空間光通信を用いた複数移動ロボットの共同作業のための相対的な作業空間地図の作成

(課題番号：17500118)

平成１７年度～平成１８年度科学研究費補助金（基盤研究(C)(２))
研究成果報告書

平成１９年５月

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はしがき

本冊子は、平成１７年度〜平成１８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「空間光通信を用いた複数移動ロボットの共同作業のための相対的な作業空間地図の作成」(課題番号：17500118)の研究成果報告書である。この研究の目的は、先に開発した光入射角度を検出できる空間光通信システムを移動ロボット間の通信に用い、それらのロボットが協同作業を行うとき、相手の移動ロボットを可動式灯台と見立てて相互に相対的な位置を求め、各ロボットの周囲の障害物の位置を相互に伝え合い作業空間の地図を作成する方法を開発することであった。

本研究ではまず、先の研究結果を基に光通信の通信信号をビーコンに見立て、信号の到来方向を検出し複数の移動ロボット間で相対的な位置を求める方法を研究した。相互の位置を三角測量の要領で導出するには、二辺と狭角（二つの辺とその間に挟まる角）または、二角と狭辺（二つの角とその間に挟まる辺）を検知する必要がある。本研究ではそれぞれのロボットで検出した光信号の到来角度と光信号に同期した超音波ソナーパルスの到達時間から、それらロボットが共に検出した仮基準点に対する二角と狭辺を求め、作業空間中の仮基準点に対する各ロボットの位置を求めるアルゴリズムを開発した。当初、移動ロボット相互の情報交換を空間光通信で行うことを計画していたが、データ伝送速度を上げるに従って誤り率が上昇し、当初の検討した光通信と信号到来角度の検出を両立するには誤り検出訂正符号の重畳など光通信方式を見直す必要があることが明らかとなった。そこで我われは実験方法の一部を変更し、光通信をロボット位置発信ビーコンとして用い、データ伝送には無線ＬＡＮを用いて研究を進めた。

また、レーザ扇状光(スリット・レーザ光)と超音波ソナーを用い、作業空間中の壁や柱のコーナ・エッジを仮基準点として検出する方法を検討した。レーザ扇状光は平面では直線に、コーナ・エッジでは折れ線の像を結ぶ。超音波ソナーは、平面あるいはコーナに向くとき強く反射信号が戻る。レーザ扇状光の結ぶ像や超音波ソナーの反射信号から作業空間中の壁や柱が作るコーナの距離・方向を検出し、それらの中で周囲のロボットから見つけやすい空間的な特徴を持つコーナを作業空間の仮基準点に決めるアルゴリズムを開発した。

移動ロボット相互の情報共有方式として Web Service を用いる方法を検討した。デプロイした WSDL を無線 LAN 経由で相手側から読み込み、プログラムを通じた情報交換手法を確認した。

研究途中で実験方法の一部を変更したため、当初の目的である複数の移動ロボットにセンサや光通信システムを搭載し、作業空間地図を完成させるには時間的な不足を生じて、計画の完遂には到らなかったが、光通信システムによるデータ伝送を除き、複数ロボットの相対的な位置検出や作業空間中の仮基準点の検出、情報共有方式の確認など、複数移動ロボットによる作業空間地図作成の基礎となる重要な考案を得ることができ、有意義な研究であった。

研究組織

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交付決定額(配分額)　　　　　　　　　　　　　　　　　(金額単位：千円)

	直接経費	間接経費	合　計
平成１７年度	1,700	0	1,700
平成１８年度	1,800	0	1,800
総　計	3,500	0	3,500

研究発表

（１） 学術誌等
なし

（２） 口頭発表

[1] H. TAKAI, G. YASUDA and K. TACHIBANA: ”Short-range Infrared Wireless Communication System for Multi-mobile Robot Team Operations”, Proceedings of The 13th IASTED International Conference on Robotics and Applications (RA2007), ID: 563-069, August 2007, (Wurzburg) Germany
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（３） 出版物
なし

研究成果による工業所有権の出願・取得
なし

研究の目的

近年、複数の知能ロボットにおける分散型知能と共同作業に関する研究が注目されている。これらのロボットは、複雑かつ不安定な周囲環境に対応可能と考えられ、災害時の被災者捜索や原子炉の保守作業など広範で多岐にわたる活動が期待されている。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お互いに協調を図り、衝突やセンサの干渉を避け、それぞれのタスクが円滑に遂行できるようお互いの作業手順などの情報を共有しなければならない。本研究では、複数の移動ロボットが同じ作業空間にあるとき、お互いにそれぞれの位置や障害物の位置情報を共有する方法を研究した。

我々は、共同作業にあたる複数の移動ロボットは、互いに近距離に位置する場合が多いと考え、研究代表者：高井博之は平成１３年度から平成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、移動ロボットの近距離相互通信を主目的とした光無線通信システムの開発に取り組んだ。この研究では、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、全方向の受信ができると同時に、相手の方向角度も検知できる空間光通信システムを開発した。さらに、平成１５年度から平成１６年度の２年間、科学研究費補助金(基盤研究(Ｃ)(一般))「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)を得て、赤外線の指向性直進性を利用して幾何学的な干渉抑制手法を研究した。また同期間、科学研究費補助金(基盤研究(Ｃ)(一般))「移動ロボット相互の空間光通信を用いた相対的位置の同定と位置情報の共有」(課題番号：15500119・研究代表者：橘　啓八郎)では、先に開発した空間光通信システムの光入射角検出機能を用いた複数の移動ロボットの相互位置同定アルゴリズムを開発した。

本研究はこれまでの研究成果を応用し、超音波ソナーやイメージセンサを用いて各ロボットの周囲の障害物位置情報を検出し、障害物位置情報を複数のロボット間で共有して共通作業空間地図を作成するアルゴリズムの開発を予定していた。一般に移動ロボットの内部で扱う位置情報は、各ロボットで基準点の位置や座標軸の向きが異なり、共通する基準点と基準座標軸に基づく座標変換を必要とする。この研究では、隣接する複数の移動ロボットが互いに仮基準点となり、レーザ扇状光などを補助光源に使用してそれらの周囲の特徴地形を検出し、それぞれのロボットの配置と検出した特徴地形の位置からロボット間で共通する基準点と基準座標軸を求め、ロボット間に共通する作業空間地図を作成することを考えた。この研究の主たる目的は、(1)人為的な基準点の位置情報に因らない自己位置同定アルゴリズムの開発と、(2)複数ロボット間で相対的な位置情報を共有する情報統合アルゴリズムの開発である。

研究の内容

この研究では、複数の移動ロボットが同じ作業空間で共同作業するための共通作業空間地図を作成するアルゴリズムの開発を考えていた。複数ロボット間の共通作業空間地図の作成に当たって２つのアルゴリズム、(1)人為的な基準点の位置情報に因らない自己位置同定のアルゴリズムと、(2)複数ロボット間で相対的な位置情報を共有する情報統合のアルゴリズム、を開発する必要があった。移動ロボットの位置同定では一般的に三角測量が用いられる。三角測量は、二辺と狭角（二つの辺とその間に挟まる角）または、二角と狭辺（二つの角とその間に挟まる辺）を検知する必要があり、それぞれの間の距離と角度が正確に求まらなければ正確な相対位置は計算できない。移動ロボットの作業空間には必ずしも人為的な基準点があらかじめ用意されているとは限らないので、ロボットに搭載したセンサを用いて作業空間中の特徴的な地形を見つけ基準点を決めなければ、障害物などの位置を一意に決めることができず作業空間地図は作成できない。

この研究では当初、平成１７年度から平成１８年度の２年間の研究期間中に、

１）空間光通信システムの通信性能の向上

２）センサ情報の統合・融合による特徴地形検出アルゴリズムの開発

３）アドホックなロボットチームにおける情報共有手法の検討

を行った。これらの実験の方法と結果について述べる。

実験の方法と結果

１．空間光通信システムの通信性能の向上

本研究で開発する空間光通信システムは、高速なデータ送受信と光入射角検出の両立を目指している。目的の実現方法として、受光素子にＰＳＤ（ Position Sensitive Device：フォトダイオード光入射角センサ）を用いた通信回路方式について研究した。光通信受信信号と光入射角検出を両立する受信機回路のブロック図を図１に示す。

この実験に用いたＰＳＤフォトダイオード(浜松ホトニクスS6560)は２つの電流出力端子を持ち、それらの出力電流比から光入射角を算出する。高速なデータ送受信のため、ＶＨＦ受信機用ＭＯＳ‐ＦＥＴ(東芝 2SK241)を用いて受信信号増幅回路を構成した。受信信号から背景光成分を除くため、ＰＳＤの出力に送信データ速度に合わせたハイパス・フィルタを付け、高周波交流信号のみを増幅した。受信信号の低周波成分除去に伴う信号の変形を補正して、デジタル信号を取り出すため、２種類の閾値判別回路について実験した。図２に閾

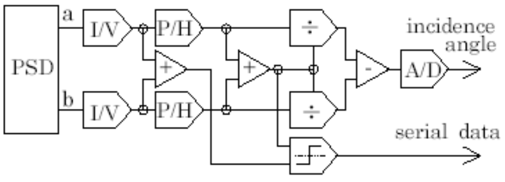
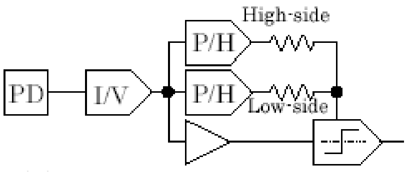
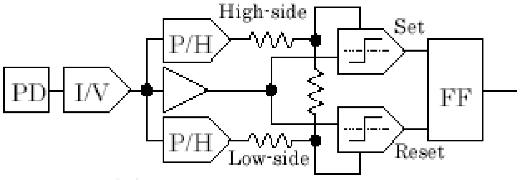


図１　受信機回路ブロック図

値判別回路を示す。(a)は受信信号の中央値を閾値とする回路、(b)は受信信号の最大値・最小値の間を三等分し信号の立ち上がり・立ち下りで閾値を変えるヒステリシスを持たせた閾値判別回路である。ピークホールド・オペアンプに LM6363(National Semiconductor)、閾値判別コンパレータに LM319(STMicroElectronics)を用いた。



(A) a median value threshold



(B) a hysteresis threshold

図２　閾値判別回路

通信方式にＮＲＺＩ符号化したＨＤＬＣを用い、伝送速度を 9.6kbps～307.2kbps、通信距離を 20cm～150cm の間で変えてデータ伝送実験を行った。中央値による閾値判別では、9.6kbps～307.2kbps すべての通信速度で受信可能であったが、増幅回路のハイパス・フィルタの影響で受信信号の歪が大きく、遅い通信速度ではより顕著となる。一方、ヒステリシス閾値判別ではより小さな信号でも判別できる反面、信号歪の影響を受けやすいことが判る。

表 1(a) 中央値閾値判別実験結果

通信速度 [kbps]	最大通信距離 [cm]	最小振幅 [V]
9.6	30	4.64
19.2	35	3.68
38.4	45	2.31
76.8	80	0.816
153.6	95	0.556
307.2	95	0.546

表１(b)　ヒステリシス閾値判別実験結果

通信速度 [kbps]	最大通信距離 [cm]	最小振幅 [V]
153.6	125	0.272
307.2	150	0.180

今回のこの実験はすべてアナログ回路で実現した。近年は変換速度の速い A/D コンバータを内蔵したワンチップ・マイクロコントローラ等が実用化されているので、それらを閾値決定に用いればより正確な信号復元に役立つだろう。今後、誤りに強い符号を使用し、受信信号の増幅率を自動調整する回路の組み込みによる、より高速で長距離の通信の実現について研究する。

２．特徴地形検出アルゴリズムの開発

一般の移動ロボットは、それぞれ独自の座標系で障害物を検出し軌道生成を行うので、複数の移動ロボットが相互に位置情報を共有するためには、ロボット内部の位置情報を共通の座標系に変換する必要がある。移動ロボットは、人為的な基準点の設置されていない未知の環境で作業する場合も多く、ロボットに搭載したセンサの情報を頼りに共通座標系を獲得し、位置同定する手法が必要である。我々は、共同作業する各ロボットはお互いに近い場所で作業していると考え、局所的な作業空間の相対的な位置情報があれば、十分に共同作業タスクを達成できると考えた。そこで、理想的な小空間において複数のロボットが特徴地形を仮基準点として検出し作業空間地図を作成するアルゴリズムを開発した。

一般的な移動ロボットには、障害物を検出し衝突を回避するため、超音波ソナーや TV カメラなどのセンサを搭載している。そこで本研究では、理想的な屋内作業空間を想定し、

ⅰ)超音波センサの測距能力の向上
ⅱ)TV カメラを用いた障害物の距離・方位検出
ⅲ)センサ情報の統合・融合による地図作成

について検討した。ここでは一般的な屋内の壁や柱で形成された“ コーナ ”や“ エッジ ”を作業空間中の特徴地形として検出する方法を検討した。

ⅰ）超音波センサの測距能力の向上

移動ロボットに搭載されるセンサは、小型軽量で低消費電力なものが望まれる。超音波センサは小型で構造が簡単なため、多くの移動ロボットに搭載されている。超音波センサは、その信号処理回路によって測距精度が左右される。精密な測距を実現するために超音波の周波数に合わせて受信反射波を同調増幅し、デジタル信号処理のためにサンプリングした。デジタル化した受信信号波から最大振幅時刻を求め、最小二乗法を用い受信信号の時間を遡って回帰直線 p と q を求め、その交点から推定される超音波発射からの時間 t から障害物の距離を計算する。図３に最小二乗法を用いた障害物の距離推定法の原理を、表 1 に従来の測距法と提案手法の比較を示す。実験の結果、提案手法は理想的な環境下で１％～２％程度の誤差で測距できることが示された。

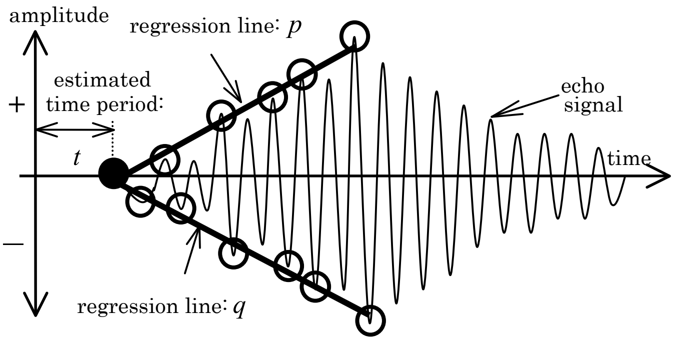


図３　最小二乗法による障害物の距離推定法

表１　障害物距離計測方式の比較

Method	Conventional			Proposed		
Horn	W/O	MIC	Speaker	W/O	MIC	Speaker
Detecting value	1372	1387	1382	1287	1294	1294
Error	72	87	82	-13	-6	-6
Deviation	1.58	0.84	0.75	0.90	0.11	0.11

Length: mm　　Target distance: 1300, Horn length: 50

ⅱ)TV カメラを用いた障害物の距離・方位検出

遠隔制御される移動ロボットには、作業空間の状態や作業の進捗状況を確認するためＴＶカメラが搭載されることが多い。本研究では、この移動ロボットに搭載されたＴＶカメラを用い、作業空間中の特徴地形検出を試みた。近年、半導体の高集積化が進み、さらに精密なプラスチック・レンズ、大出力半導体レーザ光源が実用化された。本研究ではこれらの素子を用い、屋内の壁や柱が作る“ コーナ ”や“ エッジ ”検出を実験した。

レーザ光を円筒形レンズを通して集光することで、光が扇状に広がり空間中に線を引く、小電力ライン・ジェネレータが実用化されている。このレーザ扇状光が対象物に当たって

できるレーザ照射面像から対象物の凹凸、即ち、作業空間中の“コーナ”や“エッジ”を検出する。図４にレーザ照射面画像のモデルを示す。強いレーザ光は視覚に対し有害なので、レーザの発光時間をＴＶカメラの数フレーム時間(約 30 分の数秒)に制限する。フレーム間差分画像からレーザ照射面画像を切り出し、“コーナ”や“エッジ”の頂点を検出する方法を検討した。ＴＶカメラ・パラメータの、レンズの明るさと撮像素子の感度によって角度検出能力が、レンズの画角と撮像素子の密度によって角度検出精度が決まる。ライン・ジェネレータとＴＶカメラを用いた、画像処理による特徴地形検出の実験を行い、意図通りの実験結果を得た。

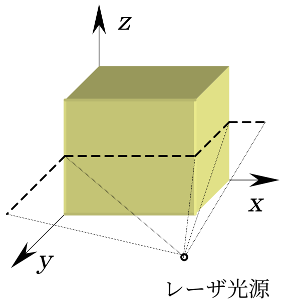


図４　レーザ照射面画像

iii)センサ情報の統合・融合による地図作成

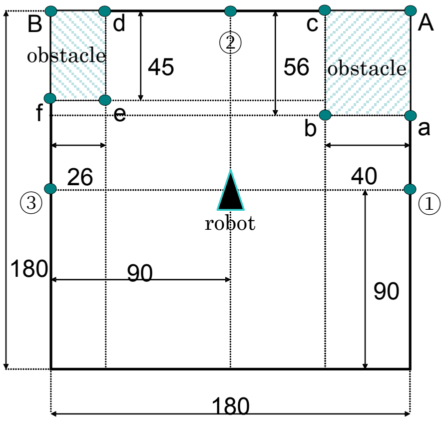


図５　実験用小空間

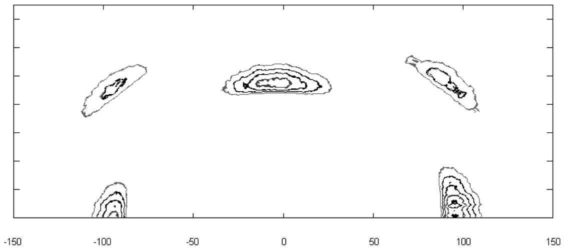
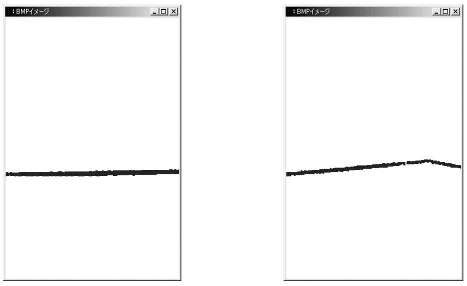


図６ 超音波ソナーによる障害物検出

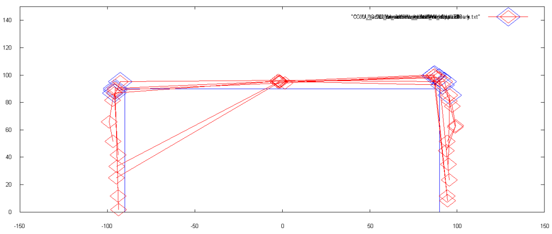


(a)平面　　(b)コーナ

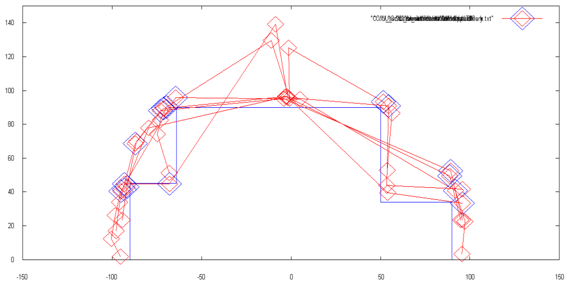
図７ イメージセンサによる特徴地形検出

先の超音波センサの測距能力向上の研究成果と TV カメラを用いた障害物の距離・方位検出の研究成果をもとに、センサ情報の統合・融合による地図作成について研究した。地図作成実験のため、図５のように 180cm×45cm×1.5cm の合板で実験用小空間をつくり、直動ステージと回転ステージで構成した移動ロボット・モーションシミュレータに超音波ソナー、TV カメラ、レーザ・ラインジェネレータを取り付ける。実験用小空間の中央から②の方向にセンサを回転させながら移動して、壁や障害物の方向・距離を検出し小空間の地図を作成した。図６に超音波ソナーによる障害物検出結果を、図７にイメージセンサによる特徴地形検出結果をそれぞれ示す。超音波ソナーの反射信号は正対する平面または、コーナからの反射が強い。イメージセンサによる特徴検出では、コーナ・エッジは線の凹凸として現れる。これらの計測結果を集約し、作業空間地図を作成する。図８にセンサ情報にもとづく作業空間地図

を示す。今後、それぞれのセンサの検出精度を高めると同時に、基準点候補の選別アルゴリズムなどの充実を図る。



(a)障害物がない場合



(b)障害物がある場合

図８　センサ情報にもとづく作業空間地図

３．アドホックなロボットチームにおける情報共有手法の検討

本研究は複数の移動ロボットによる共同作業の研究である。それぞれのロボットはそれぞれのタスクを円滑に処理するために、その場その場で周囲のロボットと共同するアドホックなチームを作る必要がある。本研究ではこのようなアドホックなロボットチームにおける情報共有手法について研究した。従来、遠隔地のコンピュータ操作には RPC (Remote Procedure Call)などが用いられてきたが、操作する側・操作される側両方のコンピュータをあらかじめ指定する必要があり、その場その場でチームを作るアドホックな使い方には向いていない。このほかのコンピュータ間の情報共有手法には、オブジェクト指向を取り入れた CORBA(Common Object Request Broker Architecture)や Web Service が実用化されている。本研究ではヒトによる操作・介入を想定し、Web ブラウザを通じて情報を確認することのできる Web Service を用いて移動ロボットの遠隔操作を行った。Web Service では、XML (Extensible Markup Language) を拡張した WSDL(Web Service Description Language) を用い、Web Service サーバを移動ロボット上に立ち上げ、WSDL を通じて移動ロボットの制御インタフェースを受け取り、移動ロボットを制御した。WSDL の記載を通じて、移動ロボットの機能・性能の読み出しやリソースの把握、センサ情報共有方法などを確認した。

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.

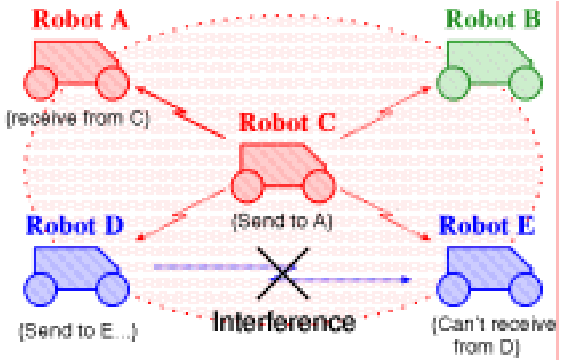


Fig. 1. Example of communication interference.

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.

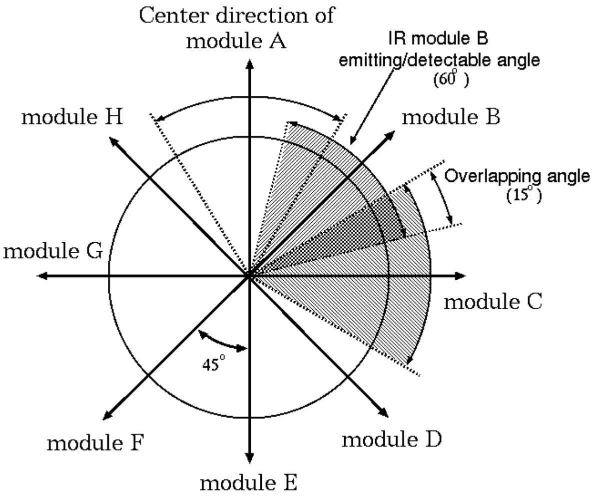


Fig. 2. Arrangement of the transceivers.

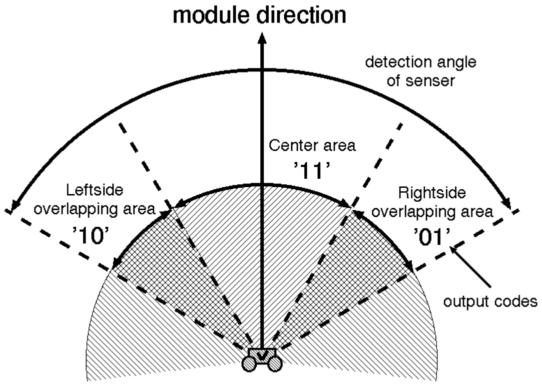


Fig. 3. Direction code for tracking.

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.

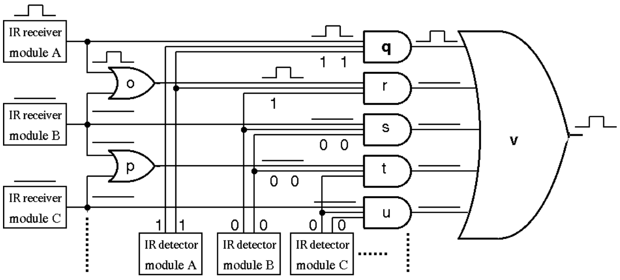
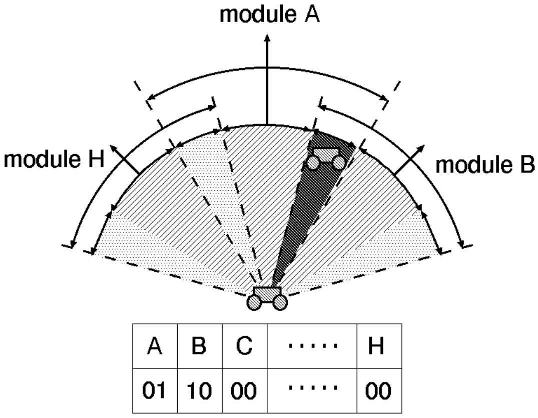


Fig. 4. The module exchange circuit.

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.

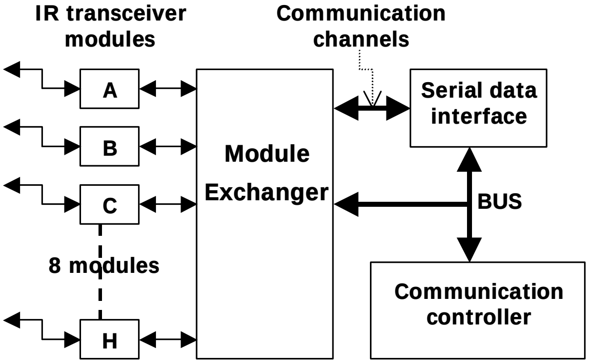


Fig. 6. Configuration of the communication system.

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.

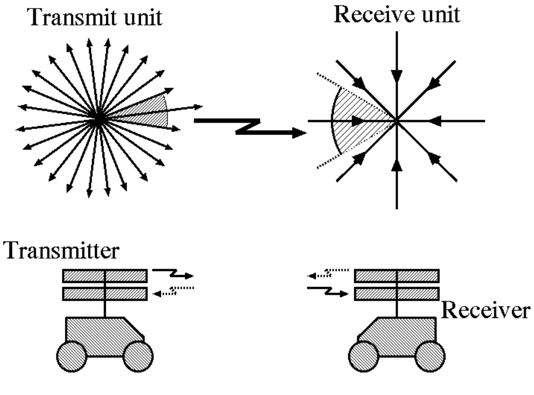


Fig. 7. Schematic of the transmitter and receiver.

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.

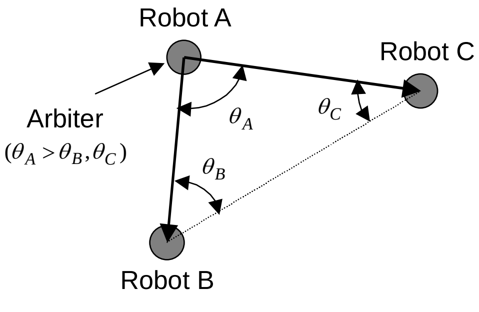


Fig. 8. The selection of the arbiter.

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.

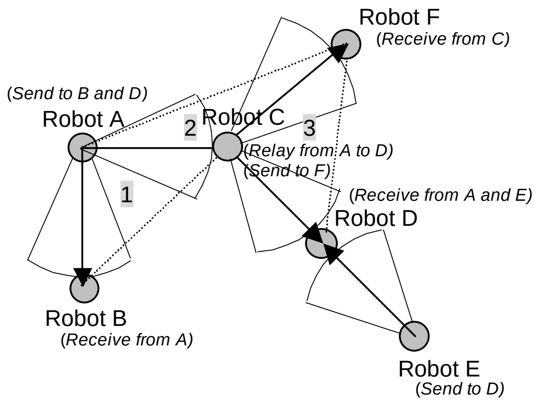


Fig. 9. Construction of communication network.

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).

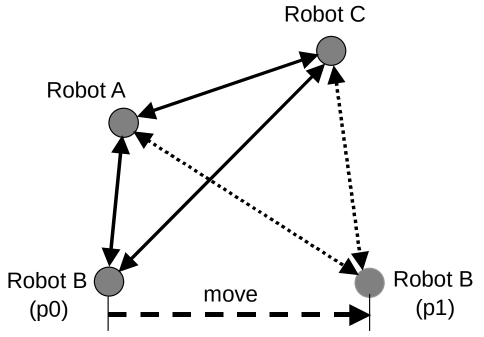


Fig. 10. Triangulation ranging using transceivers. (p0,p1:positions of Robot B)

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.

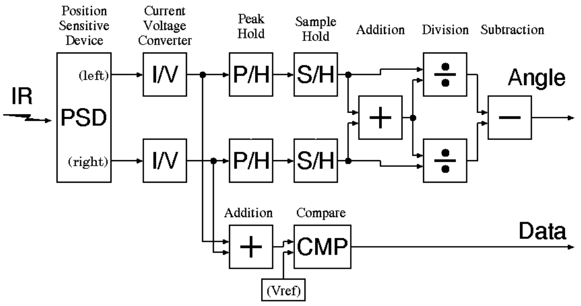


Fig. 11. Block diagram of analog computing circuit.

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.

ACKNOWLEDGMENT

This work is supported, in part, by Japan Society for the Promotion of Science Grant-in-Aid for Encouragement of Young Scientist (No.13750365), and, in part, by Hiroshima City University Grant for Special Academic Research (Encouragement for Researchers No.0087 and Support for Researchers No.1611).

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The Eleventh International Symposium on Artificial Life and Robotics 2006 (AROB 11th'06),
B-con Plaza, Beppu, Oita, Japan, January 23-25, 2006

Implementation of infrared wireless communication system for multi-mobile robots' team operations

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Abstract

Recently, mobile robots' team operation has been proposed as one of the effective solutions that enable the execution of complicated tasks [1]. These robots that join team operations need to communicate mutually for smooth task execution. Although radio waves are usually used for mobile robot's remote control or communication of mobile computer terminals, one drawback is that they spread out signals omni-directionally that can cause communication interference.

We have proposed an infrared wireless communication system that can detect angle of arrival (AOA) of infrared signals from communicating partners for mobile robots' team operations. Infrared rays have strong directivity and limited beam width. They are advantageous to communicate between adjacent robots, since they can decrease communication interference. Signal intensity decreases with the square of the communicating distance. Also the reception capability is in inverse proportion to the data transmission rate. Transmission efficiency and reception capability are also restricted by the performance of the circuit elements such as infrared LEDs and photo diodes.

A position sensitive device (PSD) PIN photo diode (HAMAMATSU S6560) that can detect incidence angle of infrared rays is used as the reception device of this infrared wireless communication system. This PSD has 2 current output electrodes and these ratios show the incidence angle. We implemented communication signal amplifiers and threshold decision mechanisms that can restore digital pulse signals from received analog signals. These electronic circuits were tested and successful results were obtained.

1. Introduction

In recent years, multiple mobile robots that can perform team operations have been developed. These robots are used for SAR (search and rescue) operation, surveillance, patrol and so on. When the number of robots increases in the same workspace to accomplish their tasks, they will often collide or interfere with adjacent robots. Therefore, they need to communicate to decrease their collisions in order to achieve their tasks smoothly. Radio waves or infrared rays are used as carriers in inter-robot communication.

Usually, radio waves are used for mobile robots' remote control or communication of mobile computer terminals. However, radio waves spread out signals omni-directionally and cause communication interference that is known in wireless communication as "the hidden terminal problem" or "the exposed terminal problem". This signal interference can be decreased using directional communication mediums such as infrared rays or millimeter waves.

Infrared rays have strong directivity and limited beam width. Moreover, infrared rays can be used in circuits easier than millimeter waves. However, infrared wireless communication often loses communication links when mobile robots move or rotate. In order to execute tasks smoothly, we have designed an infrared wireless communication system that can maintain their communication links by tracking the partner robot. This communication system communicates with partner robots and simultaneously detects an incidence angle of infrared rays that points to the partner's direction using PSDs in order to track the partner.

In this system, several transceivers used PSDs as reception devices are put on the circumference of the robot body and faced outwards. These transceivers detect angle of arrival (AOA) of the communication signals in order to maintain communication links by switching to adjacent transceivers that face communicating partners.

Infrared signal intensity decreases with the square of the distance between the communicating partners. Also the reception capability is in inverse proportion to the data transmission rate. We designed amplifiers and threshold decision mechanisms that can restore digital pulse signals from received infrared signals.

This paper describes the design and implementation of the infrared wireless inter-robot communication system.

2. Basic design of the infrared wireless inter-robot communication system

Infrared rays have strong directivity and limited beam width. Although it can eliminate communication interference, usual infrared wireless communication often loses communication links when mobile robots move or rotate. We have designed an infrared wireless communication system that can maintain communication links. The communication system is formed by several infrared transceivers that are put on the circumference of the robot body and faced outwards. Figure 1 shows the arrangement of the transceivers.

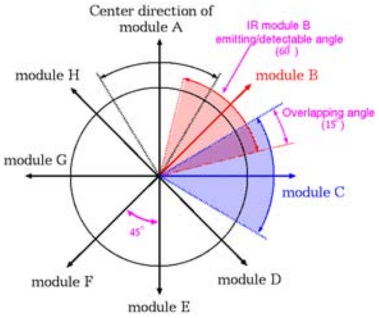


Fig. 1 Arrangement of transceivers

In this system, these transceivers used PSD photo diodes that can detect incidence angle of infrared rays as reception devices. The incidence angle of infrared rays is used in order to find the partner's direction.

The PSD photo diodes (HAMAMATSU S6560) that are reception devices have 2 current output electrodes and these ratios show the incidence angle. Figure 2 shows a schematic view of this PSD.

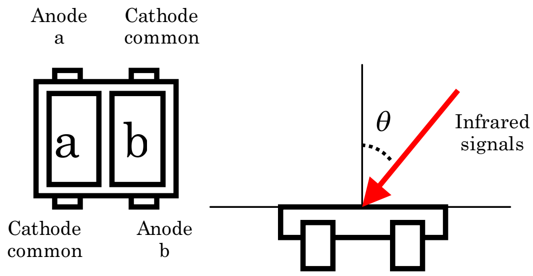


Fig.2 A schematic view of the PSD

The electric current output 'a' and 'b' of the PSD has the relations of the equation 1 with the incidence angle of the infrared signals θ.

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

The electric current output 'a' and 'b' of the PSD are feeble analog signals that need amplification. Figure 3 shows a block diagram of a signal processing amplifier. In figure 3, the signal processing amplifier outputs not only a digitized incidence angle but also serial data of communication signals.

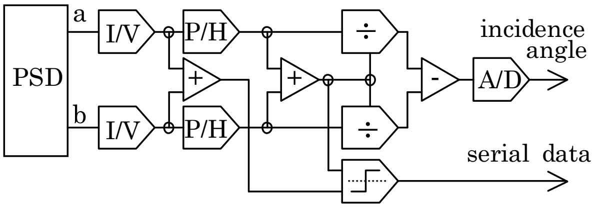


Fig. 3 Block diagram of amplifier

The detected incidence angle also encoded to the 2bit direction code in order to select transceivers that are facing to communicating partners. Figure 4 shows the direction code in an infrared transceiver.

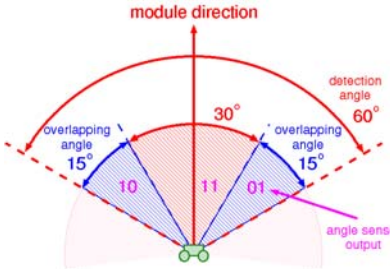


Fig. 4 The direction code and detected angle

When a partner is in the left, center, and right view of a transceiver, the partner's direction is encoded to the direction code '10', '11', and '01', respectively. When a partner moves or rotates, these transceivers detect the partner's direction in order to switch to an adjacent transceiver that is facing the partner. The direction code is used in order to maintain the communication link by switching these transceivers. Figure 5 shows transceiver exchange circuit. In figure 5, the serial data that is received by each transceiver is on the left side, and the direction code that is outputted from each transceiver is below. Since the serial data can be received from selected transceivers continuously, the infrared communication system can maintain their communication links.

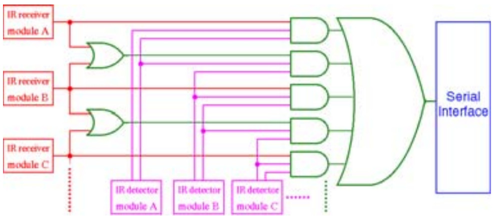


Fig. 5 Transceiver exchange circuit.

Since infrared rays have strong directivity and limited beam width, infrared communication suffers from hardly any interference, if partners are in different directions. This communication system can communicate with different partners in different directions by using different transceivers simultaneously. As a result, space-division communication can take place. When each robot relays information between different partners, a communication network is created in their workspace. It is an ad hoc communication network because each robot is independently mobile and may change position depending on their task. Figure 6 shows an inter-robot communication network.

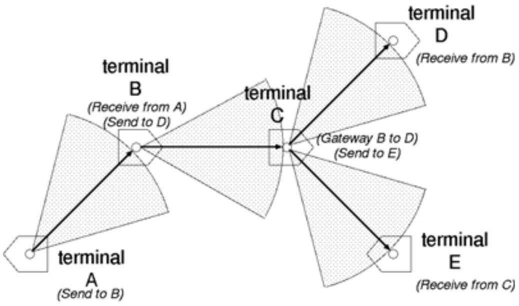


Fig. 6 An inter-robot communication network

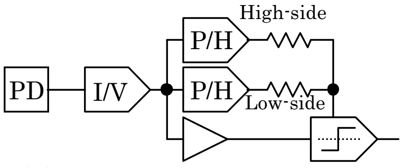
3. Feasibility study of the infrared wireless communication system

As previously mentioned, the infrared wireless communication system is able to adapt for the inter-robot communication, if its mechanism is designed appropriately. However, infrared signal intensity decreases with the square of the distance from the transmitter to the receiver. Also the communication capability is in inverse proportion to the data transmission rate. We studied the performance of the inter-robot communication system.

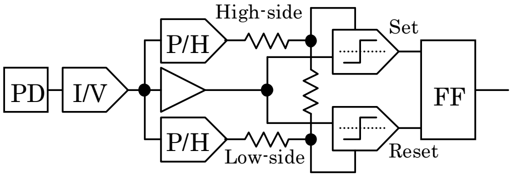
In order to operate multiple mobile robots that perform team operations such as SAR operation or surveillance by remote control smoothly, the inter-robot communication system needs high-speed data transmission. The communication system has to send not only its positional information but also gathered information such as compressed video images, direction of thermal sources, gas concentration data and so on. We determined 384 kbps as a data transmission speed of the communication system in order to design the circuit, because it is similar to the speed used for the uplink from mobile phone terminals of walking users that transmit compressed QVGA video images.

We implemented an infrared transmitter, two types of infrared receivers and two types of threshold decision circuits for feasibility study of this communication system. The infrared transmitter uses two infrared-LEDs (STANLEY DNF324U, 850nm) driven by 2SA1300 transistor. One of the infrared receivers uses a PSD (HAMAMATSU S6560, 960nm) that can detect an incidence angle of infrared rays. Another one uses a photo diode (TOSHIBA TPS703, 960nm) that has similar capabilities to the S6560 (except its angle detection) in order to test the design of amplifiers.

Two threshold decision circuits that restore serial data from received infrared pulse signals were tested. Figure 7 shows the threshold decision circuits. In figure 7, the circuit (A) calculates the median value of high side peak and low side peak as threshold voltage. Also in the circuit (B), the difference between high side peak and low side peak is divided into three in order to give hysteresis effects.



(A) a median value threshold



(B) a hysteresis threshold

Fig. 7 Threshold decision mechanisms

The infrared receiver that uses TPS703 photo diode and is connected to MOSFET (2SK241) amplifiers was used for the test. In the test, the receiver detected infrared signals of 460kbps from the infrared transmitter in 1m distances and outputted 400mVpp approximately.

In this test, the threshold decision circuits were possible to recover to digital pulse from the received signal voltage of 100mVpp, and it was also possible to receive signals up to 460kbps. However, when the outputted signals of the infrared receiver were less than 400mVpp, the wrong serial data was received because errors were included in the digital pulse sequence. At a slow transmission speed, these circuits were impossible to recover to the correct digital signals, because the threshold value is changed by the electric discharge of peak-hold capacitors.

Conclusion

We proposed and designed an infrared wireless communication system that is suitable for multiple mobile robots. We also implemented an infrared transmitter, two types of infrared receivers and two types of threshold decision circuits in order to study the feasibility of the communication system.

The infrared receivers were able to detect infrared signals of 460kbps from 1m distances and outputted 400mVpp approximately in this experiment. The threshold decision circuits were able to operate in the signal of 100mVpp 460kbps. However, when the outputted signals of the infrared receiver were less than 400mVpp, wrong serial data was received.

The photo-diode used for infrared reception detects both an infrared signal and background noise. In addition, the duty ratio of received signals influences the nonlinear character of the photo-diode, and makes amplification of signals unstable. The design of the amplifier circuit that suited the character of the photo-diode will be needed for high-speed long-distance infrared wireless communication.

Acknowledgements

This work is supported in part by Japan Society for the Promotion of Science Grant-in-Aid for Scientific Research (C) (No. 17500118).

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The Eleventh International Symposium on Artificial Life and Robotics 2006 (AROB 11th'06),
B-con Plaza, Beppu, Oita, Japan, January 23-25, 2006

Reference-position detection using fan beam laser for cooperative localization of multiple mobile robots

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Abstract

In recent years, mobile robot systems that perform team operations such as repairing industrial equipment have been researched. However, since a number of robots have to work in a small indoor workspace for cooperation, they are prone to collisions and sensor signal interference. We formed a hypothesis that their collisions were caused by the ambiguity of their positional information.

Since each robot has its own coordinate axis, they cannot compare their positional information. In order that each robot can detect the same position in the same coordinate axis correctly, they need to decide reference positions in their workspace. We considered detecting "corners / edges" which were formed by walls and pillars that are in most buildings as indoor reference positions.

In order to detect direction of "corners / edges" clearly, we propose to use the fan beam laser that can create a visual representation of the object's geometrical features. Since image sensors can capture the image of “the corner / edge”, the direction of "the tip of the corner / edge" can be detected using image processing algorithms. Because more than two robots can capture the image of “the same corner / edge” illuminated by the fan beam laser simultaneously, they can detect direction of “the tip of the corner / edge” as the direction of the reference position.

The direction detection method using a fan beam laser was proven and successful results were obtained. Each robot can acquire accurate positional information using triangulation based on detected reference position's direction and mutual localization among teammate robots.

1. Introduction

Recently, multiple autonomous mobile robots that can perform team operations have been developed. These robots are used for maintenance of nuclear reactors, repairing industrial equipment, and so on.

When the number of robots increases in the workspace for cooperative operation, they will often suffer from collisions or signal interference. One of the proposed collision avoidance methods of mobile robot teams is the exchange of their action programs through inter-robot communication. Communication signal interference known in wireless communication as "the hidden terminal problem" or "the exposed terminal problem" occurs when these robots transmit omni-directional signals simultaneously. Occurrences of these robots’ collisions or signal interference depend on their mutual location. Inaccurate positional information is one of the causes of mobile robots’ collisions or signal interference.

Accurate outdoor positional information can commonly be detected using GPS (Global Positioning System). However, indoor mobile robots cannot use GPS because they cannot receive signals from GPS satellites. In addition, since artificial landmarks also are hard to prepare for in advance in unknown workspace, accurate detection of positional information on global coordinate axis in indoor workspace is quite difficult. Therefore, we studied how to acquire the global coordinate axis among teammate robots in their workspace.

One of the proposed mutual localization methods uses teammate robots as landmarks, if these robots can detect direction and measure distance between each other. We have developed an infrared wireless communication system that can detect the angle of arrival (AOA) of communication signals from the communicating partner. Normally, an image sensor and ultrasonic sonar also have been attached to remote controlled mobile robots as embedded sensors. These robots can measure the distance to the partner based on the time difference of arrival (TDOA) of infrared communication signals and ultrasonic waves provided the communication system is used with ultrasonic sonar simultaneously. Consequently, each robot can compute it's relative location between each other by triangulation ranging based on detected direction and measured distance.

However, in order to avoid collisions with fixed obstacles and to form smooth action programs, these robots need to acquire their absolute positions in their workspace. These robots need to find out stationary reference positions used as the basis that determines their coordinate axis in their workspace to acquire their absolute positions. We considered detecting "corners / edges" which were formed by walls and pillars that are in most buildings as indoor reference positions.

Since more than two robots have to detect direction of "the same corner / edge" in order to share its positional information, we propose to use the fan beam laser that can create a visual representation of the object's geometrical features. Image sensors can capture the image of "the corner / edge" created by fan beam laser and can detects its direction as a reference position using image processing algorithms. The reference position can be calculated by triangulation ranging based on its detected direction, since each robot has computed its relative location mutually using the inter-robot communication system. These robots can exchange calculated positional information of reference positions through their inter-robot communication network. A map of their workspace also can be created from shared positional information of reference positions.

In this paper, the method of multi-robot mutual relative localization using the infrared inter-robot wireless communication system and the method of reference position detection using the fan beam laser are described.

2. Multi-robot mutual localization using inter-robot communication system

When the number of robots increases to accomplish complicated tasks in a small indoor workspace, they are prone to collisions and sensor signal interference. Occurrences of their collisions or signal interference depend on their mutual location and can be decreased by inter-robot communication using directional communication medium such as infrared rays or millimeter waves. We have designed an infrared wireless communication system for inter-robot communication.

When these robots move or rotate, usual infrared wireless communication often loses communication links owing to the directivity of infrared rays. In the system that we designed, in order to maintain communication links, several infrared transceivers are put on the circumference of the robot body and faced outwards. Figure 1 shows the arrangement of transceivers.

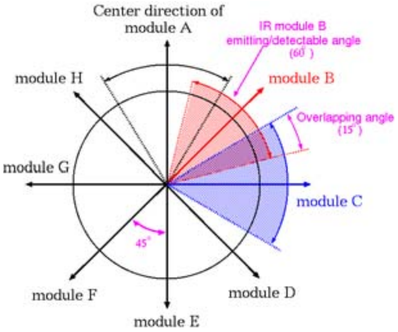

Fig.1 Arrangement of transceivers

In order to maintain a communication link by tracking the communicating partner, each transceiver receives a communication signal and the transceiver detects the AOA of the communication signal simultaneously. These transceivers are also switched to adjacent transceivers that face communicating partners when these robots move or rotate.

This communication system is able to communicate in parallel with different partners in different directions by using different transceivers simultaneously. As a result, space-division communication can take place. These robots create a communication network by relaying information among them. The created communication network is called ad hoc network, since each robot is independently mobile and may change position depending on their tasks. Figure 2 shows an inter-robot communication network.

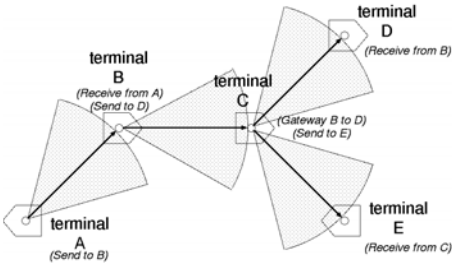

Fig.2 An inter-robot communication network

These robots can detect direction of partner robots using this infrared communication system and can also measure distance between partners using ultrasonic sonar with support of the communication system. Consequently, these robots can compute their mutual location by triangulation using information about their direction and distance.

The computation method of mutual location requires three known partners' location in the workspace. These partners' locations are arranged on coordinates from $P_1(x_1,y_1)$ to $P_3(x_3,y_3)$, and 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.

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

Parameters are computed as follows.

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

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

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

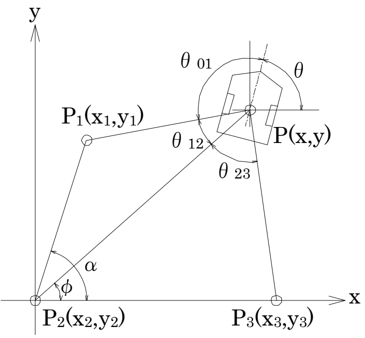

Fig 3. Localization using triangulation

Figure 3 shows mutual localization using triangulation based on the AOA of communication signals. The robot detects AOA (θ_{01}, θ_{12}, θ_{23}) of communication signals and computes coordinate P(x,y) by triangulation.

We tested this mutual localization method using PSD (Position Sensitive Device) PIN photo diode (Hamamatsu S6560) that can detect incidence angle of infrared rays as the reception devices. In an experiment of AOA detection, angle detection error is approximate 0.5 degrees and this result is able to detect an AOA precisely. The accuracy of mutual localization is approximately 90% with the true value based on the detected AOA.

3. Reference position detection using fan beam laser

Although mutual location information is extremely useful for local mutual cooperation among adjacent robots, it is not suitable for the use that needs to point to appointed positions such as stationary obstacles in their workspace. In order to point to appointed positions, these robots have to decide a global coordinate axis based on several reference positions in their workspace.

"Corners / edges" which were formed by walls and pillars can be used as indoor reference positions in most buildings, since artificial landmarks are hard to prepare for in advance in unknown workspace. The fan beam laser that can create a visual representation of the object's geometrical features is suitable for detection of "corners / edges". Figure 4 shows a model of "corner / edge" detection using fan beam laser.

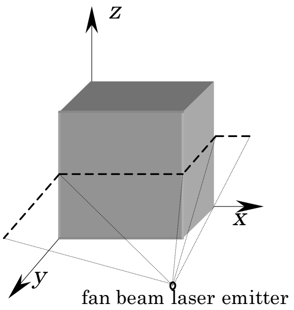

Fig 4. A model of "corner / edge" detection

We probed the feasibility of the "corners / edges" detection method using fan beam laser with experiments. The laser emitter (Coherent, LVM3 Laser-line micro 670nm 2.5mW 60deg) and the image sensor (RF system Lab, PRO-5 2CCD color wireless TV camera with lens) were used in experiments. The laser emitter and the image sensor were attached to a motorized turntable (SIGMA KOKI, SGSP-160YAW) horizontally at a 10cm interval vertically. The image sensor can capture 320 (horizontally)×480(vertically) pixel images and its horizontal view angle is approximately 23 degrees. We also measured angle detection error of this image sensor using a captured image. The angle detection error is approximately 1.5 degrees.

We also examined the positional detection method based on the "corners / edges" detection. A motorized X-Y axis linear stage pair (SIGMA KOKI, SGSP46-500(X) and SGSP65-1200(X)) was used for a simulation of a mobile robot that moves around an obstacle of cuboid set on the flat floor. The turntable in which the laser emitter and the image sensor were attached was put on the X-Y axis linear stage pair. The robot moved from $P_1(x_1,y_1)$ to $P_6(x_6,y_6)$and the position of the cuboid's edge $P_a(x_a,y_a)$, $P_b(x_b,y_b)$ and $P_c(x_c,y_c)$ were measured. Figure 5 shows experiment environment with an obstacle. Table 1 shows results of this experiment. In the table 1, “x” and “y” are arrangement coordinates. Detected angle θ and ϕ are shown in “angle”, “x’” and ”y’” are results of triangulation. The detection errors are less than 3% in this experiment.

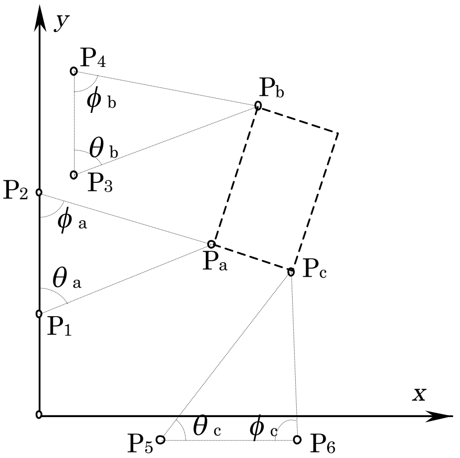

Fig. 5 Experiment environment

Table 1 Results of triangulation

	x	y	angle	x’	y’	reference
P_a	50	50				
P_1	0	30	68.8	49.8	51.0	
P_2	0	65	73.4	49.8	51.0	
P_b	63.5	90				
P_3	10	70	70.4	63.3	89.0	
P_4	10	100	78.3	63.3	89.0	
P_c	72	43				
P_5	35	-7.5	54.8	71.5	44.2	
P_6	75	-7.5	86.1	71.5	44.2	

Length: cm, Angle: deg

Conclusion

We proposed cooperative localization methods using inter-robot communication and fan beam laser. Also we examined the positioning method and successful results were obtained. In this method, accurate reference positions were detected.

If this method is used effectively, the global coordinate axis of the robots' workspace will be acquired.

Acknowledgements

This work is supported in part by Japan Society for the Promotion of Science Grant-in-Aid for Scientific Research (C) (No. 17500118).

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3rd International Conference on Autonomous Robots and Agents (ICARA 2006)
12-14 December 2006, Palmerston North, New Zealand

Feasibility Study of Sensing Methods on Cooperative Localisation for Team Operation of Multiple Mobile Robots

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Abstract

Recently, multiple mobile robot systems that perform team operations have been researched. Since the robot team often has to work without collisions in a small workspace where there are many obstacles, they need a function to detect the exact position of teammates and obstacles. In this paper, we propose a cooperative localisation algorithm that involves two steps: 1) teammate position detection and 2) temporary landmark detection. A teammate position can be measured by using infrared incidence angle detectors, since all teammate robots send infrared signals for communication. A temporary landmark can be detected through the visual representation of its spatial features using an image sensor and a fan beam laser. These two algorithms were tested in experiments in an ideal workspace and successful results were obtained.

Keywords: localisation and navigation, sensor network, network robotics

1 Introduction

In recent years, multiple mobile robot systems that perform team operations have been researched [1]. These robot teams are expected to achieve complicated tasks such as repairing nuclear reactors or waste incineration facilities. Since these robots often have to work without collisions in a small workspace with many obstacles, they need a function that detects the exact position of teammates and obstacles. To avoid collisions with teammates or obstacles and to achieve tasks smoothly, team member robots need to share positional information.

However, global coordinate systems for mobile robots are rarely preprogrammed in the robot or installed within a given workspace. Moreover, since landmarks used as reference positions to decide common coordinate axes and a common origin are not always prepared in advance in a workspace, each robot needs to define a private coordinate system. Positional information that is determined by each robot is impossible to share among teammate robots directly, because each robot operates under its own coordinate system and also the coordinate axes and origins differ from one robot to another.

We examined a cooperative localisation method for a mobile robot team in an unknown unstructured workspace. This method involves two steps: 1) teammate position detection using an infrared incidence angle detection system and ultrasonic sonar, and 2) temporary landmark detection using an image sensor combined with a fan beam laser. In the first step, temporary common coordinate axes are defined between a few adjacent robots using an infrared incidence angle detection system and these robots detect and disseminate teammates' positional information mutually. In the second step, these adjacent robots detect a temporary landmark using a fan beam laser and the landmark's positional information is calculated and shared among the robots.

In this paper, a teammate robot position detection algorithm and a temporary landmark position detection algorithm are described.

2 Communication System for Team Operation of Mobile Robots

To achieve complicated tasks smoothly, the number of robots in a workspace is increased. These robots need to communicate mutually to disseminate each robot's role and task sequence so as to avoid collision or obstructing each other's work. Usually, radio waves or infrared rays are used as the wireless communication carrier.

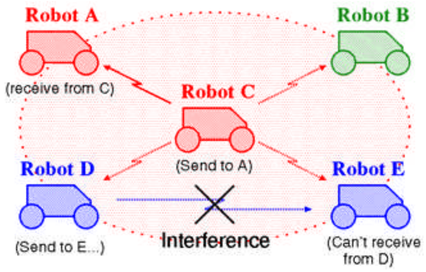

Figure 1: Interference of omni-directional signals.

As radio waves are omni-directional signals, signal interference often occurs if multiple robots use the same communication channel. Figure 1 shows interference of omni-directional signals.

On the other hand, since infrared rays have strong directivity and limited beam width, there is less signal interference. However, infrared communication systems often lose connection when robots move or rotate due to the directional nature of infrared rays. We designed an infrared communication system that can maintain connections when the robot moves or rotates.

2.1 Infrared Communication System for Mobile Robot Team

Since infrared rays have strong directivity and limited beam width, infrared communication systems often lose connection when these robots move or rotate. In order to maintain the connection, in the communication system, eight infrared transceivers are put on the circumference of the robot body facing outward to communicate in all directions (figure 2).

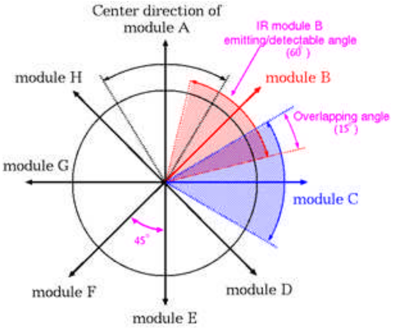

Figure 2: Arrangement of transceivers.

Each infrared transceiver is arranged so that both ends of the transceiver's reception area overlap with adjacent reception areas. These transceivers have a function that measures signal incidence angle, and for that reason the communication system can know the directions of the other robots and maintain the connections by tracking the other robots.

Yoshida et al. [2] and Arai et al. [3] have also proposed infrared inter-robot communication systems in order to avoid collisions in a small number of robots. They focused on communication with adjacent robots that are likely to collide. We thought about the creation of an inter-robot communication network and the occurrence of signal interference.

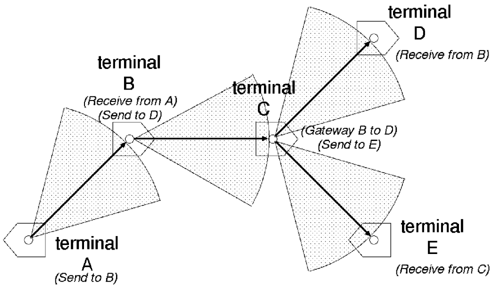

Figure 3: An inter-robot communication network.

The infrared inter-robot communication system that we designed is able to communicate in parallel with different partners in different directions without signal interference by using different transceivers simultaneously. As a result, space-division communication can take place. Since each robot can serve as a node in a communication network, they can create a communication network by relaying information among themselves. The created communication network is an ad hoc network, since all robots are independently mobile and may change positions depending on their tasks. Figure 3 shows an example of an inter-robot communication network.

When a transceiver on a robot receives signals from two or more teammate robots at the same time, the received signals become confused. If this happens, the robots in question will form a triangle. The interior angle of the triangle can be calculated from signal incidence angles of the infrared transceivers and each robot then informs other teammate 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, the robot that has the widest interior angle can communicate without signal interference with the other two. The robot that has the widest interior angle of the triangle becomes an arbiter that temporarily locally controls the other two robots thus reducing signal interference. The arbiter mediates both teammates by scheduling their transmissions. Figure 4 shows the selection of the arbiter. As the robots move and the triangle changes shape, the arbiter role is handed over to another robot.

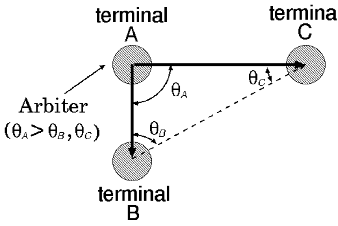

Figure 4: Selection of an arbiter.

2.2 Teammate Position Detection using Infrared Incidence Angle Detection

As previously mentioned, this infrared communication system enables the accurate detection of teammate direction by utilising the signal incidence angle measurement function. This means that it will be possible to calculate the position of teammates based on triangulation, if the distance between teammates can be measured.

Since usual ultrasonic sonar is used to measure distance to an object based on the time of the arrival of reflection signals, it is not suitable for measuring distance to a teammate. In order to measure the distance to a teammate, an ultrasonic sonar and an infrared communication system have to send their signals synchronously, because the distance can be measured based on the time difference of arrival of these signals.

Each robot can serve as a beacon transmitter for mobile robot navigation. This means that, if a certain robot serves as an origin, coordinate axes can be used together with the infrared communication between adjacent robots to infer the position of robots. When three teammates' positions are known in a workspace, a robot is able to compute its mutual position from measured interior angles and distances. These teammates' positions are arranged on coordinates from $P_1(x_1, y_1)$ to $P_3(x_3, y_3)$, and 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 the equation (1).

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

Parameters are computed as follows.

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

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

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

Figure 5 shows mutual position computation using triangulation. The robot computes interior angles $(\theta_{01}, \theta_{12}, \theta_{23})$ from measured signal incidence angles and computes coordinate $P(x, y)$ by triangulation.

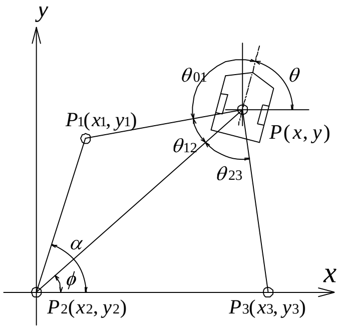

Figure 5: Mutual position computation.

Since all robots can move independently and may change their positions depending on their tasks, they have to compute their mutual positions continuously.

Takita et al. [4] have also proposed a mobile robot navigation method that detects the direction of an infrared light source mechanically. However, it cannot operate in an unstructured workspace because several infrared emitters that serve as landmarks have to be prepared in advance in the workspace.

As previously mentioned, the infrared communication system that we designed not only communicates among multiple partners but also is able to detect their mutual position. If a member of a robot team can find reference positions in a given workspace using onboard sensors, these robots are able to detect accurate positions in the workspace using this infrared communication system without landmark emitters prepared in advance.

3 Temporary Landmark Detection using Onboard Sensors

Although teammate robot position detection is extremely useful for local mutual cooperation among adjacent robots, it is not suitable for pointing to a specified position such as a stationary object in the workspace. Since there is no positional information on landmarks in an unknown workspace, it is difficult to define the global coordinate axis in order to point to a specific position. We considered a detection method of local temporary landmarks in order to define locally temporarily common coordinate axes. In order to detect objects in the workspace, an image sensor or ultrasonic sonar are used as an obstacle detector.

However a usual image sensor can capture precise images and can detect objects' directions accurately, it is quite difficult to measure depth or distance from these images. Since usual image sensor also has a slow capture interval that is approximately 30ms, it is not suitable for tracking fast moving objects.

Ultrasonic sonar has the opposite features to the usual image sensor. Since ultrasonic sonar can transmit signals in a broad area and can respond quicker than an image sensor, it is suitable for general obstacle detection. In addition, ultrasonic propagation velocity is approximately a million times slower than light velocity, making it suitable for time-based measurement of short distance up to a few meters.

In order to avoid collisions with obstacles and to plan behaviour in a small workspace, a robot team needs to know positions and features of obstacles accurately. Since it is difficult for usual image sensor to detect depth or spatial features, it needs to make other images or create shadow by using extra light sources. On the other hand, ultrasonic sonar also needs to rotate mechanically in order to detect surrounding obstacles by scanning, since sonar can only measure a distance to one frontal point.

3.1 Detection of Geometrical Feature of Landmark using a Fan Beam Laser

We examined a fan beam laser that can draw a straight line on a flat surface as an extra light source for an image sensor. The fan beam laser is also called a laser line generator or a slit laser. When the fan beam laser illuminates an object, it can create a visual representation of the object's geometrical features.

Torrie et al. [5] have also proposed an obstacle avoidance method using several fan beam lasers emitting in a vertical manner. They focused on a simple measurement method of cursory distances between obstacles in the surrounding environment for the purpose of a planetary investigation. We considered about selecting a temporary landmark in given workspace using the captured visual representation.

We examined a concept where a small number of teammate robots in close proximity can capture the visual representation of the same object. In order to confirm fundamental principles of a cooperative localisation method, we considered an ideal workspace, where a floor is flat and all objects stand perpendicularly. This ideal workspace is similar to most buildings where there are many walls and pillars on a flat floor. In addition, some of the walls and pillars create "corners/edges" to the workspace. As a result, these "corners/edges" can be used as temporary reference points in the workspace, because they are easy to detect using a fan beam laser emitting in a horizontal manner. Figure 6 shows a model of a "corner/edge" detection using a fan beam laser.

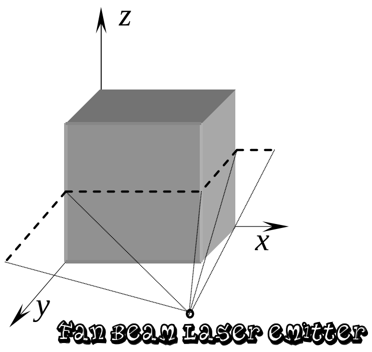

Figure 6: A model of a "corner/edge" detection.

Each robot there are in close proximity can detect the direction of a "corner/edge" by using an image processing algorithm from the captured visual representation. Since each robot has known mutual positional information from other teammate robots and can measure an interior angle between the "corner /edge" and an adjacent teammate, they can compute and share the positional information of the "corner/ edge" based on triangulation. The position of a visual representation that can easily be captured and computed from far distance can be used as a temporary landmark in the workspace.

3.2 Improvement in Distance Measurement Performance of Ultrasonic Sonar

As previously mentioned, since both incidence angle detection using an infrared communication and visual representation capture using an image sensor and a fan beam laser are not suitable for distance measurement, ultrasonic sonar measurement of distance has to be used as support. Conventional ultrasonic sonar measures a period in time when the envelope curve of received echo signal exceeds a threshold value from ultrasonic signal transmission. Since the threshold value of conventional sonar has weak theoretical background and is mostly a guess, distances measurement of conventional sonar is flawed. Even if the sonar measures a period of maximal amplitude of the received echo signal from a transmission, because it measures the distance of maximum reflective cross section, it does not represent true distance. Figure 7 shows the occurrence of the distance measurement error of ultrasonic sonar.

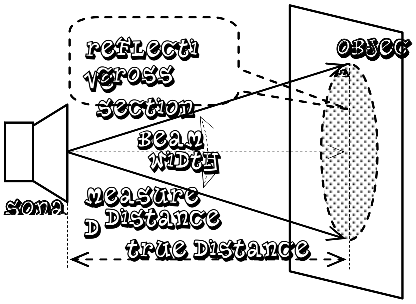

Figure 7: Occurrence of distance measurement error.

Since ultrasonic signals spread from the centre of a beam to a beam width as shown in figure 7, the amplitude of an echo is proportional to the temporal change in the size of a reflective cross section. We examined an algorithm that estimates the true value. Figure 8 shows a model of time period estimation algorithm.

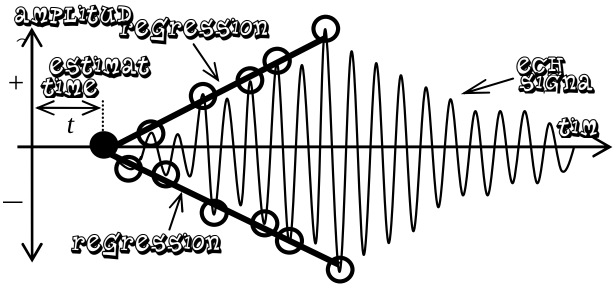

Figure 8: Model of time period estimation algorithm.

In figure 8, horizontal axis is time and vertical axis is amplitude. Several data sets of time and amplitude are measured and then regression lines p and q are computed based on the measured data sets using the least-square method. The time coordinate of intersection of regression lines p and q shows the estimated period t . The distance is transformed from the estimated time period t based on the acoustic velocity. In order to scan surrounding obstacles, ultrasonic sonar needs to rotate mechanically because sonar can only measure a distance of one frontal point.

4 Feasibility Confirmation on Multi-robot Cooperative Localisation

We tested the feasibility of multi-robot cooperative localisation by using onboard sensor systems. The cooperative localisation involves two steps: 1) teammate robot position detection and 2) temporary landmark position detection. The performances of onboard sensor systems that are used for each position detection algorithm are evaluated to examine the feasibility of cooperative localisation.

4.1 Performance Measurement of Teammate Robot Position Detection

A teammate robot's position is calculated from the incidence angles of infrared communication signals among them. The PSD photo diode (HAMAMATSU S6560) that can detect incidence angle of infrared rays was used as reception device for the infrared communication system (figure 9). This PSD photo diode has two current output electrodes and these ratios show the incidence angle.

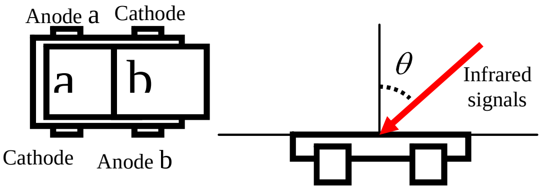

Figure 9: Schematic view of the PSD.

The electric current output *a* and *b* of the PSD are related to the incidence angle of the infrared signals θ as shown in equation (2).

$$\theta = (a-b)/(a+b) \tag{2}$$

In an experiment of incidence angle detection, angle detection error was approximate 0.5 degrees.

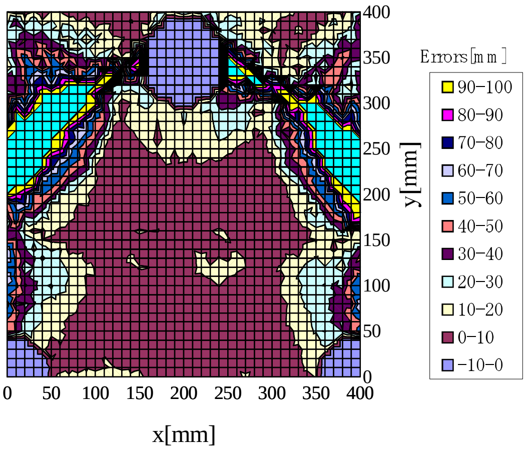

Figure 10: Accuracy of teammate position detection.

The accuracy of teammate robot positioning was confirmed by simulation. Three landmarks that were 100mm in diameters were placed on vertices of an equilateral triangle with 400mm side's length. Figure 10 demonstrates the accuracy of teammate position detection.

In figure 10, teammate robot positions can be calculated to a 90% or greater accuracy inside the triangle formed by the landmarks. Outside this triangle, there are some places where it is possible to compute positional information precisely, and some where it is impossible.

4.2 Performance Estimation of Temporary Landmark Position Detection

A temporary landmark position is calculated from a visual representation of the object's geometrical features that is created using a fan beam laser. A fan beam laser emitter (Coherent, LVM3 Laser-line micro 670nm 2.5mW 60degree) and image sensor (RF system Lab, PRO-5 2CCD colour wireless TV camera with lens) were used in the experiments. The laser emitter and the image sensor were attached to a motorised turntable (SIGMA KOKI, SGSP-160YAW) horizontally at 100mm vertical intervals.

The image sensor can capture 320 (horizontal) × 480 (vertical) pixel images; its horizontal view angle is approximately 23 degrees. The angle detection error of the image sensor capturing a visual representation was approximately 1.5 degrees in this experiment.

The temporary landmark position detection capability was examined. A motorised X-Y axis linear stage pair (SIGMA KOKI, SGSP46-500(X) and SGSP65- 1200(X)) was used for simulation of a mobile robot that moves around a cuboid obstacle set on the flat floor. The turntable on which the laser emitter and the image sensor were attached was put on the X-Y axis linear stage pair. The robot moved from $P_1(x_1,y_1)$ to $P_6(x_6,y_6)$ and the positions of the cuboid's edges $P_a(x_a,y_a)$, $P_b(x_b,y_b)$ and $P_c(x_c,y_c)$ were measured.

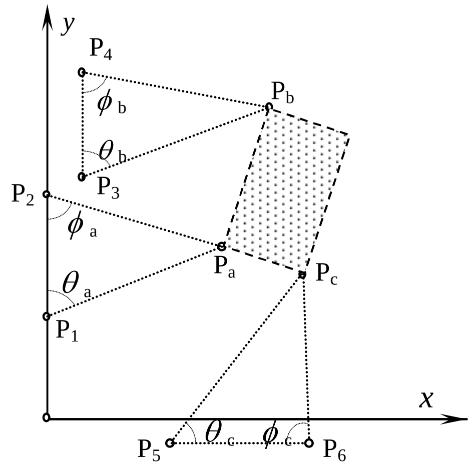

Figure 11: Experiment environment with an obstacle.

Figure 11 shows experiment environment with an obstacle. The accuracy of temporary landmark detection is shown in table 1, where 'x' and 'y' are arrangement coordinates. Measured angles θ and ϕ are shown in 'angle', detecting values 'x'' and 'y'' are the results of triangulation. The detection error was less than 3% in this experiment.

Table 1: Accuracy of temporary landmark detection (length: mm; angle: degree).

	Setting value		**Measured Angle**		**Detecting value**	
	x	**y**			**x'**	**y'**
P_a	500	500			498	510
P_1	0	300	θ_a	68.8		
P_2	0	650	ϕ_a	73.4		
P_b	635	900			633	890
P_3	100	700	θ_b	70.4		
P_4	100	1000	ϕ_b	78.3		
P_c	720	430			715	442
P_5	350	-75	θ_c	54.8		
P_6	750	-75	ϕ_c	86.1		

4.3 Confirmation of Distance Measurement Accuracy of Ultrasonic Sonar

We also confirmed the distance measurement accuracy of ultrasonic sonar. Ultrasonic speaker and microphone set (Murata MA40B5S/R, Carrier frequency: 40KHz) were used in the experiments. A resin flat panel target (1500mm tall × 1200mm wide) was installed perpendicularly at 1300mm distance. The received signal was amplified by a 40KHz tuned FET amplifier and captured by a 12bit A/D converter (Interface PCI-3525) in 200KHz sampling intervals.

Both the conventional method that measures time from the transmission to when maximum amplitude is received and the proposed method that calculate the least-square method from the received signal were compared. In addition, a horn (50mm length) was installed in front of the ultrasonic speaker or microphone. Table 2 shows the accuracy of distance measurement of the ultrasonic sonar.

Table 2: Accuracy of distance measurement (length: mm; target distance: 1300; horn length: 50).

Method	**Conventional**			**Proposed**		
Horn	W/O	MIC	Speaker	W/O	MIC	Speaker
Detecting value	1372	1387	1382	1287	1294	1294
Error	72	87	82	-13	-6	-6
Deviation	1.58	0.84	0.75	0.90	0.11	0.11

In table 2, the ultrasonic sonar was able to measure distance at approximately 1% or smaller error rate by the proposed method. Although the horn made deviation of distance measurement small, the error rate did not improve.

5 Conclusion and Future Work

We studied the feasibility of a multi-robot cooperative localisation algorithm. It was shown that a multi-robot cooperative localisation algorithm involves two steps: teammate robot position detection and temporary landmark position detection.

To detect teammate robot positions, we proposed an infrared communication system that can not only communicate mutually but also detect infrared incidence angles. By this method, it is possible to detect a teammate robot position to 90% accuracy or greater except where it is impossible to calculate positional information by triangulation.

To detect temporary landmark positions, we proposed a detection method based on a visual representation of the object's geometrical feature using an image sensor and a fan beam laser. By this method, temporary landmark position detection errors were less than 3% in experiments.

To improve the distance measurement accuracy of ultrasonic sonar, we proposed a method that calculates the least-square method from the received signal waveform. It was confirmed in the experiment that the distance measurement error of the proposed method is approximately 1% or smaller.

In future work, these position detection methods and the distance measurement method will be installed on mobile robots. Cooperative map creation in complicated situations using multiple mobile robots will be tried.

6 Acknowledgements

This work is supported in part by the Japan Society for the Promotion of Science Grant-in-Aid for Scientific Research (C) (No. 17500118).

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Cooperative Workspace Mapping for Multi-Robot Team Operations using Ultrasonic Sonar and Image Sensor

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Abstract:

In recent years, multiple mobile robot systems that perform team operations have been developed. These robots need to detect the exact position of teammates and obstacles, because they often have to work in a small workspace. In this paper, we propose a cooperative map creation algorithm using ultrasonic sonar and image sensor that are attached on mobile robots. The cooperative map creation algorithm involves two steps: 1) teammate relative position detection and 2) temporary landmark detection. An infrared communication system that can detect bearing of teammates is attached on each mobile robot. In order to create visual representations of spatial features of landmarks, a fan-beam laser emitter as an extra light source is also attached. These two algorithms were tested in experiments in a controlled workspace and successful results were obtained.

1. Introduction

In the last several years, multiple mobile robot systems that perform team operations have been studied. These robot teams are expected to complete complicated tasks such as repairing industrial facilities or removing hazardous materials. Since the robot team often has to work in a small workspace where there are many obstacles, they need to move slowly in order to avoid collisions. We assumed the robots would be able to decrease the number of collisions and to execute their tasks smoothly, if they had capability to detect the exact position of obstacles or teammates.

When working outdoors, robots equipped with GPS (Global Positioning System), receiving radio waves from GPS satellites, are able to detect their own positions accurately. However, mobile robots that work indoors or underground cannot use GPS because they cannot receive signals from GPS satellites. In addition, artificial landmarks for indoor robots are rarely preprogramed or installed within a given workspace. Since there is no landmark that serves as the point of reference of a given workspace, each robot operates under its own coordinate axes. Positional information that is determined by each robot is impossible to share among teammate robots directly, because the coordinate axes and point of reference differ from one robot to another. Therefore, we examined how to acquire the general point of origin and the general coordinate axes among teammate robots in their workspace. This method involves two steps: 1) teammate relative position detection by detecting signal source, and 2) temporary landmark detection using an image sensor and a fan beam laser emitter.

In the first step, the relative positions of adjacent teammates are calculated from their direction and distance. This is done by detecting the bearing of the communication signal source, since each robot transmits communication signals for cooperation. The distances between teammates are measured from the time differences of arrival between communication signals and ultrasonic waves emitted simultaneously. Temporary partial coordinate axes are determined among adjacent robots by using teammates as tentative landmarks.

In the second step, a temporary landmark is detected by using an image sensor and a fan beam laser, since the fan beam laser creates a visual representation of geometrical features of the landmark. The position of the temporary landmark is also calculated from its direction and distance. The direction of the temporary landmark from a robot is detected by processing captured images that represent its geometrical feature. The distance to the landmark is measured by using ultrasonic sonar. The general point of origin and the general coordinate axes are determined among teammate robots based on the detected positions of temporary landmarks in a given workspace.

In this paper, a teammate robot relative position detection algorithm and a temporary landmark position detection algorithm are described.

2. Wireless communication system for cooperation of multiple mobile robots

In order to cooperate among multiple mobile robots, wireless communication system is used to exchange information among them. Usually, radio waves or infrared rays are used as the wireless communication carrier. Since radio waves spread signals omni-directionally, communication interference often occurs if many robots use the same channel. On the other hand, as infrared rays have the directional nature, there is less signal interference than radio waves. However, infrared communication systems often lose the communication links between teammates when robots move or rotate. We designed an infrared communication system that is able to maintain communication links when the robot moves or rotates.

2.1 Infrared communication system for a mobile robot team

As previously mentioned, in the infrared communication system, the communication link between teammates is easily lost when robots move or rotate. In order to maintain the links between the partners in whole directions, we designed the infrared communication system so that eight infrared transceivers facing outward place on the circumference of the robot body. Each infrared transceiver is arranged so that both ends of reception area of the transceiver overlap with adjacent reception areas. Figure 1 shows the arrangement of transceivers. Each transceiver has a function that measures the incidence angle of the infrared rays, and for that reason the communication system is able to detect the direction of the signal source and to maintain the connection by tracking it.

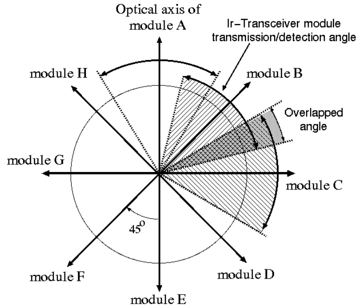


Fig.1 Arrangement of transceivers

The infrared inter-robot communication system that we designed is able to communicate in parallel with different partners in different directions without signal interference by using different transceivers simultaneously. When the robots serve as nodes of a communication network, they are able to create a network by relaying information among themselves. The created communication network is an ad hoc network, because all robots are independently mobile and may change positions depending on their tasks. Figure 2 shows an example of an inter-robot communication network.

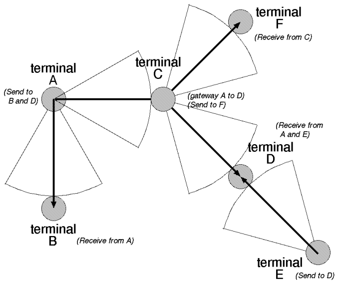


Fig.2 An inter-robot communication network

2.2 Calculating relative teammate positions among a mobile robot team

In order to maintain the communication links when the robots move or rotate, the infrared communication system tracks the partners by detecting the incidence angle of the communication signal. Therefore the communication system enables the accurate detection of teammate direction by utilizing the incidence angle measurement function. This means that the relative position of teammate is possible to calculate based on triangulation, if each robot is able to measure the distance to teammate.

As usual ultrasonic sonar is used to measure distance from the transmitter to an object based on the period from the transmission to the arrival of reflection signals, it is not suitable for measuring distance to a teammate. Because, the ultrasonic reflection signals by a teammate are as confusing as the echo of an obstacle, and it is hard to detect the signals since its intensity is weak. In order to measure the distance to a teammate accurately, if ultrasonic sonar and an infrared communication system is able to transmit their signals synchronously, the distance is possible to measure based on the time difference of arrival of these signals.

Each robot is able to serve as a beacon transmitter for mobile robot navigation by using the infrared communication system.

This means that, when a certain robot serves as a tentative landmark, temporary local coordinate axes are possible to determine between adjacent robots to estimate their relative positions.

When the positions of three teammates are known in a given workspace, a certain robot is able to calculate its relative position from measured interior angles and distances. The positions of three teammates are arranged on coordinates from $P_1(x_1, y_1)$ to $P_3(x_3, y_3)$, and P_2 is the point of 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 the equation 1.

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

Parameters are computed as follows.

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

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

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

Figure 3 shows the relative robot position calculation using triangulation. The robot measures interior angles $(\theta_{01}, \theta_{12}, \theta_{23})$ from detected signal incidence angles and calculates coordinate $P(x, y)$ by triangulation. Since all robots are able to move independently and to change their positions depending on their tasks, they have to calculate their relative positions continuously.

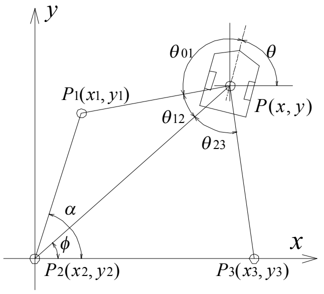


Fig. 3 Relative position calculation

3. Temporary landmark detection using ultrasonic sonar and image sensor

Although the relative teammate position detection is extremely useful for cooperation among adjacent robots, it is not suitable for pointing to a particular point such as a stationary certain object in a given workspace. In order to point to a specified position in a given workspace, a robot team need to determine the general point of origin and the general coordinate axes among teammates based on landmarks in the workspace. However, since landmarks are not always prepared in advance in an unknown unstructured workspace, the robots have to find points of reference that serve as temporary landmarks by using onboard sensors around them. We considered about finding a temporary landmark that has spatial shapes such as "a corner / edge" of walls and pillars in a given workspace using ultrasonic sonar and an image sensor.

3.1 Detecting landmark direction using an image sensor and a fan beam laser

Usually an image sensor is able to capture precise images and to detect accurate direction of object. However it is quite difficult to measure depth or distance from captured images. In order to detect depth or spatial features using an image sensor, it needs to capture other images of the same object in other directions or create shadow by using extra light sources. We examined a fan beam laser that draws a straight line on a flat surface as an extra light source for an image sensor.

When the fan beam laser illuminates an object, it creates a visual representation of geometrical feature of the object. We considered a concept that if a small number of teammate robots are in close proximity, they are able to capture similar visual representation of the same object at the same time. Thus the robots are able to detect the direction of the spatial feature of the same object by using an image-processing algorithm from the captured visual representations. Figure 4 shows a model of creating a visual representation by a fan beam laser. If a position of visual representation is possible to find and to calculate from far distance easily, it is possible to use as a temporary landmark in a given workspace.

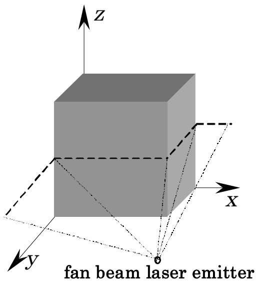


Fig.4 A model of creating a visual representation

3.2 Improvement in distance measurement performance of ultrasonic sonar

As previously mentioned, we proposed an infrared communication system that has an incidence angle detection function, and a spatial feature detection algorithm that uses an image sensor and a fan beam laser. They are able to detect direction accurately. However, both the infrared communication system and the image sensor are not suitable for distance measurement. We considered using ultrasonic sonar as support to measurement of distance.

Ultrasonic sonar measures a period from transmission of an ultrasonic pulse to reception of a signal that is reflected by an object. Figure 5 shows the occurrence of the distance measurement error of ultrasonic sonar. Since a transmission signal spreads from the center of a beam to a beam width as shown in figure 5, the amplitude of a reflected signal is proportional to the temporal change in the size of a reflective cross section. When the sonar measures a period of maximal amplitude of the echo, since it measures the distance of maximum reflective cross section, it does not indicate true distance.

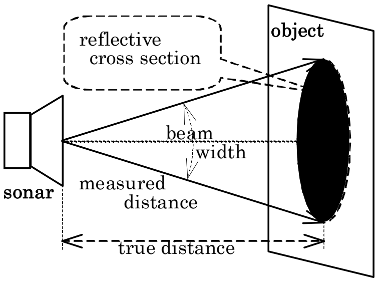


Fig. 5 Occurrence of measurement error

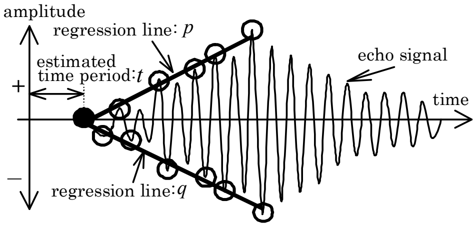


Fig. 6 A model of time period estimation

Figure 6 shows a model of time period estimation algorithm. In figure 6, the horizontal axis is time and the vertical axis is amplitude. Several data sets of time and amplitude are measured. The regression lines p and q are computed based on the measured data sets using the least-square method. The time coordinates of intersection of regression lines p and q shows the estimated time period t. The distance is transformed from the estimated time period t based on the acoustic velocity. In order to scan surrounding obstacles, ultrasonic sonar needs to rotate mechanically because sonar is able only to measure a distance of one frontal point.

4. Feasibility confirmation of cooperative workspace mapping

We tested the feasibility of cooperative workspace mapping by using onboard sensors. As previous mentioned the cooperative workspace mapping involves two steps: 1) relative teammate position detection and 2) temporary landmark position detection. The performances of onboard sensors that are used for each positioning algorithm are tested to estimate its feasibility.

4.1 Performance estimation of relative teammate position detection

A relative position of teammate is calculated from the direction of infrared signals that are used to communicate among the team. The PSD photo diode (HAMAMATSU S6560) that can detect incidence angle of infrared rays was used as reception device for the infrared communication system. This PSD photo diode has two output electrodes and their ratios show the incidence angle of infrared rays. Figure 7 shows a schematic view of this PSD.

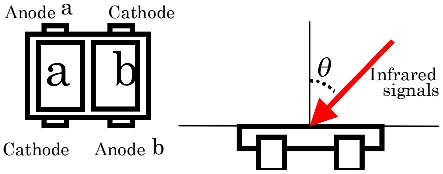


Fig.7 Schematic view of the PSD

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

The output signals a and b of the PSD are related to the incidence angle of the infrared signals θ as shown in the equation 2. In an experiment of incidence angle detection, detection error was approximate 0.5 degrees.

The accuracy of the positioning method was confirmed by simulation. Three landmarks that were 10cm in diameters were placed on vertices of an equilateral triangle with 40cm side's length. Figure 8 demonstrates the accuracy of teammate position detection.

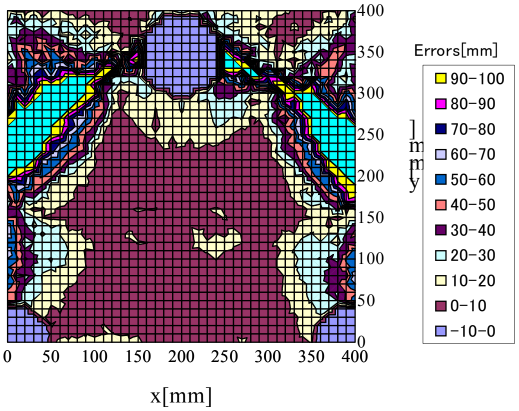


Fig.8 Accuracy of teammate position detection

In figure 8, teammate robot positions are possible to calculate to a 90% or greater accuracy inside the triangle formed by the landmarks. Outside the triangle, there are some places where it is possible to calculate position precisely, and somewhere it is impossible.

4.2 Feasibility confirmation of temporary landmark position detection

Temporary landmark position detection is achieved by using ultrasonic sonar and an image sensor. We built a sensor head that consist of ultrasonic sonar (MURATA MA40B5S/R, Carrier frequency: 40KHz), an image sensor (RF system Lab, PRO-5 2CCD color wireless TV camera with lens) and a fan beam laser emitter (Coherent, LVM3 Laser-line micro 670nm 2.5mW 60degrees) for experiments. The experimental field that is the 180cm×180cm square was created by using 180cm×45cm×1.5cm plywood. Figure 9 shows the experimental field.

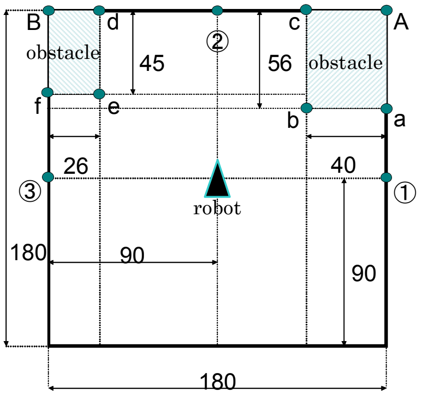


Fig.9 Experimental field (Unit: cm)

The robot motion simulator (SIGMA KOKI, SGSP46-500(X) and SGSP-160YAW) that installed the sensor head is placed in the center of the experimental field.

(a) Landmark detection algorithm

The landmark position is calculated from the result of distance detection using ultrasonic sonar and the result of direction detection using an image sensor. The position calculation algorithm involves eight steps:

1) Scan the surrounding using sonar.
2) Capture an image of spatial feature in the direction of strong sonar echo.
3) If it is an image of "corner / edge", measure direction of the corner / edge.
4) If it is an image of "flat surface", detect direction of the strongest echo in neighbor.
5) Calculate distance from sonar echo of detected direction. Determine coordinates of the detected position.
6) Transform coordinates of the detected position from polar to Cartesian.
7) Shift and rotate coordinates of the detected position according to the robot motion. Transform from own-centered coordinate to general coordinate.
8) Compare coordinates of landmarks and coordinates of detected position. If new landmark is found, it is enter to a list.

Each robot performs repeatedly from step: 1) to step: 8) and makes a list of landmarks to create a workspace map.

(b) Landmark detection in obstacle free field

In order to confirm the proposed method, we examined landmark position detection in the field where there is obstacle free. Robot goes straight from origin to 50cm in the heading direction and scans the surrounding whenever moving 10cm. Figure 10 shows a result of sonar scanning in 180 degrees. The contour line in a figure 10 shows the position of strong echo.

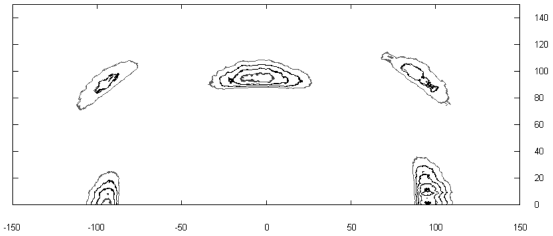
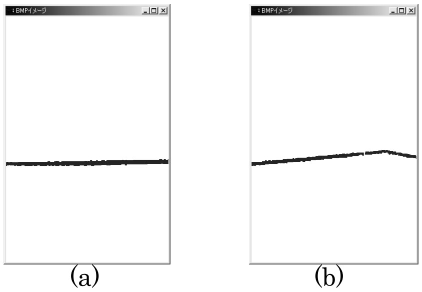


Fig.10 Position of strong echo (Unit: cm)



(a) (b)

Fig.11 Images of spatial features

Figure 11 shows captured images of spatial feature in directions of strong echo. In figure 11 (a) shows an image of “flat surface” and (b) shows an image of “corner”. The bearing angle of the corner is measured by using image-processing algorithm.

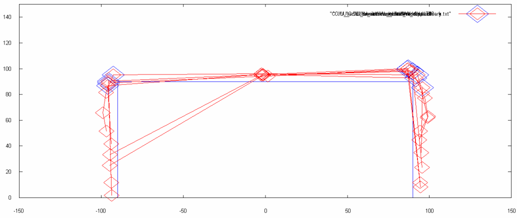


Fig.12 Mapping of landmarks (Unit: cm)

Figure 12 shows a result of landmark detection. In figure 12, corner A and corner B of figure 9 are detected. Table 1 shows detection errors in obstacle free field.

Table 1 Detection errors (Unit: cm)

Place	0	10	20	30	40	50
A	10.13	10.49	7.96	7.45	3.23	6.01
B	5.57	5.49			6.90	5.94

(c) Landmark detection in crowded field

We also examined landmark position detection in the crowded field where there are two obstacles. Robot moves the same motion as previous experiments. Figure 13 shows a result of sonar scanning in 180 degrees. In figure 13, a lot of clutter noises are shown.

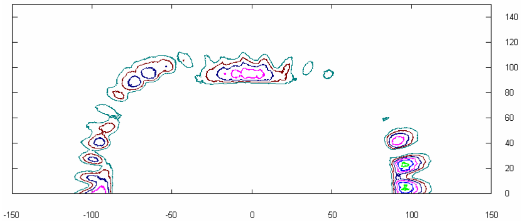


Fig.13 Position of strong echo (Unit: cm)

Figure 14 shows a result of landmark detection in the crowded field. In figure 14, corner a, corner c, corner d, edge e and corner f of figure 9 are detected and an edge b of figure 9 is not detected.

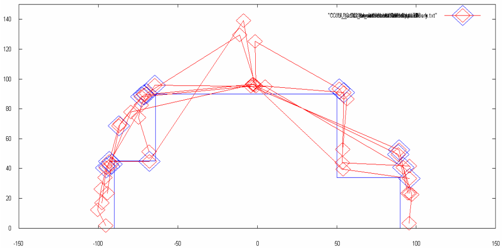


Fig.14 Mapping of landmarks (Unit: cm)

Table 2 shows detection errors in crowded field.

Table 2 Detection errors (Unit: cm)

Place	0	10	20	30	40	50
a	6.62	15.59	18.51	5.76		
b						
c					4.66	3.57
d	5.84	7.46	9.30			5.67
e					4.03	
f	6.89	23.87	2.72	4.83	3.17	

5. Conclusion and Future works

We proposed a cooperative workspace mapping algorithm that involves two steps: 1) teammate relative position detection and 2) temporary landmark detection. Teammate relative position detection algorithm was tested by simulation. Temporary landmark detection algorithm was also confirmed.

In future work, proposed algorithms will be installed on real robots and tested in real indoor environment.

Acknowledgement

This work is supported in part by Japan Society for the Promotion of Science Grant-in-Aid for Scientific Research (C) (No. 17500118).

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Short-range Infrared Wireless Communication System for Multi-mobile Robot Team Operations

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Abstract

Recently, mobile robot systems that enable team operations have been developed. Team member robots have to communicate among teammates in order to accomplish their complicated tasks. Usually, radio waves or infrared rays are used as a communication carrier. As radio waves emit omni-directional signals, signal interference often occurs if multiple robots use the same communication channel and transmit signals at the same time. On the other hand, since infrared rays have strong directivity and limited beam width, there is less signal interference. However, infrared communication systems often lose communication links when communicating robots move or rotate due to the directional nature of infrared rays.

In this paper, we propose an infrared wireless communication system for mobile robot teams that decrease communication interference and maintain communication links by tracking the direction of the communicating partner. As a result of experiments, the developed communications system had a transmission speed of 460kbps in 1m distance. The communication system also had an angle detection accuracy of 0.5 degrees and an angle detection time of 100 μ seconds.

1. Introduction

Over the last several years, multiple mobile robot systems that perform team operations have been studied [1]. These robot teams are expected to accomplish complicated tasks such as repairing industrial facilities or removing hazardous materials. Since the robot teams often have to work in a small workspace, they need to communicate in order not only to avoid collisions but also to cooperate.

Usually, radio waves are used as the communication carrier for remote control of mobile robots. They are also used for inter-robot communication systems. However, in order to accomplish team operations, the communication system needs to use the same communication channel. When the number of robots increases, occurrence of communication interference also increases if multiple robots transmit signals at the same time.

We thought that one of the causes of this communication interference is the nature of radio waves which emits signals omni-directionally. This communication interference can be decreased using directional communication carriers such as infrared rays or micro waves. Accordingly, we designed a short-range wireless communication system that uses infrared rays as the communication carrier, because infrared rays can be used in a circuit easier than micro waves.

Since infrared rays have strong directivity and limited beam width, usual infrared communication systems often lose communication links when team member robots move. In order to maintain communication links, we designed the infrared communication system that tracks the direction of a partner by using incidence angle detectors as the reception device.

This paper describes realization and performance measurements of an infrared wireless communication system for mobile robot team operations.

2. Concept of the infrared wireless communication system

In a workspace of multiple mobile robots, inter-robot communication is desired to reduce congestion and to execute tasks smoothly. However, when multiple robots send omni-directional signals freely, the signals reach not only communicating partners but also other robots and cause communication interference. Figure 1 shows communication interference by omni-directional signal emission.

If the number of robots in the communication area is decreased, communication interference will be reduced. When the communication area has a restricted radius or direction, the number of robots in the area that are able to receive the signals decreases [2][3]. However, if the radius of the communication area becomes smaller and the density of the number of robots increases, it is impossible to reduce the communication interference because it means that is back at the original problem as illustrated in figure 1.

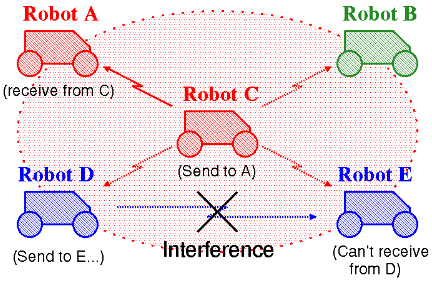


Fig.1 Interference by omni-directional signals

On the other hand, if the direction of the communication area is limited to a narrow space, it has an effect that the communication system focuses on the direction of a communicating partner and eliminates signals from other directions, thus the communication system can reduce interference effectively. Even if the area density of the number of robots increases, the communicating partner conceals signals from the other robots by using its own body and communication interference reduces as a result. Figure 2 shows the elimination of communication interference by the directional transmission.

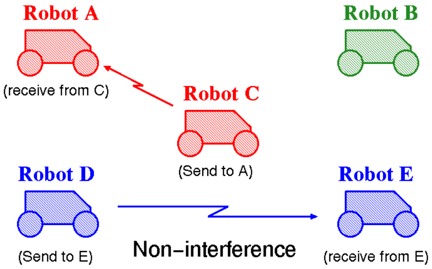


Fig.2 Directional transmission

2.1 Arrangement of infrared transceivers

Each robot has to communicate in all directions to avoid collisions, whereas the communication system that is attached to the robots needs to restrict the direction of the communication area in order to reduce communication interference. Accordingly, we designed an infrared communication system that uses a set of infrared transceivers that is arranged on the circumference of the robot body facing outwards. Figure 3 shows an arrangement of infrared transceivers. In the infrared communication system, each transceiver has a communication area of 60 degrees and eight infrared transceivers are arranged at 45 degree intervals on the circumference of the robot body. Both ends of the communication area of the transceivers overlap with adjacent communication areas. The communications system can transmit signals in the arbitrary ranges by combining transceivers.

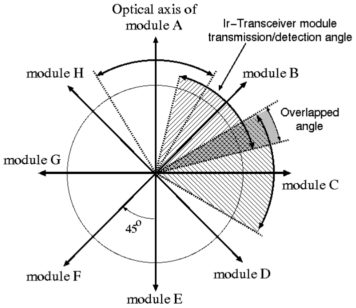


Fig.3 An arrangement of infrared transceivers

2.2 Maintaining communication links by tracking communicating partners

Since infrared rays have strong directivity and limited beam width, infrared communication systems often lose communication links when communicating robots move. In order to maintain a communication link, communication systems need to detect direction of the communicating partner and select transceivers that face the partner. The communication system that we designed uses a position sensitive device (PSD) photo diode that can detect an incidence angle of infrared signals from a communicating partner using the reception device of each infrared transceiver.

In this communication system, each transceiver not only receives communication signals but also detects direction angle of the communicating partner. The detected direction angle is encoded to the 2 bit direction code that shows the direction of the communicating partner. Figure 4 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.

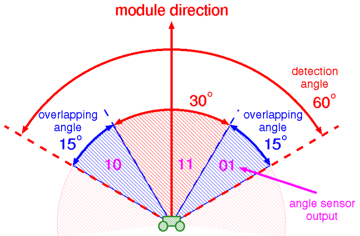
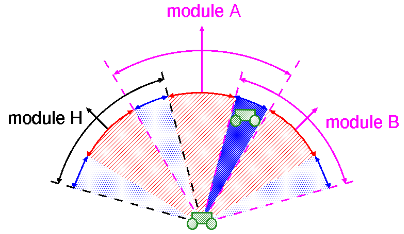


Fig. 4 The direction code of a transceiver

In order to maintain a communication link between partner robots, the communication system needs to select the appropriate transceiver facing that partner by using direction code. When the partner moves into an overlapping area of the adjacent transceivers, both of the transceivers receive the same signal from the partner. Therefore, the communication system is able to hold the connection even if it switches between adjacent transceivers facing the partner. Figure 5 shows direction of the partner and direction code.



A	B	C	·····	H
01	10	00	·····	00

Fig.5 Direction of the partner and direction code

From the transceivers, since the amplitude of received communication signals changes according to the distance between robots, the received signals are amplified and are changed to digital serial data. Since both the received serial data and the direction code are encoded to digital signals by the transceivers, the communication system is able to switch the transceivers using a simple combinatorial logic circuit. Figure 6 shows the transceiver switch circuit. In figure 6, the received serial data of each transceiver is on the left side, and the direction code of each transceiver is below.

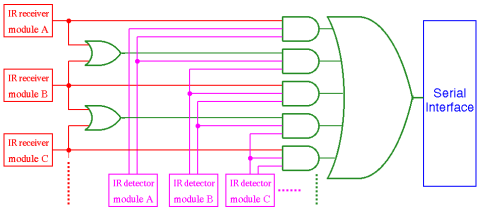


Fig.6 The transceiver switch circuit

When the output direction codes from each transceiver are enumerated in order, the direction code '11' shows the direction of the partner. The transceiver switch circuit switches to the received serial data from the transceiver that matches the direction code '11'. If the partner is in the overlapping area of adjacent transceivers, the circuit switches to the serial data that combines both transceivers.

Infrared communication suffers from hardly any interference due to the nature of infrared rays even when transceivers face different directions from transmission signals. Therefore more than one transceiver switch circuit is able to connect in parallel to each transceiver for the purpose of communication with more than one partner. In the communication system, the number of partners that are able to communicate at the same time are restricted by the transceiver switch circuit, the serial data interface and the performance of the communication controller.

2.3 Construction of communication network

As previously mentioned, since each transceiver of the communication system facing a different direction from the others is able to transmit signals independently, the communication system has the capability to communicate with different partners in parallel. In this way, space-division communication can take place.

When each robot relays communication signals among partners, a communication network is created in their workspace. It is an ad hoc communication network because each robot is independently mobile and may change position depending on their tasks. Figure 7 shows an inter-robot communication network.

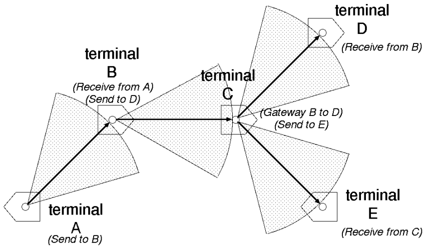


Fig.7 An inter-robot communication network

When two or more communicating partners send signals to the same robot at the same time, these signals collide and communication interference occurs when the transmission is too narrow. The communication system must reduce signal confusion. However, since the communication network is created by the robots spontaneously, there is no central controller in the network.

Therefore, one or more of the robots must be self-selected to act as an arbiter for the mediation that reduces communication interference. Each robot must be able to mediate communication, and the arbiter role should always be switched to the most appropriate robot.

2.4 Selecting an arbiter to reduce interference

Communication interference occurs when a receiver robot faces two or more transmitter robots that send signals at the same time. If this happens, the robots in question will form a triangle. The interior angle of the triangle formed by the communicating robots can be calculated from direction angles of partners. Each robot that forms the triangle then informs the partner robots of its own interior angle.

Since 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, the robot that has the widest interior angle can communicate without interference with the other two. The robot that has the widest interior angle of the triangle becomes an arbiter that temporarily controls the other two robots. The arbiter mediates both teammates by scheduling their transmissions. Figure 8 shows the selection of an arbiter. As the robots move and the triangle changes its shape, the arbiter role is handed over to another robot.

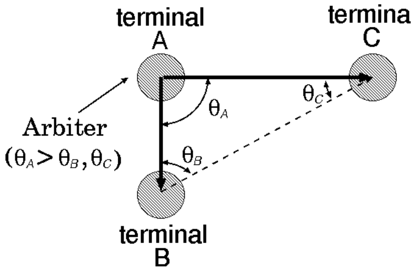


Fig.8 Selection of an arbiter

3. Feasibility study of the infrared inter-robot communication system

As earlier mentioned the infrared wireless communication system is able to adapt to inter-robot communication if its mechanism is designed appropriately. However, the intensity of infrared communication signals decreases with the square of the distance between the transmitter and the receiver. In addition the communication capability is in inverse proportion to the data transmission rate.

In the infrared communication system, each transceiver not only receives communication signals but also detects the direction angles of partners. In order to increase the performance of the communication system, we designed a system that involves three components: 1) an incidence angle detector circuit, 2) a reception signal amplifier and 3) a transceiver switch circuit.

3.1 Detection of the signal incidence angle

In order to detect the signal incidence angle, we used the PSD PIN photo diode (HAMAMATSU S6560) as the detection device in the experiments. Figure 9 shows a schematic view of the device.

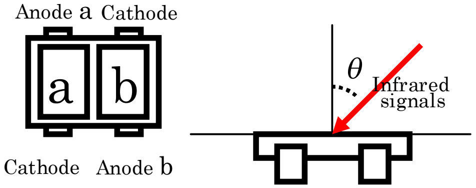


Fig.9 A schematic view of the angle detector

The incidence angle detector has two electric current outputs ‘a’ and ‘b’. The incidence angles of the infrared rays θ are calculated from electric current values ‘a’ and ‘b’ in equation 1.

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

For the experiments, an infrared signal source was placed in front of the incidence angle detector. Then the signal source was moved from 50 degrees left to 50 degrees right in 0.5 degree increments. Figure 10 shows the angle detection performance of the detector. It shows the detected angles of the received signal compared to the angles that are set from the signal source.

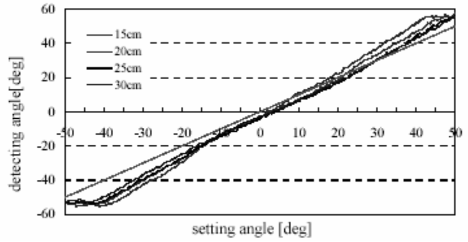


Fig.10 Angle detection performance of the detector

Since each transceiver requires a communication area restricted to 60 degrees, the reception angle of the detector is restricted by barriers of 60 degrees. Figure 11 shows an arrangement of two detectors and their barriers. In order to confirm the feasibility of the communication system design, the two detectors that are facing outwards are arranged at 45 degrees. It is the same layout of figure 3.

For the experiments, the signal source was moved from 90 degrees left to 90 degrees right in 0.5 degree increments. Figure 12 shows the receiving signal strength and receiving area of each receiver. In figure 12, each communication area is restricted to a width of 60 degrees and overlaps with the adjacent receivers by 15 degrees.

As a result of this experiment, the incidence angle detection and direction code encoding were around 100 μ s. Accuracy of the angle detection was 0.5 degrees which equals the setting angle intervals of the test.

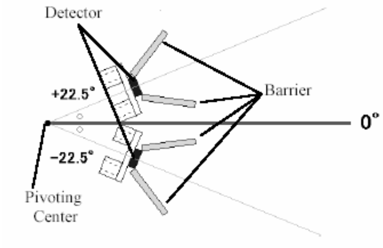


Fig. 11 An arrangement of detectors and barriers

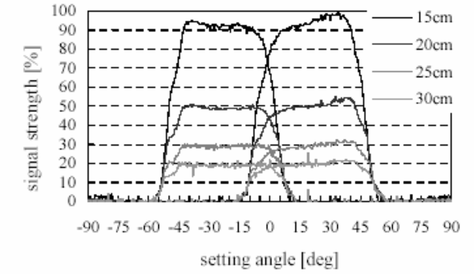


Fig. 12 Signal strength of each receiver with barriers

3.2 Implementation of the reception signal amplifier

The infrared communication system not only receives communication signals but also detects direction angles of the communicating partners. Since the intensity of received signals decreases with the square of the distance between the transmitter and the receiver, the output signals of the reception device are weak analog signals and need amplification. Figure 13 shows a block diagram of a signal processing circuit. The signal processing circuit amplifies and changes from received analog signals to digital pulse data.

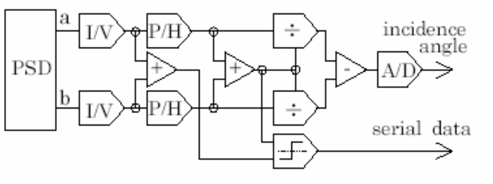
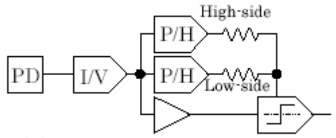
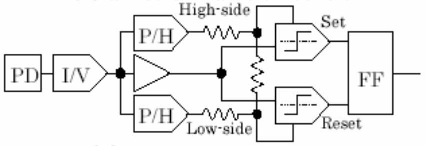


Fig. 13 A signal processing circuit

In order to design the circuit, we determined 384 kbps as the data transmission speed of the communication system because it is similar to the speed used for the uplink from mobile terminals of walking users that transmit compressed QVGA video images. For the high speed data transmission, we implemented two types of threshold decision circuits that change from analog pulse signals to digital serial data. Figure 14 shows the threshold decision circuits. In figure 14, circuit (A) calculates the median value of high side peak and low side peak as threshold voltage. Also in circuit (B), the difference between high side peak and low side peak is divided into three in order to give hysteresis effects.



(A) a median value threshold



(B) a hysteresis threshold

Fig. 14 Threshold decision circuits

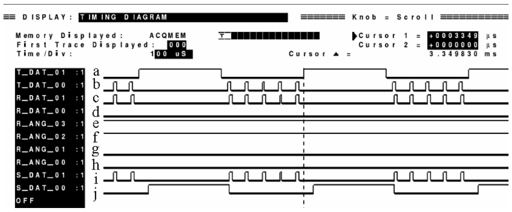
In this experiment, it was possible for the threshold decision circuits to recover digital serial data from the received pulse signals with a voltage of 100 mVpp, and it was also possible to receive signals of up to 460 kbps. At a slow transmission speed, it was impossible for these circuits to recover the correct digital serial data, because the threshold value was changed by the electric discharge of peak-hold capacitors.

3.3 Capability confirmation of the transceiver switch circuit

The communication system tracks the communicating partner and maintains the communication link that is handed over to the adjacent transceiver facing the partner. The direction of the partner is calculated from the incidence angle of the communicating signals. The diagram of the transceiver switch circuit is shown in figure 6. The experimental circuit was implemented on a CPLD (Cypress CY7C372i) using a VHDL compiler (Cypress Warp2). Figure 15 shows the operation results of the circuit.

In figure 15, result (A) shows the operation when the signal source was set in front of a receiver, and result (B) shows the operation when the source was set in an overlapping area of two receivers. The signal ‘c’ and‘d’ are reception signals and signals ‘e - f’ and ‘g - h’ are direction codes that are output from the transceivers, the signal ‘i’ is the final output.

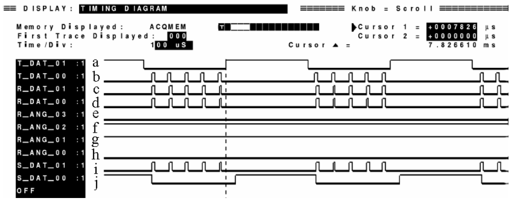
Since the CPLD device can work up to 100 MHz, the required time for switching is sufficiently short for the robot motion.



DISPLAY: TIMING DIAGRAM ======= Knob = Scroll ==========

Memory Displayed: ACQMEM
First Trace Displayed: 000
Time/Div: 100 uS
Cursor 1 = +0003349 µs
Cursor 2 = +0000000 µs
Cursor ▲ = 3.349830 ms

(A) Signal source is set in front of a transceiver



DISPLAY: TIMING DIAGRAM ======= Knob = Scroll ==========

Memory Displayed: ACQMEM
First Trace Displayed: 000
Time/Div: 100 uS
Cursor 1 = +0007826 µs
Cursor 2 = +0000000 µs
Cursor ▲ = 7.826610 ms

(B) Signal source is set in overlapping area

Fig.15 Operation results of transceiver switch circuit.

4. Conclusions and future works

We proposed and designed an infrared wireless communication system for multi-robot team operations. We also implemented and tested important parts of the communication system.

Angle detection capability of the reception device was confirmed. The incidence angle detection and direction code encoding were around 100 μ s. Accuracy of the angle detection was 0.5 degrees in the experiments.

The reception signal amplifier and the threshold decision circuits were implemented and tested. The circuits were able to operate in the signal of 100 mVpp 460kbps in the experiments. These circuits need to be improved for high speed accurate communication.

The electric partner tracking mechanism was also implemented and tested. The capability of the circuit was confirmed.

In future works, the infrared transceivers will be combined with a large scale CPLD/FPGA and a high performance micro controller. Communication protocols will also be installed and then the effective remote control of mobile robot teams will become possible.

Acknowledgement

This work is supported in part by Japan Society for the Promotion of Science Grant-in-Aid for Scientific Research (C) (No. 17500118).

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