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Relative Positioning System Using Inter-Robot Ultrasonic Localization Turret

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Abstract — **This paper focuses on the problem of relative localization system in collaborative environments based on our previous proposed relative localization methodology. We propose a low cost hardware module to achieve a relative positioning system used in research scope to develop some methods, techniques and algorithms in Multi Mobile Autonomous Robotic Systems (2MARS) applications. We discuss about existing hardware modules in literature by showing some constraints. We present some important design aspects of our proposed relative positioning system using the low cost hardware module: Inter-Robot Ultrasonic Localization Turret (IRULT).**

Keywords—omnidirectional; indoor; ultrasound; odometry.

I. INTRODUCTION

Communication between two robots in Multi Mobile Autonomous Robotic Systems (2MARS) is a very important aspect. Communication frame must be kept synchronized [1], must reach the destination at the right time and must contain the right information. One of the most important information in 2MARS applications is the origin of the signal and the coordinates from where are these coming from [2]. There are two different technologies to achieve a communication between two robots: electromagnetic waves and mechanical waves. Electromagnetic waves (for example: radio signals) are used in communication, but because the propagation is omnidirectional, propagation paths are complex and the propagation speed is too high, the coordinates of the incoming data cannot be determined with a good accuracy. An opposite electromagnetic wave example is the laser with a very narrow spectrum. Lidar (radar based on laser beams) is a method for optical distance and speed measurement used in many applications such as autonomous vehicles, robotics, spaceflight, surveying and many others. Their problem is the prohibitive cost for many categories of applications. Mechanical waves (for example: ultrasonic signals) propagate at a speed ratio 10^6 times slower than electromagnetic waves, which has the advantage that the signal's time of flight (TOF) can be measured [3] and thus, accurate origin coordinates of the communicated data can be determined [4].

In this paper we present a low cost hardware module to achieve a relative positioning system used in research scope for 2MARS applications. We discuss about existing modules in literature and some important design aspects of our proposal.

II. EXISTING HARDWARE MODULES IN 2MARS LOCALIZATION

A. *Modules with an ultrasonic transmitter and a ring of multiple receivers*

In [5] and [6] is described a long-range sonar operator with one central composite transducer that emits a sonar pulse in all directions, and eight ultrasonic receivers mounted in circle at 45 degrees to each other, thus covering 360 degrees. The problems of these hardware modules are:

- The transmitter is not typical; a composite transducer is hard to find on the sensors market.
- At least 8 external amplifiers are needed, one for each ADC channel, which results in increasing the cost besides the cost of the 8 transducers.
- In [7] it is shown that the misalignment angle is one of the factors that influence the TOF-Error. In this case, eight receivers are not a consistent coverage for high accuracy localization on greater distances.

B. *Modules with only one transducer and an acoustic reflector cone*

In [8] is presented a module consisting of an ultrasonic transducer with two functions: emitter and receiver. The transducer is positioned to face straight up and all incoming and outgoing ultrasonic waves are reflected by an acoustic reflector cone. These hardware modules have some problems:

- It is not discussed at all about ultrasonic attenuation using an acoustic reflector cone; it is not known if there are propagation losses due to reflection. If the beam intensity is lower after reflection then maximum propagation distance is smaller.
- It is very difficult to maintain on all modules the same angle of incidence for the reflected beam by the acoustic reflector cone, because the cones are not identically constructed.
- With these modules obstacles cannot be identified correctly.
- Sometimes there is a destructive interference. Obstacles can influence an incorrect distance measurement because at certain distances between the robots, the wave propagated in the direct path interferes destructively with the wave that bounces off the floor or obstacles.

C. *Modules with an ultrasonic transmitter and two receivers*

Localization systems based on ultrasonic stereo acquisition are frequently discussed in literature. The authors in [9] discuss about the angular position of a mobile robot relative to a known ultrasonic source. For the extended work in [10], each robot is equipped with an ultrasonic transmitter and two receivers. The used method is based on phase difference measurement by two ultrasonic receivers and TOF measurement. Phase difference measurement is more accurate than the TOF measurement due to its higher resolution [11]. The remarks for this approach are:

- The maximum range measurement using phase difference method is limited to one signal period, for example 25 µs for 40 kHz signal frequency which is equivalent to 8 mm range.
- Phase difference method is used for angular position determination with good accuracy but with many constraints.
- When the two receivers were 450 mm apart, a distance shorter than 88 cm was allowed by the conical wave propagation envelope to pass between the two receivers with no detection of the signals. When the receivers were 350 mm apart, the acceptable measurement interval obtained in the experimental results was [0.5 m; 5.5 m].

There are many other modules in literature used in 2MARS applications which combine some of the above mentioned technologies. For example, in [12] and [13] the systems presented consist of multiple modules with only one transducer and an acoustic reflector cone as presented in section II.B. The modules with too many sensors and actuators are too complex and expensive.

Our goal is to implement a simple and low cost module, with minimal number of sensors and actuators to research some new protocols for relative localization problem for 2MARS applications.

III. IRULT AS A PART OF THE CORE-TX SYSTEM

The proposed hardware module has a common set of requirements, imposed by CORE-TX [14], the target robotic system.

CORE-TX (COllaborative Robotic Environment – the Timisoara eXperiment) [14], is composed of a set of autonomous microsystems with embedded intelligence, called WITs (Wireless Intelligent Terminals), interconnected by a collaborative communication environment and supervised by a central entity called BRAIN (Background Robotic Activity Induction Node). The WIT consists of different modules: communication module, perception module (acquisition board), base processing module, power management module and support and operation module.

The perception module (Figure 1) is composed of a processing unit, a driver for controlling the stepper motor, accelerometer, temperature sensor, extension module (IRULT) and other interfacing circuits.

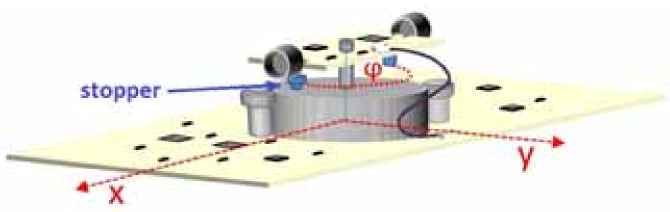


Figure 1. IRULT as part of perception module

The IRULT (Inter-Robot Ultrasonic Localization Turret) is part of the perception module (acquisition board) and is used to obtain the orientation and position of the robot in the navigation task. IRULT consists of a stepper motor and two ultrasonic transducers (Figure 1). Each transducer has a cone-shaped directivity range of about 50 degrees and can send and receive ultrasonic signals at 40 KHz frequency. These two transducers are mounted back to back at 180 degrees. By rotating the stepper motor, each transducer can cover a visibility angle of 240 degrees (see Figure 2). The visibility angle was optimal established using our *SimAlign* simulator [15].

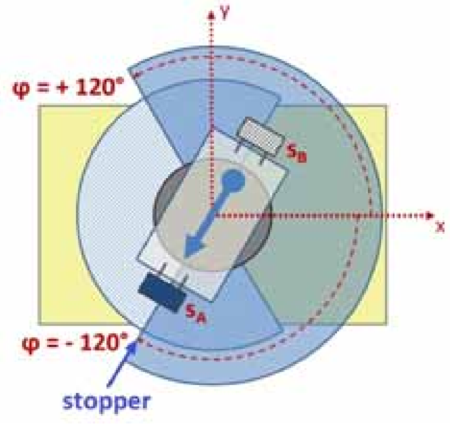


Figure 2. IRULT, top view

The schematic design of the IRULT is shown in Figure 3. The microcontroller is ATxmega128A1 (Atmel Corporation), used for fast, periodic data acquisition and processing operations. Two similar transducers are used both for transmitting and for receiving ultrasonic signals. The BPU-1640IOAH12 device (Bestar Electronics) has been selected, due to its convenient features, which include low cost, bidirectional operation, nominal frequency of 40 kHz, and maximum input voltage of 120 Vpp. The switch side at the transducer level (bidirectional operation) has been implemented using Si4894DY MOSFET circuits.

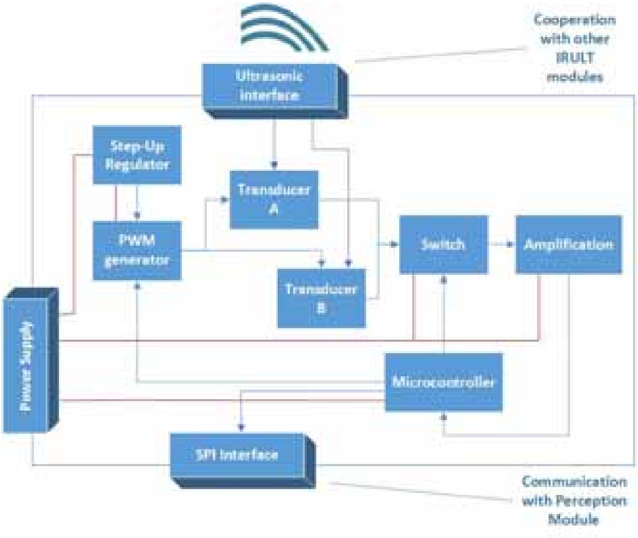


Figure 3. Schematic of the IRULT

IV. THE IRULT DESIGN ANALYSIS

Our proposed relative positioning system is based on the precision of distance measurement between two robots.

Each robot is equipped with an IRULT module. As presented in our previous work [16], to perform a distance measurement between two robots, the robots must successfully complete the alignment algorithm. Correct alignment means the ultrasonic transducers of the robots are facing each other, as close as possible to the straight line between them. There are some sources of error and problems in distance measurement and relative localization which we consider in our design.

A. Wave attenuation problem

Suppose that two correctly aligned transducers are located at a distance of 20 centimeters from each other. The first transducer transmits an acoustic wave at 40 KHz frequency by applying a burst signal consisting of 8 impulses with the amplitude ±10V. Therefore, its piezoelectric crystal is activated during an interval of 8 x 25µs = 200µs. The second transducer captures the wave and converts it back into voltage. The converted wave is measured using an oscilloscope (Figure 4). The tests were executed in a room at the temperature of 25°C and 36.3% humidity, measured with a digital thermometer.

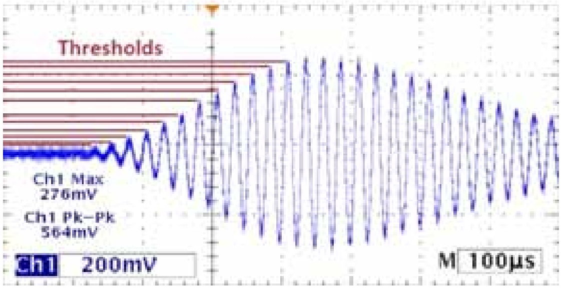


Figure 4. TOF applying different thresholds

From the figure can be observed that the received signal has a duration which is longer than 500µs. The distance is obtained by applying the next formula:

$$d = c_{air} \cdot t, \qquad (1)$$

where the c_{air} = 346.45 m/s is the velocity of acoustic waves in the air, at room temperature and at normal pressure. Applying different thresholds for wave detection as shown in Figure 4, we can obtain different values for distance measurement between two ultrasonic transducers as presented in Table I.

TABLE I. DISTANCE MEASUREMENT APPLYING DIFFERENT THRESHOLDS

No.	Threshold [mV]	Duration [µs]	Distance [mm]
1	14	57.7	20
2	26	82.7	29
3	48	107.7	37
4	67	132.7	46
5	92	157.7	55
6	113	182.7	63
7	173	207.7	72
8	188	232.7	81
9	207	257.7	89
10	225	282.7	98
11	253	307.7	107
12	262	332.7	115

Ultrasonic sound attenuates much faster than audible sound in propagation through air. Consequently, by detecting the attenuated ultrasonic wave, the target appears slightly farther away than it actually is. There exists a method in the literature to quantify this error [17], but anyway, using the threshold method for distance measurement, the right moment cannot be accurately detected. By applying the threshold method with error quantification, it is possible to detect the right delay with a certain approximation. In our case, using a 40 KHz frequency, the possible range is ±25µs. which is equivalent to ±8.7 mm, in the above example. The distance measurement with the threshold method can be improved by applying repetitive measurements and, as presented in our previous work [16], by applying the Kalman filter to these repetitive measurements, an accuracy of 1 cm can be achieved for distances of up to 3 m.

The distance can be more accurately obtained if the maximum of the envelope could be located. For example, in Figure 4, the peak cannot be detected using the threshold method because the variation of amplitude in that zone is relative low. Moreover, a small noise spike could produce a false maximum. A good method for maximum detection is cross-correlation defined in [18] as follows:

$$r_{xy}[d] = \sum_{n=-\infty}^{\infty} x[n] \cdot y[n-d], \qquad d \in Z \qquad (2)$$

In [19], using the cross-correlation method, the distances were obtained with below 0.5 mm accuracy in some cases.

B. Alignment problem

The errors in distance measurement can be caused by incorrect alignment of the ultrasonic transducers. The experimental results in [7] show that the increase of the misalignment angle results in higher distance measurement errors. All results were obtained using the threshold detection method of ultrasound. Ultrasound attenuation can be an effect of the transceiver misalignment angle.

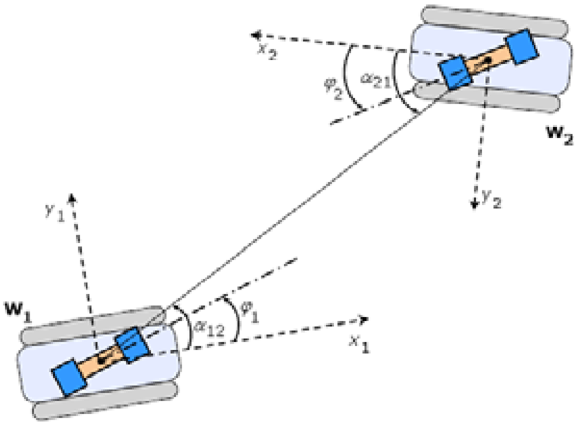
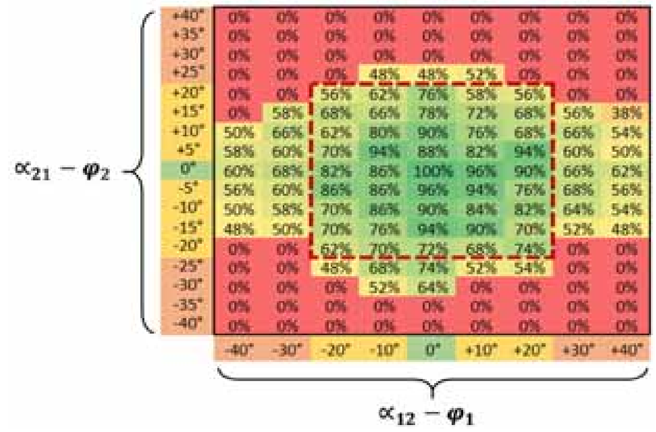


Figure 5. Angles for the alignment, top view

We conducted a set of experiments for studying the combined effect of the transmitter and receiver orientations (see Figure 5) and have measured the signal attenuation. The experiments were executed in a room at a temperature of 26°C and 38.3% humidity. Two robots were used: w_1 and w_2. The distance between the robots was 3 m. A set of results are presented in Figure 6. We denote with 100% the maximum of the envelope received by robot w_1 when the robots were aligned in the ideal case ($\alpha_{12}=\varphi_1$ and $\alpha_{21}=\varphi_2$). We also noticed that by increasing the distance, the visibility angle decreases, therefore we introduced the turret in the system to find the maximum of the envelope when the visibility (between two transducers) is reduced.



$\alpha_{21}-\varphi_2$

	-40°	-30°	-20°	-10°	0°	+10°	+20°	+30°	+40°
+40°	0%	0%	0%	0%	0%	0%	0%	0%	0%
+35°	0%	0%	0%	0%	0%	0%	0%	0%	0%
+30°	0%	0%	0%	0%	0%	0%	0%	0%	0%
+25°	0%	0%	0%	48%	48%	52%	0%	0%	0%
+20°	0%	0%	56%	62%	76%	58%	56%	0%	0%
+15°	0%	58%	68%	66%	78%	72%	68%	56%	38%
+10°	50%	66%	62%	80%	90%	76%	68%	66%	54%
+5°	58%	60%	70%	94%	88%	82%	94%	60%	50%
0°	60%	68%	82%	86%	100%	96%	90%	66%	62%
-5°	56%	60%	86%	86%	96%	94%	76%	68%	56%
-10°	50%	58%	70%	86%	90%	84%	82%	64%	54%
-15°	48%	50%	70%	76%	94%	90%	70%	52%	48%
-20°	0%	0%	62%	70%	72%	68%	74%	0%	0%
-25°	0%	0%	48%	68%	74%	52%	54%	0%	0%
-30°	0%	0%	0%	52%	64%	0%	0%	0%	0%
-35°	0%	0%	0%	0%	0%	0%	0%	0%	0%
-40°	0%	0%	0%	0%	0%	0%	0%	0%	0%

$\alpha_{12}-\varphi_1$

Figure 6. Angles of alignment, experimental results

C. *Alignment reference*

The IRULT contains a mechanical stopper for the calibration of the φ angle, relative to the Ox orientation axis of the robot. This stopper (see Figure 2) is located at -120° relative to the Ox axis. The stopper is detected using Back-EMF method. The BEMF equation is given in [20]:

$$bemf = -N \cdot B \cdot A \cdot \omega \cdot \sin(\omega t) \qquad (3)$$

where N is the number of coil turns of the stepper motor, B represents the magnetic field, A the area encompassed by the motor magnetic field, ω is the angular velocity. The parameters N, B and A are constants specific to the motor construction. The BEMF is directly proportional to motor speed.

V. CONCLUSION

In this paper we propose a Relative Positioning System, IRULT, with a common set of requirements for the target robotic system CORE-TX. Key aspects to be considered for a good approach in distance measurement and relative localization have been discussed. Based on the "Relative Localization Methodology" [21], IRULT is used as a relative positioning system for mobile robots in collaborative environments. In the future, we plan to extend the tests in order to further validate our methodology.

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