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MEASUREMENT OF ANGULAR POSITION OF A MOBILE ROBOT USING ULTRASONIC SENSORS

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Abstract

Ultrasonic sensors are commonly used in robotics for range measurement in obstacle detection and avoidance systems. They have also been used for localization by map matching techniques. This paper presents a novel use of ultrasonic sensors for the measurement of angular position of a mobile robot relative to a known ultrasonic source. The method is based on measurement of the phase difference of an ultrasonic wave by two receivers. The receivers are positioned on-board a mobile robot, and the phase difference therefore represents the angular position of the robot. The paper presents an experimental set up, in which the technique was tested. Experimental results show the accuracy and operational limitations of the technique.

Key Words: Odometry, Ultrasonic sensors, positioning, Phase difference.

I. 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, vehicle position is determined relative to the vehicle's previous position, based on its recent motion. The most common method for relative positioning is odometry, which is based on measurements of the vehicle's wheels' rotation. 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 position errors, which cannot be detected by the odometric system. Odometry is also sensitive to deviations of the vehicle's wheels diameter 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. Borenstein's mechanism, which also provides omnidirectional maneuverability, is based on a compliant linkage that physically connects two differential-drive robots, and two absolute rotary encoders (Figure **1**). The high accuracy of this mechanism is achieved due to the fact that lateral odometric errors are initially generated by small angular errors. Detection of these angular errors and appropriate corrections can significantly reduce lateral errors as shown by Borenstein's work.

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In this paper we present a system for the measurement of angular position of a mobile robot using ultrasonic sensors. Our system is closely based on the earlier work by Figueroa and Barbieri [1991], who developed a phase difference measuring system for manipulator arms. We then suggest a method, in which two mobile robots collaborate to measure their angular position relative to each other, and share odometric data to improve their positioning accuracy. Section II describes the general concept of the method, and Section III shows the experimental set up and the results. Section IV suggests a method for implementing the system in a virtual compliant linkage mechanism, and discusses the advantages and limitations of such a system. Finally, Section V provides conclusions based on the experiments conducted so far.

II. General concept

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. Measurements are 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. When the ultrasonic wave consists of more than a single pulse, the phase difference between the signals can also be measured. 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 30 ft) the phase difference measurement is limited to one signal period. According to Figueroa and Barbieri [1991] the transmitted and received waves (ν_t and ν_r, respectively) are given by

$$v_t = A_t \cos(wt) \tag{1}$$

$$v_r = A_r \cos(wt - kx) \tag{2}$$

Where $k = \omega/c$,
c – speed of sound in air,
ω – circular frequency of the wave,
x – distance between the receiver and transmitter.

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

In this work we propose to use the phase difference measurement to determine a mobile robot's angular position relative to a known ultrasonic source. The general concept of the proposed system is shown in Figure 2: two ultrasonic sensors are attached to the sides of the robot, and serve as receivers. A third sensor is positioned at an off-board location. This sensor only transmits signals at a rate controlled by the mobile robot (control and synchronization can be achieved by radio link but in our benchtop

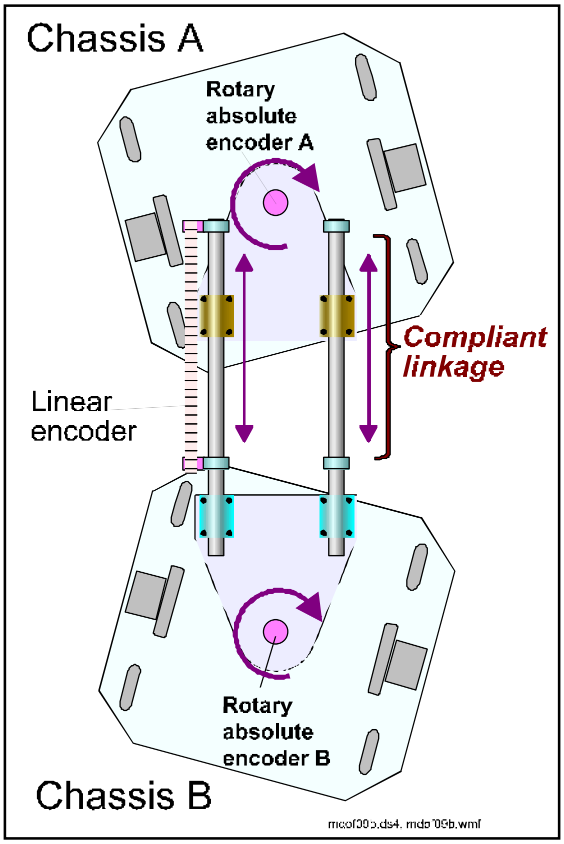

Figure 1: The OmniMate platform can detect and correct odometry errors by using redundant encoders.

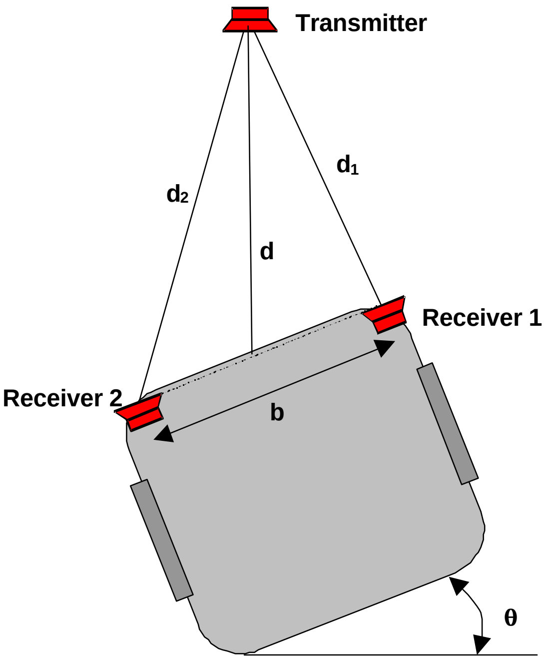

Figure 2: The basic concept for measurement of angular position.

set-up a wired link was used). When the transmitting sonar fires an ultrasonic wave, the two receivers are set for "listening mode" ready to receive the signals. A fast measurement system calculates the phase difference between the received signals in both sonars, where the magnitude of the phase difference is proportional to the difference of the Euclidean distance between the receivers and the transmitter. The angular position of the robot, θ, can therefore be determined according to

$$q = \sin^{-1}\left(\frac{d_2^2 - d_1^2}{2bd}\right) \tag{3}$$

Where

d_1 and d_2 – distances between the transmitter and the respective receivers.

d – distance between the robot's center and the transmitter.

b – distance between the two receivers.

Equation (3) can be further simplified assuming

$$d = \left(\frac{d_2 + d_1}{2}\right) \tag{4}$$

Resulting in

$$q = \sin^{-1}\left(\frac{d_2 - d_1}{b}\right) \tag{5}$$

Note that Eq. (5) does not depend on the distance between the transmitter and the robot (*d*), nor does it require the absolute measurement of distances between the transmitter and the two receivers (d_1 and d_2). The angular position in this configuration is determined only by measuring the difference in the distances of the receivers from the transmitter (d_1 - d_2). This difference is directly determined by the phase difference measurement.

III. Experimental set up and results

This section describes the experimental set up used for testing the concept of angular position measurement using ultrasonic sensors. The experimental set up consists of two ultrasonic receivers, one ultrasonic transmitter, a control computer and a fast data acquisition circuit. The sensors used in this experiment are from the commercially available Polaroid ultrasonic ranging system that includes an electrostatic transducer and an electronics circuit board. The Polaroid sonar transmits sixteen ultrasonic pulses at 49.4 kHz, with a detection range of 18 in – 33 feet (47 cm - 10 m). The absolute accuracy of the sonars and the ranging board is ±1% of the reading over the entire range [Polaroid]. Figure 3 provides a schematic overview of the set up. The computer controls the operation of the two receivers and the single transmitter. Data from the receivers is buffered by a fast acquisition circuit, which enables recording data at a rate of 1-40 MHz.

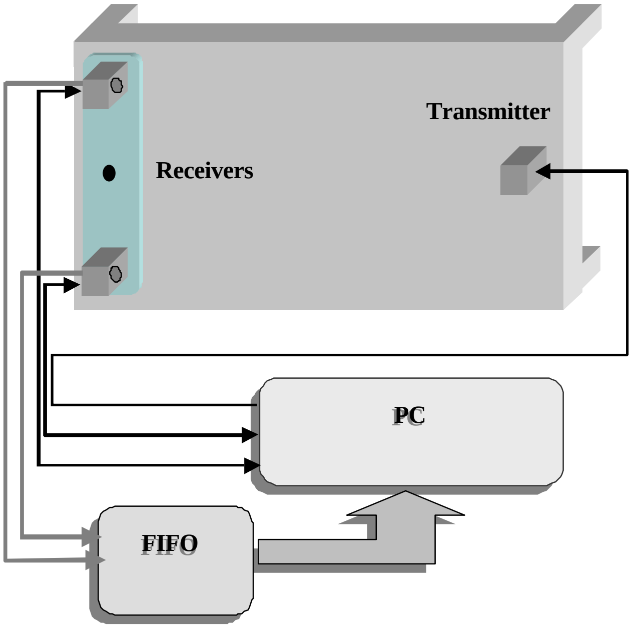

Figure 3: Schematic overview of the experimental set-up.

Data arriving from the two receivers is processed by a logic comparator that translates the ultrasonic wave signals to digital signals. An 8-bit First-In/First-Out (FIFO) dual-port memory then records the two digital signals (representing the two ultrasonic waves from the two receivers), which are processed by the PC. The FIFO loads and empties data on a first-in/first-out basis, at rates of up to 40 MHz. When a signal arrives at one of the sensors, the FIFO records its data, and when the whole ultrasonic wave is recorder, the computer compares the signals from the two receivers to determine the phase difference between them. The computer also measures the distance between the transmitter and the receivers by the regular time-of-flight (TOF) technique, using the Polaroid range board. The calculation are performed at a rate of 5 Hz, enabling continuous detection of changes in the angular position of the receivers, as well as changes in the lateral position of the receivers relative to the transmitter. In our test-bed the receivers are mounted on a rotating platform 17.5 in (45 cm) apart, and the horizontal distance between receivers and transmitters is in the range of 33-79 in (0.85-2 m). The lower value of the distance range is due to the fact that the ultrasonic wave is transmitted in a conical propagation pattern with an opening angle of 30°. A distance shorter than 35 in (0.88 cm) would allow the conical wave propagation envelope to pass between the two receivers with no detection of the signals.

Since wit the Polaroid sonars each ultrasonic wave consists of 16 periods, each lasting 20 μsec, the total wave duration is 320 μsec. Our experimental set up uses a 2-MHz clock for data recording by the FIFO, resulting in a 0.5-μsec time resolution, which is proportional to 0.0059 in (0.15 mm) lateral resolution. Assuming a distance between receivers of b = 17.7 in (450 mm), the angular resolution of the system is given by

$$\Delta q = \sin^{-1}\left(\frac{\Delta d}{b}\right) = \sin^{-1}\left(\frac{0.15}{450}\right) = 0.02^{\circ} \tag{6}$$

Figure 4 shows a typical wave pattern as recorded by the FIFO. As shown, each wave consists of 16 periods, with a phase difference between them. The waves are shown before filtering and processing by the measurement unit.

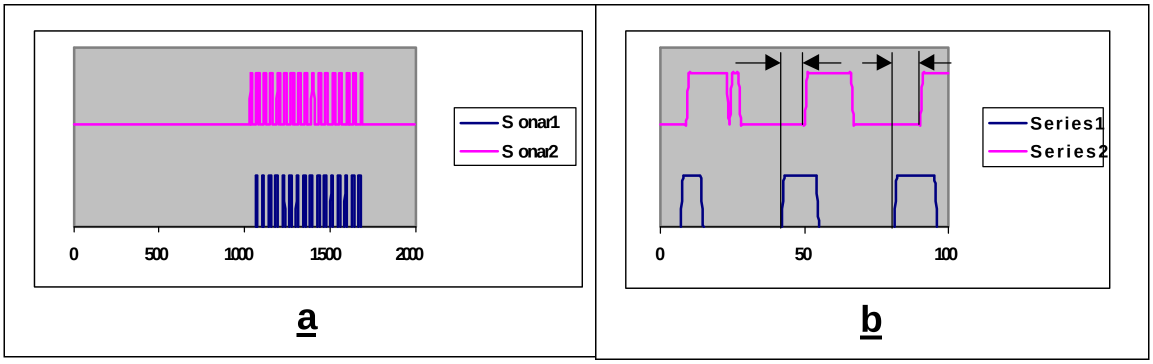

Figure 4: Received signals for both sonars. (a) Typical digitized signal pattern; (b) phase difference

Based on the set-up of Figure 3, a series of experiments were conducted to test the accuracy, repeatability, and operational limitations of the system. In the first series of experiments the receivers remained stationary while the angular position was calculated at a rate of 5 Hz. Table I summarizes the results of these experiments for various reference angular positions. The reference angle (column I in the table) is the actual orientation of the sonars measured manually. The averaged calculated angle (column II) and standard deviation (STD) of the calculated angle (column III) refer to the angular position of the sonars determined by the phase difference measuring system over the duration of the experiment (15 sec). The fourth column shows the difference between the actual and the averaged calculated angular position and represents the system accuracy. As shown in the table, averaged calculated angular positions are accurate within ±0.1° for small angles (<15°) and accuracy decreases as reference angles increase. This result is expected since the phase difference measurement is most suitable for small lateral displacements (proportional to small angular displacements).

Table I: Experimental results.

Reference angle [°]	Averaged calculated angle [°]	STD for averaged calculated angle [°]	Difference [°]
0.0	0.01	0.02	0.01
0.2	0.25	0.05	0.02
0.4	0.50	0.08	0.04
0.7	0.83	0.03	0.07
1.0	0.96	0.17	-0.08
1.2	1.33	0.14	0.07
2.5	2.53	0.03	-0.00
6.3	6.38	0.06	0.02
12.5	12.49	0.17	-0.01
19.1	18.48	0.13	-0.60
25.4	24.17	0.21	-1.28
29.0	28.92	0.16	-0.12
38.1	33.91	0.04	-4.27

In the next set of experiments the effect of lateral and angular position of the transmitter relative to the receivers was tested. Results of this experiment show that as long as the receivers are within the conical wave propagation envelope, the system can detect the signals and perform the calculation. However, best results are achieved when the receivers are in the center of the conical envelope (±10^o), as signals are stronger and clearer within this range. These results conform to the Polaroid data sheets [POLAROID] regarding the typical beam pattern for the ultrasonic range system operating at 50 kHz.

Also, the effect of small changes in the lateral distance between transmitter and receivers was tested. For the given range, 35-79 in (0.88-2 m), no significant changes in the system's performance were observed as a result of changes in that distance.

Next, the robustness of the system to noise generated by reflections from nearby objects was examined. Initially noisy data caused erroneous results as original ultrasonic signals were mixed with reflected signals. However, an additional module, which merges the TOF and Phase Difference methods, reduces the amount of noisy data and provides more reliable and accurate measurements. Figure 5 shows a schematic description of this module. The assumption behind this module is that changes in lateral distance between the transmitter and the receivers are slow. Based on this assumption we empirically determined a threshold that rejects any reading that suggests a relative speed of more than 59 in/sec (1.5 m/sec). This measure allows reliable prediction of the change in lateral distance between samples. The TOF method that measures the absolute distance between the transmitter and the receivers at sample interval i (T_i) determines the estimated time of flight of the signal for sample $i+1$ (T^p_{i+1}). This value is used by the FIFO controller, which enables data recording only one millisecond before the original signals is expected to arrive at the receivers. Once the two sonars receive the signal, the FIFO is disabled from recording further data until the next signal is expected. This way the FIFO records the incoming data for only a short period of time – the time the original signal is expected - therefore reducing the probability of erroneous signals being recorded.

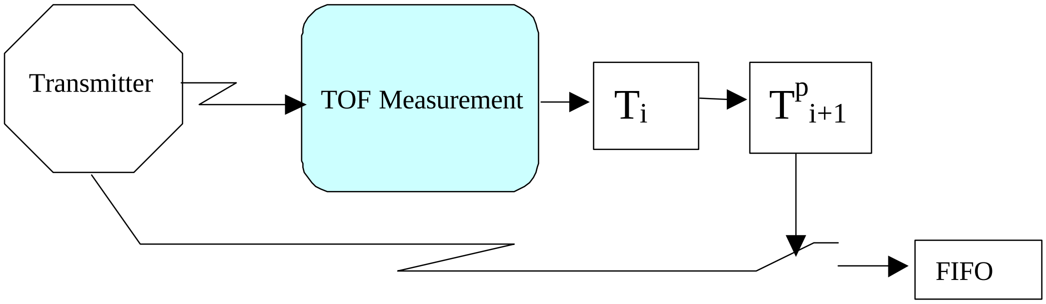

Figure 5: The FIFO time enable module

Finally, the system dynamic performance was examined. In this test, the platform carrying the receivers was continuously rotating, therefore gradually changing the reference angular position. The results of the phase difference calculations are compared to angular measurement performed by the TOF system. In the first test changes in the reference angle were slow. As shown in Figure (6a), the angular measurements in both systems are similar, with no time delays or discontinuities. However, when a rapid change in the reference angular position is introduced to the system (Figure 6b), the phase difference measurement system updates it calculation faster than the TOF measurement system. This is due to the fact that the TOF system requires more filtering of the incoming data, which generates an averaged delay of 0.25 second. For slow changes in the reference values this delay is negligible, but for fast changes it becomes significant for the system's performance. However, the TOF method is more reliable in following dynamic changes for reference angles larger than 0.5 rad (28°) as this value is closer to the limits of the phase difference method.

IV. Conclusions

This paper presents a method for measurement of angular position of a mobile robot using ultrasonic sensors. The method is based on measurement of the phase difference of an ultrasonic wave transmitted by an off board sonar and received by two on-board ultrasonic receivers. The receivers are positioned at the two edges of the mobile robot, and therefore the phase difference is proportional to the angular position of the robot. A series of experiments show the accuracy and reliability of the method both for static and dynamic conditions. The experimental results show accuracy better than 0.1^o for angular positions smaller than ±20^o, and maximum operation range of ±30^o. The fast and accurate measurements are particularly advantageous in dynamic environment where ultrasonic localization method based on time-of-flight calculation is too slow and inaccurate.

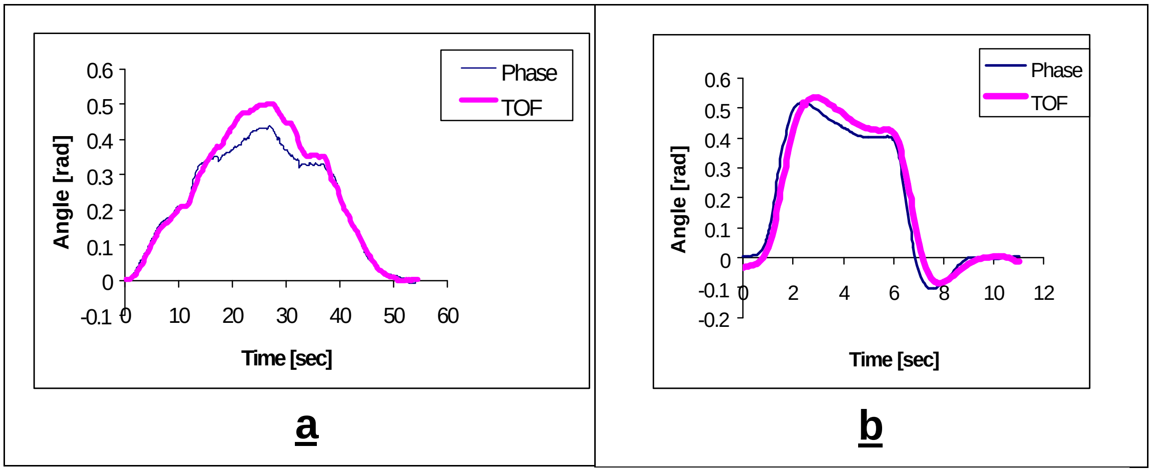

Figure 6: Response to dynamic changes. (a) slow; (b) fast

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V. References

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