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Distributed Sensor Network Based on RFID System for Localization of Multiple Mobile Agents*

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Abstract

This paper presents a distributed wireless sensor network for multiple mobile agents localization. Localization of mobile agents, such as mobile robots, humans, and moving objects, in an indoor space is essential for robot-robot interaction (RRI) and human-robot interaction (HRI). The standard localization system, which is based on sensors installed in the robot body, is not suitable for multiple agents. Therefore, the concept of sensor network, which uses wireless sensors distributed in a specified space, is used in this study. By analyzing related studies, two solutions are proposed for the localization of mobile agents including humans: a new hardware system and a new software algorithm. The first solution focuses on the architectural design of the wireless sensor network for multiple agent localization. A passive RFID system is used, and then the architecture of the sensor network is adapted to suit the target system. The second solution centers on a localization algorithm based on the sensor network. The proposed localization algorithm improves the accuracy in the multiple agent localization system. The algorithm uses the displacement conditions of the mobile agents and the recognition changes between the RFID tags and RFID reader. Through experiments using a real platform, the usefulness of the proposed system is verified.

Keywords: Multiple Robot Localization, Distributed Sensor Network, RFID System

1. Introduction

Recently, ubiquitous computing [1,2], where networks can be accessed anywhere and anytime, has garnered increasing attention. The infrastructure to build a sensor network has been developed rapidly as a result of advances in semiconductors, MicroElectroMechanical Systems (MEMS), and communications technologies [3,4]. Sensor networks are a basic element of ubiquitous computing environments and have features such as low power, efficiency, low cost, robustness, flexibility, and distribution. Sensor networks with these features have been applied to several areas such as intruder surveillance, position tracking, and motion monitoring in indoor spaces [5-8].

In the near future, multiple mobile agents are expected to co-exist and interact with each other in indoor spaces. The mobile agents include humans and objects, as well as robots. The following two examples are considered to be the types of interactions with mobile agents that will increase: robots will interact with other robots and perform cooperative functions; robots will offer services to humans and track objects. To facilitate smooth and safe interactions, more accurate and robust localization methods for these mobile agents are needed. That is, the states of all mobile agents within a specified space should be detectable.

Classic localization algorithms use sensors installed in mobile agents, and the positions of the mobile agents are estimated by analyzing the data obtained from these sensors, such as cameras, encoders, and ultrasonic sensors [9]. If multiple mobile agents are located closely in the same space, however, interference between the sensors data obtained is generated. Therefore, accurate data for localization cannot be obtained from these sensors. Also, the use of sensors is limited according to the features of the mobile agents. For example, human agents do not have general sensors such encoders or cameras for localization. Thus, the classic localization system is not suitable for multiple mobile agent localization that

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includes human agents. Recently, studies on mobile agent localization have been undertaken using wireless sensor networks: the sensors distributed in a specified space are used in the wireless sensor network system. Therefore, the problems found in the classic localization system are examined with reference to wireless sensor networks as a possible solution.

In this paper, a distributed wireless sensor network is used to effectively estimate the position of multiple mobile agents. The sensor network is organized using passive Radio Frequency IDentification (RFID) technology in order to improve efficiency and solve interference problems in the multiple agent localization process. However, there are some unknown factors in the localization process; therefore, the purpose of this study is to reduce uncertainty and to improve accuracy in the multiple agent localization system.

The remainder of the paper is organized as follows. Section 2 states the related works on the localization system using sensor network and research objectives. Section 3 presents the architecture of the sensor network. Section 4 presents the proposed algorithm for effective localization in a sensor network environment. The experiment results are presented in Section 5. Finally, conclusions are drawn in Section 6.

2. Related Works

Many researchers have attempted to improve the accuracy of localization systems based on sensor networks.

Zhang *et al.* [10] proposed a distributed sensor network using infrared sensors: the infrared sensors were suspended from the ceiling and human agents wore infrared transmitters. The transmitters spread the signal with unique data for identification, and the positions of the human agents were detected. Lee and Kim [11,12] proposed an active beacon system to fuse the RF signals and ultrasonic sensors. Their system calculated the distance between the mobile agents and the node using the time of arrival (TOA) of the transmitted signal. Villadangos *et al.* [13] proposed a sensor network composed of ultrasonic sensors. The positions of the robot agents were estimated using a combination of the distance data obtained from the ultrasonic sensors. Han *et al.* [14] proposed a localization system for mobile agents using passive RFID tags that were arranged on the floor of an indoor space.

Mehta *et al.* [15] used a wireless camera sensor network platform. Data was obtained using grayscale images from the camera sensor nodes over a wireless channel: they proposed simple arithmetic calculations, and implemented and evaluated the physical camera sensor network platform. Shenoy *et al.* [16] addressed the localization algorithm for wireless sensors in a hybrid sensor network. The hybrid sensor network consisted of a large number of static sensors and GPS signals. The static sensors were able to estimate the robots' positions based on the messages received. Their proposed algorithm worked simultaneously for both the sensor node localization and mobile robot navigation. Sheng *et al.* [17] proposed a new sensor network architecture consisting of an active sensor network. A potential-based robot area partition algorithm and a distributed localization algorithm were also developed.

The previous works are limited by issues of mobile robot localization in indoor spaces. For accurate localization, therefore, the existing research might fuse sensor networks and general sensors such as ultrasonic sensors or cameras installed on the robot body. In Section 1, HRI and RRI have been mentioned. The localization for the human agents and moving objects should also be addressed. As shown in the previous studies, robots can have extra sensors for localization on their body, except in sensor network systems. However, sensors such as encoders, ultrasonic sensors, and cameras cannot be installed in human agents and objects for localization. The position of the human agents should be estimated using a distributed sensor network. Therefore, a localization system based on sensor network for the several types of mobile agents (robots, humans, and objects) must be addressed. To date, previous studies have not considered these issues.

In this paper, the problems shown in existing studies are considered and possible solutions are proposed. The sensor network using an RFID system is organized for effective localization of multiple and different types of mobile agents. Even If they coexist, localization can be processed irrespective of this. The architecture of the sensor network is presented in Section 3. Furthermore, an algorithm to improve accuracy in the localization process is proposed based on the designed sensor network. Because the algorithm does not require extra sensors, it can be applied to human agents, moving objects, and robots alike. The algorithm is explained in Section 4.

3. Architectural Design of Sensor Network

A distributed sensor network system has an architecture where several sensor agents are connected and networked with each other, as shown in **Figure 1**. In a sensor network system, the data obtained from each sensor is transferred through a wired or wireless network. In this paper, a distributed wireless sensor network is applied to the mobile agent localization as shown in **Figure 2**. The proposed system is composed of nodes, mobile agents,

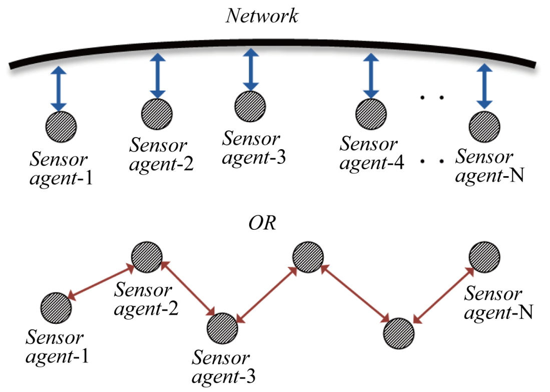

Figure 1. General concept and architecture of sensor network system that consists of several small sensors agents.

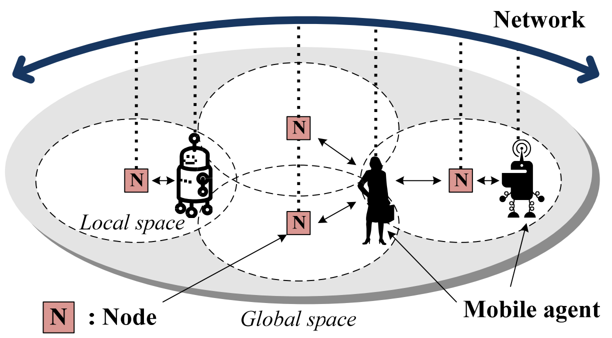

Figure 2. Application of sensor network for the localization of multiple mobile agents including humans, robots, and moving objects.

and the main network. The position of multiple mobile agents is estimated by the nodes, which consist of small sensors arranged in the specified space. One node covers a local assignment space and nodes are placed so that they overlap slightly; thus, the total coverage by the nodes is equates with the overall global space. The mobile agents are all human agents, objects, or mobile robots that exist in the specified space. When a mobile agent exists in a certain local space, the position of the agent is estimated by the node that covers that local space. If several agents are located near the same node, the positions of the agents are obtained independently using their own IDs. The main network with network servers stores and manages the IDs and states of every agent. All agents have knowledge of the position of each agent in the network.

The distributed wireless sensor network is organized using RFID technology. An RFID system has several features and functions that depend on the frequency band, nature of the power source, tags, etc [18]. A passive RFID system with an operation frequency of 13.56 MHz is used to obtain the following practical features [19,20]. Passive RFID tags use induction power through RF waves from RFID readers. Because an external power source is not used, semi-permanent use without power replacements is possible after the initial installation. The passive RFID system recognizes passive RFID tags without contact. Damage or incorrect readings caused by obstacles do not occur. Because the ID and position data are stored in the RFID tags, the positions of several agents can be addressed simultaneously without confusion.

Figure 3 shows the concept of the sensor network based on the RFID system for localization of multiple mobile agents. Passive RFID tags are arranged with a constant gap on the floor and a pre-stored coordinated value. That is, the sensor network node is a passive RFID tag in this study. The mobile agents have independent RFID readers and antennas to communicate with the RFID tags. Mobile robots have antennas installed on the bottom of their body and human agents install the antennas on the bottom of their shoes. The antenna, which is connected to a reader, radiates electromagnetic waves with a finite range in the direction of the floor. RFID tags are activated using electromagnetic waves and can then transmit their coordinate values to the RFID reader. The packet with the obtained position data and ID of the mobile robots is uploaded to the main network. Because passive RFID tags do not use a separate external power source, the position data yielded by the RFID system is indirectly uploaded through the RFID reader installed in the robot agent. As shown in **Figure 4**, the mobile agents have RFID readers and antennas, and the data obtained from the RFID tags is transferred to the main network. The protocol used in the network communication is organized as shown in **Table 1**. Through this network, each robot agent and user knows the position of every robot agent at any time.

4. Algorithm for Localization Based on Sensor Network

As mentioned in the previous section, the RFID reader is

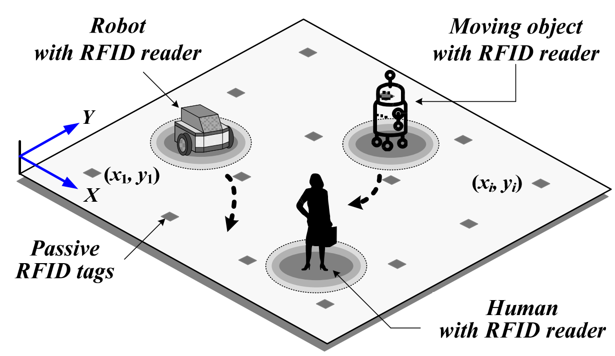

Figure 3. Concept of the sensor network based on the RFID system for localization of multiple mobile agents: distributed RFID tags in a space.

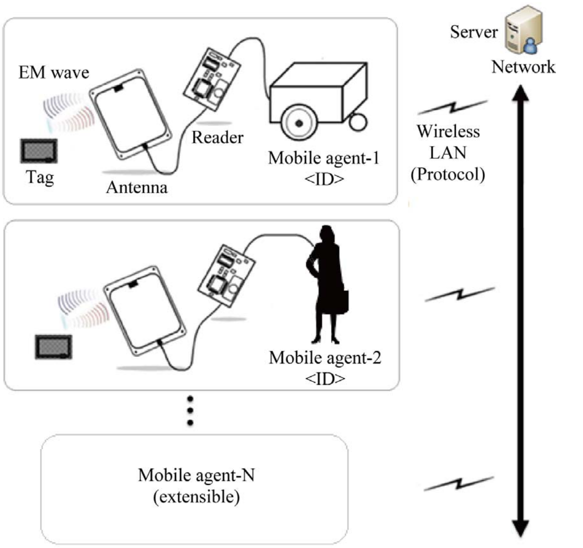

Figure 4. Localization of mobile agents using the RFID system.

Table 1. Communication protocols between the RFID reader and network server.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O

A: Mobile agent ID 0: robot-1, 1: robot-2,2: human
B: Detection by any Node (On/Off) 0: detection, 1: not detected
C: empty/dummy
D: First Activated Node ID integer
E: x-coordinate of Node integer
F: y-coordinate of Node integer
G: Second Activated Node ID integer
H: x-coordinate of Node integer
I: y-coordinate of Node integer
J: Third Activated Node ID integer
K: x-coordinate of Node integer
L: y-coordinate of Node integer
M: Fourth Activated Node ID integer
N: x-coordinate of Node integer
O: y-coordinate of Node integer

installed in mobile agents and passive RFID tags are arranged on the floor. When a mobile agent approaches a specified tag, the coordinated value stored in the tag is read by the RFID reader in the mobile agent. That is, the mobile agent is located around a coordinate value stored in the tag. However, an accurate position value of the mobile agent cannot be obtained. The distance between the node (*i.e.* RFID tag) and the mobile agent is unknown due to the technical limitations of passive RFID systems. Only limited position information can be obtained: that is, the mobile agent is located near a certain node. Previous works have used other sensor systems with a sensor network to improve the accuracy of localization. While the sensors such as encoders and cameras can be installed on the robot body, human agents do not have these sensors for localization. Thus, for successful localization of the mobile agents including human agents, a scheme that uses only the distributed sensor network must be considered.

Therefore, a localization algorithm that uses the motion of the mobile agents and recognizes changes in the RFID tags under a sensor network environment is proposed. The approach using the motion of the mobile agents is as follows. If the mobile agents move in the space, displacement for a constant time is generated according to the agents' velocity. If the velocity of agents is controlled, the displacement will be within a constant range. Therefore, the range of the next position from the initial position of the agents can be predicted and estimated. The approach using the recognition change is as follows. In the RFID system, communication and recognition between the RFID reader and tags are always conducted. However, the maximum distance for communication and recognition is fixed. If the mobile agent equipped with the RFID reader moves, the distance between the RFID reader and tag varies continuously. Therefore, two cases-case I where the RFID reader recognizes the tags and case II where the RFID reader does not recognize the tags-occur repetitively. Using the recognition change in the RFID system, the position of mobile agents can be estimated.

It is assumed that mobile agents move with a limited velocity in a specified indoor space. As shown in **Figure 5**, the RFID tags are arranged regularly and defined as the $node_1$, $node_2$, and $node_3$. The coordinate values stored in each node are $C_{N.1}$, $C_{N.2}$ and $C_{N.3}$, respectively.

$$C_{N.k} = (x_{N.k}, y_{N.k}), \quad k = 1, 2, 3 \tag{1}$$

The nodes cover a constant territory. If a mobile agent exists in the recognition territory (*RT*), the position of the mobile agent is estimated using the corresponding node. The territory recognized by $node_k$ is represented as RT_k. For example, RT_1 is approximated as a circle with constant radius, γ, and the center is $node_1$ [21].

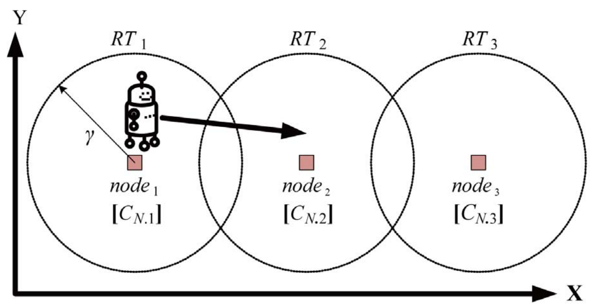

Figure 5. Localization for the movement of a mobile agent from RT_1 to RT_2.

$$(x - x_{N.1})^2 + (y - y_{N.1})^2 = \gamma^2 \quad (2)$$

Note that a mobile agent is always recognized by $node_1$ within the RT_1; however, the recognition rate for a mobile agent is low near the boundary of RT_1. That is, the reader communicates with tags in the recognition territory, and the communication is unstable at the boundary of the recognition territory. Eventually, the communication is prevented due to the mobile agent moving out of the recognition territory. However, two RFID tags simultaneously communicate with the RFID reader in the overlap region of RT_1 and RT_2. A localization algorithm is proposed using the communication state between the tags and the reader. The algorithm is explained below for the mobile agent movement from RT_1 to RT_2, as shown in **Figure 5**.

Step 1.

Assume that the mobile agent is detected by $node_1$. It can be considered that the mobile agent is located within RT1. However, the exact position within the RT_1 cannot be known. Therefore, it is assumed that there are some points that can be expected to contain the current position of mobile agent in RT_1. As shown in **Figure 6**, m points are scattered in this area. Each point has an x-y coordinate value in a 2D plane. The points are represented as follows:

$$E_i^{s1} = (x, y)_i^{s1}, \quad i = 1 \sim m \quad (3)$$

The number of points, m, is subject to the resolution of the localization and the dimension of RT_1. The point, E_i^{s1}, satisfies the following condition in Step 1.

$$|C_{N.1} - E_i^{s1}| < \gamma \quad AND \quad |C_{N.2} - E_i^{s1}| > \gamma \quad (4)$$

The probability that each E_i^{s1} is the real position of a mobile agent is the same. If the real position of the mobile agent is P_M, the sum of the position estimation errors for E_i^{s1} is represented as follows:

$$e^{s1} = \sum_{i=1}^{m} |P_M - E_i^{s1}| \quad (5)$$

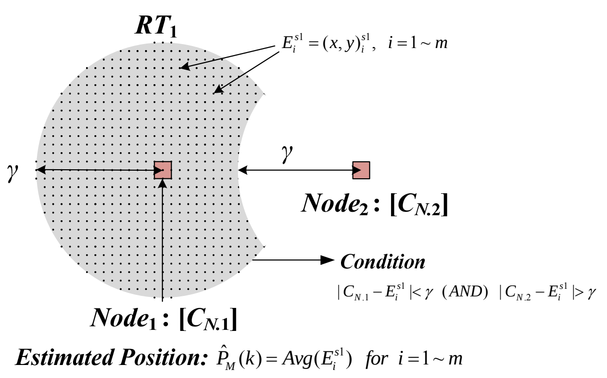

Figure 6. Shape of the recognition territory of $node_1$ in Step 1.

Because the weight of E_i^{s1} for the real position of the agent is the same, the average of E_i^{s1} minimizes the error. The estimated position of the mobile agent, $\hat{P}_M(k)$, at time k is determined by the average value.

$$\hat{P}_M(k) = \begin{bmatrix} \hat{x}_M(k) \\ \hat{y}_M(k) \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{m} x_i^{s1} / m & \sum_{i=1}^{m} y_i^{s1} / m \end{bmatrix}^T \quad (6)$$

Step 2.

The mobile agent moves toward $node_2$ within RT_1. The mobile agent is continuously detected by $node_1$. The recognition change, where $node_2$ detects the mobile agent, is generated. In this step, it can be considered that the mobile agent can be located at the boundary of RT_2 as shown in **Figure 7**. An arbitrary region along the boundary of recognition territory is set; at some points along this boundary, E_i^{s2}, it can be expected as that the position of the mobile agent is selected within an arbitrary region using the same method as explained in Step 1. The points, E_i^{s2}, satisfy the following conditions in Step 2.

$$(\gamma - \varepsilon) \le |E_i^{s2} - C_{N.2}| \le (\gamma + \varepsilon), \quad within \ RT_1 \quad (7)$$

The probability that E_i^{s2} is the real position of mobile agent is the same as in Step 1.

The estimated position of the mobile agent at time k is determined by the average of E_i^{s2}.

$$\hat{P}_M(k) = \begin{bmatrix} \hat{x}_M(k) \\ \hat{y}_M(k) \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{m} x_i^{s2} / m & \sum_{i=1}^{m} y_i^{s2} / m \end{bmatrix}^T \quad (8)$$

The mobile agent has a limited maximum velocity. Therefore, the maximum displacement of the mobile agent is calculated during the movement time from Step 1 to Step 2.

$$d_{|step2-step1|} = v_{\max} \times (T_{s2} - T_{s1}) \quad for \ \ v_M \le v_{\max} \quad (9)$$

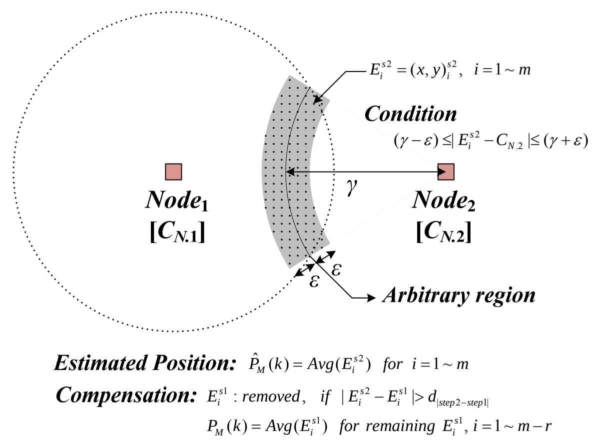

Figure 7. Shape of the recognition territory of the $node_1$ and $node_2$ in Step 2.

The distances from E_i^{s1} to E_i^{s2} are calculated; then, the E_i^{s1} values that are not satisfied with the maximum displacement are removed.

$$E_i^{s1}: removed, \quad unless \ |E_i^{s2} - E_i^{s1}| \le d_{|step2-step1|} \qquad (10)$$

The position of the mobile agent is estimated again using the remaining E_i^{s1}.

$$\hat{P}_M(k) = Avg(E_i^{s1}) \ \ for \ remaining \ E_i^{s1}, \ i = 1, \cdots, m-r \qquad (11)$$

Step 3.

If a mobile agent is stably recognized by $node_1$ and $node_2$, it is considered that the mobile agent is located in the RT_1 and RT_2 overlap region as shown in **Figure 8**. Next, the points, E_i^{s3}, where the position of the mobile agent can be expected are determined. Point E_i^{s3} satisfies the following conditions in Step 3.

$$|E_i^{s3} - C_{N.1}| < \gamma, \ and \ |E_i^{s3} - C_{N.2}| < \gamma \qquad (12)$$

The estimated position of the mobile agent at time k is determined by the average of E_i^{s3}. The distance from E_i^{s2} to E_i^{s3} is calculated, and the E_i^{s2} values that are not satisfied with the maximum displacement are then removed.

$$E_i^{s2}: removed, \quad unless \ |E_i^{s3} - E_i^{s2}| \le d_{|step3-step2|} \qquad (13)$$

The position of the mobile agent is estimated again using the remaining E_i^{s2}.

$$\hat{P}_M(k) = Avg(E_i^{s2}) \ \ for \ remaining \ E_i^{s2}, \ i = 1, \cdots, m-r \qquad (14)$$

Step 4.

As this step is the same as that of Step 2 albeit with RT_2 and RT_3, the recognition change by $node_1$ within RT_2 is generated. Instead, the mobile agent is continuously detected by $node_2$. As shown in **Figure 9**, it can be assumed the mobile agent is located in the boundary of RT_1. An arbitrary region is set and some points, E_i^{s4}, are selected as in the previous step. Point E_i^{s4} satisfies the following conditions in Step 4.

$$(\gamma - \varepsilon) \le |E_i^{s4} - C_{N.1}| \le (\gamma + \varepsilon), \quad within \ RT_2 \qquad (15)$$

The estimated position of the mobile agent is calculated as in Step1 to Step 3.

$$\hat{P}_M(k) = Avg(E_i^{s3}) \ \ for \ remaining \ E_i^{s3}, \ i = 1, \cdots, m-r \qquad (16)$$

According to the movement of the mobile robot, the recognition change of the mobile agent by the node is generated. The position of the mobile agent is continuously estimated using the aforementioned steps.

5. Experiment and Result

The proposed sensor network for localization is applied in a real system. The positions of the multiple mobile agents are obtained using the sensor network including the algorithm introduced in Section 4.

Figure 10 shows the RFID system and mobile robots used in this experiment. The RFID system, KISR300H, used for the sensor network is a passive RFID system and it operates at a frequency of 13.56 MHz. As shown in **Figure 10(a)**, the passive RFID tags fabricated from epoxy have dimensions of 0.03 m × 0.03 m. The RFID reader and antenna are installed in the mobile robots and human, as shown in **Figures 10(b)** and **10(c)**. The size of the robots' antennas is 0.15 m × 0.15 m and the size of human agent's antenna is 0.07 m × 0.07 m. The communication between the RFID reader and network server is conducted using a wireless LAN. **Figure 10(c)** shows the mobile agents: mobile robot 1 and mobile robot 2. Both robots have two-wheel differential drive and RFID read-

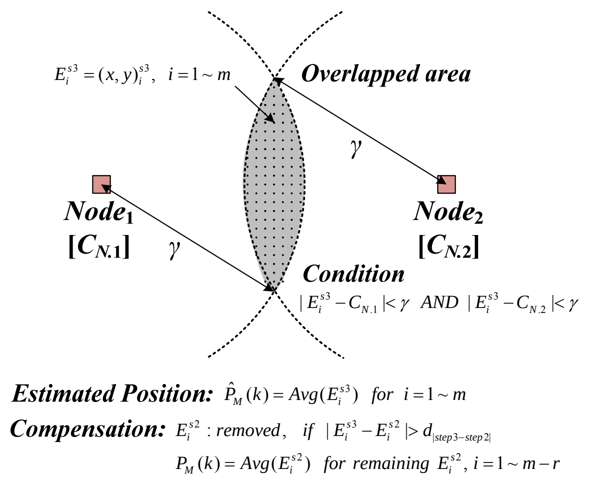

Figure 8. Shape of the recognition territory by the *node*$_1$ and *node*$_2$ in Step 3.

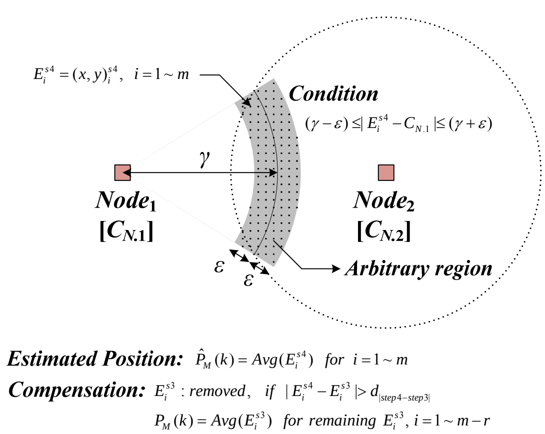

Figure 9. Shape of the recognition territory by *node*$_1$ and *node*$_2$ in Step 4.

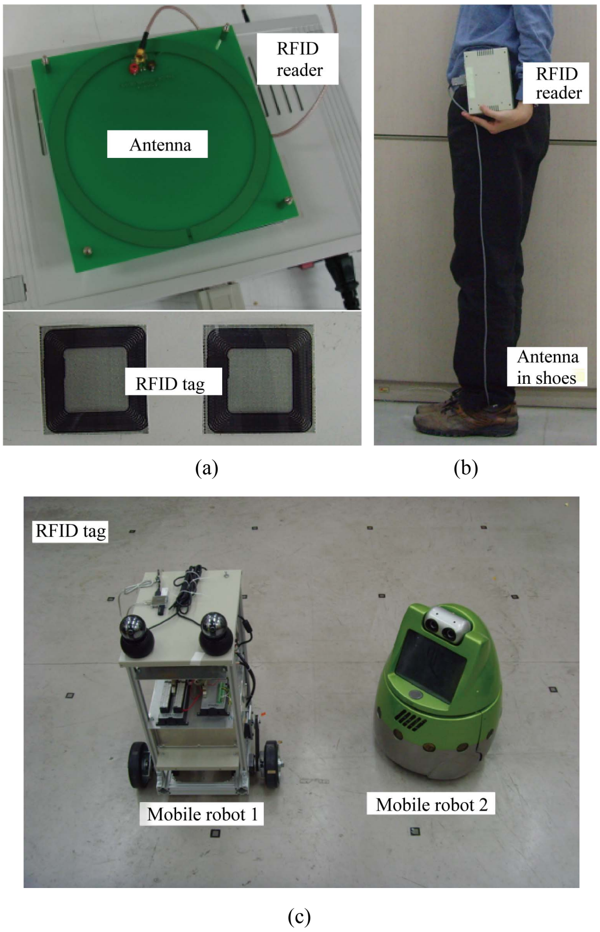

Figure 10. Experimental environment: (a) RFID reader, antenna and tags; (b) human agent with RFID reader and antenna; (c) two mobile robots in the wireless sensor network using RFID tags.

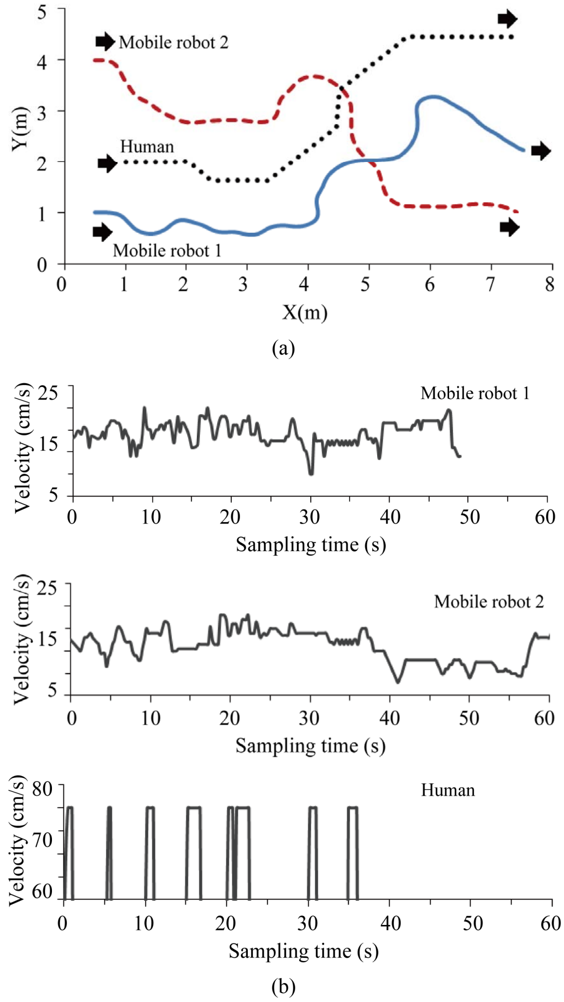

Figure 11. The predefined path and linear velocity of the mobile agents: (a) the path of all agents; (b) the linear velocity of mobile robot 1, mobile robot 2, and the human agent.

ers. The antennas (connected to the RFID reader) are installed on the bottom of body. The human agent has also a small portable RFID reader and antenna as shown in **Figure 10(b)**.

The mobile agents are driven as follows. The RFID tags are arranged on the floor and the gap between the tags is 0.5 m, as shown in **Figure 10(c)**. **Figure 11(a)** shows the driving path of the mobile agents in the specified indoor space. In order to prevent the mobile agents colliding, the driving paths were predefined. The linear velocity of each agent during the movement along the path is represented in **Figure 11(b)**. The maximum velocity of the mobile robots is limited to 25 cm/s. The human agent moves with the maximum instantaneous velocity, 8 cm/s, and steps forward one step at a time. The sensor network estimates the position of the moving mobile agents using the RFID system. The position of the mobile agents is estimated during approximately 60 s, and the sampling period of the position measurement is 0.25 s.

The error between the real position value and the measured value of the mobile agents is defined as the performance index. **Figure 12** represents the position error of the mobile agents measured using the proposed algorithm for the driving time from the starting point to the finishing point. **Figures 12(a) and 12(b)** are the position errors of mobile robot 1 and mobile robot 2, respectively. The average value of the position error during driving was 12.06 cm and 12.62 cm for mobile robot 1 and mobile robot 2, respectively. **Figure 12(c)** shows the position error for the human agent's motion. Because the human agent repeats a stopping and starting/moving motion, the human agent's error pattern is different to that of the mobile robots. The average value of error is 14.24 cm for the human agent.

The proposed algorithm from Section 4 and an RFID-base localization scheme introduced in a previous work were used to evaluate the utility and advantages of the

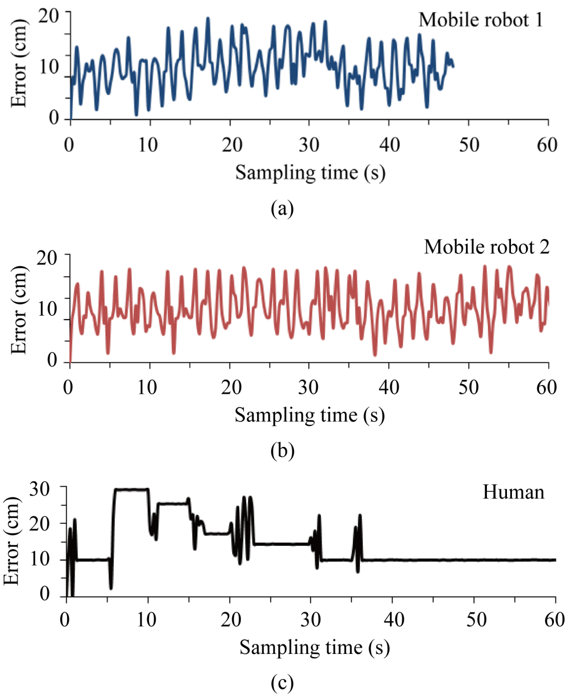

Figure 12. Error generated in the localization process based on the proposed sensor network using the proposed algorithm: (a) error for mobile robot 1; (b) error for mobile 2; (c) error for the human agent.

Table 2. Comparison for experimental result between proposed algorithm and previous algorithm.

Average value of error (proposed algorithm)		Average value of error (previous algorithm in [14])	
Mobile robot 1	12.06 cm	Mobile robot 1	23.16 cm
Mobile robot 2	12.62 cm	Mobile robot 2	25.81 cm
Human	14.24 cm		

algorithm proposed in this study. The results were then compared for each algorithm. In the RFID-based sensor network, the distribution of RFID tags affects the accuracy of localization. If the number of RFID tags is large, the accuracy generally rises.

The previous method proposed in [14] only depends on the data of the node (*i.e.* RFID tag) that is close to mobile agents. If a mobile agent is near the node, the position of the mobile agent is estimated using a coordinated value stored in the node. If the mobile agent is not located near the node, however, it is difficult to obtain a coordinated value from the node. When a small number of RFID tags is used, the accuracy of the previous algorithm [14] is drastically reduced.

The method proposed in this study uses the displacement of the mobile agent and recognition of the change between the RFID reader and tags, and can reduce uncertainty in localization systems based on a sensor network. That is, the proposed system is less affected by the distribution of RFID tags than the previous algorithm. The position of the mobile agents is estimated using factors obtained by their movement. If the mobile agents are not located near the node, the position of the mobile agents is indirectly calculated using other factors. Even when a small number of RFID tags is used, a reasonable level of accuracy can be maintained.

For the same density distribution of RFID tags, the performance of the previous algorithm and the proposed algorithm is compared. The gap between RFID tags is uniformly 0.4 m. The experiments were conducted with two mobile robots. The results from the experiments in this study are listed in **Table 2**. Through the experiments, it was verified that the performance of the proposed sensor network using the proposed algorithm exceeds that of previous research.

6. Conclusion

This work studied the localization of multiple mobile agents using a distributed sensor network. The distributed sensor network that has been used for the localization of mobile agents in previous studies had limited functions. This paper presented a sensor network and localization algorithm that can be applied to multiple mobile agents and the distributed wireless sensor network was organized using RFID technology. This concept addressed issues such as sensor interference and position estimation confusion among multiple agents. Furthermore, an algorithm that estimates more accurate position of agents was proposed using the recognition change between the RFID tag and RFID reader. This algorithm can be applied to many types of agents including humans.

In the future, the system will be organized for interaction and motion planning among agents using the proposed localization scheme based on a sensor network.

7. References

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