# Rapid and Accurate Inter-Robot Position Determination in Robot Teams

Jason Wu, Winston K. Chan, and Geb Thomas

***Abstract*—We describe a rapid and accurate method to measure robot-to-robot separations and headings. The method, which uses narrow bandwidth signals that are well suited for ultrasonic transducers and for dispersive acoustic environments, detects the difference in phase delay of an optical and an ultrasonic signal. A prototype system based on microcontrollers for signal generation and phase delay measurement determined the location of another robot with sub-centimeter accuracy over a 2.5 m range with a 53 ms measurement time. We also describe simple modifications that can be made to increase the range without loss of accuracy and to coordinate measurements among many robots.**

***Index Terms*—Acoustic position measurement, microprocessor applications, position measurements, robot sensing systems, robots.**

## I. Introduction

EXPLORATION of new or unfamiliar terrain by a team of many simple mobile robots has many advantages over exploration by a single sophisticated robot. Foremost is redundancy. The team can continue to function after some, or even most, of its members have failed. This is particularly important when exploring a hazardous terrain, such as a minefield or an unstable structure, where continued exploration is desirable even with a high attrition rate [1]. Second, a team can explore large areas in parallel much faster than a single robot can. Finally, some robots may take on specialized functions so that the team can carry out functions that a single robot, however well equipped, cannot [2]. For example, some robots may position themselves at strategic locations to serve as beacons or relay stations for others [3].

Each robot in a team needs to know the positions of all nearby robots. At the very least, knowing the positions of other robots will prevent collisions and will allow robots to share information [4]. We address the problem of accurately determining the range and direction rather than of tracking robot movement. Doing so greatly simplifies the robot hardware.

In this paper, we describe a method that accurately determines inter-robot distances and headings, and describe its implementation. The method is based on the enormous difference between the speed of light and the speed of sound. A sender simultaneously transmits a light and a synchronized ultrasonic signal while a receiver detecting both signals measures their difference with the knowledge that they were synchronized at the transmitting robot. This is exactly the same way one determines the distance to a lightning strike by timing the difference between the arrival of the lightning flash and the thunder.

Ranging by ultrasonics, or sonar, has long been used in robotics to determine the distance to a target by measuring the time-of-flight (TOF) to and from the target [5]. A major problem is that the direction to the target is difficult to obtain accurately by ultrasonics because the beam has a large angular width. To circumvent this problem, the reflection of a narrow beam of visible or infrared light is often used in conjunction with the ultrasonic reflection [6] although there has been recent effort to determine the direction by examining the reflected ultrasonic waveform carefully [7]. Light alone can be used to obtain distance and direction [8], but this is not commonly done because high-frequency electronics are needed to measure the short optical TOFs. Rather, data from ultrasonics and optics are often fused to form a single, consistent map, although this adds complexity to the software. In these works, a robot detects reflected waves that it itself transmitted. The same challenges of software complexity and hardware limitations arise when the detecting and transmitting robots are different. We describe here a method where inter-robot distances and directions are determined accurately from the ultrasonics data by having robots send timing signals and communicate through one or more optical channels. The technology may be extended to robots in motion.

## II. Principles

The simplest implementation of an inter-robot position determining system would use short light and ultrasonic pulses. The difference in arrival times of simultaneously emitted pulses yields the distance between the transmitter and the receiver. Because ultrasonic transducers are relatively narrow-band devices that distort broadband pulses, it is necessary to determine the TOF indirectly by correlating it with the detection of some feature in the received pulse [9]. The transmitter and receiver should be matched to do this, but matching all possible transmitter and receiver pairs in a team may prove ineffective because of manufacturing variations. A second limitation with a broadband signal is the effect of dispersion in the acoustic environment. If the robots were exploring a long corridor, for example, frequencies below the waveguide cut-off frequency of the corridor would propagate quite differently than frequencies above cut-off. The signal would thus be distorted.

To avoid these problems, we abandon the TOF measurement in favor of a narrow bandwidth technique. The emitted light signal has an amplitude modulation (AM) at a frequency $f_{mod}$.

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The emitted ultrasonic signal consists of a carrier at frequency $f_o$ at the peak of the transducer response that is also amplitude modulated at $f_{mod}$. The light and ultrasonic modulation are in phase at the transmitter, but become out of phase as the two signals propagate at different velocities. The receiver measures the delay $\tau$ between the phase of the two signals to determine the separation $d$ between the transmitter and receiver. The separation and delay are related by

$$d = \tau \left( \frac{1}{c_s} - \frac{1}{c} \right)^{-1} \approx c_s \tau \tag{1}$$

where $c_s$ is the speed of sound and $c$ is the speed of light. Because $c \approx 10^6 c_s$, we may safely neglect the transit time for the light signal. This measurement depends only on a phase difference and is insensitive to variations in $f_o$, $f_{mod}$ and the amplitudes of the signals.

There is an ambiguity in finding the delay. A phase shift $\phi$ of $0 \leq \phi < 2\pi$ cannot be distinguished from one that differs by $2\pi n$, where $n$ is any integer, because the modulation is periodic. Thus, the maximum range without ambiguity is $c_s/f_{mod}$. Increasing the range requires decreasing the modulation frequency or using two or more different modulation frequencies together as a vernier [10].

Each of our prototype robots has an ultrasonic transmitter, an optical transmitter, four ultrasonic receivers and an optical receiver. The four ultrasonic receivers are arranged 90° apart on a circle of radius $R$ while the other components are at the center of the circle. Because our method can determine distances accurately, we use the small differences in the ultrasonic wave delay to these four receivers to determine the direction to the transmitter. Specifically, if the centers of receiver robot **A** and transmitter robot **B** are separated by a distance $D_{AB}$ and **B** is at a heading $\theta_{AB}$ from the front of **A** (Fig. 1), then

$$D_{AB} = \sqrt{\frac{1}{4} \sum_{i=1}^{4} d_i^2 - R^2} \tag{2a}$$

$$\theta_{AB} = \tan^{-1} \left( \frac{d_1^2 - d_2^2 - d_3^2 + d_4^2}{d_1^2 + d_2^2 - d_3^2 - d_4^2} \right) \tag{2b}$$

where $d_i = c_s \tau_i$ is the separation between the ultrasonic transmitter of **B** and the $i$th ultrasonic receiver of **A** determined by measuring the delay $\tau_i$ at the $i$th receiver. The front of a robot is taken to be the side bounded by ultrasonic receivers 1 and 2. In principle, three noncollinear receivers uniquely determine $D_{AB}$ and $\theta_{AB}$, and two receivers determine these with a sign ambiguity in $\theta_{AB}$. The use of four receivers gives redundancy, provides some signal averaging and increases confidence in the measurements. Out of the several possible ways of calculating $D_{AB}$ and $\theta_{AB}$ with four independent measurements, we choose one that treats the four receivers equally. We note that four noncoplanar receivers can determine the three-dimensional coordinates of the transmitter, and can thus be used to map the topography of the landscape. However, we limited our experiments to a planar geometry to demonstrate the measurement principle.

From $D_{AB}$ and $\theta_{AB}$, **A** can determine the relative position of **B** but not its orientation. When the roles are reversed, **B** can determine the relative position of **A** but not its orientation from $D_{BA} = D_{AB}$ and $\theta_{BA}$. If the two robots share the results of their measurements, they each will be able to determine the others orientation. More generally, a large team of robots can create a complete map of robot positions and orientations by measuring the separation and heading between various pairs of robots and sharing the results of these measurements. Although measuring every pair of robots is redundant, the extra information can be used to determine confidence levels and to resolve conflicting measurements [11], [12].

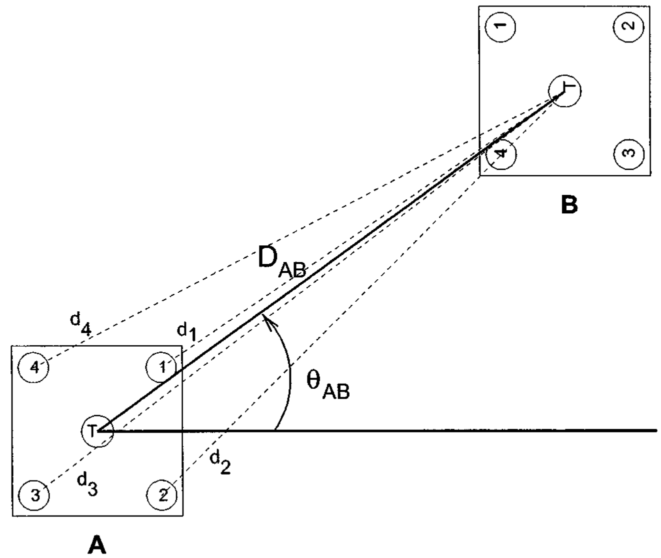


Fig. 1. Geometry of two robots. Each robot **A** and **B** has four ultrasonic receivers at locations *1, 2, 3,* and *4,* and an ultrasonic transmitter at $T$. An optical transmitter and an optical receiver are located with the ultrasonic transmitter. Robot **B** transmits telemetry signals that Robot **A** receives and uses to determine the distances $d_1$, $d_2$, $d_3$, and $d_4$. From these four distances, the inter-robot distance $D_{AB}$ and heading $\theta_{AB}$ can be determined.

## III. METHODOLOGY

We constructed the circuits outlined in the previous section. A microcontroller[1] controlled all of the receiving and transmitting transducers (Fig. 2). With a microcontroller, each robot has few electronic components, most revisions can be made in firmware rather than in hardware, and more complex tasks—such as implementation of communication protocols, data analysis and map generation—are possible with little hardware modification.

A robot's microcontroller is in either a talking or listening mode during the measurements. Using a protocol that can be implemented with some additional hardware to be described below, only one robot talks at a time. Having a single talker avoids interference and confusion arising from multiple talkers. The talking robot generates optical and ultrasonic telemetry signals for other robots to detect. After a fixed period of talking, the talker ends its turn by coordinating the transfer of data among robots, directing another robot to become the new talker, broadcasting the identity of the new talker to all robots and switching itself to the listening mode. In the listening mode, it detects and measures the optical and ultrasonic signals transmitted by the current talker.

[1]Microchip PIC17C4X, Microchip Technology, Inc., Chandler, AZ

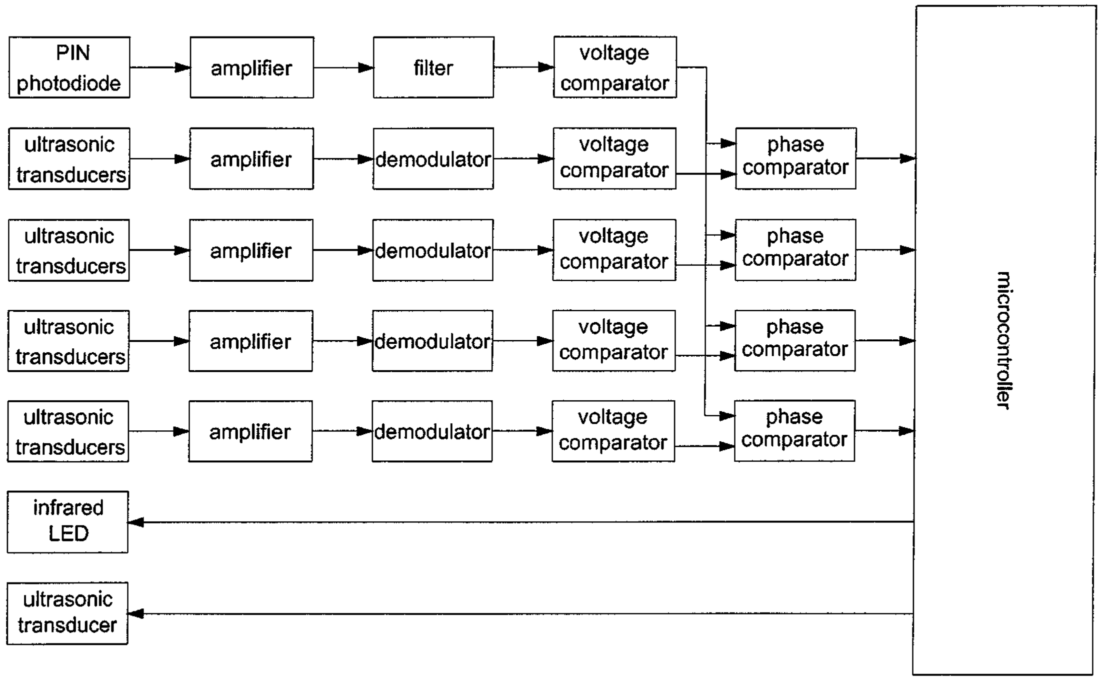


Fig. 2. Block diagram of electronics. The microcontroller generates the optical and ultrasonic signals when the robot is in the talk mode, and it measures the delay between the received optical and four ultrasonic signals when it is in the listen mode.

### A. Transmitter

The microcontroller in the talking mode generates the signal for the optical and ultrasonic transmitters. We chose $f_{mod}$ to be 75.76 Hz, which corresponds to a maximum range of 4.53 m. Although this distance is adequate for tabletop demonstrations, longer distances can be obtained with a lower $f_{mod}$ or a multiple frequency measurement, either of which is easily generated by reprogramming the microcontroller. The modulation is a square wave rather than a sine wave because a square wave provides well defined points for timing and because a square wave can be generated by the microcontroller without additional circuitry. The optical drive signal is simply a 75.76 Hz square wave that drives the infrared light emitting diode (LED) transmitter through a current limiting resistor. The ultrasonic drive signal should ideally be a sinusoidal carrier at $f_o = 40$ kHz, the center frequency of the transducer passband, amplitude modulated with a 75.76 Hz square wave at a 100% modulation depth. To simplify the electronics, the microcontroller generates a 40 kHz square wave that is logically ANDed with a 75.76 Hz square wave. The microcontroller directly drives the ultrasonic transmitter with this signal. We depend on the 5 kHz transducer bandwidth to pass only the fundamental frequency of the carrier along with its modulation sidebands. The transducer bandwidth is wide enough to preserve the square wave modulation.

### B. Receiver

Each robot has four nominally identical ultrasonic receivers placed evenly on a circle of 36 mm radius and a single optical receiver at the center of the circle. The optical receiver consists of a silicon PIN photodiode whose photocurrent is amplified and low pass filtered at 4.5 kHz. A voltage comparator then sharpens the waveform and converts it to a digital signal. Each ultrasonic receiver consists of a transducer, amplifier, AM demodulator and a voltage comparator, all of standard design.

### C. Delay Measurement

The output of the optical receiver and the output of each ultrasonic receiver go to a phase comparator. This circuit generates a pulse with a width equal to the time delay between the optical and ultrasonic signals. The microcontroller, when it is in the listening mode, takes this pulse sequentially from each of the four ultrasonic receivers and measures the pulse width by starting a software counter at the leading edge of the pulse and stopping it at the trailing edge. The distance resolution due to digitization is 0.39 mm. Better resolution if needed may be obtained with a faster microcontroller or with a hardware counter.

### D. Data Analysis

After each measurement is taken, the microcontroller uploads the result to a personal computer to determine $D_{AB}$ and $\theta_{AB}$ from (1) and (2) using $c_s$ = 343 m/s. These calculations would normally be handled by the microcontroller, but we required the raw data for analyzing the system performance. The microcontroller then repeats the measurement for another ultrasonic receiver until all four receivers are measured. Consecutive measurements of a single receiver yield the same result, so averaging is unnecessary. The time required to sequence through all four receivers is 53 ms, so we can detect translation and rotation between moving robots by comparing $D_{AB}$ and $\theta_{AB}$ obtained from one sequence to the next. To avoid systematic errors that arise from measuring robots in motion, the microcontroller cycles through all possible sequences: 1-2-3-4, 3-1-4-2, etc.

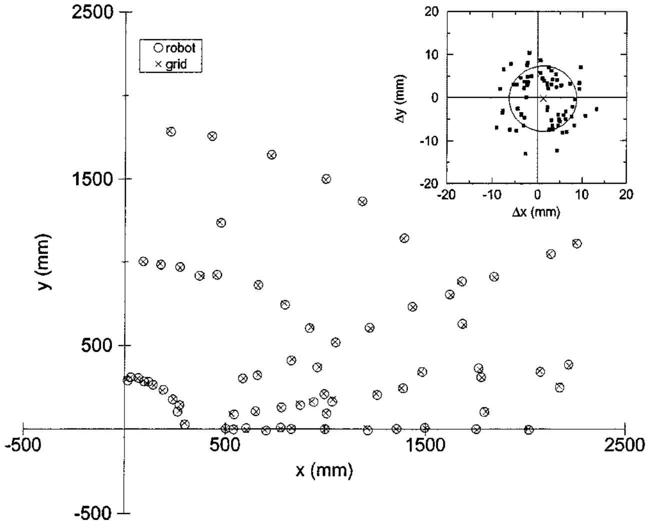


Fig. 3. Positions determined by the measurement system described in this paper (○) and by a grid on the table (x). The difference between measurements (inset) has an average value of $\overline{\Delta x} = 1.23$ mm and $\overline{\Delta y} = -0.20$ mm, marked by the X. One standard deviation, which is 7.55 mm, is indicated by the closed curve.

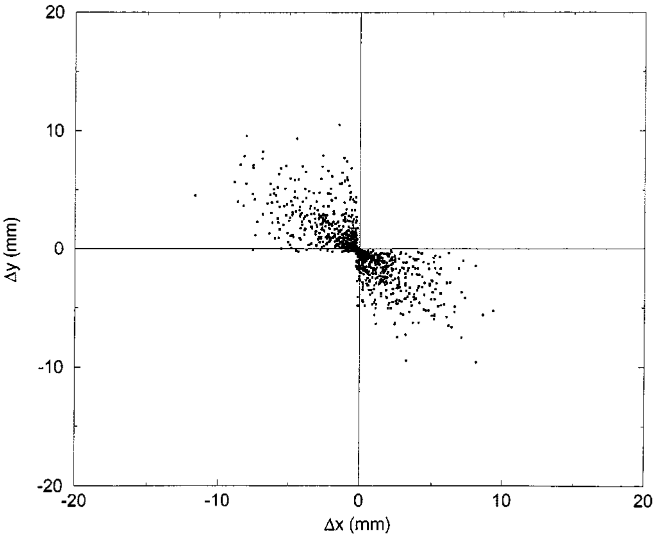


Fig. 4. Monte Carlo simulation of the differences $\Delta x$ and $\Delta y$ where only the effect of $d_i$ digitization is included. The digitization resolution is 0.39 mm, which is the experimental resolution. The digitization truncates any fractional part rather than rounds it, and leads to the slight displacement of the points to the lower left.

## IV. Results

The results of measurements with a pair of robots, one in the talk mode and the other in the listen mode, are shown in Fig. 3. The listener was stationary while the talker was placed at various locations relative to the listener. The measurements were made on a table in a large room with negligible reflection of ultrasound from its walls. From the separation $D_{AB}$ and heading $\theta_{AB}$ obtained by the measurement system with no averaging, we compute the $x$-$y$ coordinates of the transmitter. These are compared with the same quantities measured with a grid laid out on the table by hand. There is excellent agreement between the two. The inset plots the differences $\Delta x = x_{robot} - x_{grid}$ and $\Delta y = y_{robot} - y_{grid}$ between the two sets of measurements. The average difference between the measurements is $\overline{\Delta x} = 1.23$ mm and $\overline{\Delta y} = -0.20$ mm. These small averages, which were obtained without any adjustable parameters in the analysis, confirm the overall quality of the agreement between the robot measurement and the grid. The standard deviation of the difference is 7.55 mm, corresponding to 0.3% of full range. Much of this error is due to the digitization of $d_i$ and to inaccuracies in the grid, as we will now describe.

We did a Monte Carlo simulation of the ranging system to understand the small residual errors. In the simulation, we randomly pick 1000 transmitter positions in the first quadrant within 2.5 m of the origin, calculate the distances $d_i$ to the four receivers, use (2) to obtain $D_{AB}$ and $\theta_{AB}$, and find the difference between the position thus calculated and the original one. As expected, the difference is always zero in the ideal case. Fig. 4 shows the effect of digitizing $d_i$ to a resolution of 0.39 mm as is done in our implementation. The salient feature is that almost all of the difference points lie in the second and fourth quadrants of the $\Delta x - \Delta y$ plane. The points are slightly displaced to the lower left because the digitization process truncates rather than rounds, introducing a small systematic error. The reason points lie primarily in the second and fourth quadrants can be understood as follows: When the transmitter is in the first quadrant of the $x - y$ plane, points in the first and third quadrants of the $\Delta x - \Delta y$ plane correspond to differences in $D_{AB}$ while points in the other two quadrants correspond to differences in $\theta_{AB}$. The distance $D_{AB}$ depends on the sum of all the $d_i^2$'s, so slight variations in $d_i$ are averaged out in the calculation of $D_{AB}$. On the other hand, $\theta_{AB}$ depends on differences between the $d_i^2$'s, so slight variations in $d_i$ can change $\theta_{AB}$ by a large amount. Thus, we expect most of the difference points to lie in the second and fourth quadrants. We also simulated effects of noise and of in-plane and out-of-plane receiver displacements from a perfectly square array, and found that the difference points remained in the second and fourth quadrants. Although the magnitude of the difference is consistent with digitization errors, their distribution over all four quadrants of the $\Delta x - \Delta y$ plane (Fig. 3) is not consistent with any of the simulations. It is likely that errors in the hand-laid grid layout account for points lying in the first and third quadrants.

To determine the accuracy of the measurement system without a precisely laid out coordinate system, we measured the change in signal as the transmitter is translated on an $x$-$y$ micrometer stage from a starting position 300 mm away from the receiver in the $x$-direction. We compare micrometer and robot readings relative to the starting point so that an exact determination of the starting point is not necessary. As Fig. 5 shows, the two readings agreed to better than 1 mm in almost all cases. The average error is $-0.14$ mm in the $x$-direction and 0.006 mm in the $y$-direction, and the standard deviation is 0.61 mm. The error in the $x$-direction is consistent with the truncation error in digitizing $d_i$, and the standard deviation is somewhat larger than the 0.39 mm digitization resolution. This strongly suggests that the quantization of the $d_i$'s is the major limitation to the measurement accuracy.

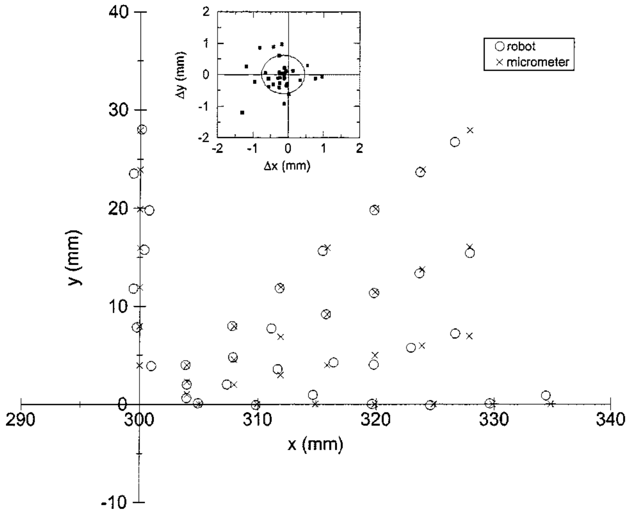


Fig. 5. Sensitivity of measurement to small displacements. The position determined by the robot measurement system (∘) is compared to the position set by an $x$-$y$ micrometer stage (x). Note that the scale is much smaller than that of Fig. 3. The difference between measurements is shown in the inset. The average difference is $-0.14$ mm in the $x$-direction and 0.006 mm in the $y$-direction. One standard deviation, which is 0.61 mm, is indicated by the closed curve in the inset.

## V. Discussion

### A. Field-of-View Limitation

We have demonstrated a method to determine inter-robot distances and headings accurately and quickly. The most important problem to be addressed is the directionality of the ultrasonic transducers. They emit and receive over a cone angle (full angle at half power) of about 60°. Covering the full horizon requires six transducers for each receiver and transmitter. As an alternative to having thirty transducers for a robot, we have tried coupling a single, upward facing transducer for each receiver and the transmitter to a cone that scatters the ultrasound 360° along the horizon. Preliminary measurements suggest that this coupling is very sensitive to alignment and is not efficient. A second alternative is to have a single transducer for each receiver and transmitter. All of the transducers will point in the same direction, so either the robot or a platform for the transducers must rotate to point them in a particular direction. This model is similar to the human visual system where two receivers (eyes) with limited fields of view and pointing in the same direction are mounted on a rotatable platform (head). A map can still be generated, though it would require additional time for the robots to scan their horizons. To ensure that the transducers of the transmitting and receiving robots face each other at some time, the scan rate of one has to be much faster than that of the other. A reasonable compromise between having many transducers and having fast rotating platforms is to use a set of six fixed transducers for the transmitter and a single transducer for each of the four receivers. The four receiver transducers point in the same direction, and can rotate either individually or as a unit. With this arrangement, receivers can slowly scan the horizon mechanically, but multiplexing among the six transmitter transducers can simulate rapid rotation of the transmitter. Regardless of the final geometry, data sharing will help because a robot can obtain information about its blind side from other robots.

The LED and photodetector also have limited fields-of-view. Because the light is incoherent, reflectors can adequately redirect the light across the horizon. Instead of light, radio waves can be used for broadcasting the reference and for communicating. The advantage is that the transducers can be vertical dipole antennas which have radiation patterns that are uniform along the horizon. But with a long coherence length, multipath interference can give rise to areas with dimensions about half the wavelength that have poor reception. This problem can be alleviated by using two or more radio frequencies.

### B. Inter-Robot Communication

Though the major emphasis of this paper is to describe the measurement technique and its implementation, slight modifications of our hardware will allow robots to coordinate measurements and to share the results of the measurements. As already discussed, information sharing is a critical part of generating a complete map. The optical channel, which is used to transmit the phase reference in the measurements, can also be used as a high data rate, free-space, optical communication channel. The additional hardware needed is a circuit that places the microcontroller in a new mode, the communication mode, when requested by another robot. The requesting robot sends an optical signal modulated at a frequency different from $f_{mod}$ before attempting to communicate. A phase-lock loop in the optical receiver of a listening robot detects this signal and generates an interrupt that puts the microcontroller in the communication mode. Once in this mode, the microcontroller can communicate with the requester to exchange data and to receive commands, including one to return it to the listening mode.

## VI. Conclusion

We have described a method that accurately and rapidly measures the distance and heading between mobile robots. In our implementation, a receiver determined the transmitter position with sub-centimeter accuracy over a 2.5 m range with a 53 ms measurement time. The electronics is based on a microcontroller, making the system compact and easily reconfigurable. Although we have only used the system for measurements, simple modifications that we described will allow robots to coordinate measurements and to share the results of their measurements. In this way, each robot can generate a map of the position and orientation of all other robots.

Work is underway to generate an accurate map from this type of measurement, which will have greater uncertainties and which may yield conflicting data in a real life environment.

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