Multi-robot Control Architecture for Hospital Delivery Service in Unstable Network Environment

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Abstract: This paper describes the problem about controlling multiple robots in a real world when the network connection is unstable. Robots are deployed at the hospital for delivery service. Robots navigate autonomously through the hospital-wide hallway while delivering items from point to point. The delivery task is assigned and sent to the robot by the server via wireless network. To increase the performance of using fleet of robots, online task assignment and fleet optimization is required. However, the robots are frequently disconnected with the network since the robot continuously moves and the mission area covers multiple floors. The online communication cannot be guaranteed at all times. Therefore, this paper proposes a control architecture to cope with such unstable network connectivity. The server has a specific message board to communicate with the robot. Task assignment of the server or status report of the robot are transferred through this message board. In general, the server uses a fixed IP address, whereas a robot uses a dynamic IP address. Therefore, the connection is always initiated from the robot's side by the heartbeat message. With this architecture, the communication between the server and the robot can be achieved in a partially online network environment. And, the delivery performance of the fleet of robots can be increased by the scheduler assigning the task online.

1 INTRODUCTION

An autonomous navigating mobile robot has drawn attention for its applicability for the wide area delivery services. One of the emerging application is the hospital delivery. A lot of various materials are transferred inside a hospital such as laboratory samples, medicines, medical supplies, food and linen.(Ali Gurcan Ozkil, 2009) Systems have been developed to automate these delivery, for example, pneumatic tube, conveyor track, dumbwaiter, and automated ground vehicle (AGV). However, these systems needs to be installed through construction and are not easy to modify their tracks once installed. Due to their low flexibility, many of the materials are still delivered by the human porter in conventional hospitals. Unlike these systems, implementation of an autonomous mobile robot does not require special construction, and robots can move through a human-existing environment. Therefore, hospitals are now adopting mobile robots for the delivery service. Tug® from Aethon and RoboCourier® from Swisslog are major autonomous mobile robots which are developed for the hospital delivery (Niechwiadowicz and Khan, 2008). An example of the delivery service robot can be seen in Figure 1.

Figure 1: A delivery robot. GoCart® from Yujin Robotics Inc.

Several hospitals adopted a fleet of robots for such delivery purpose as meals, drugs, lab results, medical equipment and supplies. (Bloss, 2011) However, these robots are able to deliver only one task at a time which is the single-task allocation (STA). It means when a robot leaves the base station, it cannot add more task while moving. However, if a robot is connected to the wireless network while moving and can receive more tasks online, the delivery performance can be increased by finishing multiple de-

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livery tasks at once. For example, if a robot is delivering a task A and a new task B within a close distance has been requested, the robot can finish both task A and B with not much effort for performing both tasks. This kind of task allocation is called 'online' multi-task allocation (on-MTA) which a robot can receive more tasks while moving and increases delivery performance. Previous research about the online multi-task allocation is done in (Jeon and Lee, 2016) and it shows that the on-MTA increase the performance of using fleet of robots than STA.

To achieve on-MTA, the robot should be connected to the network at all times. However, when operating robots in real-world, maintaining the network connectivity of a moving robot at all times is a challenge job. Even though access points (APs) of the wireless network are densely installed hospital-wide, the network is frequently disconnected due to handover of APs of the moving robot. Also, the robot's IP addresses can be changed when connected to a new AP. This unstable network environment can be a critical problem for fleet management since real-time positions and task statuses of robots affect overall optimality of task allocation.

Many of the previous researches about controlling the multi-robot system assumes robots have fixed IP addresses with online connectivity.(Ren and Sorensen, 2008)(Harrisson Fischer, 2016) There is an approach of designing the control architecture for the hospital delivery robots assigning a task via network communication, but it overlooks the importance of asynchrony and unreliable network condition.(Yasuhisa Hirata and Kosuge, 2015) There is a research about the control architecture of non-communicative environment, but it has a supervisor which monitors the behavior of robots.(Alessandro Marino, 2013) However, in our approach, there is no such supervisor that monitors the robot's status.

This paper proposes a control architecture of the multi-robot system that achieves online connectivity of robots although online connection is not guaranteed. In this architecture, the server has a specific module called the 'message board (MB)' to communicate with the robot. With this architecture, robots can report their positions and status to the server, and the server receives the robot's information through MB. The server assigns a delivery task of a robot by posting it on MB, and the robot receives the task message from MB. With this module, IP address of the robot is negligible since the communication is always initiated from the robot's side.

Another emerging issue when operating robots in real-world is the case when robots use common resources such as an elevator. Many of the conventional hospital allows one or two elevators for the robot-dedicated use. In this case, the resource controller should organize the usage when there are multiple requests from different robots. Similar concept is applied for a narrow corridor and an automatic door. Two robots cannot cross-over in a narrow corridor, and the automatic door should maintain opened until a robot completely passes-by. This kind of common resource management should be performed by the server in an unstable network environment. The handshaking process of the message to use the resource is explained in section 4.3.

The proposing architecture can cope with the real world problem which network connectivity is unstable and the deadlock situation of multiple request from robots to use the common resource.

2 DELIVERY SERVICE

2.1 Network Environment

In this project, the multiple robots work in a special environment that is wide and the network is frequently disconnected. When a robot moves, the handover of the access point (AP) occurs and the robot loses connection from time to time. Also, the IP address of the robot can be changed, in case of dynamic assignment (DHCP) of AP. Thus, the online connection between a robot and the server cannot always be guaranteed.

On the other hand, since the server uses a fixed IP address, a robot can access to the server's IP address at any time when connected. Therefore, in this delivery service architecture, the communication is always initiated from the robot's side. The connection is not always online, but, at least, we know that some time the robot will be connected to the server and receive messages. So, many of the decisions are made by the robot itself, for example, planning the path between delivery positions, avoiding obstacles, controlling movements, and deciding the human interaction behavior at each states. Network connection is mandatory only when receiving the new task and requesting for usage of common resources. In general, the robot reports its status to the server when possible.

To enable such communication method, the 'message board' concept is introduced in the server. Whenever a robot is connected to the network, the robot sends the heartbeat message to the server's fixed IP address and the heartbeat includes information of the robot about its position and status. The returning message of the heartbeat is any message that is posted on the 'message board'. The server uses the message board to assign a new task and to allow resource usage. The detail will be discussed in Sec. 3.1.3.

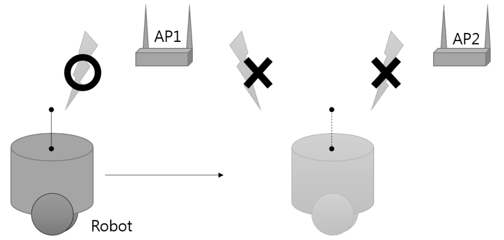


Figure 2: Network disconnection due to AP handover.

2.2 Delivery Service Scenario

The delivery contents in a hospital can be laboratory samples, medicines, and medical supplies. Users of the delivery service are nurses and staffs. They call the delivery request from all around the hospital, for example, nurses at wards on every floor, pathologists at the laboratory, or staffs at the supply storage. They will access on a web page on their computers or an application of mobile devices to order a delivery service. When a user enters a delivery task through the web site, the delivery task is sent to the server and stored in the server's delivery task queue. When the requested time has reached, the robot comes at the user to load the item and brings it to other place.

Delivery Task. The delivery task is consisted of time, contents and pick-up and drop-off positions. The delivery request can be either periodic or on-demand. The delivery waypoints can be one-to-one, one-to-many, or many-to-one places. A user can select these delivery type by the request.

The moment when the requested time has reached, the server calls the scheduler module inside the server to find an appropriate robot for the requested task. The robot selection algorithm affects the total delivery performance and is discussed in (Jeon and Lee, 2016) and explained in Sec. 3.1.2. To sum up, the scheduler reviews the current positions and task status of all robots, and finds the robot that consumes minimum cost for adding the new task.

When a robot is selected, the server assigns the task to the robot, and the robot adds the new task in its task queue. Assigning a delivery task to the robot are performed based on the following sequence. When the selection of a robot is finished by the scheduler, the headquarter posts the task on the message board of the selected robot ID such as 'Robot 3: Task 1, Way points: A-B-C-D'. Whenever the 3rd robot sends the heartbeat to the server, it receives the task as the returning value of the heartbeat. Then, the robot generates the path between the waypoints of the task by itself and starts delivery. The robot autonomously moves to the pick-up point and waits for the user to load items. When the user pushes button notifying finished loading, the robot moves to the drop-off position and waits for unloading. If the unloading task is finished, the robot moves to the next waypoint. This task is repeated for the robot all day.

While delivering, there are common resources of a building that robots use. Some of the resources cannot be used by two robots at the same time. They are an elevator, an automatic door and a narrow corridor. These places are stored separately and managed by the server to avoid conflict. When a robot arrives at the places, the robot requests the usage of the resources to the server. The server checks availability and assigns the robot for the usage. The detail of the resource usage procedure is explained in Sec. 4.3.

3 CONTROL ARCHITECTURE

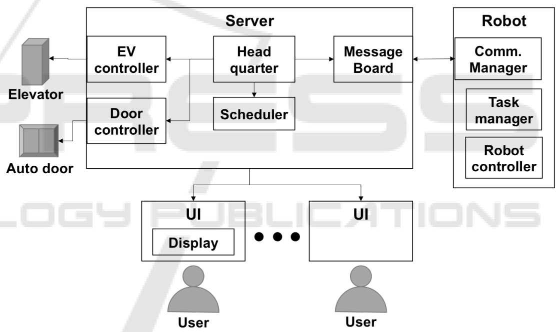


Figure 3: The architecture of the multi-robot control system for hospital delivery.

The proposing multi-robot control architecture for the hospital delivery service in an unstable network environment is depicted in Figure 3. It is consisted of a server, a UI, and a group of robots. Each agents are connected through the network. The server manages all data of robots, posts and receives messages from robots, and controls resources such as the elevator and the automatic door. The UI is for the user to order the delivery task from remote scattered places. The data from UI is transmitted to the server to organize the task. A group of robots receives delivery task from the server online and navigates the hospital autonomously to perform the delivery task. A robot can deliver more than one task at a time to increase the delivery efficiency. Each agents consisting the system is explained in detail as following sections.

3.1 SERVER

3.1.1 Headquarter

The headquarter (HQ) manages all events while operating robots. The updated information of robots is managed here. It receives delivery requests from UI and saves the delivery request in the task queue. When, the server's time meets the requested time, HQ calls the scheduler and selects an appropriate robot for the task. Then, the task is posted on the message board. When there is a request from a robot to use a common resource, such as an elevator or an automatic door, HQ passes the request to the resource controller to organize its usage.

3.1.2 Scheduler

The scheduler allocates the delivery task to an appropriate robot. If there is a standby robot, the scheduler assigns the task to the standby robot. If not, one robot has to add the new task into its existing task list. Which robot to add the new task is decided by the scheduler. The inputs of the scheduler are all task statuses and positions of robots, and the task schedule from HQ's task queue. The output of the scheduler are the selected robot's ID and its task sequence. The task allocation algorithm selects the best robot for performing the task.

The main concern of allocating a task to a robot is minimizing the total travel distance and time. Thus, the variables of the cost function becomes the distance. The best selected robot is the one which provides the minimum distance for performing the task among all robots. The remaining battery and container capacity act as constraints.

Difference in strategy of the task allocation algorithm affects overall delivery performance. In this project, we used the brute-force search method in the algorithm to find the minimum cost of a robot. (Jeon and Lee, 2016) That is, the scheduler generates all possible combinations of pick-up and drop-off positions of the task list and calculates each combination's distance costs. By sorting the cost, the minimum cost is selected, and the corresponding combination becomes the best task sequence of the robot. By comparing costs of all robots, the best robot and its task sequence is selected.

3.1.3 Message Board

The unique feature of this multi-robot system that distinguishes with other robotic system is the message board (MB). This is a part of the server that posts all messages from HQ and robots. And, both HQ and robots communicate by reading the posted message. Unlike Blackboard architecture that has been used for years, (Rudenko and Borisov, 2007) which serves as a database for knowledge-based decision making, MB exist only for posting messages. Once the message is taken by the client, it is deleted from MB. In many of the robotic system, the communication is conducted by the server sending the message directly to the robot's IP address, however, in our approach, the message is transmitted indirectly via MB.

In the real operating environment, the robot's IP address and its network signal is vague from the server's point of view. On the other hand, from the robot's point of view, the server is apparent and uses the fixed IP address. Therefore, in this structure, the server does not directly send a message to the robot but only posting it on MB. Both the server and robots communicate through this MB, regardless of the IP address of a robot or unstable network environment.

When a robot sends the heartbeat to the server, it receives the posted message as the returning value of the heartbeat. The heartbeat message from the robot includes the current position, status, task completion status, and resource usage request. The message from the server's side includes the new task and permission for the common resource usage. If a robot has to use the elevator, the robot posts the request on the message board. Then, the server checks MB frequently, and passes this message between the resource controller and robots. The messages are managed according to the robot's ID. This way online task allocation in an unstable network environment become possible.

3.1.4 Resource Controller

Since this is a multi-robot system that covers multiple floors, multiple requests from different robots can be made to use the elevator. However, an elevator cannot be used by two robots at the same time. Therefore, the resource controller (RC) organizes these multiple requests by either permitting the usage of the resource or submitting the request on the queue and let the robot to wait until the next permission. Several requests can be made at the same time, however, RC blocks other requests and permits only one usage at a time. This way the robots can avoid deadlock situation when trying to use the resource simultaneously.

The common resources for the multi-robot system includes an elevator, an automatic door, and a narrow corridor where two robots cannot move toward each other at the same time. RC manages the entry of robots to these resources. These common resources are previously set during the installation of robots by marking the resource area on the map and appointing the waiting area in front of the resource place. The waiting area is for the robot to wait before it is permitted to enter.

3.2 Robot

3.2.1 Robot Controller

The robot controller manages general autonomous navigation of the robot. The delivery task is a series of waypoints. When a task is assigned to a robot, the robot generates its path between waypoints and follows the path avoiding obstacles. It recognizes its position by sensory data. It performs the delivery task sequence including the state change, such as move-wait(load)-move-wait(unload). If a robot has to use the elevator, it asks the server for the usage. Until there is a permission from the server, the robot waits on the waiting area. The control sequence of the resource usage is explained in Sec. 4.3.

3.2.2 Communication Manager

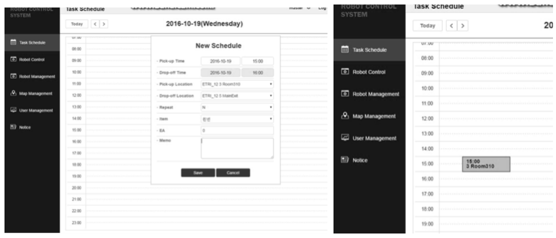
The communication manager (CM) of a robot exist not only to send a message from a robot to the server, but also to check whether the robot is connected to the network. Since the working area of the robot cannot guarantee online connectivity of the network, the CM continuously checks the connectivity by sending the heartbeat to the server periodically. The contents of sending message of the heartbeat is generated by the message handler. The returning message of the heartbeat is anything that is posted on MB, which includes the delivery task.

3.2.3 Message Handler

The message handler (MH) of a robot generates messages to send to the server and dispatches the message received from CM. Any events that should be reported to the server is managed in this module. The sending message contains the robot's position, status and task completion status. When there is a need of a robot to use the common resource, MH generates a request message for the resource usage. The robot's position and status messages are refreshed to new data continuously, whereas task status should obtain past history since the last connection with the server.

MH dispatches the message received by the server, and passes to the robot controller to behave according to the message. If the received message is a task, the robot performs the delivery. If the message is permission for the resource usage, the negotiation process for usage of resource is followed thereafter as explained in Sec. 4.3. If there exist a returning message of the heartbeat, which means the network is connected and the message is sent, the MH erases the past task completion status, and collects new task history.

3.3 UI



(a) Task request on the web GUI (b) Schedule table

Figure 4: A screenshot of the task requesting web page.

The delivery service is requested from all around the hospital, for example, nursing station of each floor, supply storage, kitchen, laboratory, or anywhere the user exists. Therefore, the user interface (UI) is separated from the server to satisfy the accessibility. UI is an independent module that generates the task and sends it to the server. It is preferred to be a web-page style or a mobile application since these can be easily implemented in any system used by the hospital. A user inputs a delivery request on UI, and the input data is sent to the server and saved in the task schedule. The example view of the web-based user interface (UI) is in Figure 4. The user inputs time, user's and receiver's name, contents, and pick-up and drop-off positions.

4 COMMUNICATION PROCEDURE

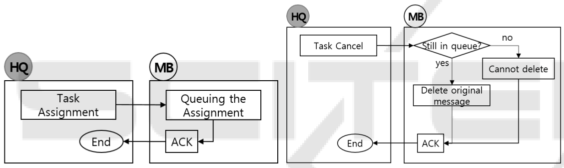
4.1 Task Assignment

When a user inputs a delivery request through UI, the delivery task is sent to the task schedule of the server. When the delivery time is reached, the server selects a robot for performing the task through the scheduler, and posts the delivery task on the message board with the selected robot's ID. This procedure is depicted in Figure 5(a).

Since the delivery task is consisted of a pick-up and a drop-off positions, the waypoints of the task is the list of these visiting positions. If the delivery task includes multi-floor task, the waypoints are segmented including the waiting position of the elevator. The server provides the list of waypoints for robot, and robot plans path between waypoints.

After posting the task message on the MB, the HQ periodically checks whether the robot has received the task. If the robot did receive the message, the robot returns the 'received' acknowlegement as the return value of the heartbeat. Unless the acknowledgement is received, the messages is regarded as 'not received' by the robot. If the task message is not acquired by the robot, the server can cancel the assignment with the timeout option to prevent stuck delivery task.

When there is a need to cancel the assigned task from the server's side, the server checks whether the robot has received the task. If the robot has not received, the server can simply retreat the assigned task by deleting the posted message. The procedure for canceling the task from the server's side is depicted in Figure 5(b). However, if a robot has already received the task, canceling the assigned task can be complicated. There is a way to retreat the assigned task at the robot's side by letting the robot cancel and regenerate its task sequence by itself and reporting the cancelled result to the server. Since this can cause confusion, enabling robot to cancel the task by itself should be decided by the policy.



(a) Task assignment (b) Task cancel

Figure 5: Task messages from the headquarter to the message board.

4.2 Heartbeat from Robot to Server

When operating the robot, all communication between the server and the robot is initiated from the robot's side. The heartbeat message is depicted in Figure 6. MH maintains the current information of a robot and binds the message for sending. CM periodically sends the heartbeat message to the server containing the information generated from MH. Since the server maintains the fixed IP address, the heartbeat is directly sent to the server's IP address. When the network is connected, the information of the robot is updated on MB. The new message on MB from the server to the robot is received as the return value of the heartbeat. The returning message can be a new task, or a message related for the usage of the resource.

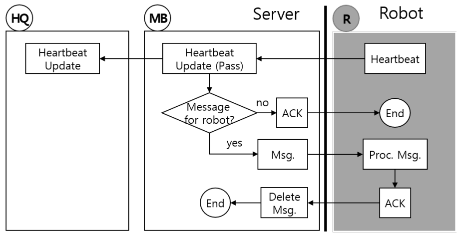


Figure 6: Heartbeat messages from the robot to the server.

4.3 Communication Procedure for Using the Common Resource

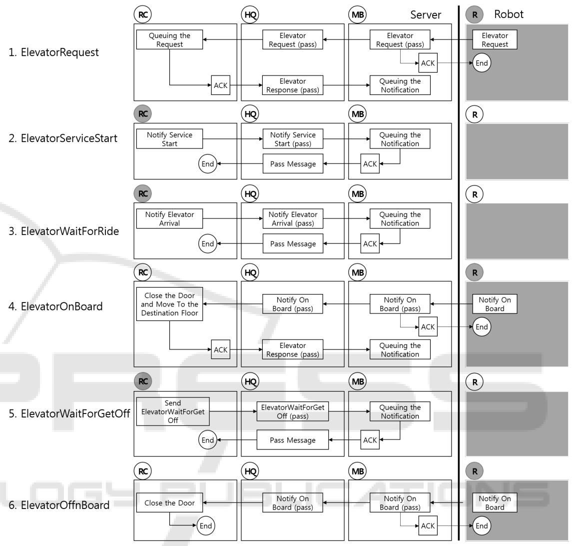


Figure 7: The negotiation procedure for the usage of the elevator.

When there is a need of a robot to use the common resource, the robot arrives at the waiting area and sends the request message. The request message is posted on MB. The HQ periodically checks MB, and when there is a request for use the resource, HQ passes the message to the corresponding RC. RC checks the availability and if available, the RC sends permission. HQ passes this permission to MB, and when the robot receives the message from MB, the robot uses the resource.

Take an elevator for example, the negotiation procedure for the resource usage is depicted in Figure 7. Similar sequence is performed for other resources such as the automatic door or the narrow corridor.

5 EXPERIMENTS

5.1 Testing Envoronment and Scenario

The proposing architecture is implemented in the robotic system for delivery service and is tested in the hospital. The robot is developed by ROS, and the server is developed with web-based javascript on Node.js. The robot and the server communicate via RESTful. The testbed is in the Eulji hospital, Daejeon, Korea. The server and UI is connected through the wired network, and the robot is connected via wireless network. The robotic system accessed the hospital's intra-network. The testing environment and the pathway is depicted in Figure 8 and the scenario is as follows.

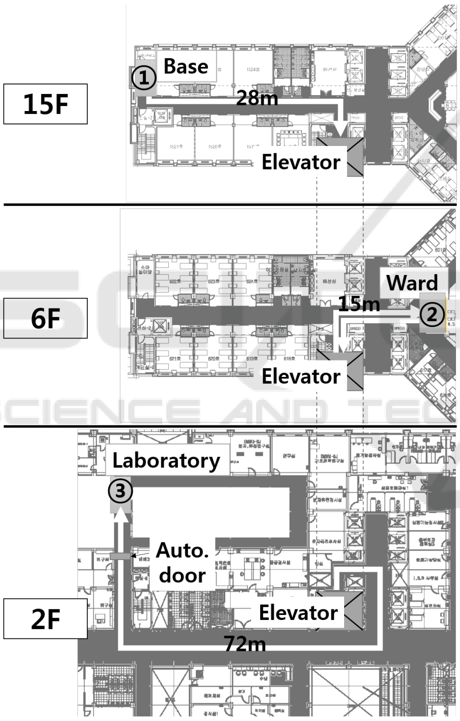


Figure 8: The testing scenario for the hospital delivery service. The nurse at 6th floor calls the robot to deliver the sample to laboratory at 2nd floor. The base station is at 15th floor.

1. The delivery request is made from the ward on 6th floor.
2. The robot starts from the base station at 15th floor.
3. The robot calls and rides the elevator, and moves to 6th floor.
4. It arrives at the ward and loads blood samples.
5. Then, it again calls and rides the elevator to the 2nd floor.
6. It moves to the laboratory on 2nd floor by passing through the automatic door.
7. It arrives at the drop-off station of the laboratory and unloads the item.
8. After finishing the task, it rides the elevator and goes back to the docking station at 15th floor.

Due to the limited number of robots, we were able to test only with one robot. However, the proposing network architecture was able to be tested, and the result shows that the network communication while moving the wide area was conducted successfully. Additional group of robots will be tested as the extension of this research.

(a) Moving to the elevator (15F)

(b) Riding the elelvator (15F)

(c) Loading samples on the ward (6F)

(d) Passing through the automatic door (2F)

(e) Arriving at the laboratory and unloading (2F)

(f) Moving back to the base (2F)

Figure 9: The experiment at Eulji hospital. Sequence from (a) to (f).

5.2 Discussion About Floor Change Detection

While testing, we found out that recognizing the floor change of a robot when using the elevator is surprisingly challenging problem for a robot. Unlike human, a robot cannot read the numbers in the elevator. Thus, the robot cannot exit the elevator because the robot is not sure that the elevator has arrived at the desired floor. Several methods are tried to solve this problem.

One approach is the robot waits for the connection to the network when the door is open and receives the floor information from the server. However, connecting to the network took as long as 1 minute, according to our experiment.

Posting a marker in front of the elevator and detecting with the vision sensor can be another approach. However, in this case, the marker should be placed in the visible area where there is no obstacle, and the marker should not be damaged. However, we couldn't find an appropriate position to place the marker in front of the elelvator since the wall is far and the hospital didn't want to place any artificial mark on the building.

Third method we tried is using the wifi signal as the fingerprint of the floor. (Lee and Kim, 2016) Since this procedure of sensing the wifi signal is not for connection but for matching the histogram of the obtained signal, the result is converged in very short time, less than 3 seconds after opening the door of the elelvator. This way the robot can recognize the floor change as well as save time for delivery.

6 CONCLUSIONS

This paper describes the problem about the multi-robot control system within the unstable network environment. A fleet of robots are used in the hospital for the delivery service. To enhance the performance of using multiple robots, online task allocation is necessary. However, since the online connectivity of the network is not guaranteed, the server cannot directly connect to the robot. Therefore, this paper proposes a control architecture, used in such unstable network environment. The proposing architecture applied the message board on the server to communicate with the robot. All messages from both the server's and the robot's sides are posted on the message board. When a robot is connected to the network, it sends the heartbeat to the server containing robot's information. The robot receives the message from the server by the returning value of the heartbeat. Always, the connection is initiated from the robot's side. This way the robot can communicate with the server not only to receive the new delivery task, but also to request the usage of the common resources such as the elevator. This architecture is tested in the real hospital environment, and the communication between the robot and the server was performed successfully. This system will be tested with more robots with the fleet optimization algorithm in the future.

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REFERENCES

Alessandro Marino, Lynne E. Parker, G. A. F. C. (2013). A decentralized architecture for multi-robot systems based on the null-space-behavioral control with application to multi-robot border patrolling. *Journal of Intelligent and Robotic Systems*, 71(3–4):423–444.

Ali Gurcan Ozkil, e. a. (2009). Service robots for hospitals: A case study of transportation tasks in a hospital. In *International Conference on Automation and Logistics (ICAL)*, pages 289–294. IEEE.

Bloss, R. (2011). Mobile hospital robots cure numerous logistic needs. *Industrial Robot: An International Journal*, 38(6):567–571.

Harrisson Fischer, Philippe Vulliez, J.-P. G. S. Z. (2016). An industrial standard based control architecture for multi-robot real time coordination. In *International Conference on Industrial Informatics (INDIN)*, pages 207–212. IEEE.

Jeon, S. and Lee, J. (2016). Multi-robot multi-task allocation for hospital logistics. In *International Conference on Advanced Communication Technology (ICACT)*, pages 339–341. IEEE.

Lee, Y.-C. and Kim, J. (2016). Multi-floor localization method for mobile robots using elevator. In *International Conference on Control, Automation and Systems (ICCAS)*, pages 869–872. IEEE.

Niechwiadowicz, K. and Khan, Z. (2008). Robot based logistics system for hospitals-survey. In *IDT Workshop on interesting results in computer science and engineering*.

Ren, W. and Sorensen, N. (2008). Distributed coordination architecture for multi-robot formation control. *Robotics and Autonomous Systems*, 56(4):324–333.

Rudenko, D. and Borisov, A. (2007). An overview of blackboard architecture application for real tasks. *Scientific Proceedings Of Riga Technical University*, 5:50–57.

Yasuhisa Hirata, Y. S. and Kosuge, K. (2015). Control architecture of delivery robot for supporting nursing staff. In *International Symposium on System Integration (SII)*, pages 345–351. IEEE/SICE.