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Intelligent emergency service system based on wireless sensor and actuator networks

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Abstract: An intelligent emergency service (IES) system is designed for indoor environments based on a wireless sensor and actuator network (WSAN) composed of a gateway, sensor nodes, and a multi-robot system (MRS). If the MRS receives accident alarm information, the group of robots will navigate to the accident sites and provide corresponding emergency services. According to the characteristics of the MRS, a distributed consensus formation protocol is designed, which can assure that the multiple robots arrive at the accident site in a specified formation. The prototype emergency service system was designed and implemented, and some relevant simulations and experiments were carried out. The results show that the MRS can successfully provide emergency lighting and failure node replacement services when accidents happen. The effectiveness of the algorithm and the feasibility of the system are verified.

Key words: emergency service; wireless sensor and actuator network; intelligent illumination; multi-robot system

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With the development of relevant technologies for home automation, mobile robots are playing increasingly important roles in indoor environments. In the favor of robots, people can enjoy convenient, intelligent, and human oriented living and working environments[1]. For the purpose of better security, various remote security systems have been proposed to detect intruders by using different kinds of robots such as wheeled robots[2], jumping robots[3], and self-reconfigurable robots[4]. Emergency systems have attracted the attention of people mainly in their applications for health care[5-6]. However, emergencies such as power failure, accidental fire, and gas leakage are all frequent accidents in indoor environments. Therefore, it is of great necessity to prepare emergency service systems in indoor environments such as homes, factories, shopping malls, and office buildings[7].

Wireless sensor nodes have been widely used in indoor security and service systems[3]. Static wireless sensor nodes were adopted by security systems for surveillance robots[4]. Lai et al. [6] proposed a personalized home physiological monitoring system by using a wireless multi-hop network. The environmental information was detected by wireless sensor nodes to help respond to emergency events[8].

In the accident site, different services may be needed at the same time. Chung et al. [9] developed a multi-functional indoor service robot system, which could successfully accomplish four target service tasks. The robot was powerful but has large size and high cost. Researchers verified that a system with multiple simple robots can complete complicated tasks more effectively than a single robot with complex functions[10-12]. Chien et al. [13] designed a security system by employing multiple robots to ensure that no zones were unmonitored. Bedi et al. [14] proposed a MRS composed of different robots to monitor the whole house. Formation keeping can significantly simplify the navigation of MRS[15]. Moreover, if the MRS with a leader knows the destination, all the robots can arrive at their corresponding targets by keeping the specified formation[16], and only the leader robot needs path planning. According to the environment requirements, a consensus formation algorithm has been designed for the MRS.

In this paper, the overall architecture of the IES system is presented and designed. The system based on a WSAN includes a gateway, sensor nodes, and a MRS. A distributed consensus algorithm is designed for the MRS. Then, the effectiveness of the system is examined through simulations and experiments.

1 System Overview

As shown in Fig. 1, the conceptual architecture of the proposed emergency service system is based on a WSAN. The system includes two parts: the remote client side and the local server side. The remote client side consists of a PC or a PDA and a home server, which can control the local server side, and collect and save the indoor environ-

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ment information. The local server side consists of a gateway, several static monitoring nodes, and a group of mobile robots. The gateway, sensor nodes, and mobile robots form a mesh topology and multi-hop WSAN. The mesh network can ensure that all the nodes have paths to each other and the gateway. The nodes are installed in the rooms to detect the ambient light intensity information of the indoor environments.

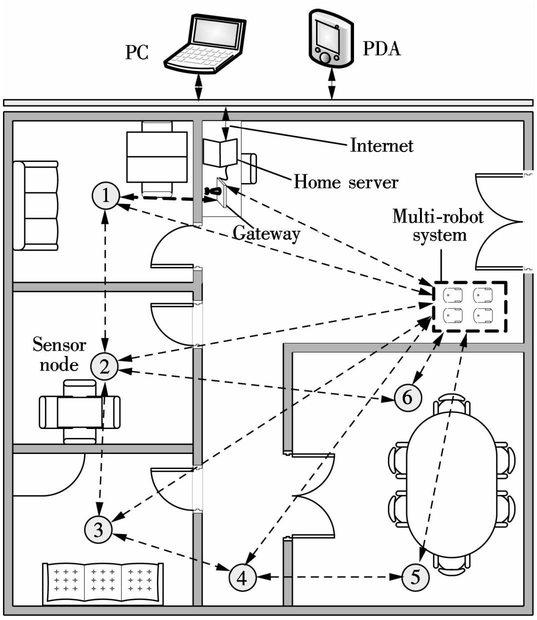


Fig. 1 The conceptual architecture of the proposed emergency service system for indoor lighting

An illuminating node or a monitoring node is installed on each mobile robot for light intensity detection. The home server can receive alarming messages if the light intensity is lower than the threshold or a monitoring node fails to work. Then the MRS will receive corresponding commands and move to the accident area by keeping formation to provide services immediately. The illuminating modules mounted on the mobile robots are controlled by the WSAN according to the light intensity in the patrolling process.

2 System Design

2.1 Design of the gateway and monitoring node

The gateway includes a microprogrammed control unit, a ZigBee/IEEE 802.15.4 compliant module, a standard nine-pin serial port Bluetooth communication interface, and rechargeable lithium batteries. The gateway connects with the home server, and the communication between them is based on the serial port. The prototype of the gateway is shown in Fig. 2. Its size is 136 mm × 90 mm × 35 mm. The gateway can receive information from the monitoring sensor nodes and the multiple robots, and send the sensor data back to the home server.

The prototype of the monitoring node for light intensity detection and the main board are shown in Fig. 3. Each

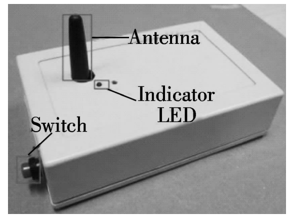


Fig. 2 The prototype of the gateway

static node is comprised of photo-resistors, a wireless module, indication LEDs, and a lithium battery group. The size of the node is 51 mm × 80 mm × 32 mm. The node collects light intensity data according to the monitor commands, and then sends the data to the gateway.

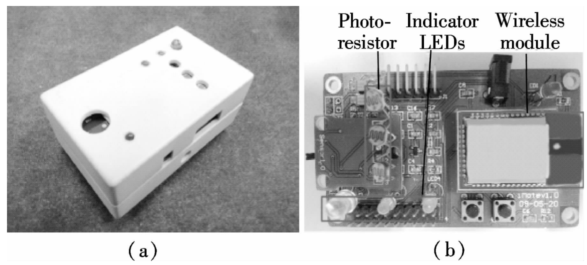


Fig. 3 The design of the monitoring node. (a) The prototype of the node; (b) The circuit board of the node

2.2 Design of the IES system

The local server side is composed of the light intensity monitoring network and the multi-robot control network. Data transmissions among the gateway, monitoring nodes, and the MRS are all based on the WSAN. The control board of the emergency illuminating node is shown in Fig. 4. Illumination is achieved by a 10 W high power LED lamp, controlled by relays through the wireless module. The lamp is off during the movement of the robot. When the light service robot arrives at the room which needs emergency lighting, the wireless module will receive corresponding commands, and the lamp will be turned on to provide illumination services.

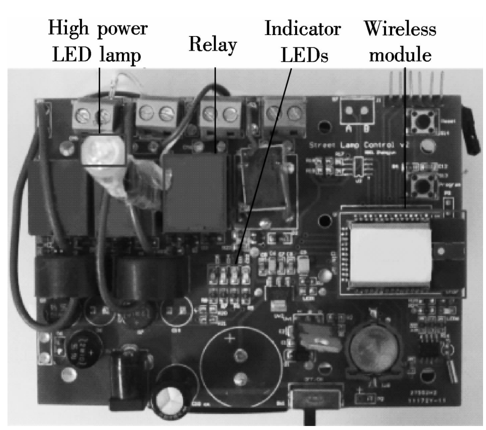


Fig. 4 The control board of the emergency illuminating node for the service system

The flowchart of the IES system is shown in Fig. 5. The monitoring network will be initiated if it receives requests from the home server. The monitoring nodes detect the light intensity of the rooms periodically, and send the data to the home server for processing. If the detected light intensity is lower than the preset threshold, or some monitoring nodes fail to work, the home server will receive alarming messages. The accident positions are obtained according to the ID of the monitoring nodes. The home server will judge which type the accident belongs to. If the accidents occur in many rooms, several robots will be assigned to different rooms to provide emergency services. If there are many kinds of accidents occurring in the same room, multiple robots will navigate to the room and provide emergency rescue. The navigation control of the multiple robots is based on formation. Each static monitoring node can detect the voltage which stands for the light intensity. If the voltage is lower than the normal value, the node will be regarded as broken. Then, one of the robots will navigate to replace the failure node.

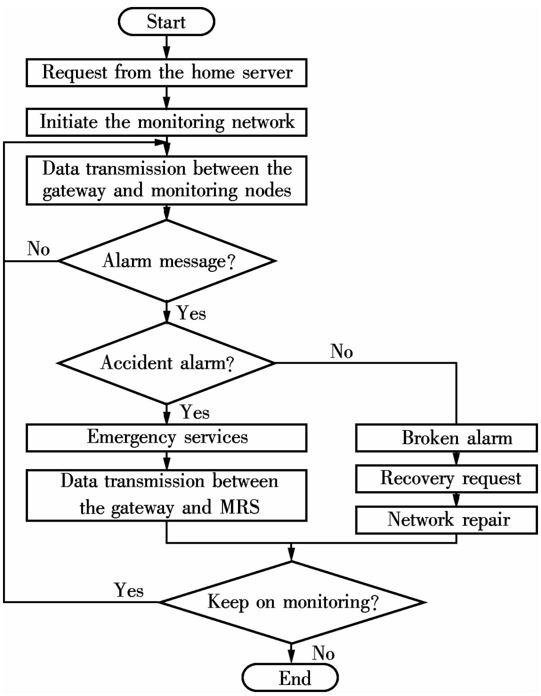


Fig. 5 The flowchart of the IES system

2.3 Design of formation controller

The service robot is with two independently driven wheels in the rear and one unpowered point in the front. The kinematic model is as follows:

$$\begin{Bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{Bmatrix} = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{bmatrix} \begin{Bmatrix} v \\ w \end{Bmatrix} \tag{1}$$

where $\{x, y, \theta\}^{\mathrm{T}}$ is the position and the heading angle of the robot; $\{v, w\}^{\mathrm{T}}$ is the linear and angular velocities, which can be obtained as

$$\begin{Bmatrix} v \\ w \end{Bmatrix} = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{b} & -\frac{1}{b} \end{bmatrix} \begin{Bmatrix} v_{\mathrm{L}} \\ v_{\mathrm{R}} \end{Bmatrix} \tag{2}$$

where v_{L} and v_{R} are the velocities of the two wheels; b is the distance between the two wheels.

The indoor environment can be modeled as a two-dimensional grid map, and the grid size is 15 cm × 15 cm. The trajectory can be obtained by the A* algorithm. As shown in Fig. 6, the polyline *SABCG* is the planned path for the leader robot. *S* is the initial position, and *G* is the target position. *A*, *B*, and *C* are three turning points, regarded as stage targets for the leader robot.

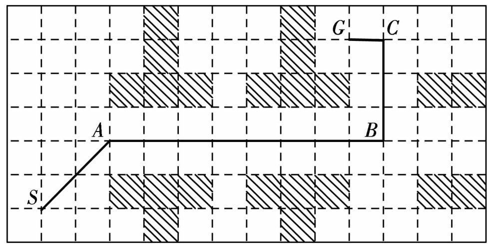


Fig. 6 Trajectory obtained by the A* algorithm

For a system with n robots, the adjacent relationships can be described by matrix $\boldsymbol{A}$, where the diagonal elements a_{ii} are all zeros. If robot i is the neighbor of robot j, $a_{ij} = 1$; otherwise $a_{ij} = 0$. The degree matrix is $\boldsymbol{D} = (d_{ij})$, where $d_{ii} = \sum_{j=1}^{n} a_{ij}$, and $d_{ij} = 0$. The Laplacian matrix is written as $\boldsymbol{L} = \boldsymbol{D} - \boldsymbol{A}$. The formation of multiple robots can be realized by a consensus protocol. Suppose that the robots of the system are all second-order integrator models, as follows:

$$\left.\begin{aligned} \dot{\boldsymbol{x}}_i &= \boldsymbol{v}_i \\ \dot{\boldsymbol{v}}_i &= \boldsymbol{u}_i \end{aligned}\right\} \tag{3}$$

where $\boldsymbol{x}_i, \boldsymbol{v}_i, \boldsymbol{u}_i \in \mathbf{R}^2$, representing the position, velocity, and acceleration of robot i, respectively. The consensus protocol is designed as

$$\boldsymbol{u}_i = -k_1 \sum_{j \in N_i} (\boldsymbol{x}_i - \boldsymbol{x}_j + \boldsymbol{r}_{ij}) - k_2 \boldsymbol{v}_i - k_3 b_i (\boldsymbol{x}_i - \boldsymbol{x}_{\mathrm{g}}) \tag{4}$$

where $j \in N_i$ means that robot j is the neighbor of robot i; $\boldsymbol{r}_{ij} \in \mathbf{R}^2$ denotes the relative distance between robot i and robot j; $\boldsymbol{b}_i$ is the access state to target position $\boldsymbol{x}_{\mathrm{g}}$, and "only the state of the leader is 1, and all follower robots are 0; k_1, k_2, and k_3 are positive gain coefficients.

By substituting Eq. (4) into Eq. (3), the dynamic equations of the system can be concluded as

$$\left.\begin{aligned} \dot{\boldsymbol{x}} &= \boldsymbol{v} \\ \dot{\boldsymbol{v}} &= -k_1 (\boldsymbol{L}\boldsymbol{x} - \mathrm{diag}(\boldsymbol{A}\boldsymbol{R})) - k_2 \boldsymbol{v} - k_3 \boldsymbol{B}(\boldsymbol{x} - \boldsymbol{x}_{\mathrm{g}} \otimes \mathbf{1}_n) \end{aligned}\right\} \tag{5}$$

where $\boldsymbol{x}^{\mathrm{T}} = \{x_i, \dots, x_n\}$, $\boldsymbol{v}^{\mathrm{T}} = \{v_i, \dots, v_n\}$; $\boldsymbol{R} = \{r_{ij}\}_{n \times n}$ is the relative distance matrix of the MRS; $\boldsymbol{B}$ is a diagonal matrix, and the diagonal element in the i-th row corresponds to b_i; $\otimes$ denotes the Kronecker product; $\mathbf{1}_n$ is a column vector of all ones with a dimension of n.

3 Simulation and Experimental Results

First, the effectiveness of the consensus formation protocol is verified through simulations and experiments, respectively. Secondly, the function of the emergency service system is tested. In the experiments, JN5139 is selected as the wireless module. The communication distance is 150 m, and the WSAN can contain 65 536 nodes, theoretically. Therefore, the design of the system can satisfy the requirements of applications in general indoor environments. The following experiments were carried out on the desk to simulate the accident scene.

3.1 Formation control

The simulation and experimental results of the formation are shown in Fig. 7. There are five key points in the path of the leader and the follower, denoted by circles and stars, respectively. The target position matrices of the leader and the follower are denoted as $\boldsymbol{T}_\text{L} = [\boldsymbol{X}_\text{L} \quad \boldsymbol{Y}_\text{L}]^\text{T}$ and $\boldsymbol{T}_\text{F} = [\boldsymbol{X}_\text{F} \quad \boldsymbol{Y}_\text{F}]^\text{T}$, respectively, and their values are as

$$\left.\begin{aligned} \boldsymbol{X}_\text{L} &= \{150, 450, 1\ 800, 1\ 800, 1\ 650\}^\text{T} \\ \boldsymbol{Y}_\text{L} &= \{150, 450, 450, 900, 900\}^\text{T} \\ \boldsymbol{X}_\text{F} &= \{0, 250, 1\ 600, 1\ 800, 2\ 100\}^\text{T} \\ \boldsymbol{Y}_\text{F} &= \{300, 450, 450, 700, 900\}^\text{T} \end{aligned}\right\} \tag{6}$$

Fig. 7 presents the processes of configuration forming,

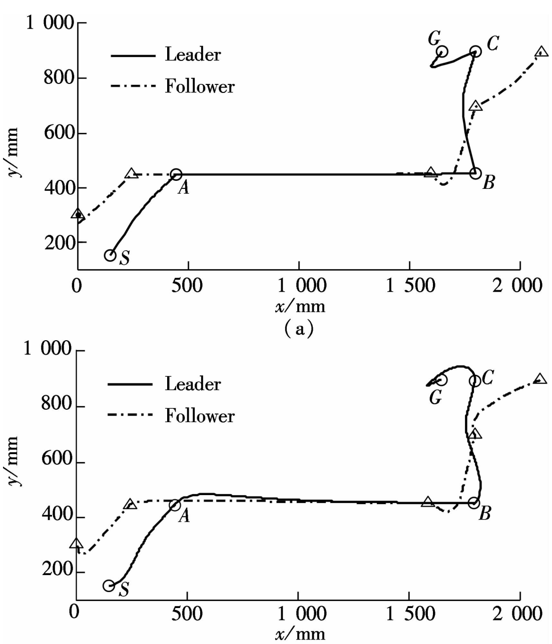


Fig. 7 Comparison of the trajectories between the simulation and experimental results. (a) Trajectories in the simulation; (b) Trajectories in the experiments

maintaining, and changing. In the experiments, the velocities of both wheels should be taken into consideration, so the actual trajectory does not match the simulated path perfectly. However, there are only slight differences between the two trajectories. Therefore, the two kinds of trajectories are seen as coincident.

In the whole navigation from point S to point G, only the leader knows the destination. The follower arrives at its target in the end by keeping specified formations. Both the simulations and experiments show the effectiveness of the protocol of the consensus formation.

3.2 Intelligent control of the light network

The effectiveness of the proposed IES system for indoor lighting is verified through experiments. The testbed setup for the emergency service testing is shown in Fig. 8. Rooms 1 and 2 are small with one monitoring sensor node, respectively. Rooms 3 and 4 are bigger with two monitoring nodes. It is supposed that the accidents happen in Room 4, composed by R41 and R42, monitored by Node 5 and Node 6, respectively. When the accidents occur, Node 5 in R1 is broken and cannot send the light intensity data to the gateway, and the data is set to be zero. The data sent by Node 6 is lower than normal value, meaning that the lamps fail to work well.

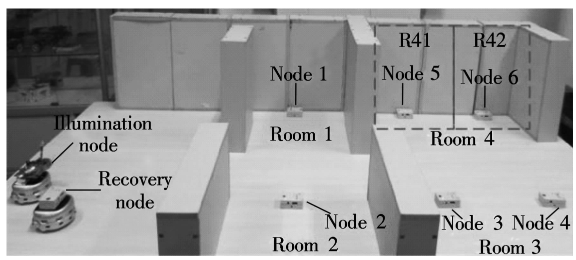
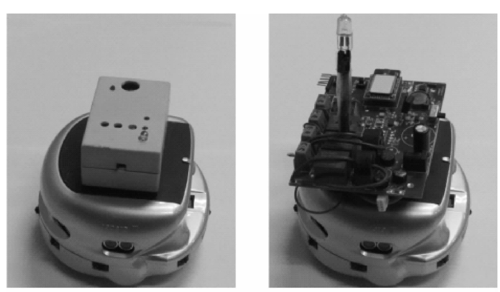


Fig. 8 The testbed of the IES system

The home server receives alarm messages and provides emergency services. Two mobile robot nodes are required to navigate to the accident room, one to replace Node 5 for monitoring the light intensity, and the other one for illumination service. Two Khepera Ⅲ robots are used as mobile robots, as shown in Fig. 9. The robot carrying a



(a) (b)

Fig. 9 The emergency service robots. (a) Leader robot for replacing the failure static sensor node; (b) Follower robot for emergency lighting services monitoring node is the leader and knows the target position. The other robot with an illuminating node is the follower. The two robots should keep the defined formations in the navigation process. The trajectory of the leader robot follows the planned path in Fig. 6.

Fig. 10 shows the voltages of all the nodes during the process of emergency lighting service. High voltage values denote high light intensity, and vice versa. During the first 20 s, all the sensor nodes send the light intensity information to the gateway. Then, two accidents are caused artificially. First, Node 5 is broken, and the data from Node 6 is abnormal. In the experiment, Node 5 is shut down manually to creat an emergency event. As shown in Fig. 10, the data from Node 5 is zero after approximately 20 s. Secondly, the lamps of the laboratory are turned off to cause a lighting accident. All the data received from the monitoring nodes is lower than before. Room 4 is regarded as the most urgent room which requires the emergency services for the two artificial accidents. In the next 55 s, the group of robots moves to Room 4, and all the voltages are maintained at lower values. The variations of the data occur when the robots arrive at the destinations and the LED lamp is turned on. The consumption time depends on the velocity of the leader. In this experiment, the average speed is approximately 43 mm/s.

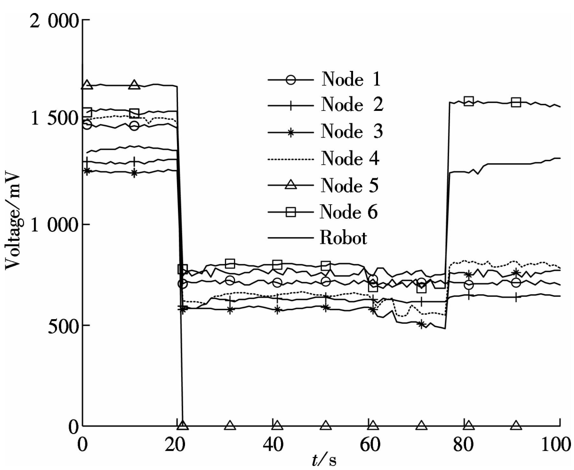


Fig. 10 The voltages of all the nodes during the process of emergency lighting service

The sequences of the emergency lighting service process are shown in Fig. 11. It can be seen that the leader robot navigates to the destination according to the planned path, and the follower keeps the specific formations. As shown in Figs. 11(a) and (b), the leader navigates to the first target A. From Figs. 11(b) to (f), the leader leads the follower to the second target B. During the process, the relative distance is 200 in x axis. At the third target C, the relative distance is 200 in y axis, as shown in Fig. 11(g). At the fourth target G, the relative distance is -400 in x axis, as shown in Fig. 11 (h).

The trajectories of the two robots are shown in Fig. 7 (b). After the two robots arrive at their target positions, the illuminating node is turned on as shown in Fig. 11(i). Then the light intensity information of Node 6 is normal again. The node carried by the leader robot is the closest node to Node 6, so the data is much greater than before. Node 3 and Node 4 are also influenced by the illuminating node, and the data information is a little greater than before. The complete process demonstrates the effectiveness of the emergency service for indoor lighting.

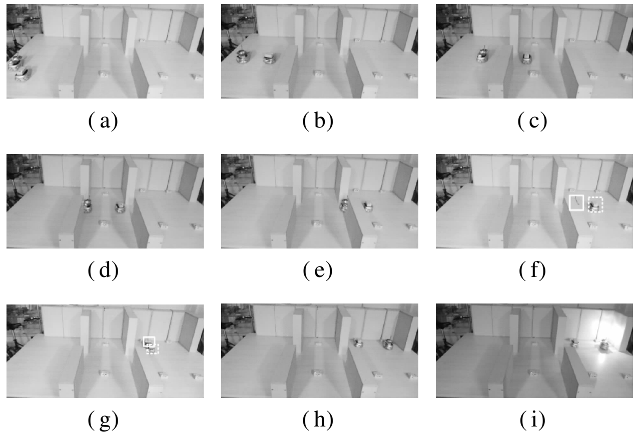


Fig. 11 The sequences of the emergency service system for indoor lighting

4 Conclusion

An intelligent emergency service system for indoor lighting is proposed and implemented in this paper. The system is based on a WSAN. If the home server receives accident alarm messages sent by the monitoring nodes, several mobile robots carrying emergency illuminating nodes will keep the specified formations and navigate to the accident position to provide emergency lighting services. If the monitoring nodes are broken, the robot carrying the monitoring nodes for intensity detection will move to replace the failure nodes to complete the monitoring tasks. For the MRS, a formation protocol is proposed and confirmed through simulations and experiments. The robots can successfully provide emergency service in 55 s at an average velocity of approximately 43 mm/s. The experimental results provide validations for the effectiveness of the proposed system.

Future work will focus on more powerful functions including other environmental information detection.

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基于无线传感执行网络的智能应急服务系统

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摘要:基于由网关、静态传感器节点和多移动机器人系统组成的无线传感和执行网络,设计了一种用于室内环境的应急服务系统. 当网络中多机器人系统接收到事故报警信息时,多机器人将导航至事故地点并提供相应的应急服务. 根据网络中多移动机器人系统的特点,设计了一种分布式一致性编队算法,使得多机器人系统能够保持队形到达目标位置. 最后设计并实现了这种应急服务系统,并进行了仿真和实验测试. 结果表明当发生事故时,多机器人系统可以成功提供应急照明和故障检测节点的替换服务. 算法的有效性和系统的可行性得到了验证.

关键词:应急服务;无线传感执行网络;智能照明;多机器人系统
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