複数移動ロボットの協同作業と情報共有のための空間分割光通信システムの開発

(課題番号：15560333)

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研究成果報告書

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はしがき

本冊子は、平成１５年度～平成１６年度の二年間、科学研究費補助金：基盤研究（C）（２）の補助を受けて実施した研究「複数移動ロボットの協同作業と情報共有のための空間分割光通信システムの開発」（課題番号：15560333）の研究成果報告書である。この研究「複数移動ロボットの協同作業と情報共有のための空間分割光通信システムの開発」の当初の目的は、先に研究代表者：高井 博之が考案した、空間分割光通信システムの開発、そして、光の直進性を利用した幾何学的な通信干渉抑制方式の原理確認であった。

この空間分割光無線通信システムの特徴の１つは、ＰＳＤ（Position Sensitive Detector = フォトダイオード光入射角センサ）を用い、通信相手が発する光信号の方向角度を検出することである。通信干渉が発生する時、空間的なロボットの配置は、受信ロボット１台と送信ロボット２台が頂点となる三角形を構成する。通信システムの受光素子の受光範囲を６０°以下に制限する時、最大の内角は６０°以上となり受光範囲に入らないので混信を生じない。ゆえに、その時の内角が最も大きいロボットが調停者となり、相互の調停を図ることで混信を解消できることをシミュレーションで明らかにした。

次に、このシミュレーション結果を実証するための、実験用通信システムの開発に取り組んだ。実験用システムとして、発光素子に赤外線ＬＥＤ、受光素子に二分割型ＰＳＤを用いたベースバンド伝送方式の光無線通信システムを検討した。光無線通信で送受信する光信号の強度は、光の拡散によって距離の２乗で減衰するので、受信信号の強度に応じて適正な増幅率を設定し信号を増幅しなければ、離れた通信相手に対する方向角度の検出や情報伝送ができない。光入射角の計算にはダイナミックレンジの広い信号処理が必要である。加えて、移動ロボットの遠隔制御には、画像データの伝送など高速大容量データ伝送に対応するために周波数帯域幅の広い信号処理が必要である。我々は、光入射角の検出と高速データ伝送を両立する、光無線通信の送受信回路に重点を置いて研究した。

光無線通信の送受信回路には、ＬＥＤやＰＳＤの寄生容量や非線形特性の影響、背景光（太陽光や照明光）の混入によるＳＮ比劣化等の問題がある。光データ通信は、光パルス信号の送受によって実現されるので、信号光と背景光の周波数の相違を利用した雑音除去方式を検討した。ＰＳＤは電流出力なので、信号増幅にはトランスインピーダンス増幅器を用いる。周波数応答特性のよい信号増幅器を検討した。また光信号の途絶検出や通信制御のため、ＮＲＺＩ符号化したＨＤＬＣ方式によるデータ伝送を検討した。

本研究の当初の目的である空間分割光通信システムの開発、および、光の直進性を利用した幾何学的な通信干渉抑制方式の原理確認は、時間的な不足を生じて研究期間中に完了しなかったが、目的の光通信システムを実現するための基礎となる光信号送受信回路、通信プロトコルに多くの知見を得て有意義な研究であった。

研究組織

研究代表者： 高井 博之 (広島市立大学・情報科学部・助手)
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研究発表

（１） 学術誌等

なし

（２） 口頭発表

［1］ H.TAKAI, G.YASUDA and K.TACHIBANA: “A Space-division Wireless Communication System for Ad Hoc Networking and Cooperative Localization of Multiple Mobile Robots”, Preprints of the 16th International Federation of Automatic Control IFAC World Congress2005, Paper ID:05004, July 2005, (Prague) Czech, -To be appeared-.

［2］ 高井 博之，橘 啓八郎：「複数移動ロボットの相互協力のための空間分割光無線通信システム」，第６回ＹＲＰ移動体通信産学官交流シンポジウム（２００４），pp.164-165，2004年7月，神奈川県横須賀市

［3］ H.TAKAI, G.YASUDA and K.TACHIBANA: “Function Integration for Team Operations of Mobile Robots: Inter-robot Communication and Mutual Localization”, Proceedings of the 11th International Conference on Advanced Robotics ICAR2003, pp.1431-1436, July 2003, (Coimbra) Portugal.

（３）出版物

なし

研究成果による工業所有権の出願・取得状況

なし

研究の目的

近年、複数の移動ロボットによる共同作業が注目されている。特に、人間型の二足歩行型移動ロボットは、人間と同等な作業環境で人間と同じ機械や道具を用いることができるので、複数ロボットの相互協力によって複雑で高度な作業が実施できると期待されている。複雑で高度な作業を効率よく処理するため、共同作業を行う複数のロボットは、それぞれのロボットが持つ位置情報や作業手順などを共有しなければならない。本研究は、複数の移動ロボットが共同作業を行うとき、相互の情報交換に用いる無線通信システムについて研究した。

共同作業にあたる複数の移動ロボットは、お互いに近距離に位置する場合が多い。そこで我々は、壁や障害物で容易に遮断できる近距離の通信に適した赤外線を用いる通信方式を検討した。赤外線は指向性が強く、ロボットの移動・回転により通信途絶の懸念がある。研究代表者：高井博之は、平成１３年度と平成１４年度の２年間、科学研究費補助金（若手研究（Ｂ））「移動ロボット相互の近距離通信のための空間分割光無線通信システムの開発」（課題番号：13750365）を得てこのロボットの移動・回転に伴う通信途絶を解消する方法を研究した。高井はＰＳＤ（Position Sensitive Device：フォトダイオード光入射角センサ）を受光素子に用い、複数の受光素子を円周上に並べて全方向の信号を受信できる空間分割光通信システムを考案した。高井は先の研究で、考案した空間分割光通信システムの基本動作原理を確認すると同時に、幾何学的な移動ロボット相互の配置情報を基に、通信干渉を抑制する方法を提案した。本研究の目的は、先に考案した空間分割光通信システムの実験システムを開発し、幾何学的な通信干渉抑制方法の原理を確認することである。

研究の内容

本研究は、ロボット相互間の無線データ通信の研究である。一般に、データ通信システムの構成はＯＳＩ参照モデルで説明される。図１にＯＳＩ参照モデルを示す。本研究の研究範囲は、ＯＳＩ参照モデル物理層と、データリンク層に該当する。
平成１５年度から平成１６年度の２年間の研究期間中に
１）幾何学的な通信干渉抑制のシミュレーション
２）赤外線信号途絶検出のための符号変復調方式の検討
３）赤外線送受信モジュール開発のための信号処理方式検討
を行った。

アプリケーション	
プレゼンテーション	
セッション	
トランスポート	
ネットワーク	
データリンク	ＬＬＣ
	ＭＡＣ
物理	ＣＯＤＥ
	Ｉ／Ｏ

図１　ＯＳＩ参照モデル

実験の方法と結果

１．幾何学的な通信干渉抑制のシミュレーション

空間分割光通信システムの開発に先立ち、分散制御型無線通信ネットワークにおける、干渉や混信の発生についてシミュレーションを行った。分散制御型無線通信ネットワークでは、「隠れ端末問題」や「さらし端末問題」と呼ばれる混信現象が知られている。ノードが使用するアンテナの、指向性の有無による混信発生の相違をシミュレーションで比較した。

分散制御型無線通信ネットワークで生じる「隠れ端末問題」や「さらし端末問題」は、信号到達範囲の境界付近に中継ノードが存在するとき、中継ノードに送る信号が他のノードからの信号と混信する、あるいは、中継ノードが他局間の信号にさらされ自ノード向けの信号が受信できないなどの現象を云う。

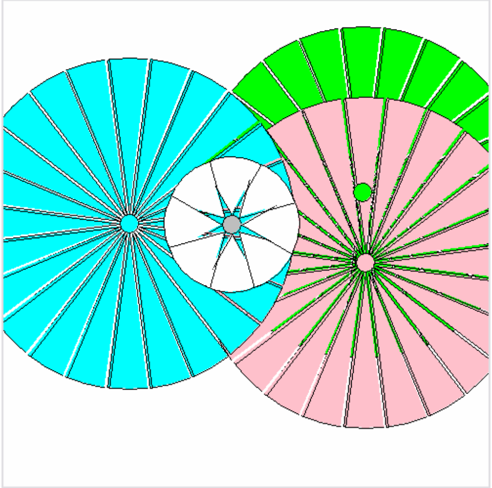
図２ ノードの配置と送受信範囲

本研究では、受信送信、アンテナの指向性の有無を組み合わせ、干渉･混信の抑制方法を検討した。送信受信と指向性からノードは、

ｉ)ＯＲＯＴ：全方位送受信
ⅱ)ＯＲＤＴ：全方位受信・指向性送信
ⅲ)ＤＲＯＴ：指向性受信・全方位送信
ⅳ)ＤＲＤＴ：指向性送受信

の４種類に分類できる。各分類について干渉・混信の様子をシミュレーションで確認した。

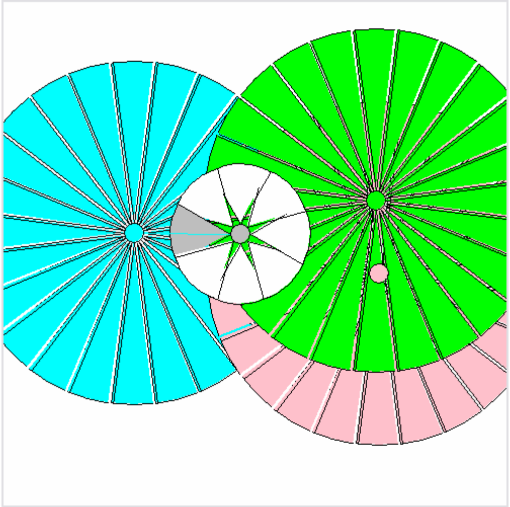
図３ 指向性受信による混信除去

ノードの配置と送受信範囲を図２に示す。図２において、全方位送受信(ＯＲＯＴ)を行う場合、右側２つと左側のノードは直接通信できず、中央部の中継ノードを介して情報を交換する。この配置図は、右側左側のノードが同時に送信した時、中央の中継ノードで混信が生じることを示している。

図３は、指向性受信・全方位送信(ＤＲＯＴ)の例を示す。中央の中継ノードは左側を向くアンテナを用いて左側からの信号を受信する。右側からの信号は中継ノードのアンテナに入らないので混信しない。

アンテナの受信と送信、指向性の有無の組み合わせによる、「隠れ端末問題」「さらし端末問題」の解消をシミュレーションで確認した。シミュレーションの結果、

・「隠れ端末問題」は指向性受信で解消できる

・「さらし端末問題」は指向性送受信だけでは解消できない

ことが判明した。

指向性送受信では、受信ノードの受信範囲に、複数の送信ノードが存在し、それらが同時に受信ノードに送信する時、「さらし端末問題」が発生する。図４に指向性送受信における「さらし端末問題」を示す。

「さらし端末問題」は、最小３台のノードが関係する。これらはノードを頂点とする三角形を形成する。ノードの受信範囲が６０°以下のとき、他ノードの角度の一つは６０°よりも必ず大きい。即ち、干渉を受けずに通信できる経路が必ず一つは存在する。本研究では、受信素子にＰＳＤ(フォトダイオード光入射角センサ)を用い、信号源の方向角度を検出する。角度が最も大きいノードがアービタ(Arbiter：調停者)となり、通信経路や送受信のタイミングを調整し、さらし端末問題を解消する。図５に幾何学的なアービタ決定法を示す。

先のシミュレーション・プログラムに、幾何学的なアービタ決定アルゴリズムを追加して、「さらし端末問題」「隠れ端末問題」の解消を確認した。

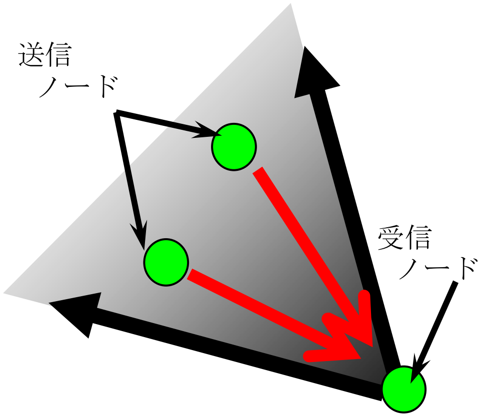

図４ 指向性送受信時のさらし端末問題

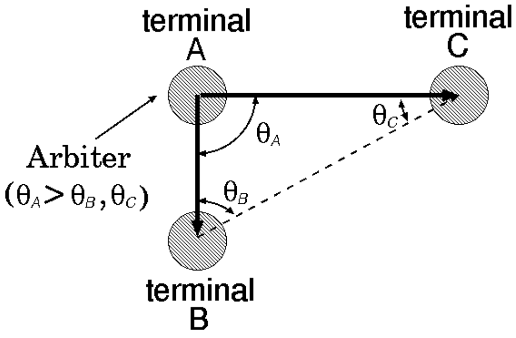

図５幾何学的なアービタ(Arbiter)決定法

本研究で、指向性送受信と幾何学的なアービタ決定を用いることによって、分散制御型無線通信ネットワークで生じる「隠れ端末問題」を「さらし端末問題」を解消できることを、シミュレーションで確認した。しかしながら、研究期間中に行ったシミュレーションでは、少数ノード間での干渉・混信の解消確認しかできなかった。今後、多数のノードが参加する通信ネットワークにおいて、検討した幾何学的な通信制御方式の効果を調べる必要がある。

２．赤外線信号途絶検出のための符号変復調方式の検討

本研究は、赤外線を用いる共同作業する複数移動ロボット相互の近距離通信の研究である。赤外線は指向性が強く、無線通信に使用する場合、壁や障害物、ロボットの移動回転によって通信の途絶が懸念される。そこで本研究では、

ⅰ）ロボットの移動回転を検知し、通信相手を追跡して通信路を保持する
ⅱ）通信の途絶が検出可能な符号変調方式を用いる

の二つの方法を検討した。

ⅰ）ロボット移動回転時の通信路維持方式

本研究で開発する空間分割光通信システムは、ＰＳＤ（ Position Sensitive Device：フォトダイオード光入射角センサ）を受光素子に用い、複数の受光素子を円周上に並べて配置し全方向からの信号受信を可能にした。図６に、受光素子の配置を示す。この通信システムでは、それぞれの受光素子で信号源の方向角度が検知できるので、ロボットの移動回転に対して、相手に向く受光素子に切換え通信路を保持する。図７に、受信信号切換え回路を示す。図７の左側から受信光パルスが、下から信号源方向の情報が入力され、意図した方向からの受信信号が右側に取り出される。ＰＬＡ(Programmable Logic Array)上に受信信号切換え回路を実装し、ロボットの移動回転を模擬する信号を使って、その通信路維持動作を確認した。

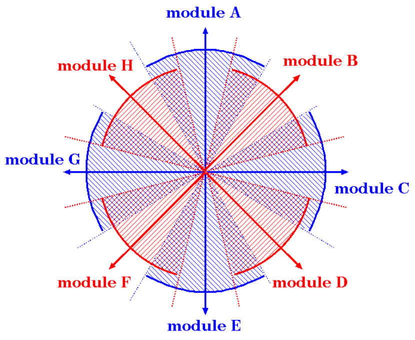

図６ 受光素子の配置

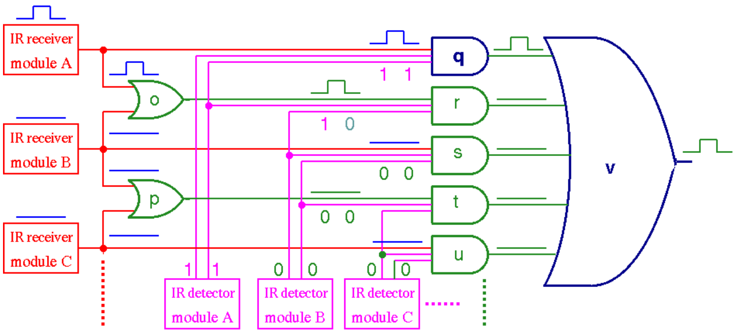

図７ 受信信号切換え回路

ⅱ）通信の途絶が検出可能な符号変調方式

通信が途絶した時、多くの場合信号レベルは一定値に固定される。通信信号が一定周期内に必ず変化するならば、一定周期内に変化がないとき、通信途絶が検出可能である。そこで、一定周期内に必ず変化が起きる符号変調方式の組み合わせを調べた。

ＨＤＬＣ方式では‘１’が６ビット続く１６進数“７Ｅ”はフラグシーケンスと呼ぶ特別な意味を持つので、通信データ中に“７Ｅ”が出現しないように、‘１’が５ビット続くと強制的に‘０’を挿入するゼロ・インサーションが行われる。しかし、‘０’が続く時には

変化を生じずに‘０’が続く。‘０’が連続しない符号化変調方式として、ＮＲＺＩ符号化がある。ＮＲＺＩでは、‘１’はそのまま出力し、‘０’はビット毎に反転する。ＨＤＬＣの出力をＮＲＺＩ符号化することで、‘０’，‘１’どちらが連続する時、最悪でも６ビット毎に変化を生じるので、通信途絶が検知できると考えた。

ＮＲＺＩ符号化ＨＤＬＣ送受回路を、先の受信信号切換え回路と一体化し、Ｌｉｎｕｘや ＩＴＲＯＮと組み合わせて使うため、ＰＬＡへの集積化を試みた。ＨＤＬ(Hardware Description Language)用いて回路設計を行い、シミュレーションで意図した結果を得ることができたが、実験機材の準備、材料入手に予想以上時間を要し研究期間中にＰＬＡ上への実装には到らなかった。

今後の研究課題として、ＬＡＮ(Local Area Network)やＰＲＮ(Packet Radio Network)に用いられる通信プロトコルＴＣＰ／ＩＰやＡＸ．２５，ＰＰＰなどと組み合わせ、移動ロボット制御に適した通信システムの研究を進める。

３．赤外線送受信モジュール開発のための信号処理方式検討

本研究では、受光素子にＰＳＤ（ Position Sensitive Device：フォトダイオード光入射角センサ）を用いる、空間分割光通信システムを開発する。研究では、発行素子に赤外線ＬＥＤ，受光素子に二分割型ＰＳＤを用いるベースバンド伝送方式の通信方式を検討した。図８にＰＳＤの構造，図９に光入射角検出回路のブロック図を示す。光無線通信の受信信号強度は、光の拡散放射によって通信距離の２乗で減衰する。よって、光受信回路には広いダイナミックレンジが求められる。また、伝送データ量の増大に伴い、周波数帯域幅の広い信号処理が求められる。広いダイナミックレンジと広い周波数帯域幅の両方を備えた増幅回路方式として、近年、電流帰還型増幅器が注目されている。本研究でも、電流帰還型増幅器を用いた光信号増幅回路を検討した。実験機材の準備、工作材料入手に予想以上時間を要し、研究期間中に回路の製作、実験実施には到らなかった。今後準備した機材を利用し、増幅回路の開発に取り組む。

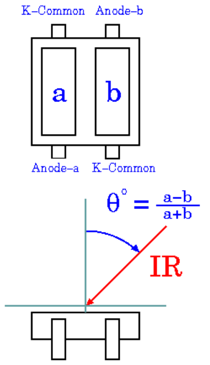

図８ ＰＳＤの構造

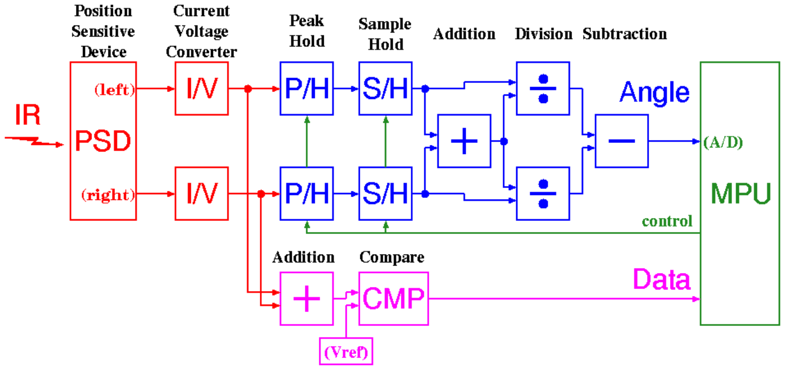

図９ 光入射角検出回路

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Function Integration for Team Operations of Mobile Robots: Inter-robot Communication and Mutual Localization

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Abstract

In recent years, multi-robot systems that perform team operations have been developed. These robots have been designed to execute tasks in hazardous environments such as assisting in rescue operations. These robots communicate with each other to execute tasks smoothly. However, in hazardous environments, expanding the working area and/or detecting positioning information is difficult, because relay stations and/or landmarks are hard to prepare in advance. If robots themselves can serve as relay stations and/or landmarks, this will improve operation efficiency in executing tasks in hazardous environments.

We propose a wireless communication system that can relay information. This communication system can compute the mutual positioning information by using the communicating partner which is sending signals as a landmark (like a lighthouse). The positioning information is computed by the triangulation based on the angle of arrival (AOA) of the communication signals. In a confirmation experiment, the accuracy of positioning information was approximately 90% with the true value based on the detected AOA.

This paper describes how to integrate the functions of inter-robot communication and mutual localization for team operations between multiple mobile robots.

1.Introduction

Recently, multiple mobile robot systems that perform team operations have been developed [1]. The Team operation of multiple mobile robots will be effective in hazardous environments for task executions such as planet investigations, deep ocean surveys, assistance in rescue operations and the maintenance of nuclear reactors.

To execute team operations smoothly, these robots have to communicate with each other and exchange information. If relay stations are arranged in the working area, then the working area of these robots can expand. Also, if these landmarks are arranged in this way then the positioning information can be detected accurately. In hazardous environments however, relay stations and/or landmarks are difficult to prepare in advance. Moreover, usual wireless remote control of mobile robots, which uses omni-directional communication carriers, increases communication interferences.

We proposed a communication system that uses infrared rays as the carrier because directional signals can reduce communication interference [2]. In addition, the communication system can detect the approximate direction of a communicating partner to maintain communication links. Since the communicating partners that are sending communication signals perform the role of landmarks (like lighthouses), and if the communication system can detect the angle of arrival (AOA) of the communicating signals accurately, then these robots can compute their mutual positioning information using triangulation.

A function of the communication system that integrates the wireless communication and the mutual localization is useful for the team operation of mobile robots in hazardous environments because it can decrease not only communication interferences but also the confusion of robots. Also, the communication system can expand the working area of the robots by creating communication networks, since it can relay information.

In the second section of this paper the concept of the wireless communication system for mobile robots is discussed. In the third section the mutual localization algorithms are described. In the fourth section results of confirmation experiments are shown.

2.A wireless communication system for multiple mobile robots

For the remote control of mobile robots wireless communication systems, omni-directional carriers are usually used because of their good connectivity. However, when the number of robots that join in team operations increases in the same working area, the management of communication channels becomes complicated. Omni-directional signals are received not only by the communicating partners but also by the other robots. These omni-directional signals can cause the communication interference. Fig.1 shows how omni-directional signals can cause communication interference. Communication interferences are influenced by the arrangement of transmitters/receivers and the properties of the communication carrier.

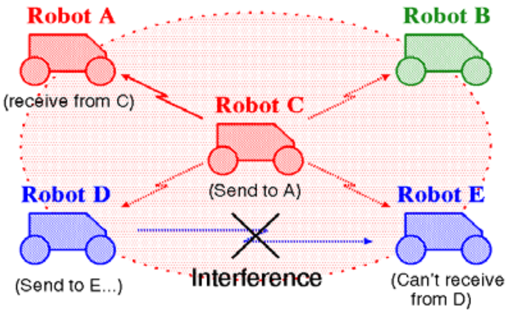


Fig.1 Interference by the omni-directional signals

As one of the interference reduction methods, a communication system transmits signals focusing on the partner's direction. It also restricts the reception angle of the receiver. However, the communication system, which uses the interference reduction method, has to track the communicating partners, because the communication signals easily lose the partner's direction when these robots move.

If the communication system can detect the partner's direction, it can track the communicating partner. Since the communicating partner that is sending signals can be found, the partner's direction can also be found by using the detection devices such as a direction finding receiver or an incidence angle detector.

The details of the mobile communication system using the directional carriers are now discussed.

2.1 The mobile communication system using directional carriers

Microwaves or infrared rays are usually used as the directional carriers in wireless communication. We propose a communication system that uses infrared rays as the carrier, because infrared rays can restrict the beam width easier than microwaves. The communication system using infrared rays can detect the angle of arrival (AOA) more easily.

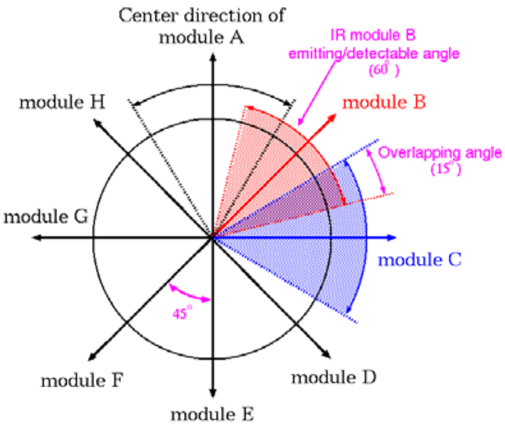


Fig.2 Arrangement of transceivers

When the communication system uses infrared rays as the carrier, a transmitter and a receiver have to face each other because the receiver that faces a different direction from the transmission signals cannot catch them. The beam width of each transmitter is made narrow so as not to send unnecessary signals. The reception angle of each receiver is also restricted to eliminate unnecessary signals. A transceiver is composed of a receiver and transmitters. In this communication system, because they have to communicate with partners in all directions, a set of transceivers are put on the circumference of the robot body and they face outwards. Fig.2 shows the arrangement of transceivers.

2.2 Tracking the communicating partner

Each transceiver detects an incidence angle of infrared signals that are sent from the communicating partner. This incidence angle shows the partner's direction. The transceiver outputs the 2bit direction code that shows the partner's direction based on the incidence angle. The communication system maintains the connection by switching to a transceiver that faces the communicating partner, when the other runs and/or rotates. Fig. 3 shows the direction code of an infrared transceiver. The transceiver outputs the direction code '10', '11', and '01' when the partner is in the left, center, and right of the communication area of the transceiver, respectively.

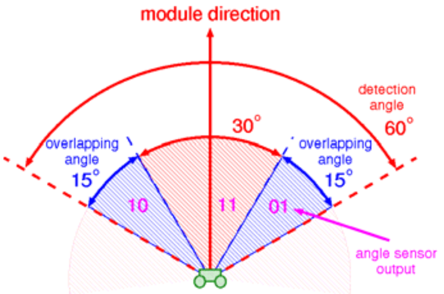
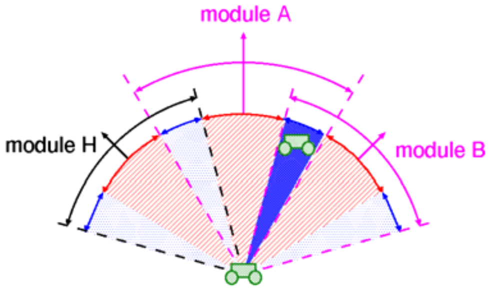


Fig.3 The direction code of an infrared transceiver

In the communication system, a part of each transceiver is overlapped by an adjacent transceiver and this overlap eliminates the short break that occurs when transceivers are switched. When the partner is in the middle of two adjacent transceivers, these transceivers receive the same signals from the partner.

Transceivers that are set on the robot body create a direction code table from the direction code that is outputted from each transceiver. Fig.4 shows the partner's direction and direction code table. The code "11" shows the partner's direction.



A	B	C	·····	H
01	10	00	·····	00

Fig 4. The partner's direction and direction code

Fig.5 shows the transceiver exchange circuit. In Fig.5, the received signal of each transceiver is on the left side, and the direction code of each transceiver is below. The exchange circuit switches to the received signal from the transceiver that matches the direction code "11". The direction code "11" shows the direction of the communicating partner.

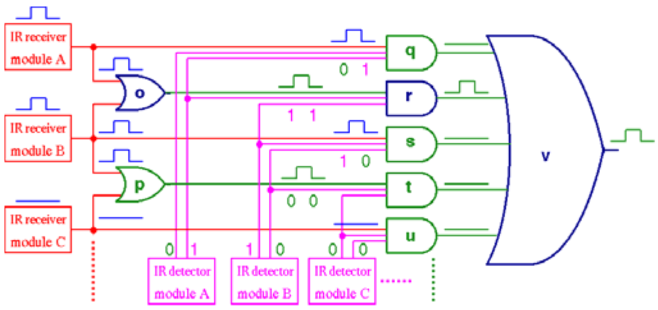


Fig.5 The transceiver exchange circuit

2.3 Creating a communication network

In infrared communication, when a receiver faces a different direction to the transmission signal this interferes with communication only slightly. The communication system can detect signals from partners in all directions by using a combination of these transceivers. Also, the communication system is able to focus the direction of each partner to exchange information by using each transceiver independently. Therefore, the communication system is able to communicate at the same time in parallel with different partners in different directions. Consequently, space-division communication can take place. Fig.6 shows the parallel transmission in different directions.

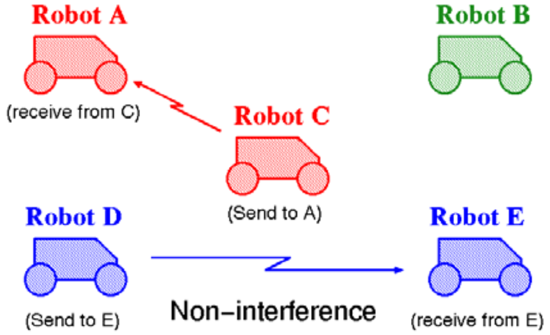


Fig.6 Parallel transmission in different directions

When each robot relays information between different partners, a communication network is created in the working area. First, point-to-point connection is established among robots. The building process of the communication network is shown as follows:

1. At first, all robots are independent of each other. Each robot repeats search signals in all directions in order to find partner robots.
2. Each partner robot catches a search signal and finds the direction from which it came. The partner robot sends back an answer signal in that direction.
3. After the reception of the answer signal from the partner robot, the robot transmits a conformation signal back to establish a connection.
4. A point-to-point connection is established between two mobile robots. These robots keep sending search signals in the directions where a partner has not yet been detected.
5. Robots spread connections among themselves and expand the communication network.

It is an ad hoc communication network because each robot is independently mobile and may change position depending on the task. Fig.7 shows an inter-robot communication network.

In an infrared communication system a transceiver cannot transmit and receive signals at the same time because it is confused by its own signals. The communication system needs to create a schedule to transmit signals and to switch the function from transmission to reception. Simplex or half-duplex communication can be used in this communication system.

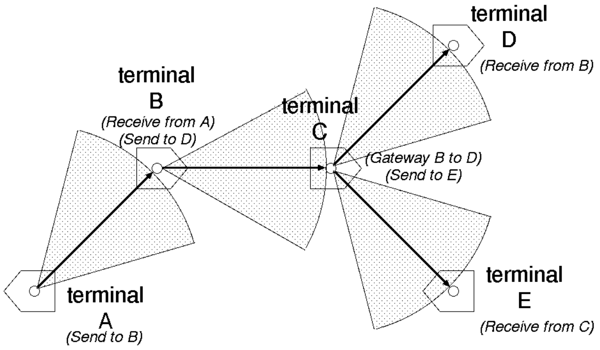


Fig.7 An inter-robot communication network

2.4 A geometrical interference reduction on directional wireless communication

When a receiver catches signals from two or more partners at the same time, received signals are confused. On that occasion, these robots are making a triangle.

The interior angle is calculated from detected AOA and each robot informs other partner robots of its own interior angle. Because the widest interior angle of the triangle is greater than or equal to 60 degrees, if the reception angle of each transceiver is restricted to 60 degrees or less, a robot that has the widest interior angle can communicate without confusion.

The robot that has the widest interior angle becomes an arbiter that is a temporary local controller to reduce the signal confusion. The arbiter mediates each partner by scheduling each transmission. Fig.8 shows a selection of an arbiter. When robots move and the triangle changes shape, the arbiter role is handed over to another robot.

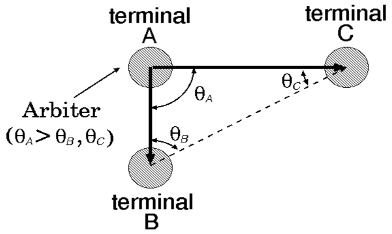


Fig.8 Selection of an arbiter

When the number of robots that join in team operations increase in the working area, these robots create a complicated communication network. Since this communication network makes a polygon, it can be divided into triangles. In this case, these robots select several arbiters for the communication network. A ranking is given so that arbiters that are in the centralized point may get priority.

3. Multi-robot mutual localization using wireless communication

As previously mentioned, the parallel transmission and/or the geometrical interference reduction can improve the performance of the communication system for mobile robots that uses infrared rays as the carrier. The performance improvement in this communication system depends on the detection of AOA. Moreover, the AOA is used for the collision avoidance and/or the localization of mobile robots.

Positioning information is extremely useful for the team operations of mobile robots. Normally, this information is global. Geo-navigation is used for detecting this information.

However, because these robots help with adjacent robots, they perform team operations that require preferentially mutual positioning information rather than global positioning information to execute their tasks. Also, in hazardous environments, detecting global positioning information of mobile robots by geo-navigation is difficult because landmarks that are put in known locations are hard to detect in advance.

Mutual localization is easier to compute than global because it is not necessary to know the location of the landmarks in advance. In addition, mutual localization can be achieved using only the communication systems on the mobile robots themselves.

If the AOA is detected accurately, these robots can compute mutual positioning information among themselves by triangulation based on the detected AOA. The computation method of this information requires more than three known landmarks in the working area. These landmarks are arranged on coordinates $P_1(x_1,y_1)$, $P_2(x_2,y_2)$, $P_3(x_3,y_3)$, where P_2 is the origin. When the coordinate of the robot is $P(x,y)$ and the movement direction of the robot is θ, these parameters are computed from equation 1.

$$\left.\begin{aligned} x &= \overline{p_2 p}\cos\phi \\ y &= \overline{p_2 p}\sin\phi \\ \theta &= \phi - \theta_{01} - \theta_{12} + \pi \end{aligned}\right\} \quad (1)$$

Each parameter is computed as follows:

$$\phi = \tan^{-1}\frac{\overline{p_1 p_2}\sin(\theta_{12}+\alpha)\sin\theta_{23} - \overline{p_2 p_3}\sin\theta_{12}\sin\theta_{23}}{\overline{p_1 p_2}\cos(\theta_{12}+\alpha)\sin\theta_{23} + \overline{p_2 p_3}\sin\theta_{12}\cos\theta_{23}}$$

$$\overline{p_2 p} = \frac{\sin\theta_{23}\cos\phi + \cos\theta_{23}\sin\phi}{\sin\theta_{23}}\overline{p_2 p_3}$$

$$\alpha = \tan^{-1}\frac{y_1}{x_1}$$

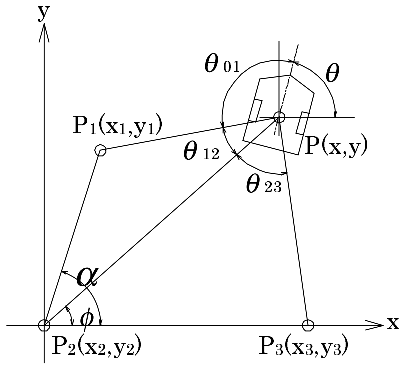


Fig.9 Location computation by triangulation

Fig.9 shows location computation by triangulation based on the AOA. The robot detects AOA (θ_{01}, θ_{12}, θ_{23}) using communication signals and computes the coordinate P(x,y) by triangulation.

When the number of robots increases in the working area the robots that serve as landmarks also increase. The robot that computes positioning information chooses a landmark that gives the most accurate computation result. The robot that computes this information verifies the computation result repeatedly to acquire the most accurate information possible.

4. Hardware realization and performance measurements

This communication system that uses infrared rays as the carrier detects the AOA using communication signals from the partner. The detected AOA is used to track connected communicating partners, to aid geometrical interference reduction, and for the localization of mobile robots.

4.1 Detection of the AOA

The AOA is computed from the incidence angle of infrared rays that are received by each transceiver. The PIN photo diode (HAMAMATSU S6560) is the detection device for the infrared rays in this experiment. Fig.10 shows a schematic view of the PIN photo diode.

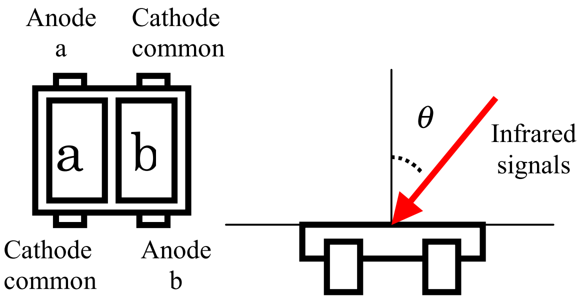


Fig.10 A schematic view of photo diode

This photo diode has two electric current outputs ‘a’ and ‘b’. The incidence angle of the infrared rays θ is calculated from electric current values ‘a’ and ‘b’ in equation 2.

$$\theta = (a - b)/(a + b) \qquad (2)$$

An infrared signal source was placed in front of the photo diode. Then the source was moved from 50 degrees left to 50 degrees right in 0.5-degree increments, and the distance between the source and the detector was moved from 15cm to 30cm in 5cm increments.

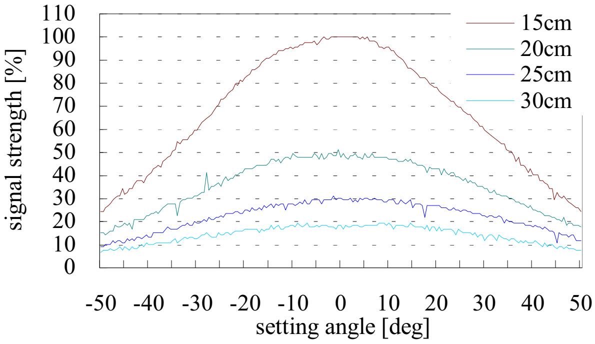


Fig.11 Receiving signal strength

Fig.11 shows the detecting signal strength using the PIN photo diode (HAMAMATSU S6560) and the analog signal processor (HAMAMATSU C3683-01). It shows the summation signal of the detector outputs ‘a’ and ‘b’.

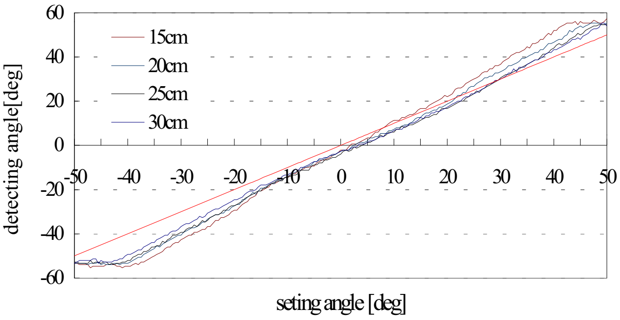


Fig.12 Angle detection error of the detector

Fig.12 shows the angle detection error of this photo diode.

4.2 Restriction of the reception angle

In Fig.11 the reception angle of the photo diode is wider than 60 degrees. To reduce communication interference the reception angle of the photo diode has to be restricted to less than 60 degrees (as discussed in paragraph 2.4). Therefore, the reception angle of the detector is restricted by barriers that open up 60 degrees in front of it. In these experiments, two detectors that are facing outwards are arranged at 45-degree intervals. Fig.13 shows the receiving signal strength and receiving area of each receiver.

In Fig.13, each communication area is restricted to a width of 60 degrees and overlaps with the adjacent receivers by 15 degrees. This result confirms the feasibility of the layout of Fig.2.

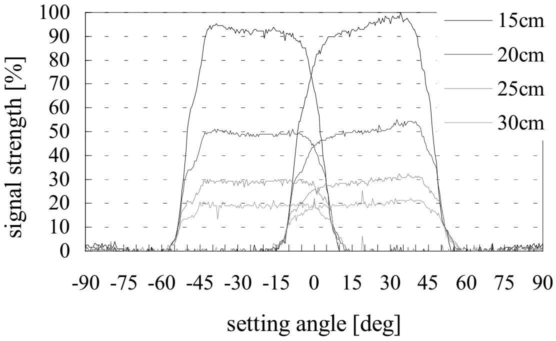


Fig.13 Receiving signal strength of restricted detectors

4.3 Computation of positioning information

We confirmed the localization ability of this communication system that used the detected AOA by simulation. Three landmarks that have 100 mm diameters were placed on vertices of an equilateral triangle that has 400 mm sides. Fig.14 shows the result of the simulation.

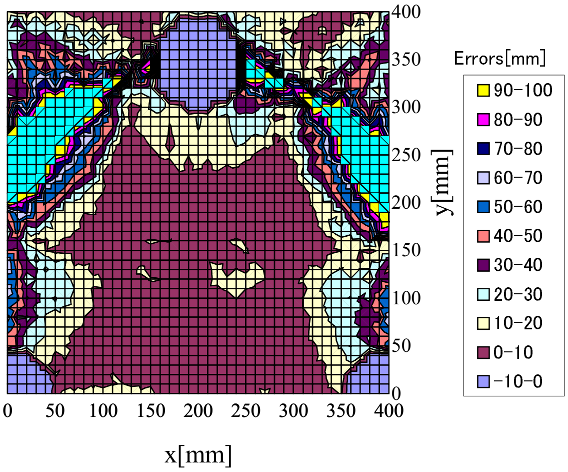


Fig14 Detection errors of location computation

In Fig.14, positioning information can be calculated to a 90% or greater accuracy in the inside of the triangle that is formed by the center of the landmarks. Outside this triangle, there are places where it is possible to compute this information precisely, and places where it is impossible.

The simulation of localization is useful for expanding the working area of mobile robots that perform team operations. When the number of robots that join in the team operations increase, the robot moves to the location that can be computed precisely, in order to expand the working area. When the robot moves to this area, the positioning information is prepared in advance. The predicted value of AOA can be calculated from the simulation of positioning information. The robot tunes the location based on the AOA of both the detected value and the predicted value.

5.Conclusions and future works

The aim of this paper was to propose and discuss the details of an infrared communication system, which could be used for mobile robots. The communication system has been designed and being developed in order to help with the team operations of mobile robots in hazardous environments. The communication system performs not only to exchange information but also to compute mutual positioning information.

Many experiments were conducted on this communication system, for example an experiment to detect the angle of arrival (AOA). This experiment was successful and showed that the communication system is able to detect AOA precisely.

The result of the reception angle restriction experiment proved the feasibility of the parallel transmission in different directions and the space-division wireless communication. As the communication system can detect the AOA accurately, the robots can geometrically select among themselves an arbiter that is the temporary local controller. Since the reception angle of the receiver is restricted, the communication system on the arbiter will suffer from hardly any interference and communicate infallibly.

The simulation of the localization showed that the communication system is able to compute the positioning information to a 90% or great accuracy. These experimental results showed that the function integration of the inter-robot communication and mutual localization was successfully.

For a future project, we plan to utilize the proposed mutual localization capability for the sensor fusion based autonomous navigation systems by using internal and external sensors.

Acknowledgment

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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.

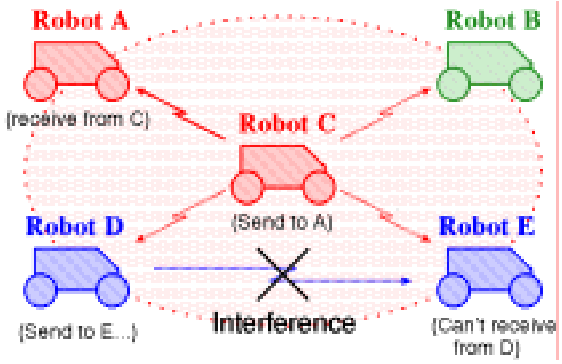


Fig. 1. Example of communication interference.

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.

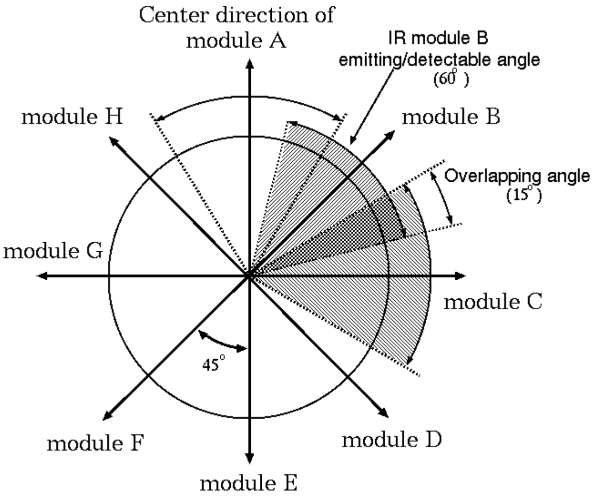


Fig. 2. Arrangement of the transceivers.

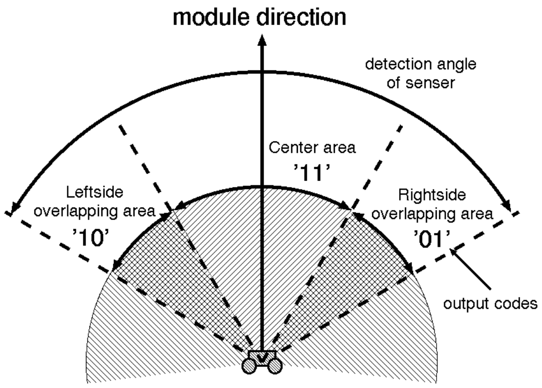


Fig. 3. Direction code for tracking.

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.

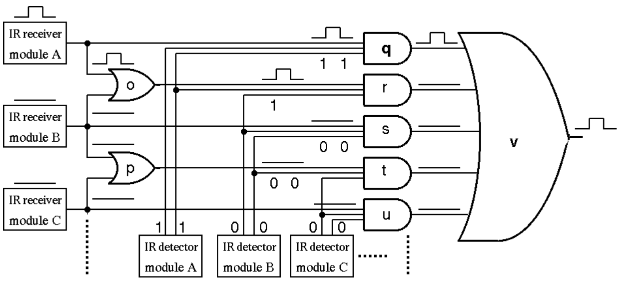
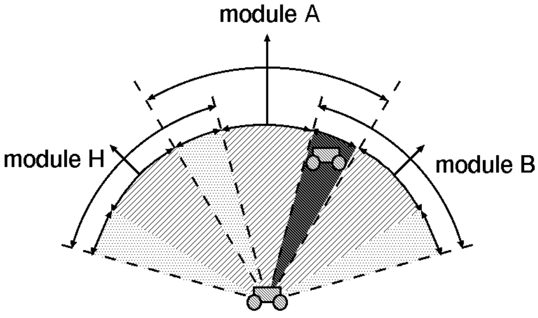


Fig. 4. The module exchange circuit.

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.

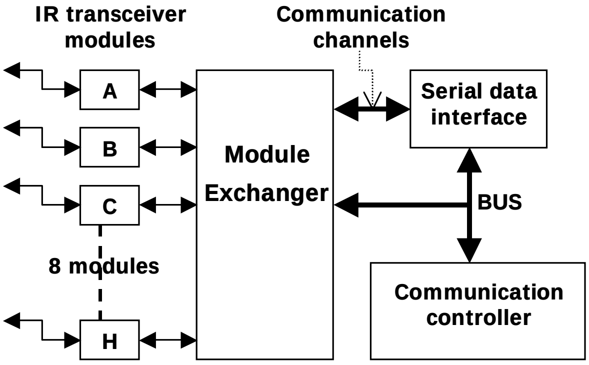


Fig. 6. Configuration of the communication system.

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.

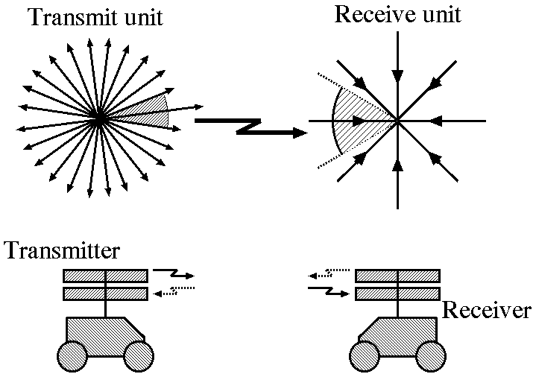


Fig. 7. Schematic of the transmitter and receiver.

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.

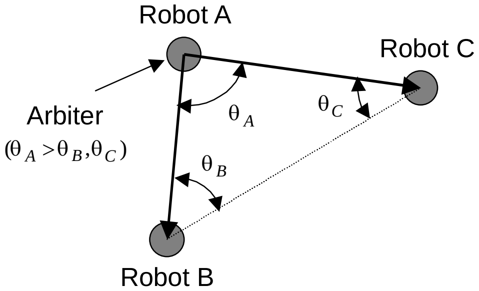


Fig. 8. The selection of the arbiter.

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.

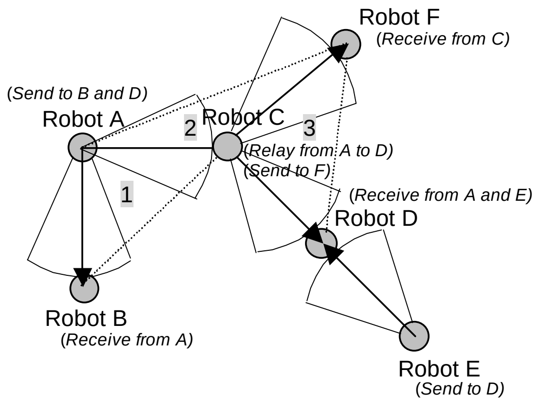


Fig. 9. Construction of communication network.

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).

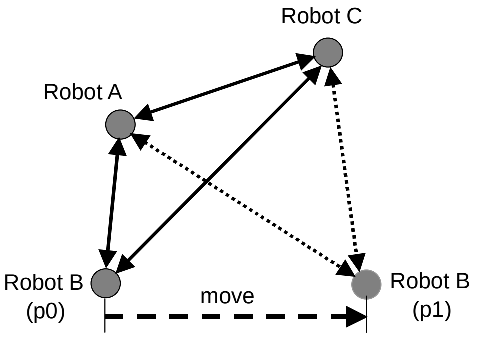


Fig. 10. Triangulation ranging using transceivers. (p0,p1:positions of Robot B)

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).

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

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.

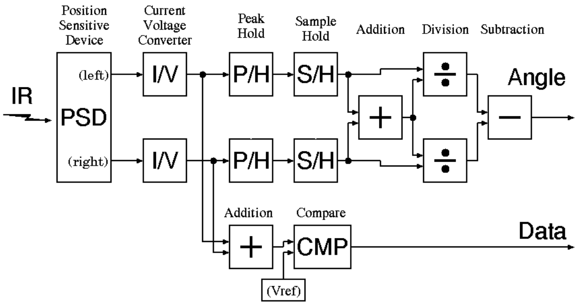


Fig. 11. Block diagram of analog computing circuit.

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 μs.

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.

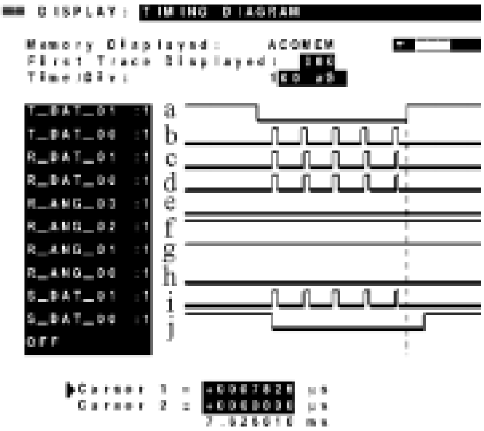


Fig. 12. Experimental result of module exchange.

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 μs, 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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