Autonomous Mobile Robots and Wireless Sensors for Regulation of Environmental Air Quality

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***Abstract*—As the standard of living rises, humans start to pay attention to the quality of life, primarily for indoor environmental quality (IEQ), especially during the COVID-19 pandemic. To improve the indoor environmental quality, various kinds of apparatus, e.g., humidifier, air purifier, or air conditioner, are used, but these devices can only improve IEQ for a specific space and its nearby neighborhoods. This paper presents a synthesized system composed of autonomous mobile robots and wireless sensors to regulate and enhance the efficiency of IEQ. The mobile robots equipped with a regulating apparatus receive the wireless sensors' sensory data to guide the mobile robot to the optimum regulation location. Additionally, the coordination between multiple mobile robots is addressed to demonstrate the proposed system's superiority for IEQ regulation. The system's efficiency and performance in regulating a room using wireless sensors and the autonomous mobile robots could greatly assist in regulating IEQ, especially in situations like the COVID-19 crisis.**

***Index Terms*—Autonomous mobile robot, indoor environmental quality (IEQ), environmental regulation, wireless sensors, navigation, multi-robot coordination.**

I. Introduction

Indoor environmental quality (IEQ) refers to the total quality of a building's environment, including thermal, humidity, and overall air quality comfort. These factors can significantly affect people's living comfort and human's health, especially during the COVID-19 pandemic. As the standard of living rises, humans start to pay attention to their quality of life, and the demand for comfortable and secure living conditions is becoming more critical. Several kinds of research focusing on monitoring environmental conditions of an indoor space have been presented in [1]–[3], and the relationship between the indoor environmental conditions and human health has also attracted significant focus in the past decades [4], [5]. Additionally, indoor social space's cleanliness is a recently emerging research topic resulting from the outbreak of COVID-19.

To improve the indoor environment, people used to utilize environmental conditioning in their daily lives. However, most apparatuses have different limitations that require amelioration. Additionally, most of the apparatuses for improving environmental conditioning can only handle one specific space, such as a room. Thus, if a user wants to utilize the apparatus in other spaces, he/she has to move and place the apparatus at the desired location manually. Even when the apparatus is placed at the right spot, their position severely affects environmental conditions' efficacy. For instance, the windows' and doors' open/close states, if the windows and doors are open or not, and the airflow will change the space's condition, and the user does not know where is the best position to use these apparatuses efficiently. Furthermore, most of them can effectively measure only in the environmental neighborhoods but not elsewhere and lack in fully capturing an entire space's environmental condition.

Since indoor environmental quality factors such as humidity and suspended particle concentrations are invisible, users will not know when and where they should utilize the apparatus with increased efficiency. Thus, various apparatuses are fundamental to acquire indoor condition. However, most sensors, especially for air quality, can only detect the condition from a particular location; therefore, only partial regulation is possible. Moreover, the environmental regulating apparatuses are stationary, which means that they cannot change their location to provide better-regulating performance. Therefore, in this paper, we proposed a synthesized system consisting of an autonomous mobile robot and wireless sensors to ensure a better and more efficient environmental regulation system. In addition to the robot and sensor coordination addressed in [6] we studied multiple robot coordination and collision avoidance in this paper. Our study also considers the influence of mobile robots on the environmental condition with apparatuses.

This paper presents a mobile robot system to cope with the issues mentioned above while working in an indoor environment equipped with wireless sensors. The proposed system contains wireless sensors separately mounted in an indoor space, and a group of autonomous mobile robots integrated with regulating apparatus for regulating the environmental condition. From the sensory information obtained by the wireless sensors in the environment, the system can evaluate the environmental condition in different spaces/regions and command the mobile robots to the spaces/regions requiring air-quality improvement. The target position for mobile robots to execute environmental regulation is determined and adjusted by the wireless sensors' data.

Upon obtaining the sensory data and determining the optimum location, the mobile robots navigate towards the target position while avoiding collision with obstacles and other robots. By using the sensors, LIDAR, IMU, and odometer, the mobile robots can build the map by exploiting Simultaneous Localization and Mapping (SLAM) [7] and localize themselves on the way of moving accurately by using Adaptive Monte Carlo Localization (AMCL) [8]. Subsequently, the mobile robots navigate towards the sensory data's optimum location by using the Probabilistic Road Map (PRM) [9], while

This paper was first submitted in December 5, 2020. This work was supported in part by the Ministry of Science and Technology (MOST), Taiwan, under grant MOST 109-2636-E-006-019, MOST 106-2221-E-006-010-MY3, and MOST 105-2221-E-006-160-MY3.

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the mobile robots are moving, the environmental regulating apparatuses mounted on the mobile robots process the indoor air to ensure the air quality is regulated to the desired value.

The remainder of this paper is organized as follows. Section II addresses the problem statement and hypothesis testing of the proposed autonomous mobile robots and wireless sensors system. The control strategy for a single mobile robot is presented in Section III, followed by the multi-robot systems approach in Section III-C. Section IV illustrates the experiments on the proposed mobile robot systems in indoor environment regulation. Section V concludes the proposed mobile-robot and wireless-sensor system on improving the environmental quality.

II. PROBLEM STATEMENT AND HYPOTHESIS TESTING

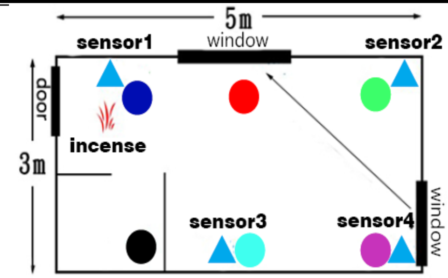
A. Problem Statement

This paper proposes a synthesized system composed of wireless sensors and a mobile robot network to regulate and improve indoor environment quality (IEQ) autonomously. With the proposed system, a group of wireless sensors is pre-installed in the designated venue to acquire the indoor environmental quality, such as the humidity or suspended particles' concentration. Each of the wireless sensor modules consists of exterior sensors, batteries, and communication devices. The sensory data in the designated environment are transmitted to the central station/server on the mobile robot.

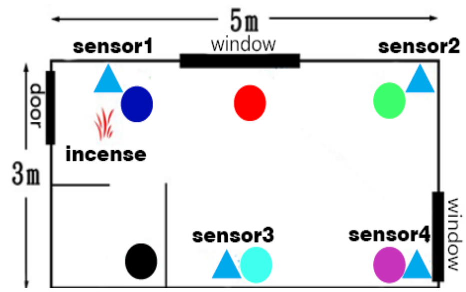
In addition to wireless sensor modules, the proposed system also includes autonomous mobile robots equipped with environmental sensors, distance sensors, and environmental regulating actuators. The mobile base allows autonomous robots to move within the designated environment, whereas the sensors are utilized to acquire environmental quantity and the distance to the adjacent objects for collision avoidance. Additionally, the regulating actuators on the mobile robots are installed to modulate the indoor environmental quantity so that the IEQ can be adjusted to the desired values.

With the synthesized system, the wireless sensors with a known location continuously measure an environmental quality. The measurement data are transmitted to the mobile robots to prioritize the regulation mission in the environment. Since the regulation performance depends on the regulation actuators' position, the mobile robots move close to the peak with higher priority. As a result, the regulation performance becomes more efficient. Therefore, our purpose is to find a suitable location for mobile robots to regulate the environment without knowing the space's whole environmental condition.

This paper considers the synthesized system in an indoor environment with an uncertain environmental condition, and wireless sensors are installed in each indoor space. Through the environmental data measured from sensors, the system knows the partial environmental condition of a space. However, it is difficult to evaluate the whole environmental condition of space with few sensors. With the wireless sensors' incorporation, the mobile robot can quickly find the best regulation based on the database on the system. After deciding a location, the robots are driven to the optimum location to regulate the environmental condition. In addition to the design of the entire system and mobile robot control, this paper also focuses on planning a suitable route and ensuring that the robots follow the route with obstacle avoidance



(a) Experiment venue with windows opened



(b) Experiment venue with windows closed

Fig. 1. Experimental setup for the hypothesis testing with: (a) windows opened and (b) closed. It consists of four wireless sensors (triangles) pre-deployed in the environment to measure particles' concentration in the designated room. An incense (fire symbol) in the room is the source of pollution, and six circular beacons are places where an air purifier is placed to regulate the IEQ.

B. Hypothesis Testing

One of the main advantages of the proposed environmental regulation system is that the actuators on the mobile robots can be controlled to adjust IEQ. However, the IEQ regulation system's efficiency depends not only on the regulating actuator's performance but also on its location. To demonstrate that the actuators' positions would significantly affect the regulation performance, we first illustrate several experiments using the regulating actuators in different locations.

We consider an indoor environment with a door, two windows, and four sensory modules, as shown in Fig. 1. The concentration of suspended particles is considered to be the quantity of the IEQ for measurement and regulation. In this paper, the source of suspended particles is the incense, and the system's regulation actuators are the air purifiers. The hypothesis testing was conducted with the windows opened and closed, as shown in Fig. 2 and Fig. 3, respectively.

At the start of the experiment, the incense at the fire symbol's location in Fig. 1a and Fig. 1b is burned for five minutes. After the dust concentration measured from the four sensors is close to 80 µg/m3, the air purifier is placed at various locations to regulate the environmental air quality. The experimental results from the air purifier located at each of the six positions with windows opened are collected, and the evolution of the dust concentration for the air purifier placed close to Sensor 1 to Sensor 4 are shown in Fig. 2a, 2 b, 2c, and 2d, respectively. We can observe that when the windows are open, the regulating actuator being close to the pollutant source would have better regulation performance, i.e., the suspended particles' concentration decreases faster. For example, putting the air purifier next to the incense, the wireless sensors' measurement result shows that the dust concentration decreases faster than at other locations for almost 5 minutes.

Fig. 3a, 3b, 3c, and 3d, respectively, show the preliminary experimental test results when both of the room's windows are closed. Putting the air purifier next to the pollution source would not yield the best regulation performance. Since the windows are closed, the airflow is less than when the windows are opened. In this case, the best regulation performance is when the air purifier is placed close to the environmental center. If the convection is strong in the indoor environment, e.g., when the windows are opened, the regulation actuator should be close to the pollution source. As a result, the cleaning process speeds up at the location of strong convection. Contrary to this, if the convection is weak, it would be better to put the regulation actuator at the center of the environment to adjust IEQ entirely better.

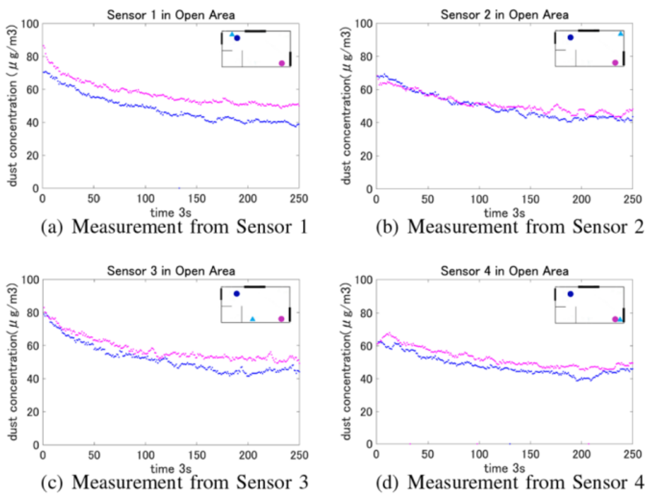


Fig. 2. Evolution of dust concentration when windows are open, and the air purifier is placed close to and far from the incense source.

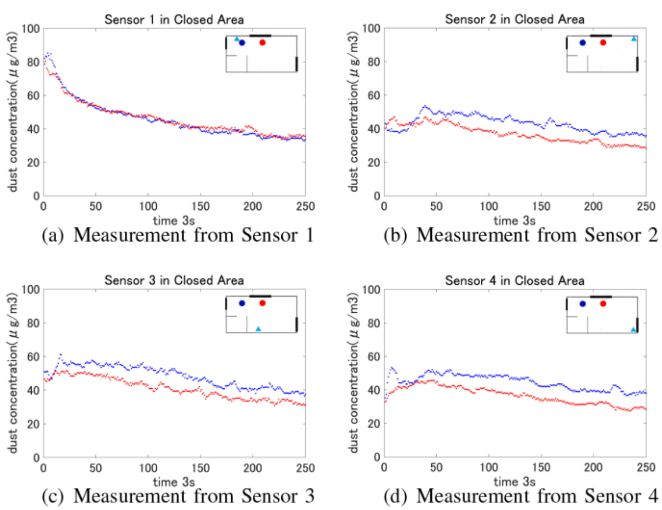


Fig. 3. Evolution of dust concentration when windows are closed, and the air purifier is placed close to and far from the incense source.

III. AUTONOMOUS MOBILE ROBOT CONTROL

A. *Target Location of Mobile Robot for Regulation*

Before implementing the proposed system in an unknown environment, the first task is to build an indoor space map. In this paper, we utilized the sensors, including LiDAR, IMU, and odometer, to conduct SLAM [7], [8], [10]. From the IMU and odometer, mobile robots can evaluate their movement, and from LiDAR, mobile robots can detect the spatial structure surrounding them. Every movement, the system finds the feature points from the laser point and compares them to the previous states. According to these feature points, the system can merge the map detected at different moments and create a map of the entire indoor space.

After setting the wireless sensors in an indoor environment, the sensors can acquire environmental sensory data. These sensory data are further utilized to provide an approximated IEQ distribution for the regulation target space, *S*, is given as

$$S = \max\left(P_i \times \max(C_i)\right), \tag{1}$$

where C_i denotes the estimates of the condition in the i^{th} space, and P_i is the priority of the i^{th} space. The space deciding function (1) in this paper includes the environmental conditions and the priority of the space. The primary purpose of the space's prioritization is decided by the user preference and importance of the space. For instance, the living room's environmental quality is more important than the guest room. Hence, a living room's priority is higher than the guest room.

As addressed in the hypothesis testing in Section II, the regulation actuator's position will significantly affect the environmental regulation's efficacy, even when the apparatus is in the target space. Therefore, we propose a two-step approach for autonomous mobile robots to move towards an appropriate regulation location. The first step is to determine whether the environment is with strong or weak convection. Since the environment with weak convection is highly uncertain, e.g., when windows are closed, we set this case as the basis for mobile robots to decide the desired location for regulation. If the regulation performance from the wireless sensors' measurement is not satisfactory, the mobile robot can consider an environment with strong convection. Thus, the first step is to judge the environmental condition wherein the regulation standard is given as

$$\mu_{\text{standard}} = f\left(E_{\text{robot}}, A_{\text{space}}\right). \tag{2}$$

The regulation ability of the mobile robot E_{robot} is mainly dependent on the regulation actuator and the types of apparatuses used. If we consider an air purifier as the regulation actuator, then CADR (Clean Air Delivery Rate) can be considered as the regulation ability. A_{space} is the regulation space obtainable from the indoor environmental map. Furthermore, the regulation condition denoted as *V* is defined as the changing rate of the sensory data from the wireless sensors δC, and given as

$$V = \delta\bar{C}, \tag{3}$$

where $\delta\bar{C}$ is the average of δC within a specified time. When the difference between the regulation condition, *V*, and the regulation standard, μ_{standard}, is within a predefined error, ε, such that

$$V - \mu_{\text{standard}} \le \varepsilon\ . \tag{4}$$

Then we can consider the environment is with weak convection. On the contrary, if the difference is higher than ε, then the regulation performance of the environment is not as satisfactory even when the regulation apparatus is placed at the center of the environment. Thus, the environment is considered as having strong convection. Then the mobile robot needs to navigate to a location close to the source of pollution.

The second step is to judge the indoor environment condition to assign an appropriate location for regulation. If the environment is determined to be with weak convection, then the mobile robot is controlled to the center of the environment such that

$$G(x,y)=\frac{\sum_{j=1}^{n} s_j(x,y)}{n}, \quad (5)$$

where $s_j(x,y)$ denotes the position of the j^{th} wireless sensor, and n is the number of the wireless sensors in the environment. Fig. 4 illustrates the scenarios where the mobile robot, which is already located at the center, navigates towards the environment with strong convection and the wireless sensor with a higher regulation error. The mobile robot moves first to the center of the venue as the default location and stays there if it determines the environment is with weak convection, as shown in Fig.4 (a). If the mobile robot determines the environment with strong convection from the evolution of the sensory measurement, then it will move towards the sensor with higher particle concentration.

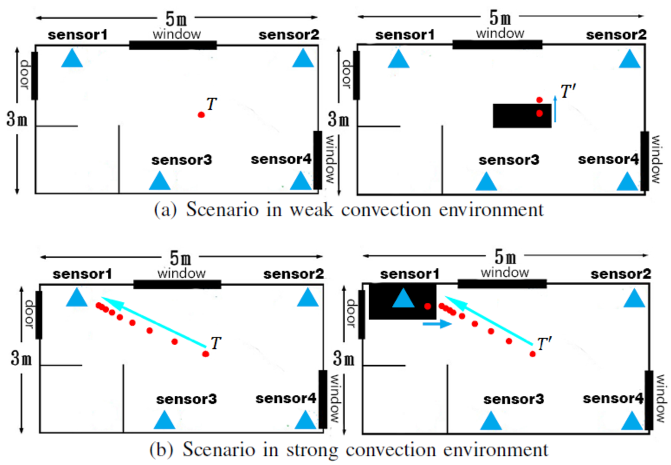


Fig. 4. Scenarios of the mobile robot in the proposed system with the windows opened (strong convection) or closed (weak convection).

B. Path Planning and Navigation

The localization of the mobile robot is necessary before navigating the environment in the proposed system. In this paper, we utilize the method of Adaptive Monte Carlo Localization (AMCL) [10], [10], [11], which is a kind of particle filter where each particle represents a possible position of the robot, to localize the mobile robot. According to the comparison between the LiDAR points and indoor structure *real*, the system gives the particles s^i a different weight ω^i such that [12]

$$\omega_{k+1}^{i}=p(real_k \mid s_k^i). \quad (6)$$

For particles with larger weights, the position has a higher probability for the mobile robot's actual location [12]. After getting the mobile robot's location and the target position in the previous Section, the next task is to navigate the mobile robot to the optimum position requiring regulation.

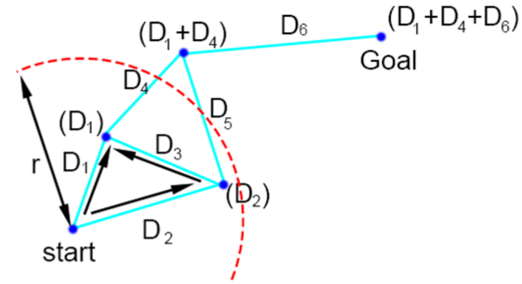


Fig. 5: Optimal route computing methods from PRM nodes.

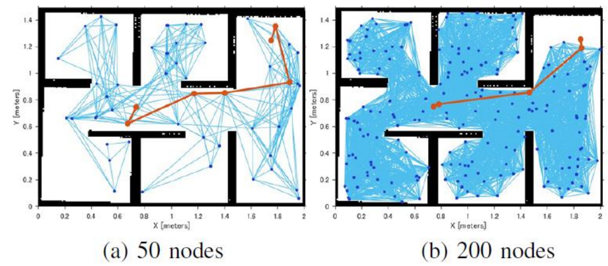


Fig. 6. Implementation of PRM with different number of nodes.

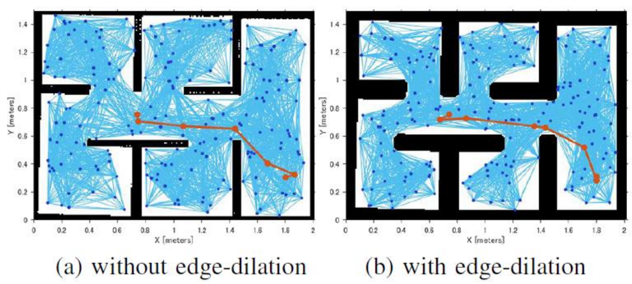


Fig. 7. Robot path by using PRM with/without edge dilation.

In this paper, we exploit the Probabilistic Road Map (PRM) to generate the path for the mobile robot navigation [13]–[15]. By using PRM, the system takes a few nodes randomly from the map first, and only the nodes in free are valid [9]. For each node, the algorithm will find the nearby nodes and connect them by a straight line. After computing the distance between these nodes, the system chooses a route with the least summation of the distance to be the optimal route. Fig. 5 illustrates the concept of computing the optimal route from the nodes, where every node will record their shortest distance to the start node.

In implementing PRM for the proposed system, the number of nodes would influence the optimum route where more nodes would ensure a shorter path but with a higher computational cost. As shown in Fig. 6 (a), the route might not connect in a short path to the target if the number of nodes is 50; whereas, for 200 nodes, the path is shorter, as shown in Fig. 6 (b). Fig. 7 depicts the obtained path via PRM. The mobile robot follows the route for approaching the target position. Hence, the obtained route ensures avoidance of an unwanted collision. In addition to the node number, wall and edge dilation is applied to prevent the mobile robot from moving very close to the edge of the space.

Since the path obtained from PRM is not continuous, the mobile robot with differential-drive would rotate at each of the nodes. Therefore, the mobile robot's motion is divided into a rotational and translational movement to reduce the probability of un-modeled drift when taking turns. From the localization via AMCL, the mobile robot can obtain its position $P(x,y)$ and orientation θ. With the knowledge of the target position, $G(x,y)$, the distance, D, and orientation, the orientation A, from the mobile robot position to target can be obtained by

$$D = \sqrt{\left(P(x) - G(x)\right)^2 + \left(P(y) - G(y)\right)^2}, \tag{7}$$

$$A = \tan^{-1}\left\{\frac{G(y) - P(y)}{G(x) - P(x)}\right\}. \tag{8}$$

In the control of the mobile robot, the mobile robot will first make turn until A smaller than a threshold, $A_{\text{threshold}}$. Subsequently, the mobile robot moves forward to the desired position $G(x,y)$. The illustration of the navigation by using this method with PRM is shown in Fig. 8.

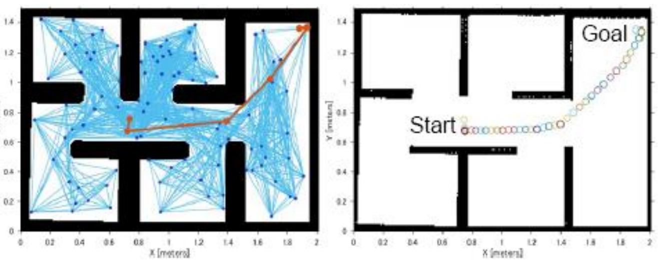
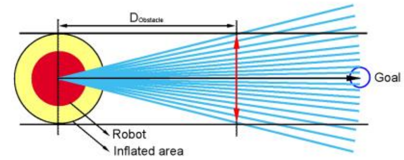


Fig. 8. Illustration of the navigation control for mobile robot by using PRM and the distance/orientation control approach.

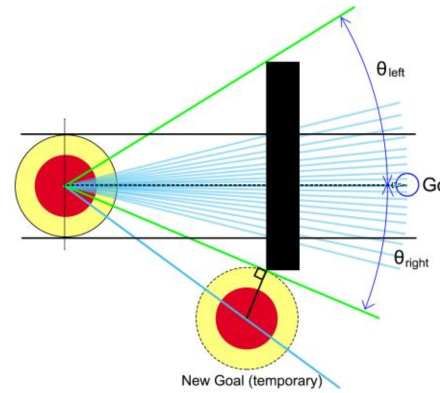
The mobile robot uses the LiDAR sensor and the position information computed from AMCL to avoid collision with obstacles or other robots in the same venue. If the mobile robot encounters an obstacle on its path to the next target position, it should re-route the path and bypass the obstacle. A three-step collision avoidance algorithm is implemented in this research. First, the mobile robot utilizes LiDAR to detect whether there is an obstacle in front of the mobile robot on the path. By considering the mobile robot's size, if the robot can collide with an obstacle, then the LiDAR is utilized to detect the obstacle's two edges from the mobile robot's position. Subsequently, the mobile robot needs to detour from the original path to bypass the obstacle. Fig. 9 illustrates the proposed approach for obstacle detection and avoidance.

The first step to the implementation of the collision-avoidance algorithm is to detect whether there is an obstacle in front of the mobile robots' designated path or not. In Fig. 9, the red circle is the mobile robot's size, and the yellow circle is the safe region that the mobile robot can pass through. If there is no obstacle detected within the minimum obstacle- detection distance, D_{obstacle}, then the mobile robot can keep moving toward the goal point. However, if an obstacle is detected within D_{obstalce}, then the mobile robot needs to deviate its path to avoid colliding with the object.

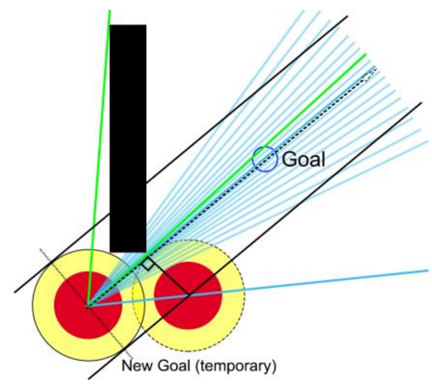
The subsequent step is to detect the edge of the obstacle so that the goal can be modified for the mobile robot to avoid the collision. In Fig. 9 (b), the LiDAR measures the edge to an obstacle in front of the mobile robot to get θ_{left} and θ_{right}. The mobile robot will then move towards the side at a smaller angle. For instance, if $\theta_{left} < \theta_{right}$, then mobile robot turns left to bypass the obstacle. After the mobile robot bypasses the obstacle, it will repeat the first two steps to ensure that the goal is reachable and move toward the original goals obtained from PRM.



(a) An obstacle is detected by the mobile robot



(b) Definition of the new target based on the size of the obstacle



(c) Setting new target position after passing the obstacle

Fig. 9. Illustration of the obstacle detection and avoidance approach for an mobile robot in the proposed system.

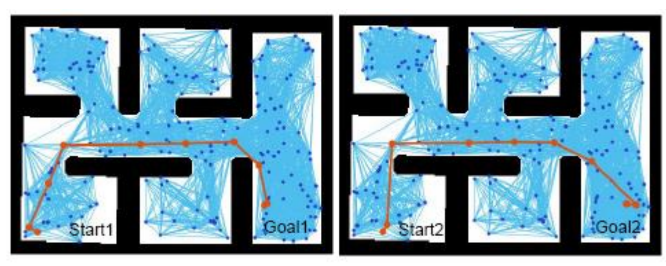


Fig. 10. Comparisons on using PRM for path planning of two mobile robots in closed initial positions.

C. *Multi-Robot Control Strategy*

The control strategy for a single mobile robot was addressed in the previous Section. However, if the designated environment is too large, then the use of multiple mobile robotic systems would be more efficient for environmental regulation. Moreover, using more robots simultaneously in regulating an environment, lifespan and energy management can be ensured and applied to enhance the system's performance. In this

Section, the extension to the multi-robot control strategy is presented to maintain the IEQ for a larger space. For systems with multiple mobile robots, localization, path planning, navigation, and collision avoidance is similar to a single robot's strategy. However, the inter-robot collision and avoidance are significant and requires attention. In the following Section, we address multi-robot coordination and collision avoidance.

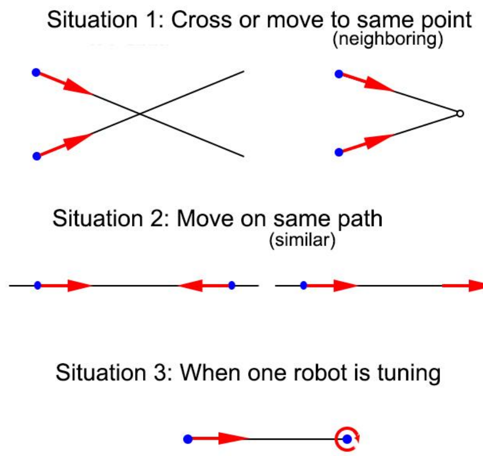
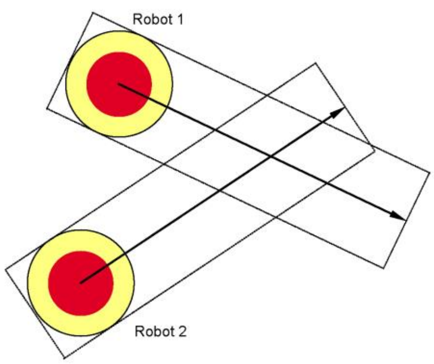
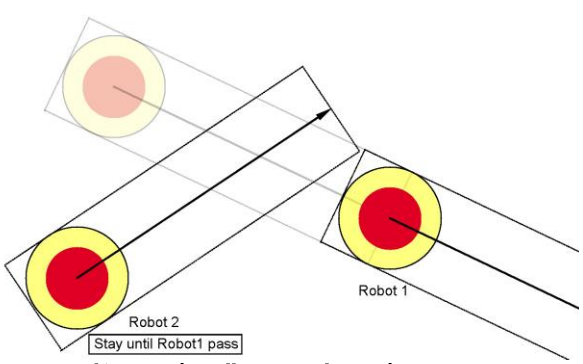


Fig. 11. Multiple mobile robots moving toward the same node from the PRM.



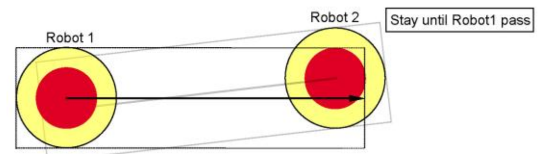
(a) Step 1 for collision avoidance of Situation 1



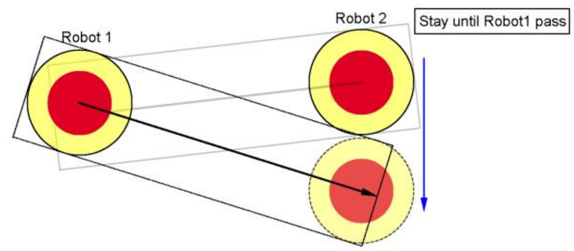
(b) Step 2 for collision avoidance of Situation 1

Fig. 12. Collision avoidance of Situation 1 – Cross or move to the same node.

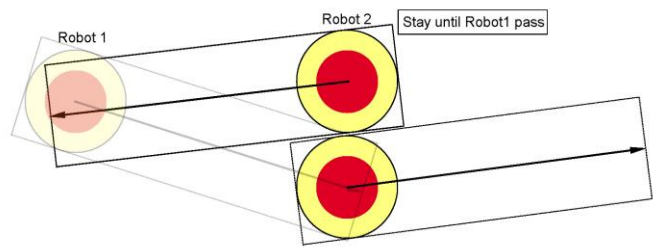
In this paper, PRM is utilized to generate the desired path for mobile robots moving to the region with higher importance and regulation needs. Since multiple robots are using the same approach, they might move towards the same target position with higher regulation requirements, as shown in Fig. 10. Nevertheless, controlling all the mobile robots to the same maximum important position could not be efficient because using one mobile robot can regulate the region. Moreover, there might be other critical regions that need regulation from mobile robots. Hence, how to allocate mobile robots in regulating tasks is crucial. The multiple mobile robots are controlled separately without communication and coordination in regular use, but the distance between the importance and distance is considered. If a mobile robot is far from the highest importance region, it might take the second-highest region within a shorter distance to an individual mobile robot's location.



(a) Step 1 for collision avoidance of Situation 2



(b) Step 2 for collision avoidance of Situation 2

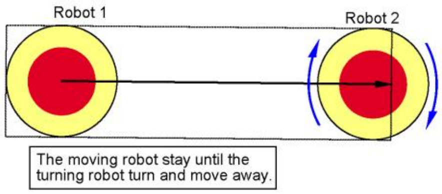


(c) Step 3 for collision avoidance of Situation 3

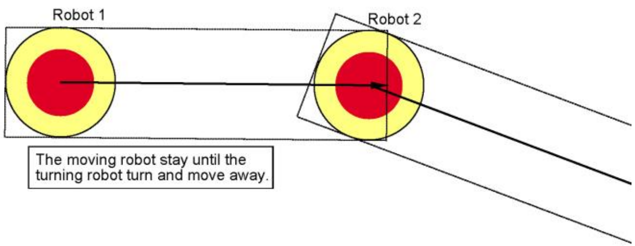
Fig. 13. Collision avoidance of Situation 2 – Move on the same path.

Additionally, the mobile robots might collide with each other when they move toward the same nodes, as seen in Fig. 11. These three situations are treated separately for mobile robots to avoid the collision, as illustrated in Figs. 12 to 14. In the first situation, one mobile robot's path intersects with another robot's path, and the mobile robot will base it on a predefined order to move through the path. As shown in Fig. 12, if Robot 2 keeps moving, it will collide with Robot 1. Thus, in this case, Robot 2 will start first at a certain safe distance and wait for Robot 1 to move first so that collision avoidance can be guaranteed.

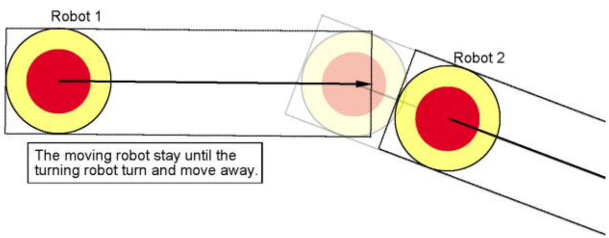
Fig. 13(a), 13(b), and 13(c) illustrate the second situation, where two mobile robots are moving toward each other or after one another on the same path. In this case, each mobile robot considers another robot as an obstacle, and the strategy presented for collision avoidance of a single robot is utilized. After deviating from the path to avoid the collision, the mobile robots move back to their original path. For the third situation, the mobile robot on the path is controlled to stop within a certain distance waiting for the robot on the node to finish making a turn. Until the mobile robot occupied the node move away, the waiting robot on the path moves forward to the target node.



(a) Step 1 for collision avoidance of Situation 3



(b) Step 2 for collision avoidance of Situation 3



(c) Step 3 for collision avoidance of Situation 3

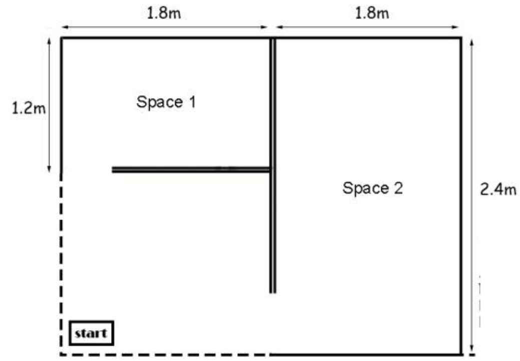
Fig. 14. Collision avoidance of Situation 3 – Move to a node where another mobile robot making a turn.

IV. Experiment Validation

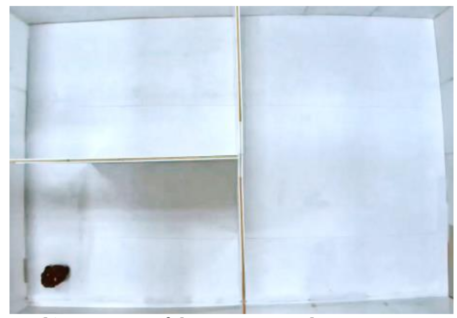
A. *Experimental Setup and Configuration*

This section presents the experimental validation of the proposed mobile robot network with a wireless sensor system. The mobile robots are the Turtlebot3 Burger, whose size is 138*mm*×192*mm*, and weight is 1 kg with 0.22 *m/s* and 2.84 rad/s for the maximum translational and rotational velocities, respectively. These robots have an embedded IMU and Laser Distance Sensor (360 LDS-01) to implement SLAM to localize the space's mobile robot. To clean the air particles, a mini air purifier, HANLIN-CarPM, is installed on Turtlebot Burger so that the air can be purified while the mobile robot is moving in the indoor environment. For the wireless sensors, the particle sensors, PMS3003, are installed in the environment to acquire the real-time concentration of particles. The specifications for the particle sensors are as follows: The detectable particle sizes are 0.2~1.0μm, 1.0~2.5μm, and 2.5~10.0μm. The operation temperature is 20~50ºC with the operation relative humidity of 0~99%. The measure of accuracy is $\mu g/m^3$.

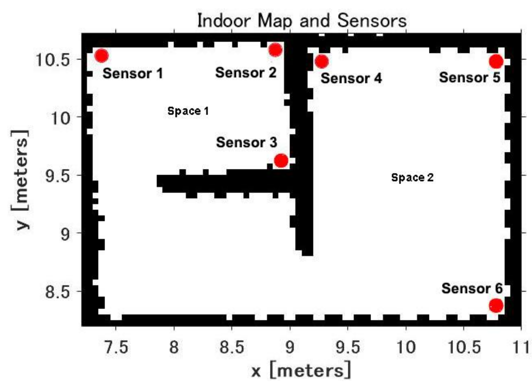
An indoor environment, including two spaces with six preinstalled wireless sensors, is considered for the experiment. While Fig. 15 (a) illustrates the experimental space dimension, Fig. 15 (b) represents the indoor environmental top view. During the experiment, the indoor environment ceiling was covered to seal the air particles in the space. The six wireless air particle sensors' locations are pre-deployed in the environment, as shown in Fig. 15 (c). In the following experiment, mobile robots, installed with an air purifier, HANALIN-CarPM, are controlled with the proposed method to move within the environment while cleaning and purifying the air particles. The experimental results are addressed in the next two sections.



(a) Sketch and dimension of the experimental environment



(b) Top view of the experimental environment



(c) Notation of the space and locations of wireless sensors

Fig. 15. Environmental configuration and wireless sensors in the experimental validation.

B. *Multiple Mobile Robot Collision Avoidance*

The proposed approach for an autonomous mobile robot with wireless sensors to regulate environmental quality is presented in this section using only one mobile robot. The mobile robot starts from an initial position that is closed to the left-bottom of the environment. Based on the sensory data collected by the six wireless sensors, the mobile robot is controlled, moving toward the space or the region with higher particle concentration. Fig. 16(a), 16(b), and 16(c) show the sensory data's initial value, the mobile robot's path planning using PRM, and the mobile robot's trajectory, respectively. We can observe that Space 1 has higher air particles, so that Sensor 1, Sensor 2, and Sensor 3 have relatively higher air particles compared to Sensor 4, Sensor 5, Sensor 6, as shown in Fig. 16(a). Therefore, the mobile robot moves toward Space 1 in the environment to conduct air purification. Additionally, Fig. 16(b) and 16(c) illustrate the path of the mobile robot and PRM.

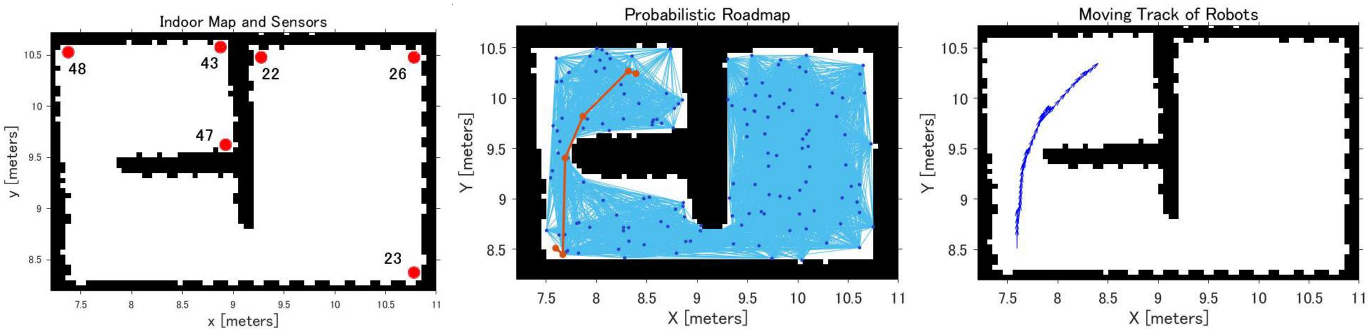


Fig. 16: Experimental results of a single mobile robot moving to the space with higher air particle density: (left) Experimental environment and initial sensory data from wireless sensors; (center) Path planning by using PRM based on the sensory data; (right) Trajectory of the mobile robot based on the PRM.

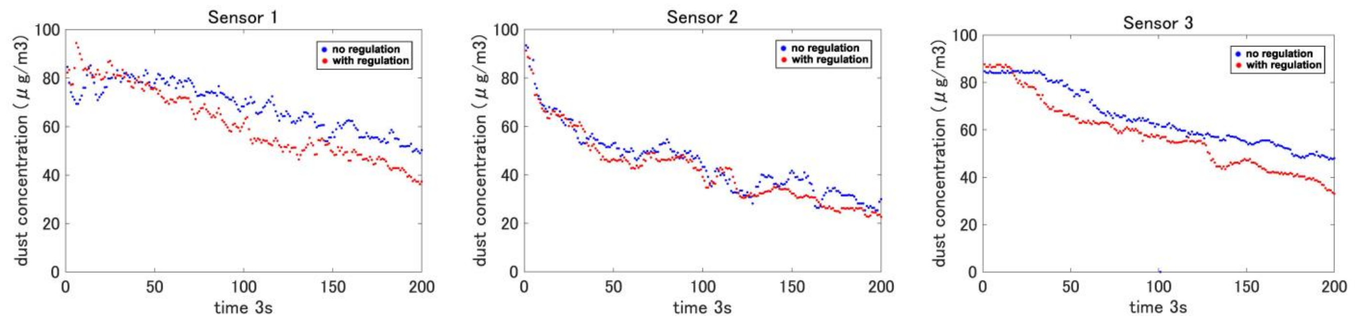


Fig. 17: Evolution of air particle concentration measured by sensors using the mobile robot for purifying air quality: (left) Evolution of sensory data from Sensor 1; (center) Evolution of sensory data from Sensor 2; (right) Evolution of sensory data from Sensor 3.

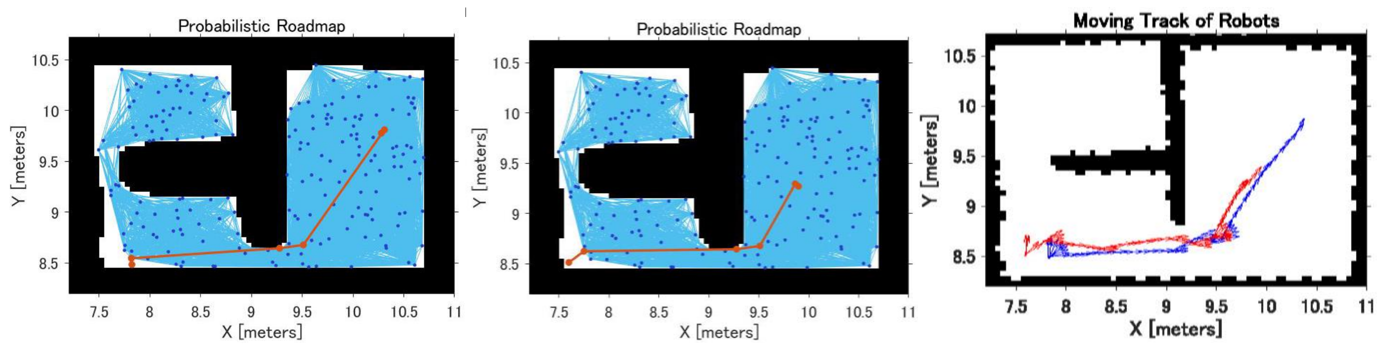


Fig. 18: PRM and mobile robot trajectories of the proposed system using multiple mobile robots: (left) Trajectory of mobile robot 1 moving to regulate environmental particle; (center) Trajectory of mobile robot 2 moving to regulate environmental particle; (right) Trajectories and orientations of mobile robots in the scenario.

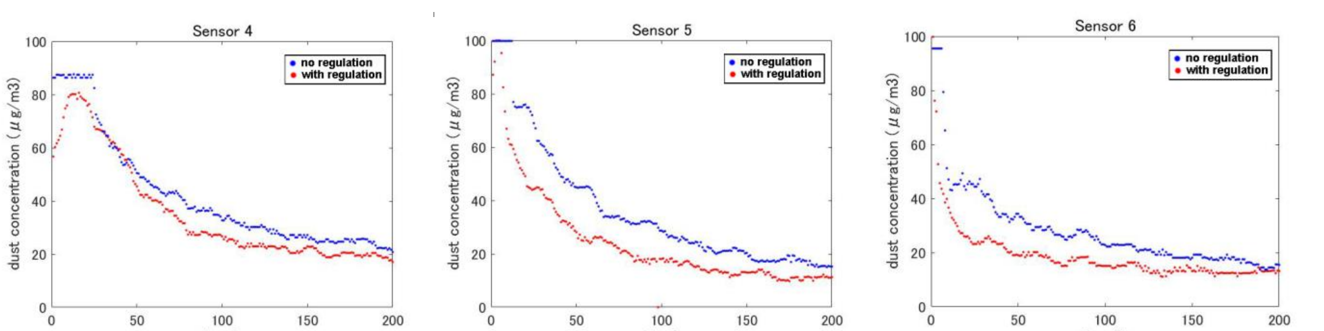


Fig. 19: Evolution of air particle concentration measured by sensors using multiple mobile robots in an environment with door/window opened: (left) Evolution of sensory data from Sensor 4; (center) Evolution of sensory data from Sensor 5; (right) Evolution of sensory data from Sensor 6.

The evolution of sensory data from Sensor 1, Sensor 2, and Sensor 3 are shown in Fig. 17. From the experimental results, we observe that with the proposed mobile robot system to regulate the air quality, the particle concentration decreases faster than the situation without an air purifier.

C. Environmental Quality Regulation

We also conducted an environmental regulation using two mobile robots equipped with an air purifier. Similar to the single robot, we commanded these robots to clean and purify the environmental air particles. Both of the robots start from an initial position close to each other. With the implemented path planning and collision avoidance approach, the robots can move towards the location with higher particle concentration, Space 2, in the environment. Fig. 18 shows the PRM, path planning, and mobile robot trajectories. We can see from Fig. 18 (c) that the mobile robots would stop and wait for other to move first to avoid the collision. If all the robots move to the same location for environmental regulation in the system with multiple mobile robots, they could co-locate in the same position. Since airflow would bring particles to different spaces, commanding the mobile robots in the same place would not be helpful for air regulation. Therefore, based on the proposed approach, when one mobile robot has arrived at the optimum location, the other mobile robots move towards the second location for regulation. Therefore, from Fig. 18 (c), the second mobile robot, red color, stop in a different position to conduct air purification. Fig. 19 illustrates the evolution of wireless sensors in Space 2. It can be observed that with multiple mobile robots, the decreasing speed of the particle concentration is faster than using only one mobile robot, which demonstrates that the superiority of multiple mobile robots.

V. CONCLUSION

In this paper, a synthesized system for an autonomous mobile robot in cooperation with wireless sensors is proposed to acquire environmental information and regulation. The proposed approach utilizes wireless sensors to acquire environmental information and command the mobile robots to the optimum position requiring regulation. The path planning and trajectory tracking are presented for a mobile robot to move within the environment, and subsequently, collision avoidance and coordination for multiple mobile robots system are presented. The experimental results of environmental regulation demonstrate the feasibility of the navigation of single and multiple robots and verify that the environment can be improved faster with the use of the proposed approach. We conclude that an environmental regulating device's location significantly influences indoor environment quality and the regulating efficiency of the apparatus. Future work of this research encompasses the coordination of heterogeneous regulating apparatuses in indoor environments and a better estimation of the distribution of useful quantities using various sensors.

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