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Autonomous Indoor Ultrasonic Positioning System Based on a Low-Cost Conditioning Circuit

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Abstract

This work presents a low cost 3-D location system based on ultrasonics and implemented with low-cost FPGAs. The mobile nodes of the system use distance estimation to several anchor points in order to trilaterate their positions with an accuracy of few centimeters. The ultrasonic transducers are handled with an ad-hoc conditioning circuit based on instrumental amplifiers which provides high amplification keeping low noise. The proposed system is autonomous so there is no need of an external PC or other devices. A prototype of the system has been attached to a mobile robot to check the viability of the location system in a real scenario.

Keywords:
location, ultrasonics, instrumental amplifiers, trilateration, Field Programmable Gate Array, Wireless Sensor Network

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1. Introduction

In the past, many location systems have been deeply investigated. Outdoor and indoor location systems have different requirements in accuracy and reliability. Indoor location systems have been frequently used in robotics and in Wireless Sensor Networks [1] with mobile nodes. Indoor environments demand an accuracy of centimeters in the location system. GPS, Glonass, or the planned Galileo system cannot be used because neither of them provide enough accuracy

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and their coverage at indoor scenarios decreases even more. Indoor location systems have been developed based on several techniques. Image recognition [2, 3] offers accurate results but its price is too high. RFID (Radio-Frequency IDentification) [4] can be used to know if a receiver node is at a maximum distance, which depends on the transmitting power of a radio-frequency signal. Altering this power, the location system can estimate the distance between the receiver and itself with several tries. This system is inexpensive but the provided accuracy is poor. Other possibility is to use the received signal strength (RSS) of a standard wireless protocol, such as IEEE 802.11 or IEEE 802.15.4, to estimate the distance to transmitters and therefore the location of the receiver. However, the precision obtained through this method is usually in the range of meters [5].

Using ultrasonics, the distance between a transmitter and a receiver can be estimated measuring the time-of-flight [6] of the ultrasonics and taking into account the speed of sound. High accuracy can be achieved due to the slow propagation speed, respect to the processing speed of a cheap digital device. Ultrasonic positioning can be achieved by measuring distances between transmitters and receivers and applying trilateration.

Ultrasonics have been used in several indoor location systems because ultrasonic transducers are inexpensive. However, none of the previous proposals are low-cost systems because they all require a PC to obtain a location accuracy of centimeters. Bat Ultrasonic Location System [7] implements an active architecture. The active architecture uses a matrix of receiving anchor points whereas the clients of the system, usually mobile nodes, transmit location signals. In the Bat System, a set of anchor points are attached to the ceiling, and the mobile nodes transmit ultrasonics and radio frequency signals. The position of the mobile nodes is calculated by an external PC. The MIT Cricket Indoor System [8, 9] uses a passive architecture (transmitting anchor points and receiving mobile nodes), being decentralized. The mobile nodes calculate their positions with a room-sized granularity but the system provides an interface to allow better accuracy with an external device such as a PC. Both systems use RF transmissions in order to synchronize transmitters with receivers. The location system of Randell and Muller [10] also has a passive ultrasonic-based system using radiofrequency. Later, these authors improved the system [11, 12] eliminating the radiofrequency, but requiring harder processing, such as the use of the Kalman filter. The system of Single Compact Base Station [13] uses a structure of three transmitting anchor points to cover a room. This system provides an easy installation but its accuracy is affected by the proximity of the anchor points. On the other side, the Constellation System [14] is a system, commercialized by Intersense [15], which combines ultrasonic positioning with gyroscopes, magnetometers and accelerometers. This system provides fine accuracy but its cost is about thousands of US dollars.

This work presents an ultrasonic-based 3-D location system with transmitting anchor points and receiving mobile nodes which calculate their position with fine accuracy and being autonomous. The main novelty of this proposal is accomplishing the calculus of the location in the mobile nodes, neither using a PC nor any external PC. The system is based on a low-cost FPGA [16, 17] and also inexpensive electronics. Nonetheless, the proposed system achieves a similar or better accuracy (few centimeters) than previous systems using a PC [7, 8, 9, 10, 11, 12, 13] with the exception of [14] which obtains an accuracy of millimeters but using also inertial sensors. The key component of the system, which is also a novelty, is the ad-hoc conditioning circuit for the amplification of the received ultrasonic signal. This circuit has been specifically designed using an instrumental amplifier in order to get high gain amplification and keeping low noise. The interface with the digital block does not use any ADC (Analog to Digital Converter). Besides, a mobile robot has been designed to check the accuracy of the location system in real situations.

The rest of the paper is organized as follows: Section II explains trilateration and section III the proposed location system. Section IV describes the designed ultrasonic conditioning system. Section V shows the mobile robot, and the experiments that have been carried out with their results. Finally, section VI presents the conclusions.

2. Location

There are two main strategies to calculate the position of a mobile node: Triangulation and trilateration. Triangulation uses the measurement of the angles between a transmitter and a receiver. On the other side, trilateration uses the measurement of distances between them. Triangulation requires more complex hardware such as unidirectional antennas, and the mathematical calculus is also harder. The estimation of distances can be accomplished measuring the time-of-flight of a signal, which is easier and cheaper.

2.1. 3-D Trilateration

3-D Trilateration provides target location measuring the distances between some anchor points and the target. This method requires, in the general case, four anchor points whose distances to the mobile target are measured. However, if the schema of the anchor points is adequate, distances to just three anchor points are needed, as shown in Fig. 1. Each distance defines an sphere, whose center is the position of the anchor point, and whose radius is equal to that distance. The mobile node is located at a point of this sphere. If two measurements are taken into account, two spheres (s1, s2) intersect at one circumference (c1). The last sphere (s3) intersects with the circumference at two points (P1, P2), which are the possible results of trilateration. P1 and P2 have the same x and y axis components, but the z-axis component varies in the sign. If the anchor points are attached to the ceiling, one of the results is located above the ceiling, while the other result is located under it. The first one can be discarded because it can be assumed that ultrasonics do not go though walls. Therefore, the result P2 is the selected value.

In this work, three anchor points are used applying this simplification. In this configuration, the target is at position (x_t, y_t, z_t), and the anchor points are at the points $(0, 0, 0)$, $(a, 0, 0)$ and $(c, b, 0)$. If the distances between the target and the anchor points are d_1, d_2 and d_3, three spheres can be defined as:

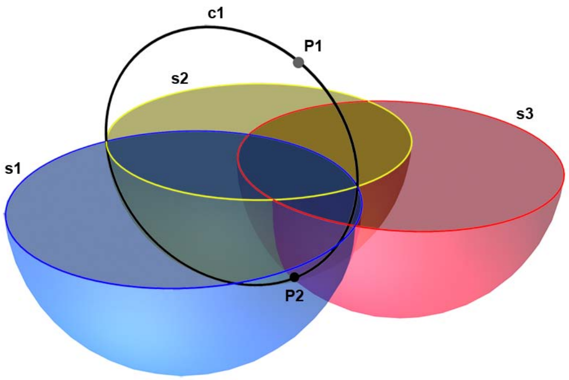

Figure 1: 3-D Trilateration using three anchor points

$$\begin{aligned} d_1^2 &= x_t^2 + y_t^2 + z_t^2 \\ d_2^2 &= (x_t - a)^2 + y_t^2 + z_t^2 \\ d_3^2 &= (x_t - c)^2 + (y_t - b)^2 + z_t^2 \end{aligned} \quad (1)$$

This equation array can be solved, clearing the variables x_t, y_t and z_t:

$$\begin{aligned} x_t &= \frac{d_1^2 - d_2^2 + a^2}{2 \cdot a} \\ y_t &= \frac{c^2 + b^2 + d_1^2 - d_3^2}{2 \cdot b} - \frac{c}{b} \cdot x_t \\ z_t &= \pm\sqrt{d_1^2 - x_t^2 - y_t^2} \end{aligned} \quad (2)$$

Although the system uses three anchor points to provide 3-D location, more anchor points can be used in order to extend the range of the location system or to improve the accuracy adding redundant distance estimations.

2.2. Distance Estimation

The accuracy of the trilateration process is limited to the accuracy of distance measurements between anchor points and the mobile target. For this reason, this is the key component of the location system. The estimation of the distance between a transmitter and a receiver is accomplished measuring the time-of-flight of an ultrasonic signal. The use of ultrasonics instead the use of radio is due to its low propagation speed. The speed of radio signals is approximately $3 \cdot 10^8 m/s$, whilst the speed of sound is around $3.4 \cdot 10^2 m/s$. For this reason, any device may sample ultrasonics with a distance resolution 10^6 times greater, approximately. In this work, ultrasonics are used because their use improves the accuracy of the system allowing low-cost devices.

The distance between a transmitter and a receiver is defined by:

$$d_{t-r} = (t_{US} - offset) \cdot v_{US} \qquad (3)$$

where t_{US} is the estimated time of ultrasonics flight, v_{US} is the speed of sound and $offset$ is a delay that can be empirically checked. This delay is caused by the amplification and digitalization stages (which are explained in section 4) and experiments conclude that it is almost constant when using the same electronic components in the conditioning circuit. In our designed circuit, $offset$ is 35.54 μs.

Both, transmission time and reception time should be known to measure the time-of-flight the ultrasonics. The reception time is, obviously, known by the receiver, but the transmission time is not known. To get the transmission time, devices need synchronization between them. This can be achieved transmitting simultaneously a radio frequency signal. This signal arrives at the receiver around 10^6 times faster than ultrasonics. Taking into account both signals, the distance is defined by:

$$d_{t-r} = (t_{RF} + t_{diff} - offset) \cdot v_{US} \qquad (4)$$

where t_{RF} is the time-of-flight of radio frequency, and t_{diff} is the difference of arrivals between both signals. t_{RF} is around 10^6 times lower than t_{diff}, so it can be ignored. This way, the distance between a transmitter and a receiver is:

$$d_{t-r} = (t_{diff} - offset) \cdot v_{US} \quad (5)$$

3. System Design

Taking into account the role of the anchor points and the receivers, there are two architectures: active and passive. As it was explained in the introduction, in active architecture mobile nodes are the transmitters and the anchor points are the receivers. Passive architecture is based in the opposite idea: the anchor points transmit the location signals whilst the mobile nodes receive them.

In active architecture, the mobile nodes must take turns to transmit the ultrasonic signal, so the number of clients of the system is limited. Besides, any device of the system may listen the transmissions and know the position of other devices. Nonetheless, the accuracy of the position while moving is not affected because just one transmission is needed to trilaterate as the same signal will be received in several anchor points.

The passive architecture is scalable because any number of mobile nodes may use the system simultaneously. Moreover, the clients do not transmit any signal so the privacy of the location is preserved. The main disadvantage of the passive architecture is the accuracy when a node is moving. The anchor points take turns to transmit, so the different location signals are received when the mobile node is at different points, worsening noticeably the accuracy.

The proposed system is based on a passive architecture because of the scalability and privacy preservation. However, the specific hardware designed in this work is suitable for both architectures.

Fig. 2 shows the architectural design of the location system. Both, anchor points and nodes, are based on low-cost FPGAs. Just one FPGA controls all the ultrasonic transmitters and the radio used for synchronization. Each mobile node has an FPGA which does the trilateration process.

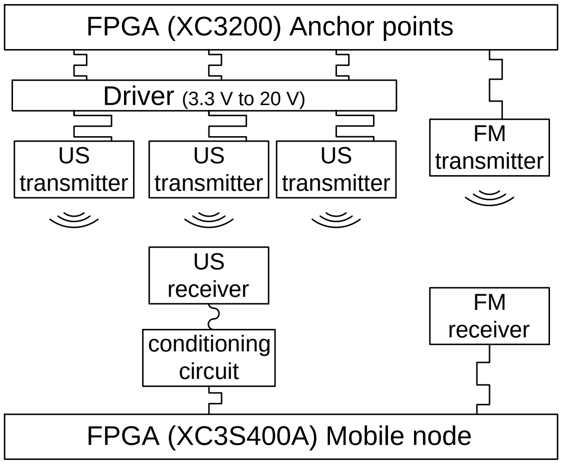

Figure 2: Architectural design

3.1. Anchor points

A low-cost Xilinx Spartan 3 FPGA (XC3200) is used to generate the location frames. Each frame has ultrasonics and RF transmissions, simultaneously launched. The ultrasonic wave is a train of square pulses at 40 kHz generated by the FPGA. In order to increase the range of the ultrasonics, a push-pull driver L230B is used to convert the pulses between 0 V and 3.3 V to pulses of 0 V to 20 V. Finally, the pulses are driven to an ultrasonic transmitter Prowave 400ST200. The radio frequency signal is a sequence of Manchester-coded bits, with two start bits, several bits indicating the ID of the transmitting anchor point, and one stop bit. In the present work, three bits are used as anchor point ID, but more bits can be added if necessary. The generated sequence is sent by a 433 MHz FM transmitter (FM-RTFQ1-433) with a data rate of 9.6 kbps. In this case, transmission protocols usual in robotics or WSN, like Zigbee or Bluetooth, cannot be used for synchronization because the time between the transmission order and the real transmitting time is not deterministic due to their media access protocols. That is why an FM transmitter with no media access protocol is used for synchronization. In order to avoid interferences between consecutive ultrasonic transmissions and their reflections, there is a guard interval of 200 ms between location frames. The electronic details of the proposed anchor points are explained in paper [18].

3.2. Mobile nodes

The mobile node has a Xilinx Spartan 3A FPGA (XC3S400A) as its main component. Besides, it has an ultrasonic receiver, Prowave 400SR200, and a 433 MHz FM receiver, FM-RTFQ1-433. The FM receiver outputs the received information as a digital serial interface from 0 V to 5 V, so a level translator is used in order to adapt the level to 3.3 V so the FPGA can handle it. The ultrasonic transducer outputs a dim signal, so a high-amplification stage is required. Besides, the signal must be digitalized. For these tasks, an ultrasonic conditioning circuit has been designed, which is explained in section 4.

Positioning requires two main tasks: measuring distances and math calculation. The first one is accomplished by specific hardware based on an FPGA. Only the math calculation is done in software by using an embedded microprocessor, so almost all the processor time is free to carry out other jobs. This way, the microprocessor can be used as a main processing unit of a robot, node of a WSN, or any other autonomous device.

Specific hardware has been implemented to measure the difference of time of arrivals between RF and ultrasonic signals. A state machine waits until the reception of the RF signal begins and it starts a 32-bit counter (see Fig. 3). When the ultrasonics are received, the counter stops. The final value of the counter represents the distance to the transmitter if the clock frequency and the speed of sound are taken into account. The RF signal arrives before the ultrasounds. Nonetheless, the ultrasonic signal may arrive before the whole RF signal has finished, because the period of the modulated RF signal is bigger than the ultrasonic one. The state machine deals with all situations, and has to check both signals in parallel.

The specific hardware checks the two start bits of the transmission, the ID of the transmitter, and the stop bit of the radio frequency. It also checks the frequency of the ultrasonics which should be around 40 kHz, and the frequency

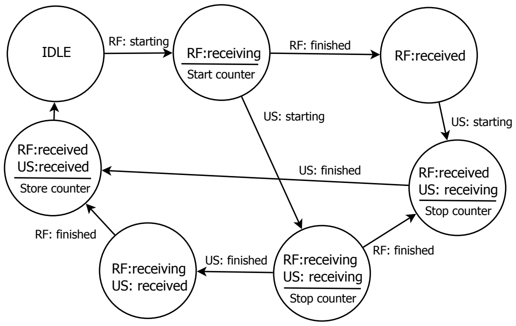

Figure 3: State Machine implemented in custom hardware

of the data of the FM transmission (9.6 kbps), see Fig. 4. The verification of the ultrasonic frequency is applied because any ultrasonic noise in the environment can cause wrong distance estimations. However, checking the frequency of the ultrasounds, most of the noisy signals can be rejected. The verification of the frequency of the FM transmission is also applied for rejecting noisy communications. For both signals, time constraints are applied for complete periods, being more relaxed with the US because of the poor reliability of the ultrasonic communication. When a measurement has been taken and checked, it is stored into a register, which can be read by a processor implemented in the FPGA. The processor that has been used is a 32 bits Xilinx Micro-Blaze. The designed specific hardware behaves as a peripheral connected to the processor though a Xilinx PLB bus. The translation of clock ticks stored in the register to distance is accomplished in the processor with eq. 5. Once a set of distances has been taken, trilateration can be done by the processor with eq. 2. The integration between the custom location hardware and the Microblaze system depends on the application of the system but a possible integration can be found in [19].

Sometimes, a distance estimation is clearly different from the real distance. The estimation can be smaller if there are interferences in the ultrasonic communication. Besides, an estimation can be bigger if the ultrasonic signal arrives through a rebound of the signal, e.g. in a wall. To reject these outliers, the

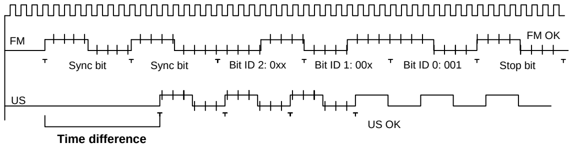

Figure 4: Example of a location frame sent by anchor point 1

processor applies a median filter in the distance measurements before trilateration. This filter gets three estimations, discards the maximum and the minimum one, and outputs the intermediate estimation. The filter is applied to the measurements to each anchor point, and it outputs three distances that are used in the trilateration. This filter is not useful when all the inputs are noisy, but it can reject isolated wrong inputs, even when the error is noticeable, and the computational cost is negligible.

4. Ultrasonic Conditioning Circuit

This section describes the ultrasonic conditioning circuit which has been designed with the aim of obtaining a simple and low-cost implementation but with a high accuracy. This circuit is implemented in the mobile nodes using the passive architecture. In any case, the proposed circuit is also valid for an active architecture, because it is a conditioning circuit for a receiver node based on low cost and highly resonant piezoelectric ceramic transducers.

The high-level view of the conditioning circuit is shown in Fig. 5. The incoming signal is so dim that it must be amplified. The first step of the conditioning circuit is a high pass filter in order to eliminate its DC component which must not be amplified. In second place, an amplifier is used to increase the amplitude of the 40 kHz received signal and finally the signal is digitalized so a digital system can directly process it. This differs from the traditional approach which uses envelope or tone detectors for the 40 kHz component. In our case, the 40 kHz detection is accomplished inside the FPGA with a state machine and timers, reducing the cost of the system and avoiding the delay and uncertainty introduced by envelope detection, as shown in [10]. Furthermore,

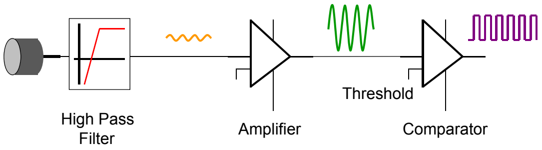

Figure 5: High-level view of the receiving circuit

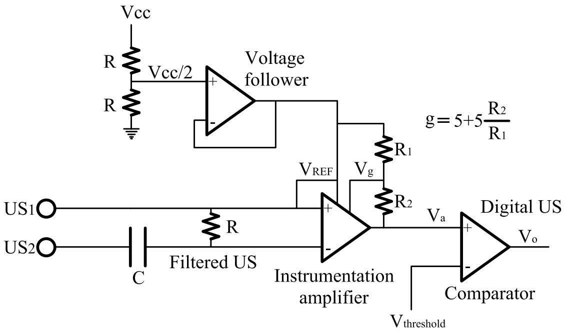

Figure 6: Schematic of the conditioning circuit

the interface between the analog and digital blocks is made without ADCs, using a voltage level comparator whose output is already a digital signal.

The schematic of the proposed conditioning circuit is shown in Fig. 6. The high pass filter is a simple RC circuit. The selected values of R and C are 100 kΩ and 1 nF respectively. To calculate the cutoff frequency the parasite capacitance of the piezoelectric sensor must be taken into account. Most piezoelectric sensors have capacitances between 2 and 4 nF. This capacitance is added to the capacitance of the filter in series, reducing the cutoff frequency. Even if the parasite capacitance is near 0 nF, the cutoff frequency of the filter is below 40 kHz (the frequency of the piezoelectric transducers), so the desired frequency is barely attenuated. Bandpass filters are not necessary because the ultrasonic receiver is highly resonant.

The amplification stage is implemented with an instrumentation amplifier (INA2331) supplied at 5 V, which is the only supply voltage of the proposed circuit. An instrumentation amplifier is chosen because it amplifies differential signals while keeping high input impedance. It can achieve higher gains than operational amplifiers with low-noise. It is therefore suitable for amplifying weak differential signals, such as the output of an ultrasonic receiver. The gain is fixed with two resistors (R_1 and R_2) attached to the amplifier. The gain of the amplifier is given by: $g = 5 + (5\frac{R_2}{R_1})$, being 1655 in our configuration. There is also a reference input, VREF, which fixes the DC output voltage. However, it is not a high impedance input, so a voltage follower (in our case implemented with an operational amplifier TLC2274) is added in order to fix this voltage at 2.5 V. Finally, the amplified signal, Va, must be digitalized in order to be sampled by the digital circuit. An operational amplifier (also a TLC2274 operational amplifier) is used as a voltage comparator to a threshold, fixed at 1.78 V in our case. The most natural choice would have been to use a voltage comparator, but an operational amplifier has been used as a comparator because the TLC2274 package provides two operational amplifiers, using one as a voltage follower and the other as a comparator. In this way, the number of components and the cost of the circuit are reduced. The operational amplifier is supplied at 5 V, thus the output is directly compatible with digital circuits. Because of this, there is no need for ADCs, and the cost of the circuit is reduced. If there is no received signal, the output of the amplification stage is approximately 2.5 V, and the comparer therefore sets a '1' at its output. Otherwise, if an ultrasonic signal is being received, the amplified signal periodically crosses the threshold voltage, generating an almost square signal at 40 kHz. The FPGA samples the digitalized ultrasonic wave at 52 MHz. Taking into account the speed of sound, the resolution of the distance measurement is 6.54 μm. However, as it is explained in the results, the accuracy of the complete system is in the order of centimeters.

5. Results

A prototype of the system has been developed in order to check its viability and its accuracy. Fig. 7 shows an oscilloscope snapshot of the received signal,

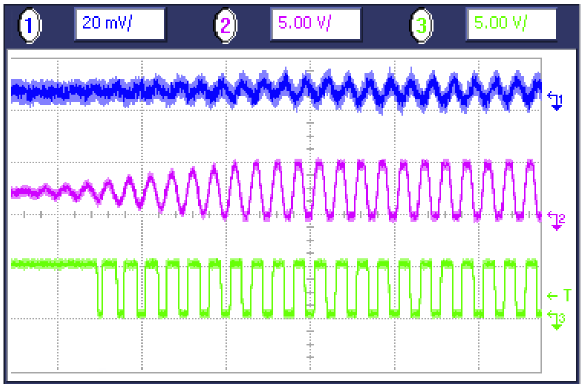

Figure 7: Oscilloscope snapshot. 1) Received ultrasonics (20 mV/div) 2) Amplified signal (5 V/div) 3) Digital signal (5 V/div)

before and after the amplification stage, and the digital signal after the comparator. With an ultrasonic transmitting amplitude of 5 V, the location circuit detects the signal up to 820 cm under 0° (straight line) and 158 cm under 70°. The higher the transmission voltage, the longer the range of the ultrasonic wave. Also under 70°, the range is 302 cm with 10 V, and 577 cm with 20 V. In the proposed system, the transmission voltage is set to 20 V in order to increase its range.

To check the accuracy of the system, two experiments have been done: distance and position estimations. In the distance estimation experiment, a receiving node was placed at several distances from a transmitting anchor point. These distances are $20 \cdot n$ cm, where $n \in [1, 17]$. Using RF synchronization, 10 distance measurements were obtained at each point.

Fig. 8 shows a histogram with the number of cases inside each error interval. The mean error in distance estimation is 0.68 % regarding the absolute distance, whilst the standard deviation is 0.95 %.

For the trilateration experiment, three anchor points have been placed at points (0, 0, 0), (1200, 0, 0) and (0, 1800, 0) mm. A mobile node has been placed 10 times at each point defined by $(n \cdot 400, m \cdot 400, -2570)$ mm where $n \in [0, 3]$ and $m \in [0, 4]$. The z-coordinate is fixed because the mobile node

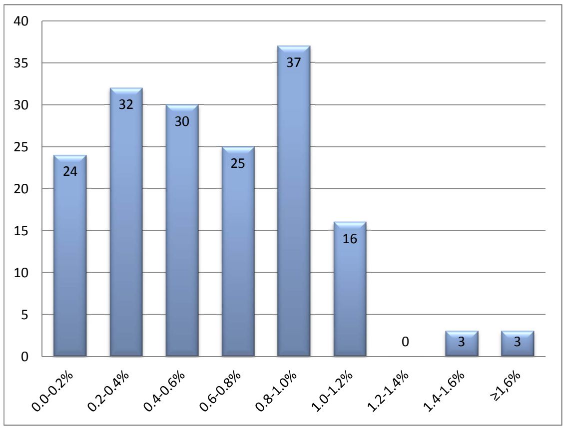

Figure 8: Histogram of the error in distance estimation

is always on the floor. Fig. 9 shows the results of this experiment in the X-Y axes. The average error of position estimation in the X-Y axes is 33.47 mm while the standard deviation is 13.31 mm. The positions which are far away from the anchor points suffer bigger errors in position estimation, up to 73.38 mm, because of geometric reasons. This accuracy deterioration is due to the configuration of the location system when the mobile node has a distance to the anchor points greater than the distance between them, and therefore the angle to both anchor points is very different from 90°, which is the optimal. Fig. 10 shows the error in the Z axis of the same experiment. In this figure, the Z axis has been enlarged for the sake of clarity. The average error in the Z axis is 55.68 mm and the standard deviation is 6.51 mm.

In the previous experiment only three anchor points have been used covering a small area of 1.2x1.8 m^2. As seen before, the range of the ultrasonic transmitters is much greater than 1.8 m, so the transmitters can be farther apart. For instance, with a separation of 3 m, 9 m^2 would be covered using three transmitters. If more area must be covered, more transmitters can be used and only the three nearest anchor points would be used for trilateration. However, as a passive architecture has been chosen, the transmitters take turns to transmit. Therefore, adding more transmitters implies more latency between consecutive

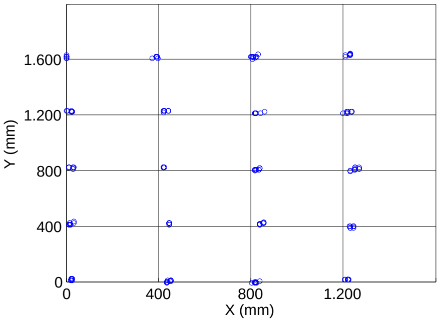

Figure 9: Results of trilateration in the X-Y axes (mm)

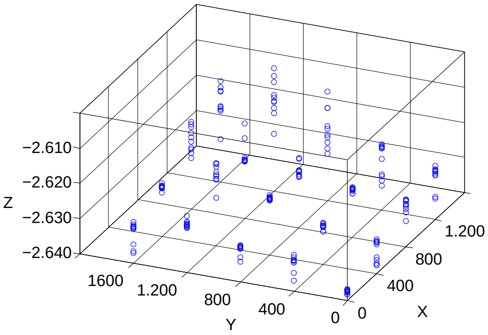

Figure 10: Results of trilateration in the Z axis (mm)

position estimations. On the other hand, very distant transmitters can transmit simultaneously. Taking this into account, very big areas can be covered using less time slots than transmitters. For instance, Fig. 11 shows 36 transmitters using only nine time slots. The transmitters which have the same number in the figure can transmit simultaneously. In this example, the latency of location is $9 \cdot 200$ ms, i.e. less than 2 s. The only coverage restriction is that the proposed system is designed to be used with a single RF transmitter. In our case, the used RF transmitter has a theoretical range of 250 m.

A problem which arises when using ultrasonics is the acoustic shadows — areas which do not receive ultrasonic signals from a transmitter. One robot does not interfere with other robots in the same room because the transmitters

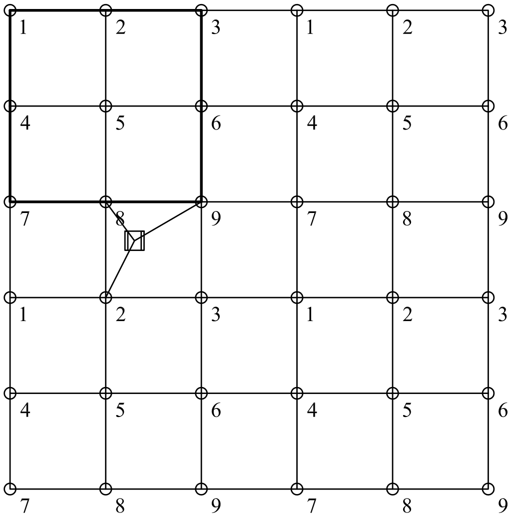

Figure 11: Example of big area coverage

are attached to the ceiling. However, shadows can be caused by objects such as the furniture of the room. In order to avoid the acoustic shadows more anchor points can be deployed. If there are unavoidable shadows, another position system should be added, such as encoders. In that case, a fusion of several location systems should be used.

For the purpose of checking the positioning system in a real situation, a mobile robot has been implemented, Fig. 12. The robot uses two DC motors with quadrature encoders. This robot plays the mobile node role in the positioning system, receiving and amplifying the US signal and measuring its distances to the anchor points. The robot knows its position using the proposed system, and it can move to another point using its motors, and the encoders in order to know the distance to move. The relative position respect to an origin can be known just with the use of encoders. Nonetheless, this odometry system integrates accumulative error during movement, so the error becomes too big over time. The proposed ultrasonic-based system is an absolute system which does not accumulate position errors and its accuracy is suitable for indoor environments. Besides, the ultrasonic system allows the robot to orientate itself taking

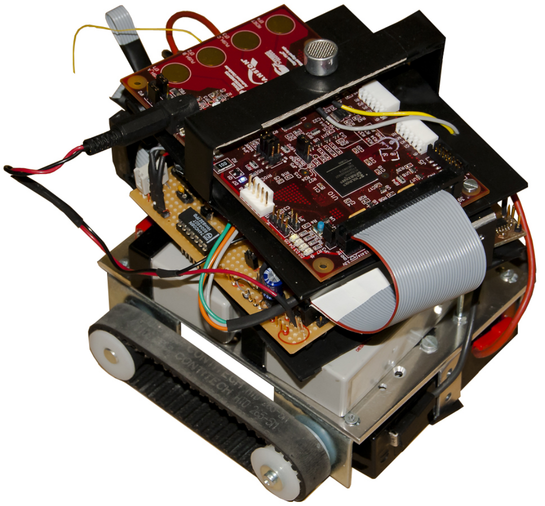

Figure 12: Implemented robot to check the positioning system

the position at an initial point, moving a predefined distance in straight line, and taking another position estimation, so a movement vector can be inferred with both points.

An orientation estimation experiment has been made. The robot has been ordered 20 times to take its orientation moving 50 cm in straight line, and taking position estimations before and after movement. The average error is 1.65° and its standard deviation is 1.63°. Moreover, movement experiments has been carried out with the robot, using the encoders and the proposed positioning system [20]. The robot has been ordered 10 times to move to a point which implies to turn about 70° and move 80 cm in straight line. If the robot finishes the movement at a point with an error greater than 5 cm from the target point, the robot iterates the navigation algorithm to decrease the error. Results shows that in 80 % of experiments the robot arrives the target point in the first try. In the remaining 20 %, the robot arrives the target point in two tries.

6. Conclusion

This work presents a low-cost 3-D location system based on ultrasonics. Measuring distances to some transmitting anchor points with the help of radio frequency synchronization, mobile nodes can trilaterate and calculate their positions. The system is autonomous and it does not need any external device or PC. Using an ultrasonic conditioning circuit based on an instrumental amplifier, the 3-D location accuracy is around 3.3 cm, which is suitable for most indoor applications. The location system has also been tested in a mobile robot.

Acknowledgment

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