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Measuring The Relative Position And Orientation Between Two Mobile Robots With Binaural Sonar

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ABSTRACT

This paper presents a method for measuring the relative position and orientation between two mobile robots using a dual binaural ultrasonic sensor system. Each robot is equipped with a sonar transmitter that sends signals to two receivers mounted on the other robot. It is assumed (but not implemented in our tests) that the two robots can synchronize events with an infrared or radio link. The receivers measure the distance to the transmitter on the other robot, and a geometric model determines the relative position and orientation of the two robots based on a combination of the data from all four receivers.

This paper describes the theory and experimental set-up to test this technique. Experimental results show the accuracy and operational limitations of the technique.

Key Words: *Odometry, Ultrasonic sensors, Positioning, Phase difference, Binaural.*

1. INTRODUCTION

The pose of a planar mobile robot is defined by its lateral (x, y) and angular (θ) position. In absolute positioning, both lateral and angular positions are measured relative to pre-defined objects, the locations of which are known in advance. Common methods for absolute positioning are triangulation, trilateration, GPS's etc. In relative positioning, on the other hand, the vehicle position is determined relative to its previous position, based on recent motion.

The most common method for relative positioning is odometry, which is based on measuring the rotation of the vehicle's wheels. Odometry offers an independent, easy-to-implement, and fast method for relative positioning, and it does not require prior knowledge of the work environment. However, odometry is subject to several drawbacks, which reduce its accuracy and reliability. First, odometric calculation is an accumulative procedure, therefore errors within the process are also accumulative. As a result, odometry can generate unbounded position errors that increase with travel distance. Another drawback of odometry is its sensitivity to the terrain. Irregularities in the terrain can generate significant

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position errors, which cannot be detected by the odometric system. Odometry is also sensitive to deviations of the diameter of the wheels from their nominal value, and to unbalanced wheel alignment, which can cause slippage of the vehicle's drive wheels.

In spite of the above drawbacks, odometry is used in most mobile robots, and many researchers have developed systems and methods to improve its accuracy and reliability. Borenstein [1995] shows that by using redundant information from onboard encoders, which measure the relative angular position of two mobile robots, odometry errors can be detected and corrected during motion without external references. As a result, the odometric accuracy is 10-100 times greater than that of conventional (2-DOF) mobile robots. Kurazume and Nagata [1994] tested (in simulations) another approach aiming at overcoming the shortcoming of odometry without external references. This approach uses multiple cooperating mobile robots divided into two groups. When members of one group move, the members of the other group remain stationary and provide positioning beacons that members of the first group can use for absolute positioning. After a while, members of the first group stand, and members of the second group move.

Another approach to the independent position determination of mobile robots is based on inertial navigation with gyros and/or accelerometers. Results published by Barshan and Durrant-Whyte [1993], and Borenstein and Feng [1996] show that the accuracy produced in such systems can improve performance of odometry alone.

In some applications the absolute positioning accuracy of the mobile robots is less important than their position relative to other mobile robots or objects in their surroundings. One example is the cooperative motion of two mobile robots jointly carrying a load. In such a case the robots are required to maintain a constant relative position between them while moving towards the target position.

In a different type of application, mobile robots are required to determine their position relative to a fixed object or point e.g. during docking tasks for loading and unloading missions [Shoval et. al., 1996]. Typically, Automated Guided Vehicles (AGVs) and mobile robots require high precision while approaching their docking station – far more accurate than during regular motion. Again, the robot must accurately determine its updated position relative to the docking spot and adjust its motion accordingly.

In this paper we present a system for the measurement of relative lateral and angular position between two mobile robots or between a mobile robot and critical points such as docking stations, narrow passages and doorways using binaural ultrasonic sensors. Our system is closely based on the earlier work by Figueroa and Barbieri [1991], who developed an ultrasonic phase difference measuring system for manipulator arms. Our system also uses an ultrasonic phase difference measuring system, but our application differs in that it measures the relative lateral and angular position of two collaborating mobile robots. Because of the difference in application our implementation of the phase-difference measuring system and its specifications differ substantially from that of Figueroa and Barbieri.

Section 2 describes the general concept of our method, and Section 3 shows the experimental set up and the results of several experiments that investigate the performance of the relative measurement system in various operational conditions. Section 4 analyzes the results and discusses the advantages and limitations of the system. Finally, Section 5 provides conclusions based on our experiments.

2. GENERAL CONCEPT OF THE BINAURAL ULTRASONIC SYSTEM

Ultrasonic sensors (sonars) are commonly used for range measurements between the sensor and solid objects ahead of the sensor. Sonars consist of an acoustic transmitter and receiver, which are sometimes combined into a single transducer. The most common range measurement using sonars is based on the time-of-flight (TOF) of the ultrasonic wave front from the moment of transmitting to the time of receiving an echo. Commercially available ultrasonic sensors operate at various frequencies from 20 kHz to 200 kHz and the ultrasonic wave can consist of continuous or pulsed signals.

2.1 Binaural sonar

Kleeman and Kuc [1995] proved that two sonar transmitters and two receivers are necessary and sufficient for discriminating geometric features (planes, corner and edges) of common objects. They developed a vector sensor that can accurately identify multiple objects in two dimensions and at ranges of up to 8 m. Other systems [Peremans and Van Compenhout, 1993; Sabatini, 1992], consisting of one transmitter and three receivers, can also discriminate between planes, corners, and edges, but they require movement of the sensors, which is equivalent to placing additional transmitters. Barshan and Kuc [1990], Hong and Kleeman [1992], and Sabatini [1992] have suggested systems consisting of one transmitter and one receiver to determine the relative orientation of a plane based on amplitude measurements.

Our dual binaural system uses a total of six off-the-shelf Polaroid ultrasonic sensors. Two Polaroid sensors function as transmitters and four sensors function as receivers as shown in Figure 1. One pair of receivers is mounted on each robot, so that they can receive the sonar signal of the transmitter mounted on the other robot. The transmitters emit bursts of ultrasound (called “chirps”) at a rate controlled by the mobile robots. We assume (but have not yet implemented in our current system) that control and synchronization between the two robots is achieved by radio link. When a transmitter fires a chirp, the two corresponding receivers on the other robot are initialized to a “listening mode,” ready to receive the chirps. A fast measurement system accurately measures the ranges between the transmitter and each receiver as well as the phase difference between the signals arriving at each receiver (and vice versa), using total of 4 ranges. Information is exchanged between the two robots (again using the radio link) or alternatively sent to a remote agent that performs the relative positioning procedure.

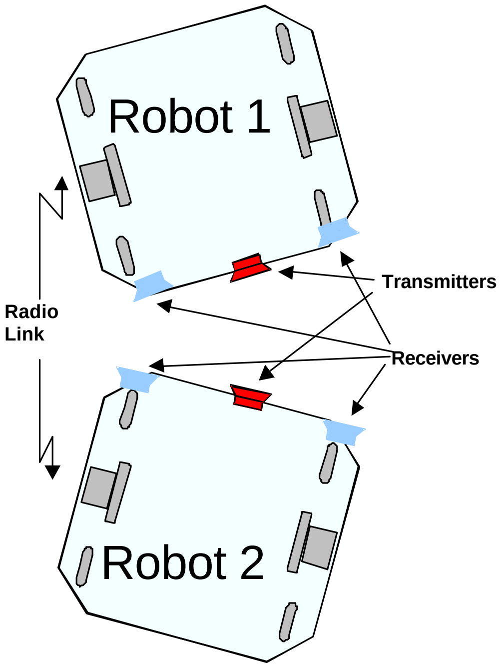

Figure 1: The basic sensor arrangement for measuring the relative position and orientation of two mobile robots using binaural ultrasonic sensors.

2.2 Phase difference

A more refined range measurement method with ultrasonic sensors is based on the phase difference between the transmitted and received signals. Measurement of phase difference is more accurate than the TOF measurement [Figueroa and Barbieri, 1991] due to its higher resolution. However, while the TOF measurement is suitable for long ranges (up to 35 ft) the phase difference measurement on its own is limited in duration to one signal period. According to Figueroa and Barbieri [1991] the transmitted and received waves (ν_t and ν_r, respectively) are given by:

$$v_t = A_t \cos(wt) \qquad (1)$$

$$v_r = A_r \cos(wt - kx) \qquad (2)$$

Where $k = \omega/c$,

c – speed of sound in air,

ω – circular frequency of the wave,

x – distance between the receiver and transmitter or twice the distance between the transducer and the object.

According to Eq. 1 and Eq. 2, the maximum distance that can be detected by the phase difference measurement alone, using a 40 kHz wave, is limited to 8 mm (0.3 in), and for a 80 kHz wave that distance is only 4 mm (0.15 in).

3. THE BINAURAL PHASE-DIFFERENCE MEASURING SYSTEM

Our proposed system is based on a combination of phase difference and TOF measurements, using conventional Polaroid ultrasonic sensors [POLAROID], and a fast data acquisition circuit [Shoval and Borenstein, 1999]. A typical measurement cycle consists of robot 1 sending a radio signal that prompts robot 2 to fire a chirp towards the receivers on robot 1. The two receivers on robot 1 receive the wave front and a logic comparator translates the analog wave signals to a series of binary signals as shown in Figure 2. A First-In/First-Out (FIFO) dual-port memory then records the two binary signals (representing the two ultrasonic waves from the two receivers). When the whole ultrasonic wave is recorded, the computer calculates the time of flight (TOF) of each wave and also compares the signals from the two receivers to determine the phase difference between them. Our experimental set up uses a 2-MHz clock for data recording by the FIFO, resulting in a 0.5-μsec time resolution, which corresponds to 0.15 mm (0.0059 in) lateral resolution. The process is then repeated (actually, this can be done simultaneously), but this time robot 1 emits the chirp for the receivers on robot 2.

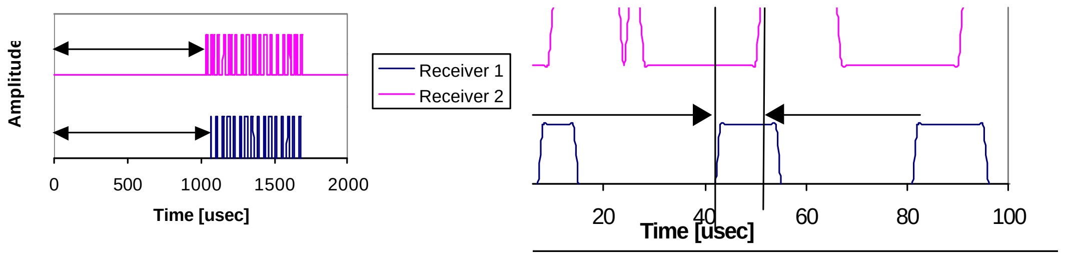

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Figure 2: The combined TOF (a) and phase-difference (b) range measurement, after conversion of the received signals into binary pulse trains in the FIFO.

After all four binary pulse trains (i.e., one from each of the four receivers) have been sampled, the relative position and orientation between the two robots can be calculated. To illustrate this process, consider first the case where the robots are facing in the same direction (as shown in Figure 3).

Let $r_{i,j}$ be the distance between receiver *i* on robot *j* to the transmitter on the opposite robot. Let (X_i^t, Y_i^t) be the location of the transmitter on robot i, measured by a coordinate system attached to the opposite robot. The transmitter is located on one of the intersecting points of the two circles $C_{1,2}$ and $C_{2,2}$ (their radii are $r_{1,2}$ and $r_{2,2}$ respectively) as shown in Figure 3. The selection of the correct intersecting point is trivial because the intersecting point located behind the receivers is automatically invalid. In general, the intersection of two circles with radii $r_{1,2}$ and $r_{2,2}$ and centers at are (x_1, y_1) and (x_2, y_2) respectively is given by:

$$X^i{}_{1,2} = \frac{My_1 + x_1 - MN \pm \sqrt{D}}{1+M^2}$$

and (3)

$$Y^i{}_{1,2} = MX^i{}_{1,2} + N$$

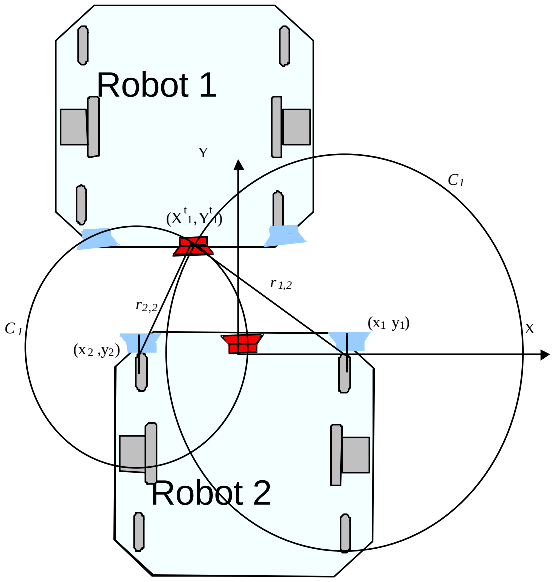

Figure 3: Relative position between the two robots when facing in the same direction.

where

$$M = \frac{x_1 - x_2}{y_2 - y_1} \tag{4}$$

$$N = \frac{x_2^2 - x_1^2 + y_2^2 - y_1^2 - r_{1,2}^2 + r_{2,2}^2}{2(y_2 - y_1)} \tag{5}$$

$$D = (MN - My_1 - x_1)^2 - (1 + M^2)(x_1^2 + y_1^2 + N^2 - 2Ny_1 - r_{1,2}^2) \tag{6}$$

In the case shown in Figure 3, the cordinate system is attached to the center point between the two receivers on robot 2, and the position of the receivers in this system is $(x_1, y_1) = (-b/2, 0)$ and $(x_2, y_2) = (b/2, 0)$, where b is the distance between the two receivers. The calculations in this case requires some modifications to Eq. 6 to avoid singularities in M and N, but provide unique solutions. Note that when the two robots are facing in the same direction, the relative position between them is symetric (i.e. each robot "sees" the opposite robot at the same relative position) due to the symetric ranges measured by the respective receivers ($r_{1,1} = r_{1,2}$ and $r_{2,1} = r_{2,2}$).

In the general case there is a relative lateral as well as angular offset between the two robots, as shown in Figure 4. Similar to the previous case, a coordinate system is attached to each robot at the center point between the two receivers. The relative lateral positions of the transmitters, (X_1^t, Y_1^t) and (X_2^t, Y_2^t) can be determined according the procedure previously described, based on the range measurements of the receivers (two on each robot). The relative orientation between the two robots does not affect the procedure, because a coordinate system is attached to each robot. To determine the relative orientation between the two robots, q, the two robots must share their information regarding the position of their respective opposite robot, using two additional angles - a_1 and a_2 (Figure 4). These angles are uniquely determined once the positions of the two transmitters are determined, according to:

$$a_1 = \tan^{-1}\left(\frac{x_1^t}{y_1^t}\right) \tag{7}$$

$$a_2 = \tan^{-1}\left(\frac{y_2^t}{x_2^t}\right) \tag{8}$$

Once a_1 and a_2 are known, q, can be determined by:

$$q = p/2 - a_1 - a_2 \tag{9}$$

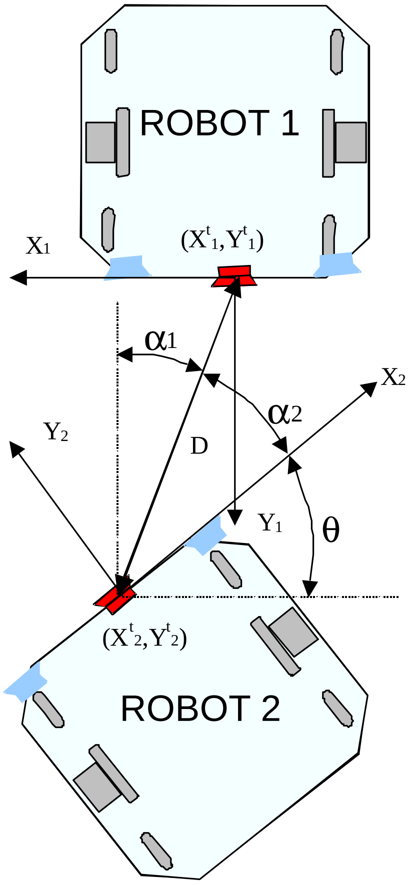

Figure 4: Relative lateral and angular measurements.

In the special case of the two robots being exactly aligned, $\alpha_1 = \alpha_2 = 90°$, resulting in $\theta = 0°$. In the special case of the robots facing in the same direction but with a lateral offset, $\alpha_1 + \alpha_2 = 90°$, again resulting in $\theta = 0°$. And in the special case of the robots being aligned but facing in different directions, $\alpha_1 = 0°$ and $\theta = (90° - \alpha_2)$.

It should be noted that the above procedure requires information exchange between the measurements of the two robots using the radio link. For example, if robot 1 is to compute the relative orientation, θ, then robot 2 must provide its calculation for a_2, and vice versa. Alternatively, if θ is computed by an off-board computer, then robot 1 must submit its calculation for α_1 and robot 2 must submit its calculation for α_2.

4. EXPERIMENTAL SET UP AND RESULTS

This Section describes the experiments conducted in our laboratory with the purpose of establishing the basic feasibility of this method. To investigate the performance of the system, the first experiment was conducted under optimal conditions, where the two robots remained aligned and faced in the same direction, while one robot increased the distances from the other robot along a straight line. The two receivers on each robot were 350 mm apart, and the initial distance between the two robots was 0.5 m. As shown in Figure 5, the measurements of both the relative lateral and the relative angular positions were accurate for distances of up to 5.0 m: The relative lateral error was less than 3 cm for close ranges (up to 3 m) and increases to 10 cm when the range reaches 4 - 5.5 m. Error of the relative orientation between the two robots is maintained at ±0.05° throughout the entire experimental range.

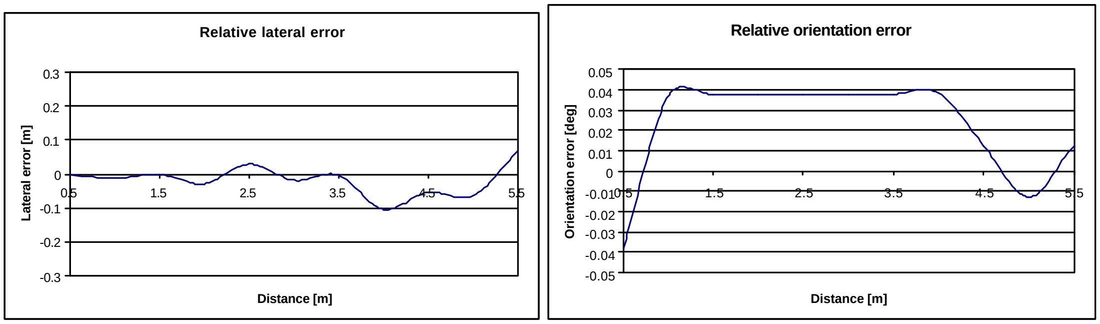

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Figure 5: Relative lateral (a) and angular (b) position between the two robots during increase of range.

The initial conditions of the two robots in the next experiment were similar to the previous one. Both robots were aligned and parallel to each other 1.5 m apart. During the experiment one robot was moved sideways along a straight line and the results are shown in Figure 6. As shown, the lateral and angular measurements were accurate up to an offset of 0.3 m. The maximum lateral error within that range was less than 3 cm, and the maximum orientation error was 1.2°. Average errors within that range were 1.0 cm for the lateral offset and 0.4° for the relative angular position.

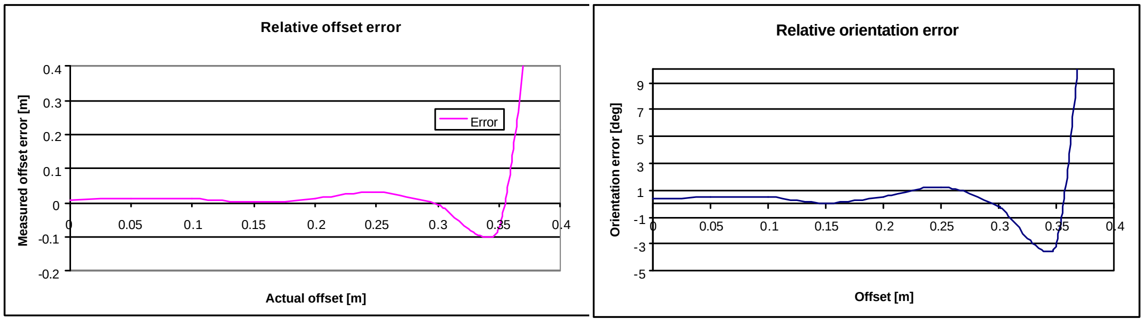

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Figure 6: Relative lateral (a) and angular (b) position between the two robots during relative sideways motion.

Figure 7 shows the results of an experiment where robot 2 remains stationary with an orientation of 9.5° relative to robot 1, which is moving sideways in a straight line along its negative X-direction. As shown in Figure 7a, the measurement of the orientation of robot 2 is stable around the initial value with a maximum error of 0.7° and an average error of 0.02°. Figure 7b shows the position of robot 1, measured in the coordinate system of robot 2. Similarly, Figure 7c shows the position of robot 2, measured in the coordinate system of robot 1. Robot 1 "sees" robot 2 moving in a straight line parallel to its X coordinate from the initial position (0.06,1,443) to the final position (0,29,1.438), while robot 2 "sees" robot 1 moving from (0.23,1.38) to (0.56,1.34

Figure 8 shows the results of the simulator for identical parameters as the experiment shown in Figure 7. As shown, the actual experiment results match the simulated results, with a minor error in offset of 3 cm in the relative position of robot 1 measured by robot 2. This offset can be related to the accuracy of the initial set up of the system, in which small errors are magnified due to the different orientations of the receivers on robot 2 relative to the transmitter on robot 1. No major errors are detected on the relative position of robot 2 measured by robot 1. Comparison of the simulated and actual results shows accuracy better than 1 cm in measurement of the relative position of robot 2 by robot 1 and 3 cm offset of relative position of robot 1 by robot 2. When compensating for the constant offset of 3 cm, the absolute error between the simulated and actual results is again smaller than 1 cm.

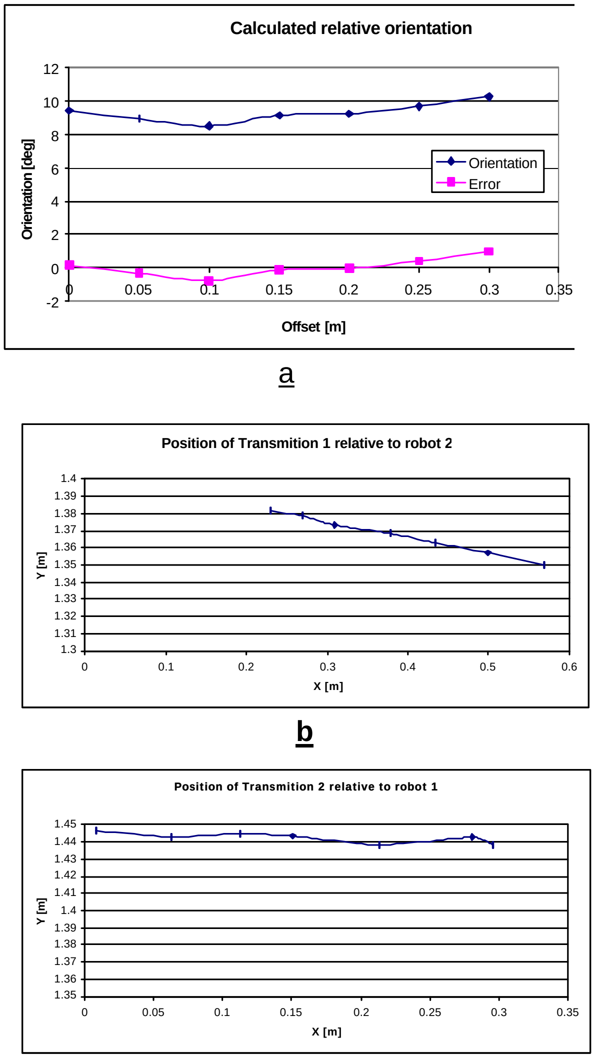

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Figure 7: Measurements of relative lateral and

The next series of experiments examines the effect of various parameters on the consistency and accuracy of the system's performance. The parameters examined in these tests are related to actual real environment conditions of mobile robots due to uneven surfaces, bumps, holes, uneven wheel's diameter, uneven load etc.

4.1 Height difference between the robots

In this experiment a height difference between the two robots is introduced (Figure 9a). This experiment represents the case where one robot is higher than the other due to uneven surfaces, bump, or holes. The robots are aligned and parallel to each other, 1.5 m apart. According to Figure 9b and Figure 9c, measurements of the relative orientation and lateral positions between the two robots are accurate up to a height difference of 0.25 m, and deteriorate sharply above that range. The lateral relative position errors remain under 4 cm and angular position error remains under 1.5°.

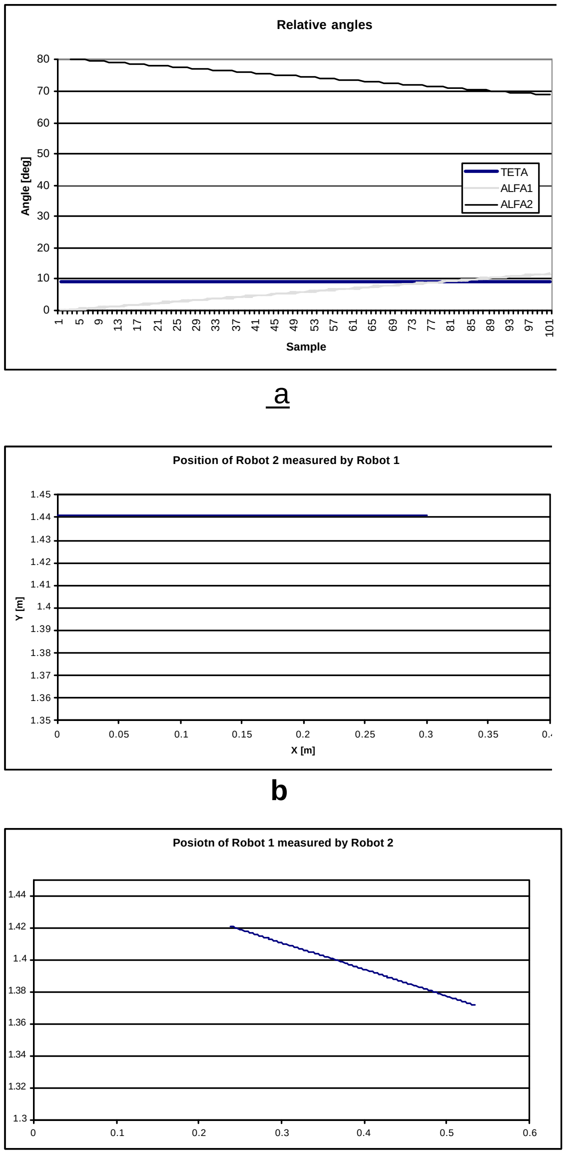

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Figure 8: Simulated measurements of relative lateral and angular positions

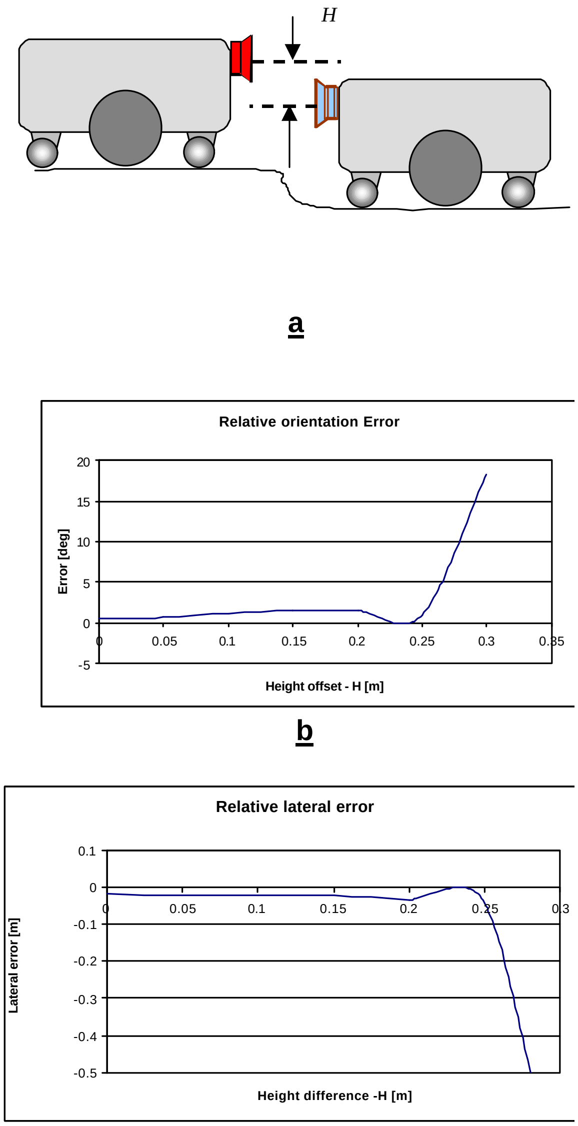

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Figure 9: Height difference between transmitter and receivers

4.2 Relative vertical tilt between the robots

On rugged terrain the relative vertical tilt between the two robots is affected (see Figure 10a). As a result, the transmitting sonar is also tilted relative to the receivers on the opposite robot. The result of this experiment, shown in Figure 10b, indicate a good relative angular measurement for tilt angles of up to ±35°. The accuracy of the relative lateral measurement in this experiment is similar to the angular measurement, and therefore is not shown in Figure 10.

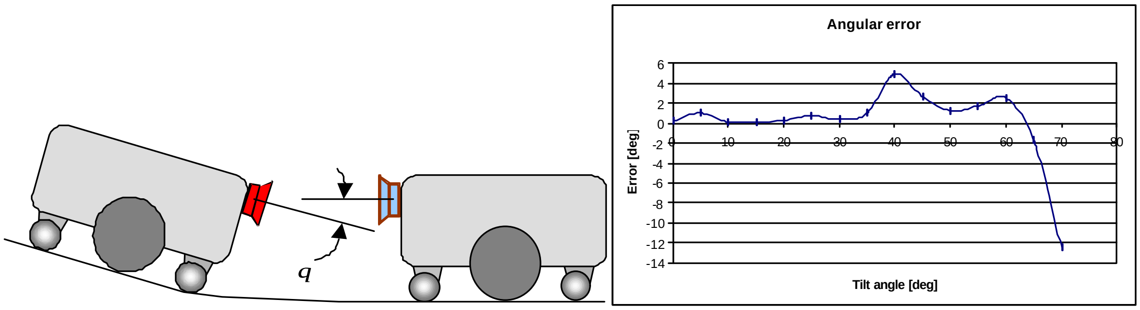

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Figure 10: Effect of tilt along the vertical plane.

4.3 Angular constraints

This experiment investigates the system limitation in measuring the relative orientation between the two robots. As with the previous experiments, the two robots are aligned and 1.5 m apart, while the relative orientation is gradually increased as shown in Figure 11a. The result of this experiment, shown in Figure 11b, indicates that the orientation is accurately measured within a range of ±25° (averaged error of 0.06°). Outside that range the error increases sharply to unaccepatable values, together with a sharp increase in the error measurements of the relative lateral position.

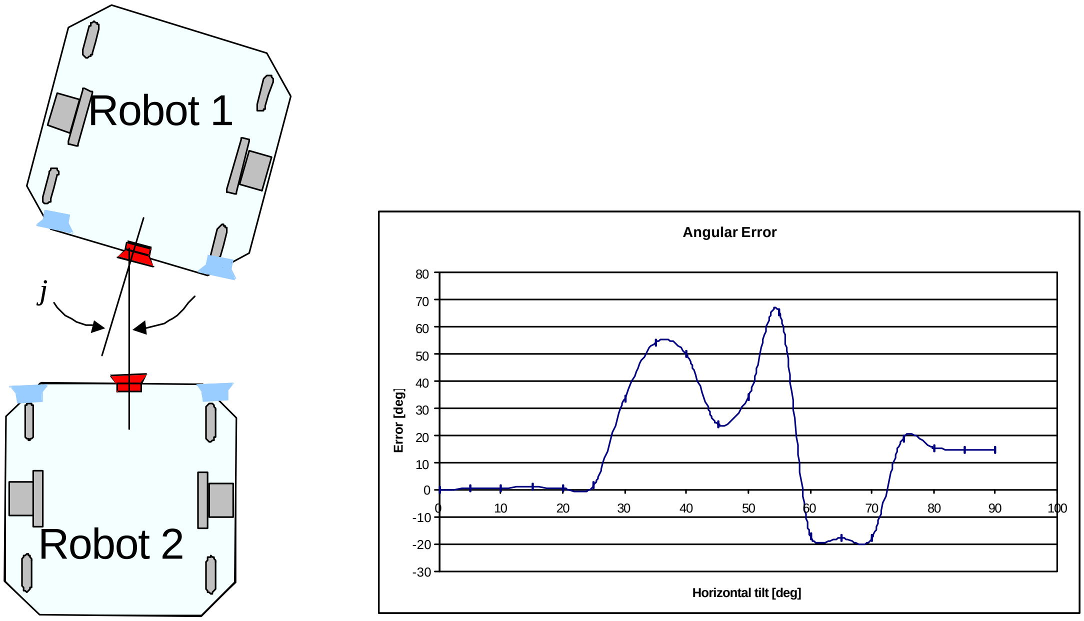

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Figure 11: Relative angular constraints

4.4 Effect of nearby objects

Finally, the effect that nearby objects have on the system's performance is investigated. For this purpose objects are placed in strategic positions between the two robots in order to add reflected ultrasonic signals to the original wave, or to obscure the perception of signals by the receivers. The objects selected for these tests have smooth and straight surfaces so that the ultrasonic wave fronts are specularly reflected.

Figure 12 describes these experiments: In Figure 12a the object is positioned parallel to the direction of propagation of the ultrasonic wave front, but it does not directly obscure the line-of-sight between the two robots. This configuration does not interrupt the travel of the ultrasonic wave but can generate additional noise, caused by specular reflections. In Figure 12b the object partially obscures one of the receivers allowing only partial perception of the ultrasonic wave by that receiver, and in Figure 12c the object totally obscures one receiver. In Figure 12d one object fully obscures the line-of-sight between the two robots but another two objects are positioned alongside the robots to reflect the ultrasonic wave. This way only indirect signals are perceived by all receivers. In all these experiments the two robots are aligned and facing in the same direction, with 1.5 m between them.

Table 1 summarizes the results of these experiments. Each experiment is repeated 5 times and the average and standard deviation of the relative angular and lateral positions, are determined by the system. As shown, objects that do not directly obscure the line-of-sight between the two robots (experiment #2) do not effect the system's performance (almost identical results as with no objects). However, when an object partially obscures the line-of-sight, the performance significantly deteriorates, and when the object totally obscure the line-of-sight the accuracy continues to deteriorate. When the two robots are partially or fully obscured by an object (experiment #5), the method cannot be applied due to insufficient data.

5. DISCUSSION

Analysis of all the experimental results reveals one major drawback of the relative measurement system. Since the method is based on the combined measurement of TOF and phase-difference, it is sensitive to the clarity of the received signals in terms of the magnitude and shape of that signal (compared with the original transmitted signal). This is due to the fact that the amplitude of the ultrasonic signal decreases at a ratio of 1:100,000 as the range changes from 3 to 35 ft [Polaroid]. These results are also consistent with previous results by Kleeman and Kuc [1995] and Bozma and Kuc [1991] that showed the effect of the angle of the receivers with respect to the transmitter. The signal generated by the Polaroid range sensor varies significantly within the propagation cone, and the intensity is reduced as a function of deviation from the center of the wave front (see Figure 13). Since our system translates the analog echo received by the sonars to a series of binary signals (Figure 2), those parts of the echo under the threshold value are ignored. As a result, only the central segment within the propagation cone affects the measurement calculation. The experimental results show that when the transmitter is not aligned with the receivers, due to either lateral or angular

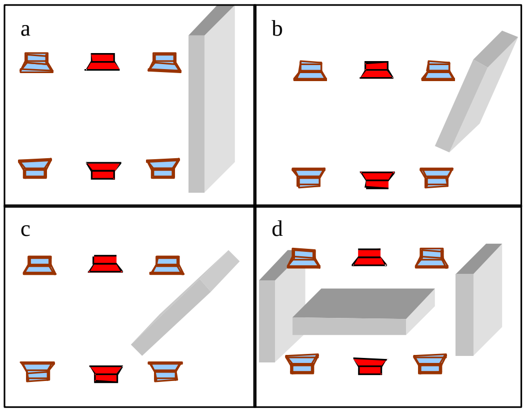

Figure 12: The effect of nearby objects.

Table I: Results of either none, partial, or the full obstruction of the line-of-sight between the robots

Experiment	Average orientation error [°]	Average lateral error [m]
No objects	0.038	0.0023
Objects in proximity (no direct obstruction of line-of-sight)	0.036	0.0021
Object partially obscures line-of-sight between transmitter and one receiver	3.65	0.019
Object fully obscures line-of-sight between transmitter and one receiver	21.38	0.137
Object partially obscures both receivers	-	-

offsets, the measurement is inaccurate or false. This also occurs when objects partially obscure the line-of-sight or when the signal is reflected from objects before reaching the receivers. This explains the small acceptable lateral offset (0.35 m) shown in Figure 6, compared with the large acceptable maximum distance (5.5 m) obtained in the experimental results shown in Figure 5. It also explains the difference between the horizontal orientation limitations (±25°), shown in Figure 11, compared with the vertical tilt limitations (almost ±60°) shown in Figure 8. In the first case the receivers are subject to asymmetric wave intensities, which effects the calculation of the relative orientation between the two robots, as compared with symmetric intensities in the later case.

The system provided accurate measurements better than 0.05° for relative orientation, and 1 cm for lateral position between the two robots, as long as the sideways offset is smaller than 0.25 m for a distance of 1.5 m between the robots. Beyond this range, measurements become inaccurate due to the sensors' beam pattern shown in Figure 13. Signals within the ±10° range (corresponding to a 0.25×1.5 triangle) are strong enough to pass through the logic comparator and be included in the calculation, while weaker signals are ignored.

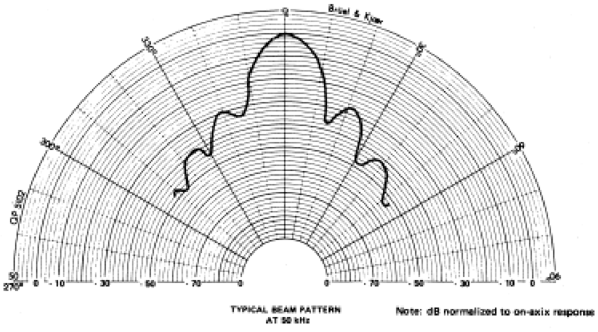

Figure 13: Typical beam pattern of the Polaroid ultrasonic sensor at 50 kHz [Polaroid]

6. CONCLUSIONS

A binaural ultrasonic system aiming at measuring the relative position and orientation of two mobile robots was examined. Each robot is equipped with one transmitter and two receivers pointing towards the other robot. The system is based on the combined measurement of Time-of-flight (TOF) and the phase-difference of ultrasonic signals transmitted by each robot and perceived by two ultrasonic receivers mounted on the opposite robot.

Experiments included several tests, in which the effects of different parameters corresponding to various possible configurations of the robots were tested. Results of these experiments indicate that measurement of relative position using the binaural ultrasonic system is applicable for cases where the ultrasonic beam is perceived clearly and consistently by the receivers. The clarity of the ultrasonic signal depends mainly on the lateral and angular position of the receivers relative to the conical wave propagation profile, as well as on reflections from objects and obstruction of the line-of-sight between transmitters and receivers. It was found that there are limitations on the relative orientation of the transmitter or the receiver and to the distance between the receivers and the transmitter. Tilt of the transmitter in any possible direction, as well as vertical tilt of the receivers, did not affect the performance of the angular measurement system within ±30°. On the other hand, horizontal tilt of the receivers was accurately detected within ±0.1° for small tilt angles and ±5° for larger angles, up to a tilt of ±30°. These figures can be improved using more sensitive hardware that incorporates the weaker parts of the echo that are currently being ignored, in addition to the major part of the echo in the central propagation cone.

The described method can assist multi-robot systems where cooperation is required in terms of relative position and orientation. In addition, the system can be implemented in tasks where a single robot is required to accurately position itself against other point. For example, a stationary transmitter/receiver setup can be installed in docking stations, doorways or narrow passageways to guide the robot to the desired position and orientation regardless of the accuracy of its other positioning systems. The simplicity of operation and the low cost for the obtained accuracy make the system advantageous for implementation is multi-robot system or in industrial environments.

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