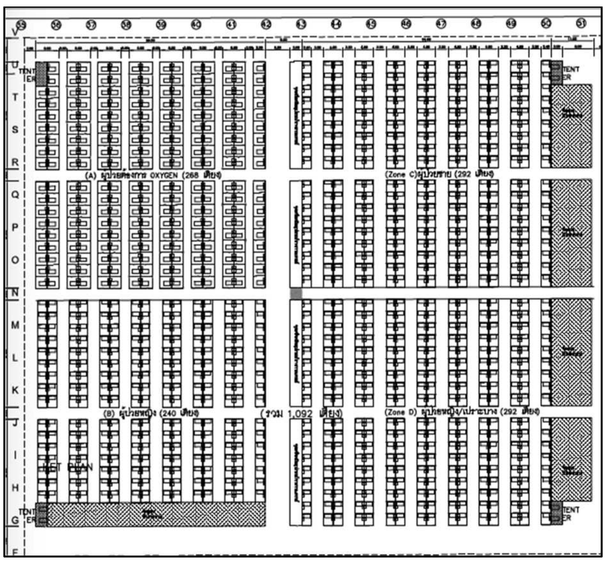

Fig. 2 Pattern of 1,080 beds in a a field hospital patient area

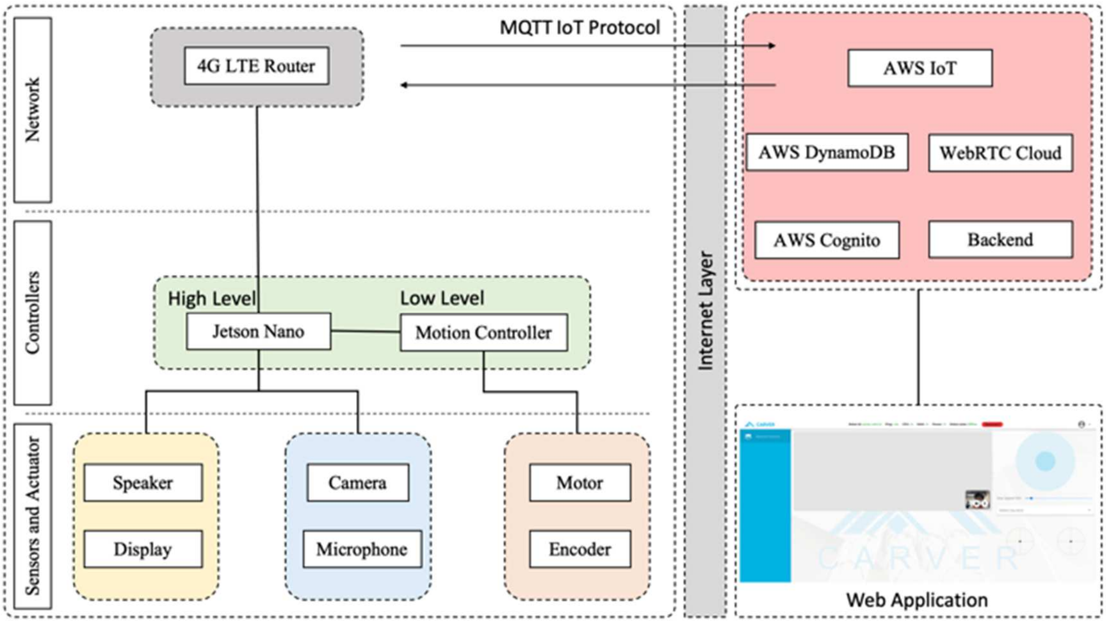

Fig. 3 System overview of the mobile robot

B. System Overview

The system overview (see Fig. 3) consists of two parts: *Robot part* and *Cloud services part*. The platform works reliably on a cloud service. Users can control the robot through the web-app. *AWS Cognito* [9] provides the solution to access the platform, where each user will need to login to the system with provided username and password for accessing the robot. The data between the user and the robot can be transferred via the MQTT protocol [10] with JSON format. Robot properties data sent from the robot to the cloud is automatically stored in an AWS Dynamo Database [9]. The video call for teleoperation is real-time streaming process with WebRTC.

(a) ***Robot part*** consists of sensors and actuators layer, controllers' layer, and Network layer.

The sensor and actuator layer: the components consist of microphone, speaker, camera and display for tele-conference between patient and healthcare staff. Motor and encoder are used for robot movement.

The controller layer: the components consist of a motion controller of a motion controller interface with *rosserial package* [11]. The main controller is operated with Robot Operation System (ROS) noetic version under UBUNTU 20.04 LTS running on a Jetson Nano.

The network layer: 4G LTE router to receive 4G signal for communicate between mobile robot and cloud service. MQTT is a lightweight protocol to transport robot status and receive command message between device to device.

(b) ***Cloud services part*** are primarily based on AWS services, namely AWS IoT Core is used to mediate device to device communication; and AWS DynamoDB is NoSQL database for storage collecting user information and data logging storage. AWS Cognito is the gateway for access control of the platform.

IV. Implementation

A. Hardware Design

The mobile robot (named "CARVER-mini") consists of three parts: *AMR platform*, *attachment*, and *user interface device* (see Fig. 4)

(a) *AMR platform* is designed to be used in hospital area, so that the size must be compact enough to access standard doors. A Rocker Bogie mechanism is used with the suspension system in order to overcome obstacle on the floor and reduce vibration.

(b) *Attachment*, in this case, is a storage 400mm x 400mm stainless steel rack which is designed for storing food and medicine. The robot can serve 10-20 sets of food and medicine per round. The rack is designed based on hospital carts and hygienic design, so that the cleaning process can be done for disinfection.

(c) *User interface device* consists of a camera with fisheye lenses and a display. The camera is for robot movement tele-operation control and communicate with patients. The display is for video call with patients.

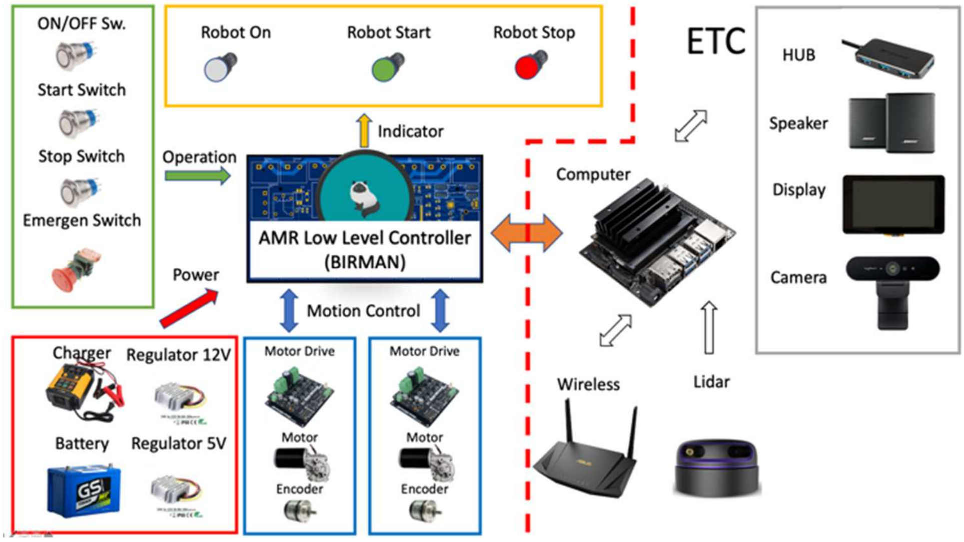

Fig. 5 Component diagram of Low-level and robot control

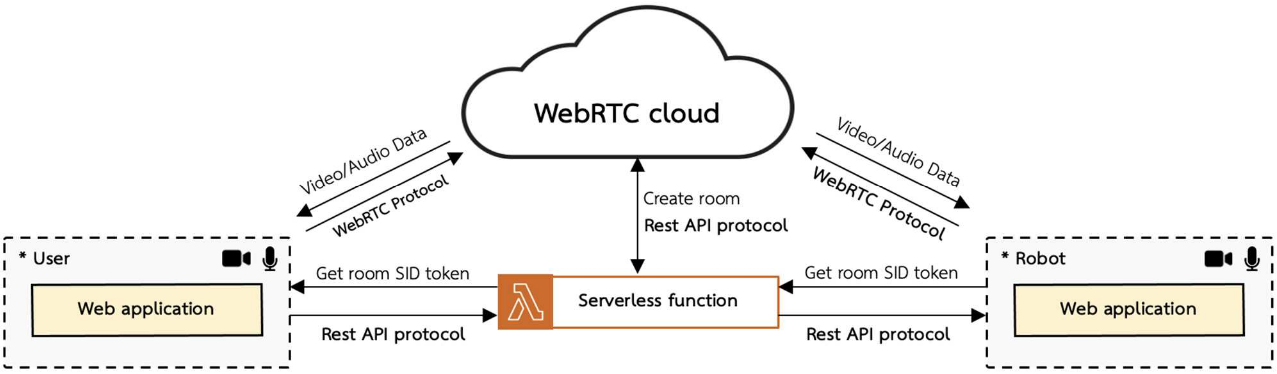

Fig. 6 Real-time streaming diagram

Fig. 4 Mobile robot "CARVER-mini" hardware design

B. *Software – Low-level and robot control robot*

The Low-level and robot control is shown in a diagram in Fig. 3 and Fig. 5. The software divided into two main parts.

(a) *Computer part* is the center controller of the robot and it is a connection point for many devices, including a camera, AMR Low-level controller, display and speaker. ROS is for manage the node in the mobile robot. This mobile robot consists of 5 main ROS node: AMR Low-level Controller, Cloud service, Recovery robot, safety control, and internet recovery node.

(b) *AMR Low-level controller* used to control state of the power components of robot with the operation button and shown in the indicator for identify power state of the robot. PID controller is used for motion control. This controller is able transfer the robot power state, speed of motion, and safety state to the center controller via *rosserial*.

C. *Software – Hi-level and streaming*

The video and audio communication in this tele-operation is based on *Web Real-Time Communication* (WebRTC). WebRTC Protocols is a peer-to-peer communication between each of client with standard-based. This technology is an open-source platform and available as regular JavaScript APIs in all major browsers [12].

The process in regard to WebRTC is shown in Fig. 6. Initially, the web-app of client sends the room information with Rest APIs to WebRTC cloud provider via the serverless function (AWS Lambda). The WebRTC cloud provider is able to create and manage the communication room, then return room SID and certificated keys. After the clients receive information from serverless function, it can connect to the communication room to transfer video and audio data with the other client in the same room via WebRTC protocols with user identification by room SID and certificated key.

D. Simulation

FlexSim is a software for 3D simulation modeling and analysis of systems and processes, including manufacturing, warehousing, material handling and healthcare [13]. In this research, this software is used to find suitable solutions for the process related to robots operation, e.g. amount of mobile robots required, amount of loading's stations and staffs required, process time, and etc.

The scenario used in this simulation is based on the information from one section (approx. 30,000 sqm and over 1,000 patients) in one of the largest field hospital in Thailand. The floorplan consists of *patient zone* and *staff zone*. The patient area is called "*Dirty zone*". Staff and health workers are arranged in clean zone. People who across to other zone must wear personal protective equipment (PPE) for reducing the risk of infection (see floorplan in Fig. 7).

In the actual operation, the users control the robots from the *command center* located in the clean zone. The items, food and medicine, are loaded to the AMRs in the anteroom located before the entrance to the patient area. Then, the AMRs go into the patient area and do the service. The AMRs will stop at the drop-off points where 40 patients share one common drop-off point (see Fig. 8). Each round, after all medicine have been successfully dispensed the AMRs will return to the anteroom for re-loading.

The selected scenario concerns only medicine delivery. To simplify the 3D model, 1 block represents 40 patient bed (see Fig. 8). Loading capacity of robot is 20 sets of medicine each round. Therefore, mobile robot must go to each drop-off point twice in order to complete serving. The paerometers setting is as follows:

- Using 10 mobile robots;
- Mobile robot max travel speed 0.4 m/s;
- Loading item by staff using time average 60 s; (using random valuation from normal distribution mean = 60 s and S.D.= 2.00 s);
- Unloading item by staff using time average 10 min (using random valuation from normal distribution mean = 10 mins and S.D.= 1.00 mins).

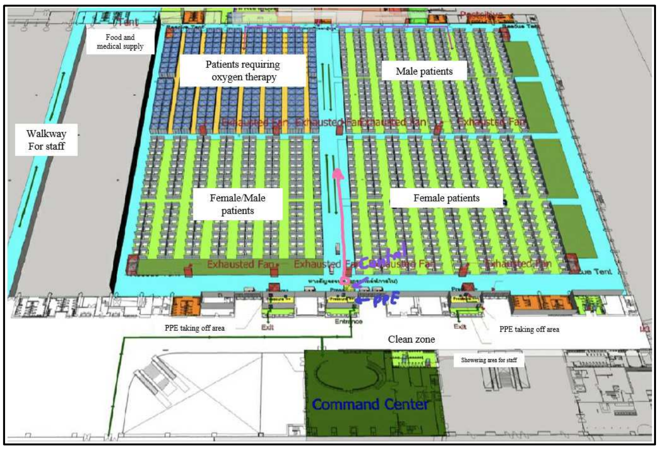

Fig. 7 Floorplan of the field hospital


Fig. 8 Modeling and simulation

V. EXPERIMENT

A. Prelimnary Testing Result

This section will give the preliminary results in two perspectives:

(a) *Operation*: the tests were done both in the lab an on-site. The AMR was able to be controlled from anywhere given that the internet connectivity is available. In regard to the tele-operation, the time delay between 0.5-1s were occurred. This can be an issue for safety and controllability at the high speed movement. However, the speed of AMR is limited at 0.5 m/s maximum. The risk of crash accident is reduced.

(b) *Training and user experience:* The AMR was delivered to the hospital but the training was done on-line via video conference application. The test was done with 5 groups of users who are nurses (1 group per a hospital). As a result, the users were able to complete the process (setup, connect to the server, control basic robot movement, and tele-conference) within 10-20 mins.

B. Simulation

This simulation model is set as a process flow simulation for mobile robots. It provides the total time spent and the total time estimated for the execution of all tasks assigned to each of them. This experiment is designed to compare 3 solutions to find the appropriate number of loading stations by using 10 mobile robots.

TABLE I Result from simulation

		Idle (s)	Travel empty (s)	Loading (s)	Travel loaded (s)	Unloading (s)	Total time (min)
Staff 1	Avg.	123.70	75.00	59.65	119.95	592.31	103.65
	Max	735.48	180.22	63.92	187.78	756.87	
Staff 2	Avg.	84.75	84.63	64.85	172.65	541.72	100.89
	Max	335.02	180.22	172.74	687.24	691.54	
Staff 3	Avg.	72.7 8	97.47	59.70	118.62	591.81	100.89
	Max	231.56	213.32	63.92	180.17	756.87	

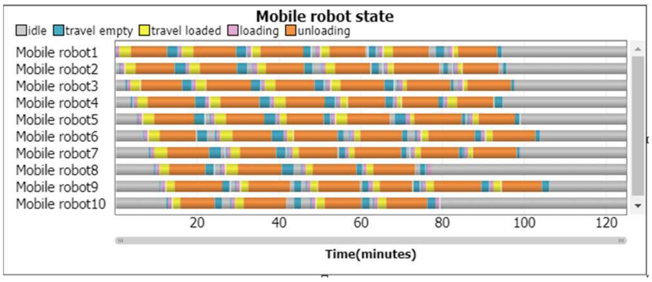

Fig. 9 state of mobile robot with one loading's station
***(Idle**: waiting for running task.; **Loading**: loading item; **Unloading**: unloading item; **Travel empty**: moving without loads; **Travel loaded**: moving with loads.)*

The result of the simulation is shown in Fig. 9. It describes the scheduling tasks of each mobile robot. TABLE *I* is summarized from Fig. 9. It shows the average and maximum time for each task, as well as the total time. Although 3 staffs are required for loading items, the total time was nearly using 1 or 2 staffs. It is because the waiting time for loading is approximately 1-2 mins, and the total time depends most heavily on unloading time.

Unloading time is a random value from the normal distribution. It means that unloading time could be around 9-13 mins. Although setting unloading and others, except idle state, are equally important in different situations.

Focusing only on the idle state, 1 staff takes around 12 mins as a maximum time of idle state of, while 3 staffs take around 4 minutes. Therefore, It is not worth using 3 staffs and the total time spent using 1 staff member is still acceptable (around 103 mins which is less than 2 hrs.). Consequently, using just 1 staff with 10 mobile robots is the best option as using two more staffs can only reduce work time by approximately three minutes.

VI. CONCLUSION

In this research, a tele-operation mobile robot, name CARVER-mini, is developed for items delivery in field hospitals in order to help reducing infection risk of health worker by physical distancing. The robot is adapted from the previous work, CARVER-AMR, which is an autonomous mobile robot platform with automatic navigation. However, for CARVER-mini, some functions need to be adjusted according to the constraints and restriction of the hospitals.

As a result, the tele-operation mobile robot is able to controlled manually from anywhere if the internet connection is available. The robot is controlled via the web-app which consists of robot movement and tele-conference function in order to allow the nurse to communicate with patients. However, time delay of 0.5-1s is concerned as a controllability and safety issue if the robot moves too fast. About the simulation, the system was planned to operate in a large patient area. The preliminary simulation result shows the proper number of staffs and mobile robots should be deployed to finish the task in time.

In regard to the implementation at the hospital, the process from setup, training, to starting operation can be done in less than 20 mins. The video-conference is effective enough for an on-line training. Therefore, this helps avoiding on-site training which can reduce the risk of infection one way.

For the future work, the system will be implemented in more general hospitals not limited to the COVID-19 wards. The experiment on the real situations will be conducted and the result will be analyzed.

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