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# CONSTRUCTION OF INFRARED WIRELESS INTER-ROBOT COMMUNICATION NETWORKS FOR DISTRIBUTED SENSING AND COOPERATION OF MULTIPLE AUTONOMOUS MOBILE ROBOTS

**Hiroyuki Takai*, Gen'ichi Yasuda**, Keihachiro Tachibana***

**Department of Information Machines and Interfaces, Hiroshima City University, 3-4-1 Ozuka-higashi, Asaminami-ku, Hiroshima 731-3194, Japan*

***Department of Mechanical Engineering, Nagasaki Institute of Applied Science, 536 Aba-machi, Nagasaki 851-0193, Japan*

Abstract: This paper presents a space-division optical wireless inter-robot communication system for multiple mobile robots. Infrared optical wireless communication is suitable for the mobile robots, because of its low level of interference in multiple directions. However, optical wireless communication is lost when either of the robots runs and/or rotates due to the nature of infrared rays. The proposed communication system has a set of infrared transceivers, which face all directions. The system can maintain circuit connections by exchanging transceivers. Furthermore it can communicate at the same time with more than one robot in different positions by using different transceivers. Spontaneous construction of inter-robot communication networks based on the selection of arbiters is described. As an example of local sensing capabilities of the system, mutual localization using transceivers on three communicating robots is also described. Hardware realization and performance measurements are illustrated to reveal the effectiveness of the proposed system.

Keywords: Optical wireless communication, space division, adhoc communication networks, localization, multiple autonomous mobile robots.

## 1. INTRODUCTION

In recent years, multiagent robotic systems based on mobile robots, which perform cooperative operations, have been developed (Asama, *et al.*, 1994). Such multiple robots have to coordinate their movements and cooperate in accomplishing tasks such as playing football, carrying a large baggage, and/or supporting rescue operations, among other tasks, although, for the moment, these projects tend to be at the research stage. They are called mobile robot based multiagent systems. The coordination of vehicles, when they are moving on the same road, falls within this area of applications.

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. These methods of cooperation between robots have been realized using radio wave or infrared radiation as a means of wireless communication.

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. Existing communication media access protocols, such as BTMA (Busy-Tone Multiple Access) and ISMA (Idle Signal Multiple Access), which resolve hidden terminal problems in CSMA (Carrier Sense Multiple Access), cannot be used for distributed autonomous control of communication networks, as shown in Fig. 1, because they rely on a centralized mechanism. The RTS/CTS mechanism used in wireless LAN (IEEE 802.11b) induces the appearance of hidden terminals and inefficiency in sending a number of small packets.

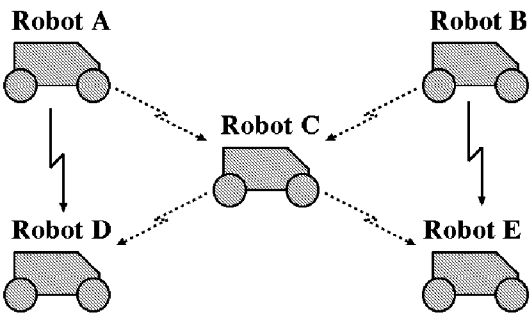


Fig. 1. Distributed communication structure.

On the other hand, infrared radiation is restricted to a limited direction because of the directivity of infrared rays. In addition, it hardly interferes in the communication in other limited directions. The local area communication using limited directivity is suitable for the communication of mobile robots, because interference decreases.

However, the directivity of infrared rays makes it lose a circuit connection of infrared wireless communication when a robot runs and/or rotates, because the robot runs out of the communication area. We have developed an infrared wireless communication system, which can maintain circuit connections when a robot runs and/or rotates (Takai, *et al.*, 2001b). Hardware realization and preliminary experimental results are illustrated to reveal the effectiveness of the proposed system.

## 2. INFRARED WIRELESS COMMUNICATION SYSTEM

The proposed infrared wireless communication system has many infrared transceivers. The infrared transceivers are evenly spaced in all directions. In addition, a part of the communication area of an infrared transceiver overlaps parts of the communication areas of adjacent transceiver. 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 directivity of infrared rays. Using the overlapping communication area, it can maintain circuit connections when another robot is moving.

### *2.1 Tracking of the direction*

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 circuit connection for one robot. Therefore, the system can communicate at the same time with more than one robot in different positions by using the different infrared transceivers on the robot. So it is a space-division infrared wireless communication system.

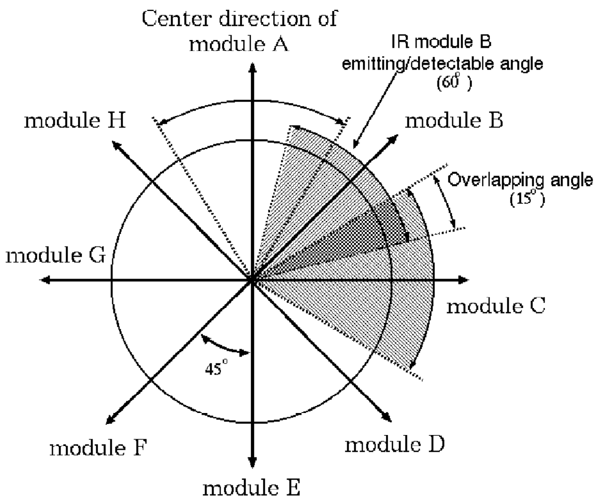


Fig. 2. Arrangement of the transceivers.

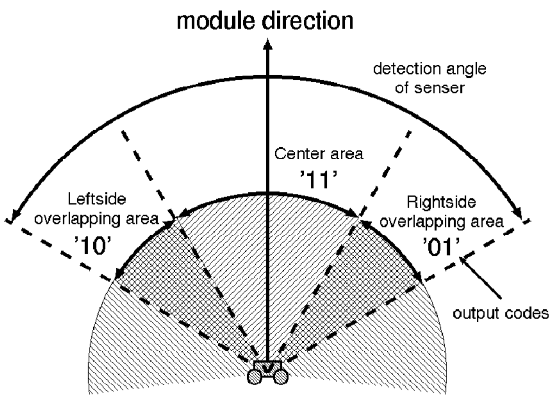


Fig. 3. Tracking of the direction.

Fig. 3 shows the tracking of the direction of another robot by the infrared transceiver. In Fig. 3, the transceiver outputs a direction code '10', when the robot is to the left of the transceiver, outputs a direction code '11' when the robot is in front of the transceiver, and outputs a direction code '01' when the robot is to the right of the transceiver. 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 circuit connection caused by the movement of the robot.

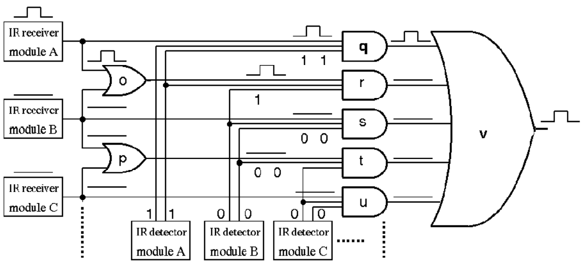


Fig. 4. The exchange circuit.

Fig. 4 shows the exchange circuit, which shifts between infrared transceivers by the direction code. This exchange circuit has more than one channel. And it is made up of the logic gates. The receiving pulse signal and the direction code are directed into the AND gate. When a direction code is '11', this AND gate is sending out a receiving pulse signal. When another robot is in a communication area which overlaps with the next, both receiving pulse signals are directed into the OR gate. This OR gate combines both receiving pulse signals. Then, the receiving pulse signal which has been combined in the OR gate, and a direction code are directed into the AND gate. If the direction code of this transceiver is '01(10)', and a direction code of the right (left)-adjacent is '10(01)', then this AND gate sends out a receiving pulse signal. Then the OR gate combines the receiving pulse signal chosen with the direction code. This flow of the signal constitutes one channel.

A table is made based on the direction code of all transceivers. The direction code of a robot with no other 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. This exchange circuit can separate receiving pulse signals from the different robots to different channels by using the direction code table.

Fig. 5 shows the construction of the space-division infrared wireless communication system. The space-division infrared wireless communication system is composed of eight infrared transceivers (module A – module H), an exchange circuit, a serial data interface, and a microcomputer.

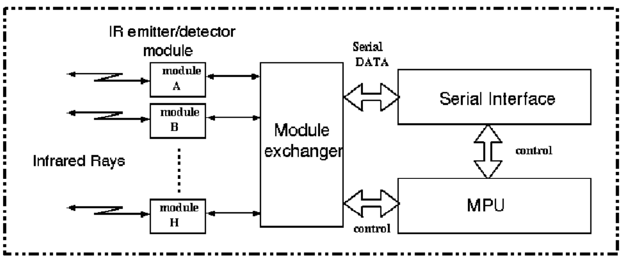


Fig. 5. System overview.

### *2.2 Construction of inter-robot communication*

Infrared wireless communication is a simplex and/or a half-duplex communication. An infrared transceiver doesn't make transmission and reception simultaneous. This is because a transmitting signal interferes in the receiving signal of the same transceiver. Fig. 6 shows the schematic of the transmitter and the receiver in inter-robot communication.

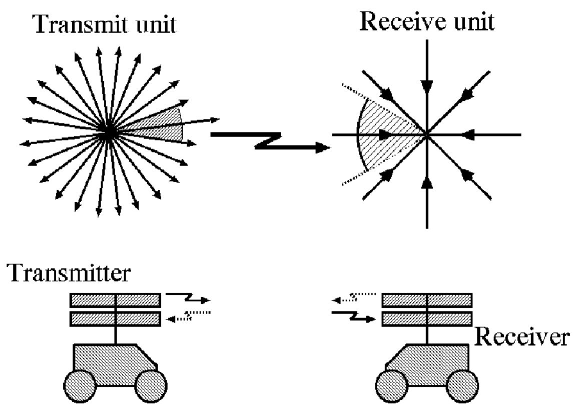


Fig. 6. Inter-robot communication.

The robot, which finds no robots, sends search signals to all directions. This is repeated until any robots are found. The robot, which received the search signal, sends back an answer signal in that direction. Thus one robot is found in the direction of the answer signal. The robot, which received the answer signal, sends a distinction signal in that direction. The point-to-point communication link is established between two robots.

The robot keeps sending a search signal in the direction where another robot isn't found. Another robot is found with the same rule, and a communication link is established with another robot in different position. Thus a communication network is composed around the robot.

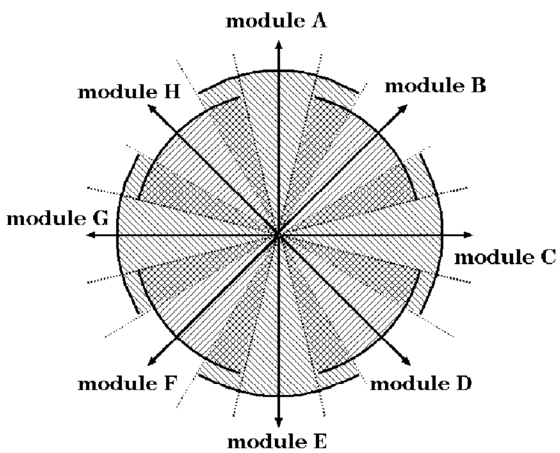


Fig. 7. The communication area of the infrared transceivers.

Fig. 7 shows the communication area of the infrared transceivers in this infrared wireless communication system. 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. These infrared transceivers can talk to the different robots independently.

*2.3 Communication networks for multiagent systems*

Fig. 8 shows an example of the wireless communication network constructed by this space division infrared wireless communication system. The communication network consists of the circuit connections between the robots in different positions. Communication between the different robots happens with minimum interferes. But, it is an adhoc communication network because these robots run and/or rotate. When a robot runs and/or rotates, the robot changes its position. The network changes by the movement of the robot, too. Communication is interfered with when two and more robots face the same direction. Any robot can become the arbiter for this robot communication.

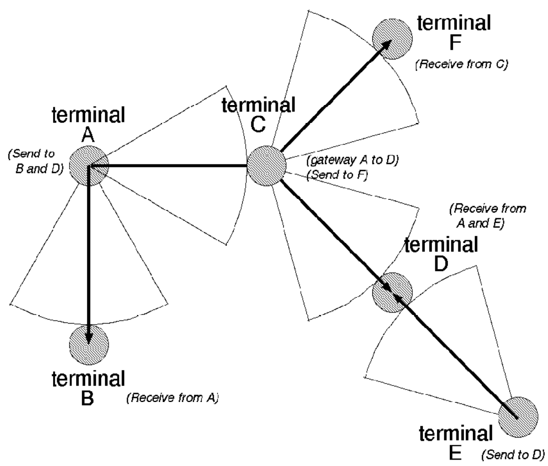


Fig. 8. The mobile robot communication network.

The infrared transceiver includes a sensor, which detects the angle of incidence of the infrared rays. This sensor in the infrared transceiver detects an angle between the robots in the different directions. Three 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 to two other robots. The robot whose angle becomes the widest becomes the arbiter for this robot communication network. Fig. 9 shows the election of the arbiter.

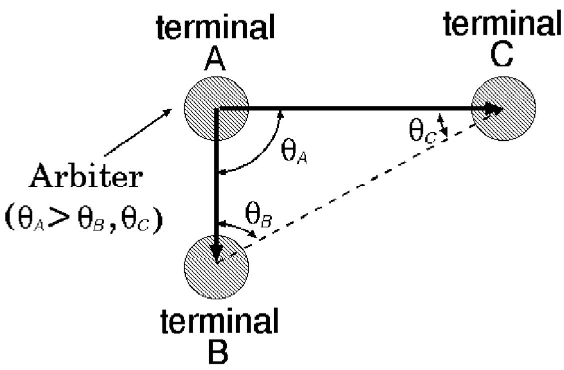


Fig. 9. The election of the arbiter.

As an example of local sensing capabilities using the system, the robot can detect the position of its colleague robot based on triangulation ranging as shown in Fig. 10, which is useful for autonomous navigation through local inter-robot communication in multiple robot systems.

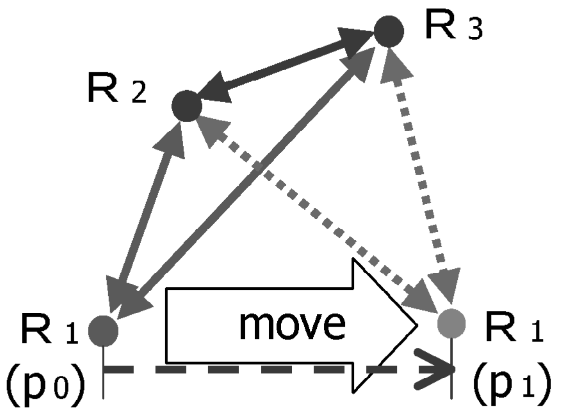


Fig. 10. Triangulation ranging using transceivers. (R1,R2,R3:robots; p0,p1:positions of R1)

## 3. EXPERIMENTS AND RESULTS

This space division infrared wireless communication system detects the angle of incidence of the signal from another robot, and tracks it. The detection of the angle of incidence of the signal and the tracking of the robot were confirmed in the experiment.

### *3.1 Detection of the angle of incidence of infrared rays*

We conducted the experiment, which confirmed 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 PIN photo diode can detect the angle of incidence of infrared rays. The PIN photo diode has two electric current outputs ‘a’ and ‘b’ as shown in Fig. 11. The electric current outputs ‘a’ and ‘b’ of the PIN photo diode have the relation of the equation (1) with the angle of incidence of an infrared ray $\theta$.

$$\theta = (a-b)/(a+b) \tag{1}$$

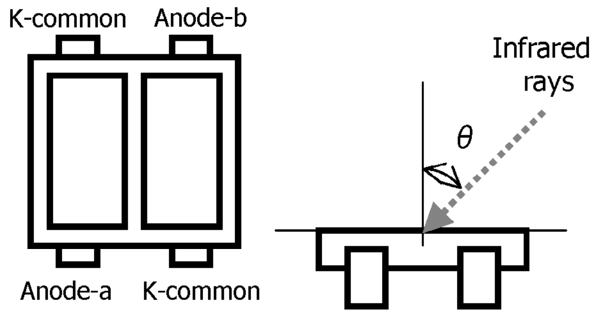


Fig. 11. Schematic view of the HAMAMATSU S6560 detector.

The circuit of the angle of incidence sensor is an analog signal processing circuit (Fig. 12), because the signal strength changes when a robot runs and/or rotates. The change in the signal strength influences the detection of the accurate angle of incidence. The circuit of the sensor of the angle of incidence includes the receiver of the infrared wireless communication.

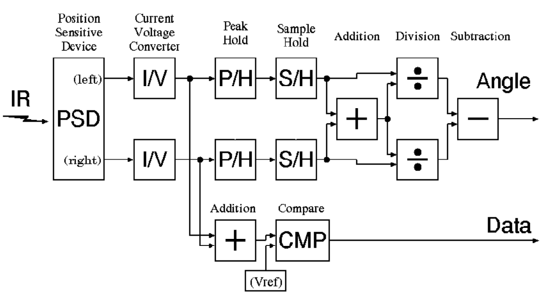


Fig. 12. Block diagram of analog computing circuit.

The infrared transceiver was made to receive 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 source was moved from the left 40 degrees to the right 40 degrees in 5 degrees each. The distance between the source and the sensor was moved from 15cm to 30cm in 5cm each. The experimental results are shown in Fig. 13. The angle detection error of this sensor circuit was ± 5 degrees. The circuit detects an angle in the input of the signal in 100 $\mu$ s.

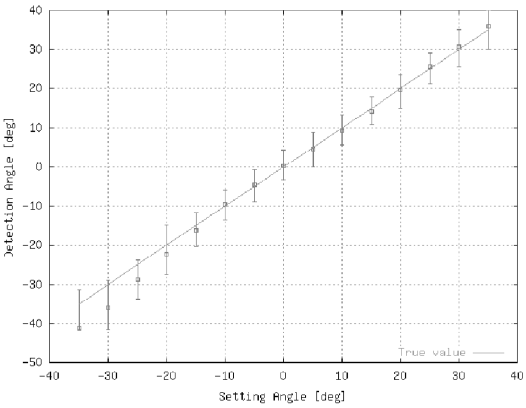


Fig. 13. Experimental results of angle detection.

*3.2 Shifting between transceivers*

We conducted the experiment of confirming the function, which shifts between transceivers, of the exchange circuit. The exchange circuit, which is 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 exchange circuit changed enough in short time to the IrDA-SIR, 9.6kb/s standard signal.

## 4. CONCLUSIONS AND FUTURE WORKS

We developed a space-division infrared wireless communication system for mobile robots. And then, we confirmed the ability of this communication system using the IrDA-SIR, 9.6kb/s standard signal. This communication system could maintain a communication connection through the running and/or rotation of another robot. This communication system could detect the direction of another robot with 100 $\mu$ s. And, the detection angle error was $\pm 5$ degrees.

Already, an infrared wireless LAN has had ability beyond 10Mb/s. Furthermore, an infrared wireless communication system, which can communicate in the distance of 100m in the open air, has been developed. If the infrared transceiver circuit becomes part of an integrated circuit, this system will be able to increase communication ability in the above-mentioned systems.

Next, we discussed the communication network, which this communication system was used for. This communication system selects an arbiter geometrically. A robot can select an arbiter without complex decision algorithms.

As a future work, we will utilize the proposed mutual localization capability for the sensor fusion based autonomous navigation scheme using external and internal sensors (Takai, *et al.*, 2001a).

If autonomous routing algorithms are combined with this communication system, the effective remote control of multiple robot systems becomes possible. Such a robot system will be useful for a variety of applications, including rescue in dangers environments, emergency construction around active volcanoes, and so on.


## ACKNOWLEDGMENT

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