Performance Evaluation of Multi-Hop Communication Based on a Mobile Multi-Robot System in a Subterranean Laneway

Qing-Ling Liu* and Duk-Hwan Oh*

Abstract—For disaster exploration and surveillance application, this paper aims to present a novel application of a multi-robot agent based on WSN and to evaluate a multi-hop communication caused by the robotics correspondingly, which are used in the uncertain and unknown subterranean tunnel. A Primary-Scout Multi-Robot System (PS-MRS) was proposed. A chain topology in a subterranean environment was implemented using a trimmed ZigBee2006 protocol stack to build the multi-hop communication network. The ZigBee IC-CC2530 modular circuit was adapted by mounting it on the PS-MRS. A physical experiment based on the strategy of PS-MRS was used in this paper to evaluate the efficiency of multi-hop communication and to realize the delivery of data packets in an unknown and uncertain underground laboratory environment

Keywords—Multi-hop Communication, Wireless Sensor Network, Multi-Robot System, Disaster Exploration, ZigBee Technology, Underground Environment

1. INTRODUCTION

The unprecedented number and scales of natural and human-induced disasters in the past decade have urged the emergency community around the world to seek newer, more effective equipment to enhance their efficiency [1, 2]. Natural disasters such as hurricanes, tornados, and land and ocean earthquakes have claimed millions of lives and destroyed an astronomical amount of assets [3, 4]. Among these disasters, the frequent occurrence of mine disasters and earthquakes including the latest, which occurred in Honshu Japan on the 12th of March 2011, all claimed deadly and costly tolls from the affected societies, as shown in Fig. 1[31].

Rescue personnel are often at the mercy of inaccessible and hazardous spaces, such as subterranean environments. Consequently, intelligent robots equipped with sensors are attracting more and more attention for application and research at home and abroad [5]. A desire for underground exploration and surveillance motivates the development of robotics technology [6].

These robots range from being tethered to being wirelessly operated and in size range from being the size of a lawnmower to the size of a lunch box [7].

However, a single large corresponding mobile agent can be difficult to move into the destination zone or to fulfill exploration tasks in a tight area. Moreover, the use of heavy and large ma-

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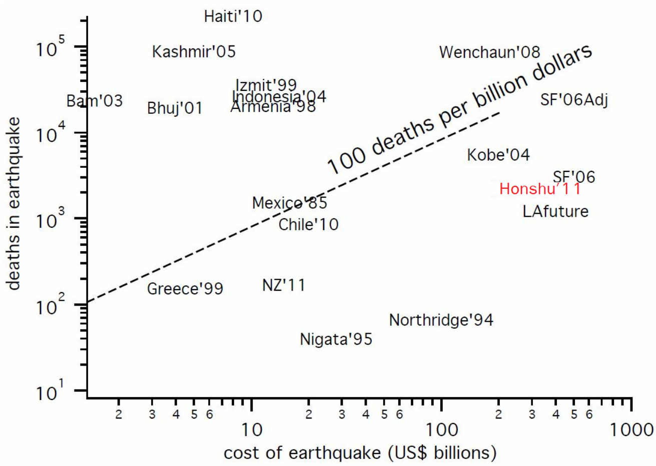


Fig. 1. The comparative cost of recent earthquakes

chinery is prohibited because it could destabilize the structure, thereby risking the lives of rescuers and of victims who are buried in the rubble. Meanwhile, the loss or destruction of even a single robot may seriously compromise mission integrity [8]. Thus, the coordination and specialization of robotic agents is emerging at a much-needed moment.

Multiple robots can often perform missions that a single robot would not be able to do or that would do them slower and less effectively. Mobile Multiple Robot Systems (MMRS) [9, 10] have traditionally been studied to coordinate the tasks of environmental monitoring and survivor rescue. Hence, when intelligent mobile multi-robot systems are directly incorporated into Wireless Sensor Networks (WSN), the advantage is obvious and explicit.

WSN nodes can closely sense their surroundings in a convenient and distributed way. For this reason, these nodes can be viewed as terminals connected to a network [11]. Recently, due to their great potential for applications such as in disaster emergency response, military, medical, civil, environment research, and factory automation, a trend has arisen to combine WSN and MMRS [10]. With the support of WSN, a mobile robot can extend its sensing limit, and can coordinate and interact with other partners due to the WSN's ability to convey data over long distances with a high level of power efficiency, which is particularly suitable for the exploration of subterranean fields [12].

In the past decade, there has been an active interest in deploying a multi-robot system with a distributed-based topology network [13, 14]. The application of mechanics-based robotics has been explored (e.g., [16, 19]) and the power plants for robotic movement and behavior have recently been introduced (e.g., [7, 15]). However, most of these papers have not tackled the problems of multi-hop communication quality and of conveying data packets between robots, especially in underground environments.

For this reason, this paper presents a new application, using a mobile primary robot to deploy the scout robots in a subterranean tunnel. Conventionally, sense nodes have been dispersed by man-controlled, aircraft-controlled, or vehicle-controlled means [18]. This paper proposes the scout robot distribution method, in which distribution is controlled by a mobile primary robot during its movement. Furthermore, a multi-hop communication chain that is composed of these scout robots is formed. Through the experiment we evaluated the performance of multi-hop communication and realized the delivery of data packets in an underground laboratory.

This paper begins with an overview of a PS-MRS that consisted of a mobile primary robot and scout robots and describes the procedure of this system's execution. In Section 3, the chain-based topology model used for the subterranean tunnel, which modifies the ZigBee technology and chain-based multi-hop communication topology by trimming the ZigBee protocol stack to be applicable to the scout robots' deployment, is addressed. In Section 4 the design of the hardware module sensor node that is based on ZigBee IC-CC2530 is explained. Section 5 presents some metrics to evaluate communication quality between scout robots and the relative performance of packet transmission, and then it shows the analysis of the results in detail. This paper closes in Section 6 with a summary and a discussion of the challenges of future research, as well as explaining the significance of the application.

2. The Structure of Mobile PS-MRS For Underground Exploration

Disasters can affect anyone without warning. They can disrupt the economic and social balance of society. Among these unknown and uncontrollable disasters, subterranean accidents including mine disasters and earthquakes have frequently taken place recently [6, 7, 15]. Therefore, specialized robots may help to alleviate these problems in underground tunnels. Furthermore, information collection, data packet transmission, and communication are necessary to cover a monitored region.

Typically, this issue will be addressed either by (1) a motion scheme for a mobile primary robot that moves in the designated area and that auto-disperses nodal robots in the path or (2) a multi-hop network that delivers control orders to target robots and guarantees the transmission of information between them.

In both cases, the problems of queue ordering and multi-hop communication occur. One possible compromise is to combine the two methods. A mobile agent that is capable of long-distance travel can cover a relatively large area and arrange smaller, less mobile agents in various positions. The smaller agents can be given the responsibility of surveying a smaller range, and they can have the flexibility to transmit their commands to make sure that all of their movements are controlled.

Then, a coordination agent can communicate between robots, query them for information, and move them remotely to increase their viewed area. Corresponding to the two types of robotic agents, this paper proposes a primary-scout multi-robot system as shown in Fig. 2.

In the case of a PS-MRS, this composite robot consists of two types of robots: a mobile primary robot and some patrol-like robots, which are referred to as scout [19] robots in this paper. The primary robot is an independent and complete individual that is connected by several hinge joints. It is composed of four units: the head, mount, control & sensor, and tail units. The mount unit is designed to hold scout robots. It can open the hatch of the cabin and release a scout robot when needed [20]. The primary robot can carry the scouts into position over longer distances, giving the scouts a longer effective range. For the scout robots, this paper produces exploratory, patrol-like behavior. They act as local signposts for robots that subsequently return to their vicinity. Each scout robot is equipped with a sensor that has a small processor, a limited-range radio, and a transceiver. By deploying such scout robots into the surroundings, the primary robot

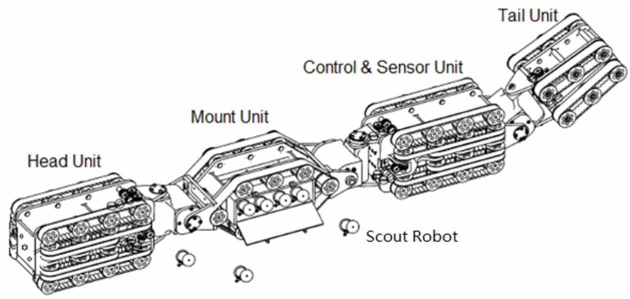


Fig. 2. The overall structure of the primary-scout multi-robot system

can establish a chain-based multi-hop communication network.

These scout robots are composed of a multi-hop communication network to convey data packets and detected information. It is necessary to evaluate the reliability and practicality of this coordination using simulation and experiment. Our solution to the problem relies on the deployment of scout robots into the underground environment as a support infrastructure, which the robots use for communication.

3. ZIGBEE WIRELESS PROTOCOL AND CHAIN TOPOLOGY DEPLOYMENT OF MRS

Automatic underground exploration and surveillance systems with Micro-Electro-Mechanical Systems (MEMS) and other sensors are becoming more common and popular. These typically use wireless devices and sensors that are either connected ad hoc or, increasingly, through the shared communication lines of "intelligent buildings" [15]. The overall condition of the subterranean tunnel is significant to the assignment of scout robots and the establishment of the multi-hop communication network. A ZigBee communication module installed in each of these mobile robots offers an opportunity to build a chain-based topology and transfer information between robots. The following paragraphs will describe how the ZigBee network interacts with a narrow and long tunnel to build the topology.

3.1 ZigBee Wireless Network Technologies

Popular wireless communication standards include Bluetooth, Ultra-Wide Band (UWB), ZigBee, and Wi-Fi [21]. ZigBee wireless communication technology, which is based on the IEEE 802.15.4 standard, is a kind of flexible wireless network technology that offers low power consumption, interoperability, reliability, and security for controlling and monitoring applications with low to moderate data rates.

From the point of view of applications in an unknown subterranean environment, ZigBee is designed for reliable wireless monitoring and the controlling of networks. It features the formation of a Personal Area Network (PAN) that is made up of coordinators, routers, and end devices [22]. ZigBee supports many network topologies, including the Cluster-Tree as illustrated in Fig. 3. Cluster-Tree networking can extend the range of the network through routing, while its self-healing ability increases the reliability of the network by re-routing a message in case of a node

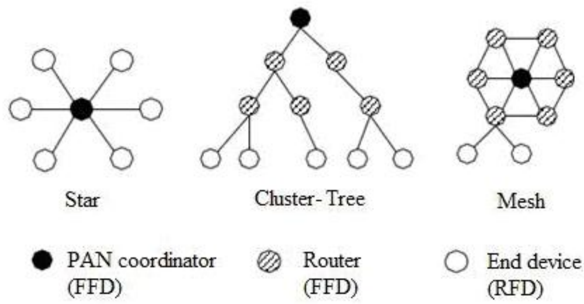


Fig. 3. ZigBee network topology

failure. The device types supported by IEEE 802.15.4 and ZigBee are the Full Function Device (FFD) and the Reduced Function Device (RFD). The FFD can communicate with both the FFD and RFD, and it can be the PAN coordinator, router, and end device. These unique features are highly desirable for scout robots that are operating in unstructured environments, such as an underground laneway.

3.2 Chain Topology of Multi-hop Communication Based on WSN

We are particularly interested in the regime where the number of scout robots is such that there is no static assignment of nodes to vantage points, thereby guaranteeing information about the environment. Here, considering the difficulties caused by a complex and narrow tunnel and long-distance communication below ground, we propose a chain-based topology that is trimmed from the ZigBee Cluster-Tree network topology. The chain topology applied to a real subterranean tunnel is illustrated in Fig. 4.

The system for modeling buildings typically models the environment using planar surfaces or other simple geometric primitives. Such simplifications provide an efficient and effective reference for real conditions [23]. The node configurations of the multi-robot system for mine exploration closely relates to the directions and distances provided by tunnel engineering plans and graphs. Thus, it is beneficial to model the tunnel environment for the MMR system on the available conditions.

The chain topology shown in Fig. 4 is used to simulate multi-hop communication. The Base Station (BS) is viewed as node 0, which acts as the PAN coordinator. Scout robots that are composed of nodes 1-6 are shown as red solid circles. The mobile primary robot is seen as node 7. All of the nodes are FFD for both the sending and receiving of information.

From the viewpoint of data transmission, node 7 is the source, while node 1 is the destination. For convenient debugging, node 1 is connected to a laptop (node 0) as a monitor.

The overall process of PS-MRS distribution is as follows: a primary robot takes the scout robots in its carrying chamber. The primary robot monitors the Received Signal Strength Indication (RSSI) and when it detects the radio signal from the BS or previous node fading below the Standard Threshold Data (STD) value, it will open the hatch of the chamber and release a scout robot. Then, the scout will act as a wireless communication relay and maintain contact with the BS.

By setting the STD, the closest neighbor distance is about 8 m and the transmission range is

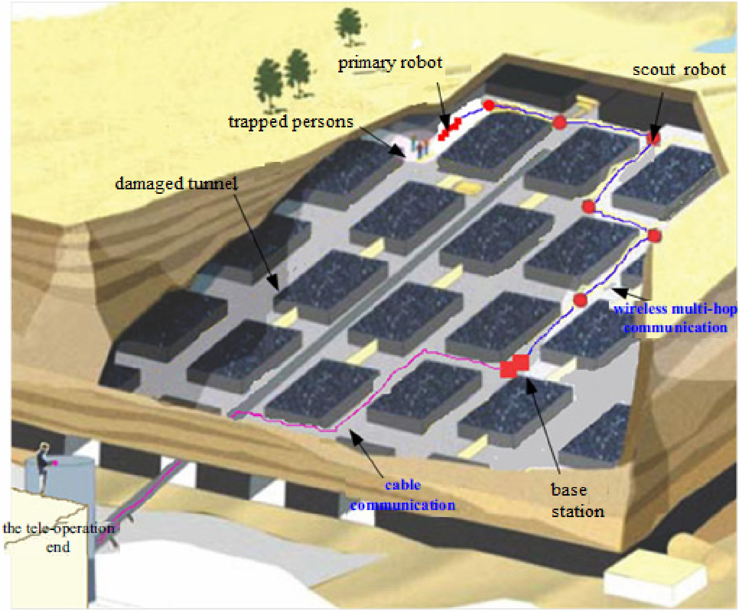


Fig. 4. The chain-topology of the multi-hop communication network

10 m. With respect to the motion scheme and node deployment, the mobile robot carries the scout robots into the tunnel and deploys them along the route as it proceeds. By comparing the RSSI and STD values [24], the primary robot recognizes the route conditions and executes a distributive strategy to return the information. On the other hand, with respect to multi-hop communication and data packet transmission, the mobile robot can connect to the remote control center continuously in order to guarantee real-time performance and the reliability of decisions.

4. ZIGBEE MODULE CIRCUIT

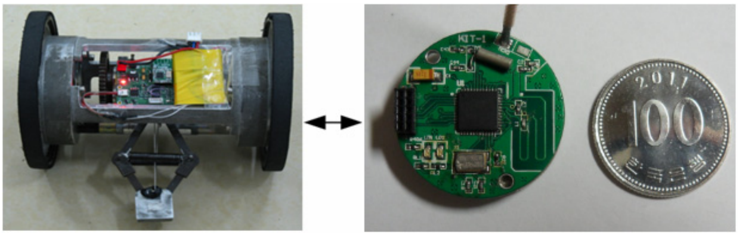
4.1 Physical Robot and Sensor Node

With the advancement in sensor miniaturizations and exponential increase in the speed and capability of microcontrollers, scout robots that are small enough to thread through rubble are rolling out of experimental laboratories and into catastrophic areas. In a real system, the sensor would be mounted on a scout robot. We assume that the robot moves on a flat 2D surface and that obstacles are at the height of the laser range scanner.

ZigBee is a wireless technology developed to address the need for a standards-based wireless networking system for low data-rates and low-power consumption applications.

The low-power wireless communication node hardware employed in this research is built on the SoC wireless communication Chipcon 2530 series, which is based on the standard ZigBee shown in Fig. 5. The scout robot, shown in Fig.5 (a), is composed of a main controller, a sensing module, a motion controlling module, and a wireless communication module. The wireless communication module uses a KIT-1 ZigBee sensor, as shown in Fig. 5(b).

The main tasks of a sensor node in a sensor field are to detect events, perform quick local data



(a) (b)

Fig. 5. The mobile single robot and a sensor node

processing, and then transmit the data. Power consumption can hence be divided into three domains: sensing, communication, and data processing. A Chipcon 2530 RF transceiver is integrated into the scout-sensor node [33]. The maximum communication speed is 250 kbps.

4.2 Physical Experiments

These robots were equipped with wireless communication modules to facilitate data and image transfer. These untethered wireless robots can navigate freely in obstructed environments, but it becomes difficult to link and communicate with each other or with the controller once they wander out of the transmission range, as judged by setting a threshold value. The ZigBee communication module mounted on each of these mobile robots offers an opportunity to build a multi-hop network and to transfer information.

In the real experiments, we set up a basement corridor with a 3-meter high ceiling as the underground experiment setting. The corridor is long and narrow and contains some obstacles. The STD of RSSI is set to make the distance between robots be close to 4 m. During the robots' distribution, six nodes are used to form the chain network between the base gateway and the robot terminal.

The robot's communication system is set up to validate the designed distribution strategy. In order to overcome the difficulties that the complicated shielding environment exerts on the communication system, a standard PCI optical fiber bus interface card is adopted to form a high-speed fiber pathway. Moreover, the robot utilizes several Radio Frequency (RF) nodes to form a multi-hop network to communicate with the BS.

The wireless multi-hop communication network adopts an IEEE 802.15.4 standard wireless physical layer interface. The Media Access Control (MAC) provides network association and disassociation, has an optional super frame structure with beacons for time synchronization, and has a guaranteed time slot (GTS) mechanism for high priority communications. The channel access method has Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) [17]. The data link layer adopts the 802.15.4 MAC protocol. In reference to the tree topology of the ZigBee 2006protocol stack [25, 26], the network layer uses an equivalent chain topology network by restricting the maximum depth (L_m), maximum number of routers (R_m), and the maximum number of children (C_m) in the tree topology [22]. The nodes calculate the energy loss to judge the lifetime of the network by the energy monitoring method.

First, the coordinator initialized the ZigBee network and configured the network parameters such as L_m, R_m, C_m, and the working channel (13, 2.4GHz). Then the coordinator added routers and end devices into the network and distributed the network address to these devices. Once node 6 successfully joined the network, it continued to send data packets to node 1.

While the network is active, data packets will return to the base through the chain network hop by hop. The nodes can also actively send information. A data packet is generated by the constant bit rate flow generator, and the MAC layer data monitor is initiated to record the process. The results of the experiment are considered for measuring the characteristics of the chain multi-hop network in terms of the following indices of [27-30].

5. Results

5.1 Metric

The packet loss ratio: a data packet can be lost under the influence of many factors, like signal attenuation or the quality of the network. The packet loss ratio is the ratio of non-received data packets to received data packets. For this network, the packet loss ratio is given by:

$$R_{loss} = \frac{P_{drop}}{P_{send}} \tag{1}$$

The time delay in transferring a data packet from one node to another may be caused by many factors, including the time delay of packing and unpacking and the time delay of the network's transmission and so on. The focus of this analysis is the time delay of the network's transmission. The latency of the whole network is defined as the average of each data packet's time delay:

$$T_{delay} = \frac{\sum_{i=0}^{n} Latency_i}{n} \tag{2}$$

where $Latency_i$ is the time delay of the i-th data packet.

The throughput is the parameter we are primarily concerned with in the network capacity evaluations. The handling capacity is the amount of data that one node sends and receives per time unit, and it is summed up across the entire network to yield the throughput. It is defined as the number of data packets that the robot sends to the gateway node per time unit, as shown by:

$$C_{throughput} = \frac{\sum_{i=0}^{t} Throughput_i}{t} \tag{3}$$

5.2 The Theoretical Analysis

The packet sending velocity varies from 0.01 to 5.0. Graphs of the rate of packet loss, the time delay, and the handling capacity are shown in Fig. 6.

In Fig. 6(a), the packet loss ratio seems to be as small as possible. There is significant packet loss at the start. It becomes slightly different at velocities of 0.3 to 1.4. When the packet sending velocity rises to 1.5, the loss rate goes up suddenly. At higher rates, the curve remains low and level.

In Fig. 6(b), the average time delay is ideally as low as possible. In the beginning, it changes over a wide range. From 0.5 to 0.8, the latency value is around 0.1/s. Above that, it is unstable and continually fluctuates until 2.0, at which point the curve shows linear growth.

In Fig. 6(c), the throughput ideally reaches as high as possible. It is large at the very beginning, then decreases sharply when the velocity of sending packets increases. At a velocity of 0.5, the throughput drops 213.6 bps. Beyond that, the curve converges to horizontal.

From these graphs, it can be seen that there are seemingly small differences between the velocities of 0.3 and 1.5. We expand the data from this range in detail in Table 1. According to these pieces of data, the packet loss ratio decreases to 0.033 and the latency drops to 0.079, but nonethless the throughput reaches 0.214kbps only at a velocity of 0.5. The experimental results are specifically shown and the numeric results in bold are the optimal points.

Using these pieces of data and the curves from the three graphs, we can observe, analyze, and sum up as follows: the ideal compromise among the packet loss ratio, the time delay, and the handling capacity can be reached when the data velocity is 0.5 packets/s (1.12kb/s).

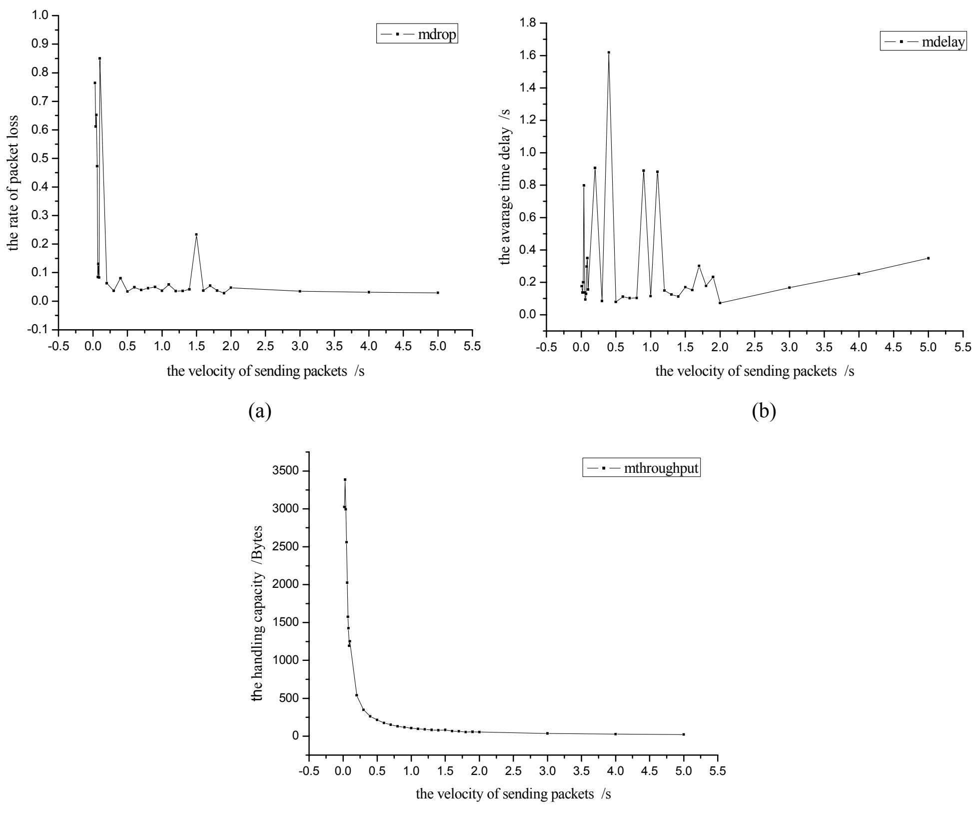


Fig. 6. Performance graphs of the multi-hop communication

Table 1. Experimental data

	The velocity of sending packets /s												
Metrics	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5
R_l	0.036	0.080	**0.033**	0.049	0.039	0.046	0.050	0.036	0.058	0.035	0.036	0.042	0.234
T_d	0.085	1.618	**0.079**	0.112	0.102	0.104	0.889	0.114	0.882	0.149	0.125	**0.042**	0.171
C_t	0.347	**0.261**	**0.214**	0.174	0.151	0.130	0.117	0.105	0.096	0.090	0.082	0.077	0.083

6. Conclusion and Future work

We described a reasonable solution for application in long and narrow tunnels that are below ground that performed the exploration task successfully by using a PS-MRS. The chain-based MRS deployment method facilitated the exploration of the route and maintained multi-hop communication. Such a capability is of obvious use in the detection of unfriendly targets (e.g., military operations), monitoring (e.g., security), or urban search and rescue in the aftermath of a natural or man-made disaster (e.g., building rubble due to an earthquake or other causes). Furthermore, these static sensor nodes mounted on the mobile scout robot might perceive information about the surroundings and deliver data more dynamically from locations that a big robot might have difficulty accessing. Simultaneously, a wireless chain topology structured multi-hop communication network in the subterranean tunnel made this a feasible solution.

At present, disasters seem to be occurring increasingly often, which strongly motivates for the development of detection and communication schemes for mitigating disasters. The application of viewing robots as network nodes aids in developing such a surveillance system, so it has great significance for both the research to develop practical robots and as being a key technology. In the near future, the influences of multi-reflection and occlusion of the RF signal will be considered so that the communication can be made practical and reliable. Data transmission using a more complex topology network will also be carried out effectively. It may have a bright future in industrialization, not only for use in subterranean tunnels, but also in rescues that are conducted during natural and man-made disasters.

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