A SPACE-DIVISION WIRELESS COMMUNICATION SYSTEM FOR ADHOC NETWORKING AND COOPERATIVE LOCALIZATION OF MULTIPLE MOBILE ROBOTS

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Abstract: This paper presents a space-division wireless communication system for nonhierarchical, cooperative control of multiple mobile robots. The proposed communication system has the following features: 1) it has a set of infrared transceivers arranged on the circumference of the robot body to communicate in all directions; 2) it can maintain communication links by exchanging transceivers when either of the robots runs and/or rotates. An arbiter is introduced to reduce communication interference when two or more robots are in the same communication area. Adhoc communication networks are constructed based on the selection of arbiters. As an example of distributed sensing and cooperation using the system, cooperative localization of communicating mobile robots is also described. Some performance measurements using an experimental system have been carried out to show the viability of the proposed approach.

Keywords: Space-division wireless communication, adhoc networking, arbiter selection, cooperative localization, multiple autonomous mobile robots.

1. INTRODUCTION

Over the past few years, multiagent systems have become more and more important in robotics, by introducing the issue of collective intelligence and of the emergence of structures through interactions. In multiagent robotic systems based on mobile robots, multiple robots have to coordinate their movements and cooperate in accomplishing tasks such as cleaning the floor, monitoring buildings, playing robotic soccer, intervening to help people, or exploring distant or dangerous spaces. The coordination of vehicles in intelligent transportation systems also falls within this area of application. Their movements must be coordinated in such a way that each of them can go where it wants to go without having a collision. For exploration of hazardous areas, the use of a roving complex of autonomous mobile robots moving together in a cooperative manner is recommended instead of the control of a single robot (Arkin and Balch, 1998). The distributed sensing and cooperation through local inter-robot communication extends its individual information acquisition potentialities and enables mutual aid in adverse situations. This use of the principle of nonhierarchical cooperative control may be of decisive importance for overcoming obstacles and finding a viable route to the goal. This principle is also well-known from bionics: a swarm of insects, a school of fish, a flock of birds, a herd of animals, etc. The problem is that the robots have to move together in such a way that the structure of the formation remains constant, although some robots are requested to advance in formation.

These robots have to communicate to perform their tasks; otherwise, they will interfere with each other. Communication constitutes one of the fundamental means of providing for the distribution of tasks and the coordination of actions. For example, mobile robots must be arbitrated to avoid collisions using the local area communication. Conflicts over objectives or resources must be resolved through a negotiation process. When the number of robots increases in a working area, the possibility of collisions among robots increases. Therefore, the importance of wireless local area communication increases, too.

We examined the communication carrier suitable for wireless inter-robot communication. Each robot must communication with other robots in all directions on the common communication carrier. Communication interference occurs due to mixing signals from unnecessary directions, as shown in Fig. 1. Existing multiple access methods on the common communication carrier, such as BTMA (Busy-Tone Multiple Access) and ISMA (Idle Signal Multiple Access), aren’t suitable for wireless communication among multiple autonomous mobile robots, because they rely on a centralized mechanism suited for communication with fixed stations.

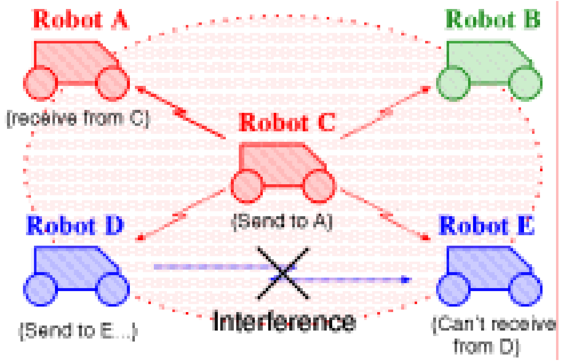


Fig. 1. Example of communication interference.

As a carrier of wireless communication for mobile robots, radio wave or infrared radiation has been used. Radio wave spreads out in a wide area in all directions, so it can easily cause interference in the same local area. Non-directivity of radio wave induces hidden terminal problems and complicated resource control.

On the other hand, infrared radiation has strong directivity, so infrared wireless communication hardly suffers from any interference. The local area communication using limited directivity is suitable for the communication of mobile robots, because of low level interference. However, the connectivity of infrared wireless communication is low, because the communication links are easily broken when robots run and/or rotate. To overcome the low connectivity, we have designed an infrared wireless communication system, which can detect and track the direction of colleague robots to maintain communication links, using transceivers arranged on the circumference of the robot body to communicate in all directions (Takai, *et al.*, 2001b). Hardware realization and experimental results are illustrated to show the viability of the proposed system.

2. INFRARED WIRELESS COMMUNICATION SYSTEM

The proposed infrared wireless communication system has a set of infrared transceivers. The infrared transceivers are evenly spaced in all directions. The communication area of each transceiver has left and right overlapping areas with the left and right adjacent transceivers. Using the infrared communication system a robot can talk to other robots in all directions. The system hardly interferes in communication in any direction by the strong directivity of infrared rays. The overlapping communication area is used to maintain the communication link with a colleague robot.

2.1 Tracking of the direction of robots

Fig. 2 shows the arrangement of the eight infrared transceivers, which composes the infrared wireless communication system. Each infrared transceiver has a sensor, which detects the angle of incidence of the infrared rays. So it can detect the direction of another robot. Different infrared transceivers detect the directions of robots in the different positions. The system uses an independent communication link for one robot. Therefore, the space-division system can communicate at the same time with more than one robot in different positions by using the different infrared transceivers.

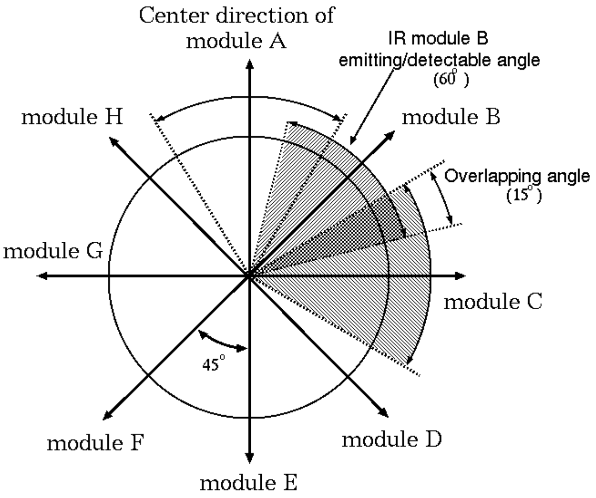


Fig. 2. Arrangement of the transceivers.

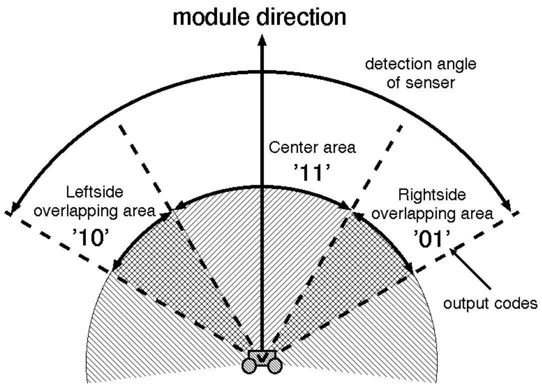


Fig. 3. Direction code for tracking.

Fig. 3 shows the direction code by an infrared transceiver for tracking of the direction of another robot. In Fig. 3, the transceiver outputs direction code ‘10’, when the robot is in the left overlapping area, outputs direction code ‘11’ when the robot is in front of the transceiver, and outputs direction code ‘01’ when the robot is in the right overlapping area. When the robot rotates clockwise, the direction codes that the infrared transceiver outputs change in the order of left - front - right. When the robot runs into the right-adjacent communication area, the infrared transceiver to the right detects the same robot in the communication area overlapping the one of the left adjacent. While the robot is in an overlapping communication area, the system uses both infrared transceivers. When the robot comes out from the overlapping communication area, the system changes the infrared transceivers based on the change in the direction code. The system reduces the short break and/or the loss of the communication link caused by the movement of the robot.

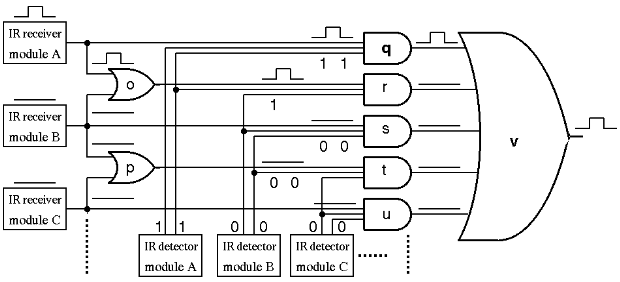
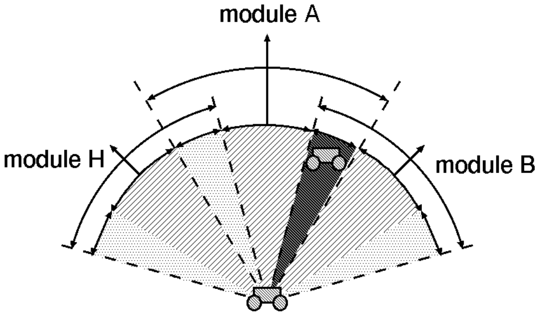


Fig. 4. The module exchange circuit.

The communication system exchanges transceivers to maintain the same communication channel for the same robot using the direction code. Fig. 4 shows the exchange circuit, which shifts between infrared transceivers using the direction codes. This exchange circuit has more than one communication link, and it is made up of combinatorial logic gates. This circuit combines and separates the received signal using the direction codes. The circuit selects the receiver module to maintain the communication channel for the same robot. In Fig. 4, the received signal comes from the left side and the direction code comes from below. When the direction code from module A is ‘11’, AND gate q sends out the received signal. When the robot is in the overlapping area between modules A and B, both received signals are directed into OR gate o. The combined signal and the direction codes '01' and '10' from modules A and B are then directed into AND gate r. Finally, the received signal sent out from the AND gate is combined into the OR gate v.



A	B	C	·····	H
01	10	00	·····	00

Fig. 5. Direction code table.

A direction code table of a robot is made based on the direction codes of all modules. An example is shown in Fig. 5, where one robot is the overlapping area between modules A and B. The direction code of a module with no colleague robots is ‘00’. At least one of the code ’0’ between the codes '11' on the direction code table shows the different robots, which are in different positions. So, even if the direction codes of adjacent modules are the same ‘11’, two different robots cannot be distinguished. This exchange circuit can separate received signals from the different robots to different channels by using the direction code table.

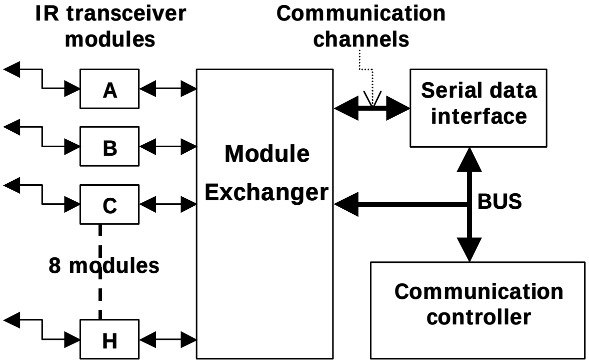


Fig. 6. Configuration of the communication system.

Fig. 6 shows the configuration of the infrared wireless communication system, composed of eight infrared transceivers (module A – module H), a module exchanger circuit, a serial data interface, and a communication controller.

2.2 Inter-robot communication

The infrared wireless communication system uses the simplex and/or half-duplex transmission. It cannot use the full-duplex transmission, because each transceiver doesn’t emit and receive signals at the same time due to communication interference with its own emitting signals. Fig. 7 shows the schematic of the transmitter and the receiver in inter-robot communication, where the transmitter has more units than the receiver for searching a colleague robot.

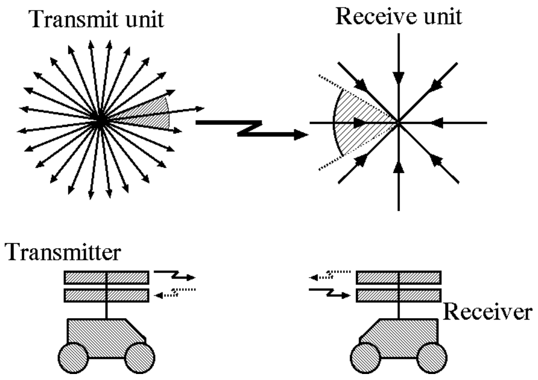


Fig. 7. Schematic of the transmitter and receiver.

The communication system spreads point-to-point communication links as follows. Supposing at first all the robots are isolated from one another, a robot repeatedly sends out search signals in all directions in order to find colleague robots. When a colleague robot receives a search signal and detects the direction from which it has come, it sends back an answer signal in that direction. After the reception of the answer signal, the robot sends a confirmation signal back to establish a communication link.

The robot keeps sending a search signal in the direction where another colleague robot isn't found. Another robot is found with the same rule, and a communication link is established with it in different position. The infrared transceivers can talk to the different robots independently. Thus a communication network is autonomously constructed around the robot.

The infrared wireless communication is restricted to limited directions by using the directivity of the infrared rays. Interferes are mild except for the infrared transceivers of the communication area, which face opposite to each other. However, arbitration is required to reduce communication interference when two or more robots are in the same communication area. The infrared transceiver includes a sensor, which detects the angle of incidence of infrared rays. Two sensors can detect an angle between the robots in the different directions. Three neighboring robots make up a triangle, which positions them on its apexes. If an angle becomes narrow, the others become wide, because the sum of the triangular interior angles is fixed at 180 degrees. Each robot communicates its angle with the other two robots. The robot whose angle is the widest becomes the arbiter for this three-robot communication network. By this arbiter selection rule, an arbiter is located in the place where interference of the signal is likely to become least, so that the arbiter regulates the timing of signal transmissions, as the TDMA access scheme. Fig. 8 shows the selection of the arbiter.

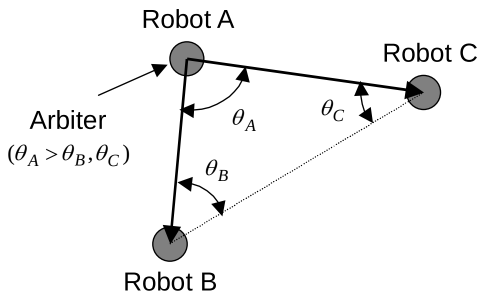


Fig. 8. The selection of the arbiter.

2.3 Construction of communication networks

Fig. 9 shows an example of communication network constructed by the wireless communication system. Each robot relays information to/and from robots in different positions. It is an adhoc communication network because these robots are moving. The network structure changes due to the movements of the robots. Communication is interfered with when two and more robots face the same direction. Then any robot can become an arbiter, as a local and temporal controller, for the communication network. In Fig. 9, Robot A is selected as the arbiter of triangle 1, while Robot C is selected as the arbiter of triangles 2 and 3.

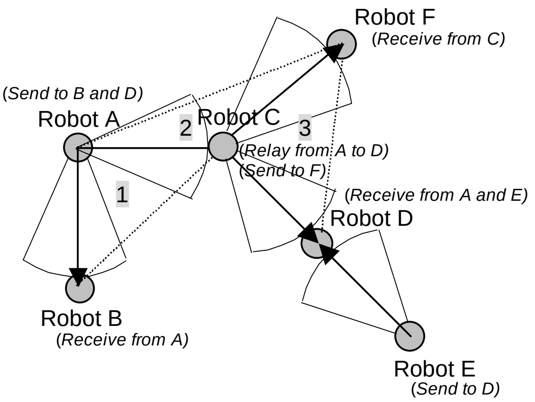


Fig. 9. Construction of communication network.

As an example of distributed sensing and cooperation on the communication network, mutual localization is illustrated in Fig. 10, which is useful for autonomous navigation of a group of mobile robots. Each robot can detect the direction of colleague robots using the communication system. When a robot moves from the position p0 to p1, communication links change directions. The robot which moved detects the distance between p0 and p1 by the odometer and compute its own relative position using triangulation ranging (Takai, *et al.*, 2001c).

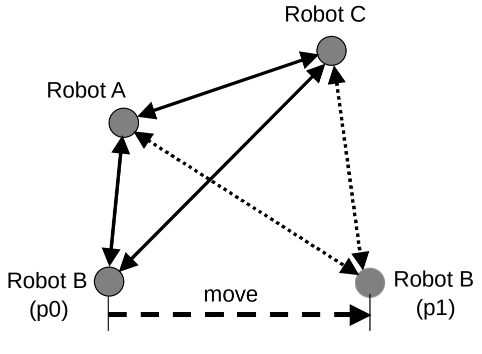


Fig. 10. Triangulation ranging using transceivers. (p0,p1:positions of Robot B)

3. PERFORMANCE MEASUREMENTS USING EXPERIMENTAL SYSTEM

The proposed infrared wireless communication system detects the angle of incidence, and tracks the direction of a colleague robot. The detection and the tracking were confirmed through hardware realization made on an experimental basis and its performance measurements.

3.1 Detection of the angle of incidence of infrared rays

We conducted an experiment to confirm the detection of the angle of incidence of the infrared rays. We used the PIN photo diode (HAMAMATSU S6560) for the detection device of infrared rays in this experiment. The angle of incidence is related to the two electric current outputs 'a' and 'b' of the detector and computed using the equation (1).

$$\theta = (a-b)/(a+b) \qquad (1)$$

Fig. 11 shows a block diagram of the analog computing circuit for sensing the angle of incidence. The circuit performs analog signal processing, because the signal strength changes when the robot runs and/or rotates. This circuit outputs not only the detected angle but also the received pulse data. The circuit is controlled by an embedded microcomputer.

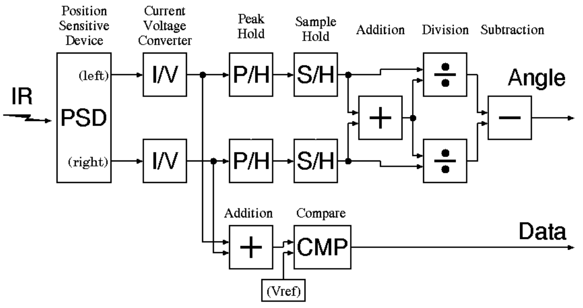


Fig. 11. Block diagram of analog computing circuit.

The detector received the IrDA-SIR 9.6kb/s (duty = 18.8%) standard signal. A source of infrared rays was placed in front of the sensor of angle of the incidence. Then, the signal source was moved from the left 40 degrees to the right 40 degrees in 5 degree increments. The distance between the signal source and the detector was moved from 15cm to 30cm in 5cm increments. From the experimental results, the accuracy of detected angles was ± 5 degrees, and the overall analog processing time of the detector was around 100 μ s.

3.2 Shifting between transceivers

We conducted an experiment to confirm the function of the module exchange circuit that shifts between transceivers. The module exchange circuit shown in Fig.4 was composed on a CPLD (Cypress CY7C372i), using the VHDL (Cypress Warp2-VHDL compiler). The IrDA-SIR, 9.6kb/s (duty = 18.8%) standard signal was inputted to the exchange circuit, and the time to the output was measured. This module exchange circuit changed enough in short time to the input signal. Fig. 12 shows the result of confirmation of the function of the exchange circuit. The exchange circuit maintained a communication link when another robot moved or rotated.

Fig. 12. Experimental result of module exchange.

4. CONCLUSIONS AND FUTURE WORKS

An infrared wireless communication system for multiple mobile robots was proposed. The function of the IR modules was confirmed using an experimental circuit. The accuracy of angle detection was ± 5 degrees, which depends on the accuracy of the experimental equipment including analog computing circuit. The overall processing time was around 100 μ s, which largely depends on the analog to digital converter.

We discussed the construction of communication networks, which this communication system was used for. The communication system selects an arbiter geometrically. An arbiter can be selected without complex decision algorithms. The process of communication network construction can be shown by computer simulations.

As future works, the parallel communication ability in different directions, the function of selecting an arbiter, and mutual localization will be confirmed. Also the signal processing circuit to improve the data transmission speed and the angle detection accuracy will be re-designed.

The proposed mutual localization capability will be integrated with the sensor fusion based autonomous navigation scheme using external and internal sensors (Takai, *et al.*, 2001a). The proposed communication system has relations with the physical and data-link layers in the framework of the open system inter-connect (OSI) layers. The next layer, that is, the network layer, will decide the route of relays from the source to the destination. If autonomous routing algorithms are combined with the communication system, the effective cooperative control of multiple robot systems becomes possible. Such a robot system will be useful for a variety of applications, including adaptive formation control of a group of mobile robots in hazardous environments with multiple obstacles.

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