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Low Cost Indoor Ultrasonic Positioning Implemented in FPGA

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***Abstract*— This paper presents a low cost indoor ultrasonic-based positioning system. This system allows the mobile nodes of a Wireless Sensor Network to know their location using radiofrequency and ultrasonics. To achieve this goal, a matrix of transmitting anchor points is installed whereas the mobile nodes receive these transmitted signals and estimate the time-of-flight of the ultrasonic signals. Using two time-of-flight measurements and trilateration equations, the location of the mobile nodes can be inferred in a 2-D space.**

***Keywords*— Wireless Sensor Network, location, ultrasonics, trilateration, Field Programmable Gate Array.**

I. INTRODUCTION

In recent years, Wireless Sensor Networks (WSN) have been thoroughly studied. Specific topics like deployment of the nodes, security or the incorporation of mobile nodes in the network have been continuously investigated. If mobile nodes are added into the network, the location and tracking of these nodes turn into important tasks [1-5]. If the application of the WSN is in indoor environment, traditional outdoor location systems, like GPS (Global Positioning System) or the forthcoming Galileo, cannot be used. These systems provide a precision of a few meters, which is usually not enough for indoor purposes. Besides, their indoor reliability is poor because of the scarce coverage of these systems inside a building. Indoor location is relevant not only for WSN but also for many other applications such as robotics, warehouse management, domotics, etc.

There are several indoor location technologies based on RFID (radio-frequency identification), image recognition, ultrasonics, etc. RFID technology allows to know if the distance between an anchor point (transmitter) and a mobile node (receiver) is lower than a fixed distance, depending on the transmitting power. Modifying the transmitting power, the system can take several measurements estimating the position of the mobile node. However, the achieved precision is not sufficient for many applications. Image recognition provides fine precision but requires expensive hardware such as cameras and strong processing. Ultrasonics is an inexpensive and accurate technology. Transmitting an ultrasonic signal between two points, the time-of-flight of the signal can be measured, obtaining the distance between the receiver and the transmitter. Taking several measurements between one point and some well-known points, the location of the first can be estimated.

Some of the existing indoor location systems use ultrasonics, with the support of radiofrequency signals. The MIT Cricket Indoor System [6-7] uses a matrix of transmitting anchor points which are installed at the ceiling. The receiving mobile nodes measure the distance to the anchor points, but they don't locate themselves. The objective of the system is to know the room where the mobile nodes are. Nevertheless, a precise location can be made with an external PC. In the Bat Ultrasonic Location System [8], a matrix of receiving anchor points is installed at the ceiling as well. The mobile nodes, which are attached to people, transmit at the same time ultrasonics and a radio signal to the anchor points. The calculus of the position is centralized in a PC and the result must be transmitted back to the mobile nodes. The system of Randell and Muller [9-11] uses transmitting anchor points and receiving mobile nodes, providing an accurate location. An evolution of this system uses just ultrasonics, although it requires stronger processing. The system of Single Compact Base Station [12] uses just a small base with three transmitting anchor points, reducing the precision of the system, as well as the installation of the location system. There are also some commercial systems of the company InterSense [13-14] which offer high precision combining ultrasonics and magnetometers, gyroscopes and accelerometers. However, these commercial systems cost thousands of dollars.

In the present work, an inexpensive 2-D ultrasonic-based location system is presented. As in the Cricket System, there are some transmitting anchor points whilst the mobile nodes receive the transmissions of the first ones. Nonetheless, the calculus of the location is executed in the mobile node, without any external device (no need of external PC) and using low cost devices. The rest of the paper is organized as follows: Section 2 explains the trilateration technique. Section 3 explains how to estimate distances between nodes and the mathematical problem of trilateration. Section 4 describes the proposed architecture. Section 5 shows the experiments that have been performed and their results. Section 6 presents the conclusions.

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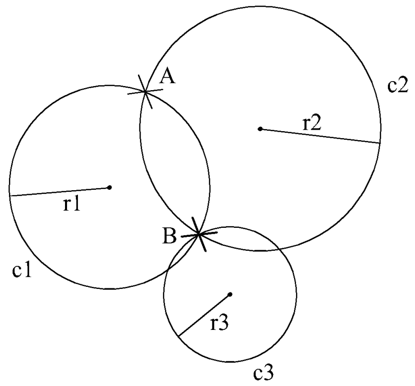

Fig. 1. Trilateration problem in 2-D space.

II. TRILATERATION

The location of a mobile node in a WSN could be calculated measuring angles between the node and some well-known anchor points, which is called triangulation, or it can be measured calculating distances between them, which is called trilateration. Triangulation requires more complex hardware and software, increasing the cost of the system. For example, it needs unidirectional antennas, and trigonometric equations which are more complex than trilateration equations.

Trilateration requires three measured distances between the node (target of the location) and the reference points in a 2-D space, whereas four measurements are needed to trilaterate in a 3-D space. In any case, with a proper configuration, just two and three anchor points are needed for 2-D and 3-D spaces respectively. An example of a possible configuration for 2-D trilateration with only two anchor points is presented in section III. In the general case, once the measurements are taken, the 2-D point where the node stands is the intersection of three circumferences whose geometric centers, which can not be colinear, are the reference points and their radiuses are the measured distances. Fig. 1 shows this geometric problem. With two distance measurements (r1 and r2), the receiver location is in the intersection of two circumferences centered in the points where the respective anchor points are, and whose radiuses are r1 and r2. The intersection gives two possible solutions: A and B. If the receiver gets a third measurement from another anchor point, the new circumference with radius r3 intersects with only one of those points. This point is the unambiguous position of the receiver.

If a 3-D space is considered, the target is in the intersection of four spheres whose geometric centers, which can not be coplanar, are the reference points and their radiuses are the measured distances. Fig. 2 shows the problem of trilateration in a 3-D space. If the receiver achieves the distances r1, r2, r3 and r4, it can calculate unambiguously its position. The intersection of two spheres, s1 and s2, of radiuses r1 and r2 is a circumference c1. The receiver is in this circumference. If a third sphere is considered, s3 with a radius of r3, it intersects with c1 in two points: A and B. The fourth sphere, s4 with a

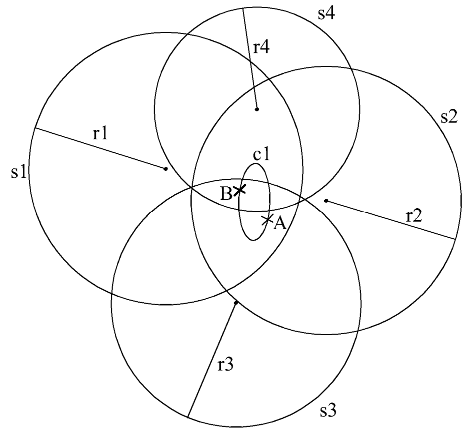

Fig. 2. Trilateration problem in 3-D space.

radius of r4, intersects with one of the two points. This is the point where the receiver stands.

Although trilateration in a 2D and 3D-space is possible with three or four measurements respectively, the more measured distances, the more precision is obtained. When more points are used, it is called multilateration.

The explained trilateration technique is called TOA (Time of Arrival), in which the receiver knows the time the signal arrives relative to the emitting time. In this case, the receiver must know the time when the signal was emitted. There is another method called DTOA (Difference of Time of Arrival), in which the transmitters emit their signals at the same time (in different channels or with a fixed and known time offset between signals), so the receiver can measure the time difference between their arrivals. The receiver doesn't have to know the time of emission, but the problem of trilateration turns into the calculus of intersections between hyperbolic surfaces rather than spheres, increasing the complexity.

WSN nodes use radio frequency communication (RF) to collaborate in their tasks. This hardware can be used to indicate the start of the emission**.** If the transmitter of the ultrasonics emits an RF signal at the same time, the receiver knows the time when the ultrasonic signal is emitted because radio propagation speed is about 10^6 times greater than ultrasonics propagation speed. Obtaining the time interval between emission and reception of ultrasonics, TOA method can be applied, which involves easier processing. Besides, the use of RF in WSN to location purposes, which is explained in Section 3, does not imply added costs because RF is already present in WSN. In the present work, the 2-D TOA method is chosen for these reasons.

III. LOCATION

Before trilateration can be performed, a set of distance measurements must be taken, translating the time-of-flight of a signal into distances.

A. Distance Estimation

The distance between two points can be calculated measuring the time of flight of a signal which is emitted from one point to the other. In indoor positioning, ultrasonics are commonly used due to their slow speed of propagation and, therefore, estimation can be more accurate. The speed of sound is approximately of $3.4 \cdot 10^2$ m/s, whereas the speed of radio is around $3 \cdot 10^8$ m/s. For that reason, if a system samples the incoming signals at 100 MHz, the resolution of the sampler could be up to $3.4 \cdot 10^{-6}$ m (0.0034 mm) with ultrasonics (but it is usually lower because of the frequency of the ultrasonic signal), while the resolution with radio signals is only up to 3 m. In any case, the receiver can estimate the time of flight just if it knows the time when the signal was emitted, so time synchronization is needed. The easier way to achieve that is emitting a radio signal at the same time of the ultrasonic one. Radio propagation speed is much greater than ultrasonics, so radio can be used as a synchronization method.

The distance between each anchor point and the mobile node can be represented as follows:

$$d_{t-a} = (t_{us} - offset) \cdot v_{us} \quad (1)$$

where t_{US} is the measured time of flight of the ultrasonic (US) signal, v_{us} is the speed of sound, which depends on the temperature of the room, and *offset* is a set of fixed delays empirically checked.

t_{us} is not known but the time difference between the arrival of radio and US signals can be measured. t_{US} is the sum of the time of flight of the radio signal (t_{radio}) plus the time difference between the arrival of both ($t_{difference}$):

$$d_{t-a} = (t_{difference} + t_{radio} - offset) \cdot v_{us} \quad (2)$$

Considering that the time of flight of the radio wave is insignificant due to the speed of light, the distance can be calculated just with the time difference.

$$d_{t-a} = (t_{difference} - offset) \cdot v_{us} \quad (3)$$

B. Location

Once distances are estimated, the location can be accomplished. The configuration proposed in the paper is the location of a target (x_t, y_t) in a 2-D space with two anchor points placed at (0, 0) and (b, 0). Fig. 3 shows this problem. The mobile node is in the intersection of two circumferences centered in the anchor points. When the distances d_{t-a1} and d_{t-a2} are measured, there are two equations that must be satisfied:

$$d_{t-a1}^2 = x_t^2 + y_t^2 \quad (4)$$
$$d_{t-a2}^2 = (b - x_t)^2 + y_t^2$$

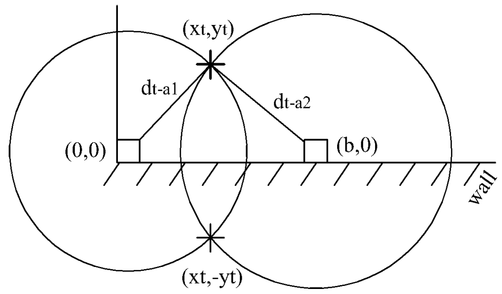

Fig. 3. Trilateration in a 2-D space with two anchor points.

Solving the equation system, the coordinates x_t and y_t are:

$$x_t = \frac{d_{t-a1}^2 - d_{t-a2}^2 + b^2}{2b} \quad (5)$$
$$y_t = \pm\sqrt{d_{t-a1}^2 - x_t^2}$$

As two reference points are used in a 2-D space, there are two solutions. Nevertheless, the anchor points can be deployed close to a wall of the room so just the positive values of the Y axis are considered. Without this restriction, another anchor point would be needed to know unambiguously the position of the mobile node.

IV. DESIGN

A. Architectural Design

Both anchor points and mobile nodes can play whether transmitting or receiving role. An architecture in which anchor points transmit and mobile nodes receive is called passive. On the other hand, an architecture in which anchor points receive and mobile nodes transmit is called active. These architectures have some differences that must be considered. A passive system is more scalable. The transmitters must take turns to emit their signals and the number of anchor points is, usually, lower than the number of mobile nodes. Therefore, the latency in an active architecture is much higher than in a passive architecture. With receiving mobile nodes, an undefined number of them can coexist with a fixed number of anchor points. The system can support any number of nodes with the only condition that they are in range. One disadvantage of the passive architecture is the precision of the location with moving nodes. If the mobile node is moving, the distance measurements are taken at different geometric points, increasing the error of trilateration. However, in the active architecture, just one emission of the signals is needed because all the anchor points receive that signal, avoiding this accumulative error.

The active architecture has another inconvenient. The mobile nodes emit their location signals and the anchor points receive them. The calculus of the location is made out of the mobile nodes. Consequently, the result has to be transmitted back to the node. That last transmission contains the location of the mobile node, and any node or external device knows that position, threatening the user privacy. On the other hand, passive architecture allows the calculus to be made in the mobile nodes, not requiring the transmission of the location. Location systems like GPS or Galileo use a passive architecture.

A passive system has been choosen because of its scalability and user-privacy. The aim of the present design is a low-cost indoor location system achieving the maximum reachable precision. The system has been implemented in a Xilinx FPGA because it permits rapid-prototyping. However, a less accurate but low-cost design can be developed with an 8-bit processor.

B. Electronic Design

Fig. 4 shows the top level design of the presented indoor location system. In the anchor points, an ultrasonic transmitter (400ST120) is excited using square pulses of 20 V peak-to-peak. A Spartan3 Xilinx FPGA drives a 15-pulses output signal at 40 kHz. This signal, which voltage is between 0 and 3.3 V is converted into 0-20 V with a L293B push-pull driver. This higher voltage increases the range of the transmission. At the same time of the ultrasonic transmission, a radio frame is emitted by a 433 MHz FM transmitter (FM-RTFQ1-433). The frame consists of six Manchester-coded bits: two start bits (used for synchronization), one stop bit, and three bits which specify the ID of the transmitting anchor point. A 3 bit identifier has been chosen due to the slow transmission rate of the FM transmitter (9.6 kb/s). With a long frame, the US signal can arrive before the anchor point identifier has been decoded, increasing the latency of the positioning. Eight anchor points can coexist in the same coverage area, over-defining the equation system 5 and improving the global accuracy.

The mobile nodes have a 433 MHz receiver (FM-RTFQ1-433), an US receiver (400SR120) whose output is amplified

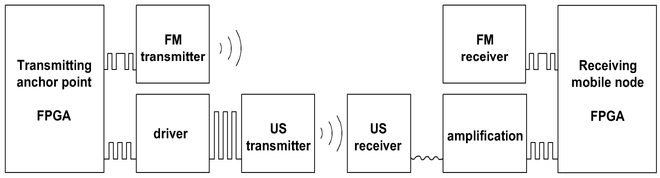

Fig. 4. Top level design of the indoor location system.

and a Spartan3A Xilinx FPGA which samples both signals to decode the identifier of the transmitting anchor point and measures the time difference between them. The ultrasonics amplification is needed because the reception signal is dimmer as the receiver moves away from the transmitter. Fig. 5 shows the amplifier circuit, which consists of two-stage amplification, whose gains are 100 and 33 respectively. The capacitors and the resistors in series before the input of the amplification stages behave like high-pass filters at 16 kHz (the ultrasonic signal is emitted at 40 kHz). High frequencies are attenuated by the LM324 operational amplifiers due to their narrow bandwidth. The circuit is supplied with 5 V. The reference voltage of the amplification is 2.5 V, which is obtained by a voltage divider. The ultrasonics receiver generates a voltage difference at its terminals with a frequency of 40 kHz which is amplified twice by the operational amplifiers. One-stage amplification with a higher gain is not possible because of the technical limitations of the operational amplifier. The output of the second stage is driven into a TLC2274 comparator with a threshold of 3.12 V. The comparator sets its output at ‘1’ when the amplified signal exceeds the threshold and otherwise it sets a ‘0’. If there is no receiving signal, the output of the amplification will be the reference voltage (2.5 V), which is fed in the positive terminals of the operational amplifiers. When an ultrasonic signal is received, the output voltage will exceed the threshold (3.12 V) periodically creating a square signal at 40 kHz, which can be detected by the FPGA.

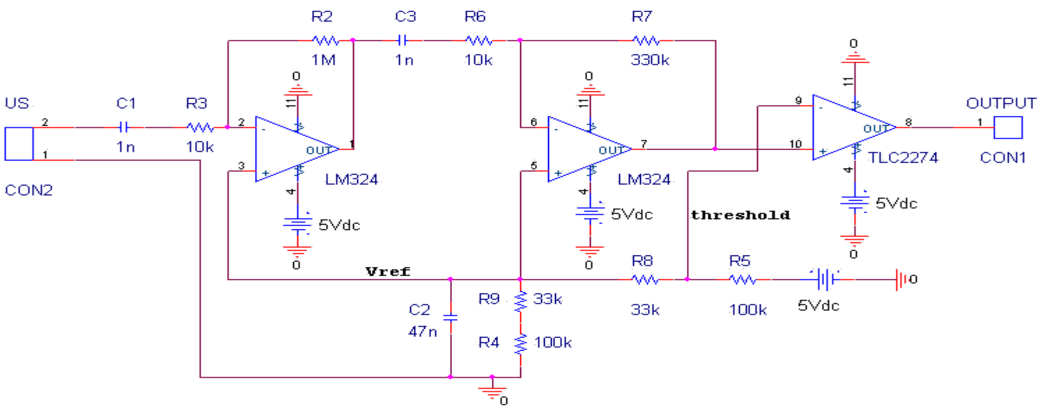

Fig. 5. Schematic of the US amplifier circuit.

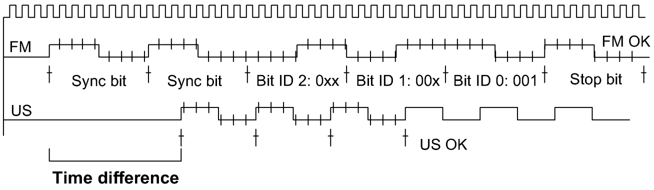

Fig. 6. Example of a frame from anchor point number 1.

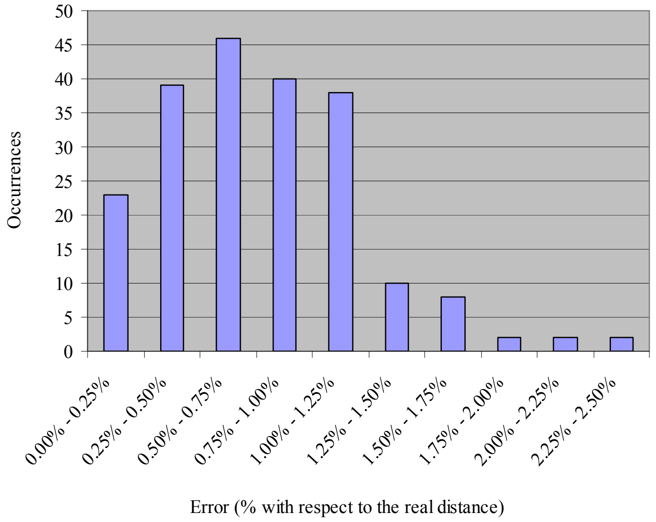

Fig. 7. Histogram of % of error in distance measurements over 135 samples.

The FPGA waits for an incoming FM signal. Just at that moment, the FPGA starts a counter which keeps counting until the ultrasonic pulses arrive. The FM sampler takes the two first bits to measure the period of the signal to synchronize with the transmitter. If the period meets the time constraints, the sampler takes the other bits, using this period. If the period doesn't meet them, or the full frame is not valid, the operation will be aborted. The third, fourth and fifth bits of the radio signal express the ID of the anchor point that transmits this frame. Likewise, the ultrasonic pulses are sampled to check if they satisfy some timing constraints (basically the frequency which should be 40 kHz). Because of the poor reliability of the ultrasonic communication, that constraint will be more relaxed than the FM one. For both signals, the timing checking is applied to complete periods, instead of semi-periods. Although several US pulses are received, when three well-formed ultrasonics pulses are sampled, the US frame is approved. Fig. 6 shows the sampling of the two signals: ultrasonics, and the Manchester-coded FM bits.

When a time difference is measured, and both signals are successfully checked, the time difference will be stored in a register. There are eight registers: one per possible anchor point, so the last valid distance measurement to each anchor point is available. The registers contain the time difference between the ultrasonic and radio signals, expressed in number of cycles. The FPGA implementation includes a Xilinx MicroBlaze soft-processor which collects the measurements. The number of cycles written in the registers must be multiplied by the clock period to be translated to real time. Constantly, a program running on the processor reads the eight registers which store the last measurements from each anchor point. The program translates the time differences into distances using Equation 3. With those distances, the program is able to trilaterate using Equation 5, taking two distances simultaneously.

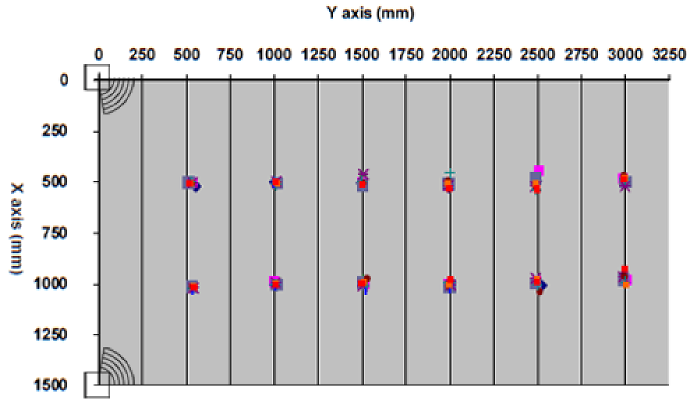

Fig. 8. Results from the trilateration process.

V. RESULTS

The system has been tested in an experimental setting. The distance estimation has been checked using Equation 3. 15 distance measurements between an anchor point and the mobile node have been taken each 20 cm inside an interval between 40 and 300 cm. Fig. 7 shows a histogram which represents the number of occurrences inside a specific percentage error interval. The represented percentage shows the relation between the error measurement and the real distance. The histogram shows that 148 of the 210 samples get an error lower than 1.00%. The average error is 0.78% and the standard deviation is 0.60%.

Trilateration has been tested with two anchor points and one mobile node, using equation 5. The distance between the anchor points is 1.5 m. A grid of 1.5 m x 3 m has been used to check the real position of the mobile node. The node has been positioned in several points to check the error between the real position and the position estimated by the system.

Fig. 8 shows the results of the estimated location of the mobile node compared to the real location. The points where the location has been estimated are (a·500, b·500) mm where $a \in [1,2]$ and $b \in [1,6]$. 10 measurements have been taken in every point where the mobile node has been positioned, for a total of 120 measurements. The maximum detected absolute error is 72.46 mm in position (1000, 3000) mm. The average absolute error is 20.08 mm and the standard deviation is 13.44 mm. The inaccuracies of the grid partly cause this error, which

TABLE I

ERROR WHEN D_{T-A1} AND D_{T-A2} ARE SKEWED

Mobile node in (250, 250) mm, 90º to anchors	D_{t-a2} – 10 mm		D_{t-a2}		D_{t-a2} + 10 mm	
	x_t	y_t	x_t	y_t	x_t	y_t
D_{t-a1} – 10 mm	0.0	-14.4	-7.0	-7.2	-14.1	-0.2
D_{t-a1}	7.0	-7.2	0.0	0.0	-7.2	7.0
D_{t-a1} + 10 mm	14.1	-0.2	7.2	7.0	0.0	14.0

Mobile node in (250, 1000) mm, 28º to anchors	D_{t-a2} – 10 mm		D_{t-a2}		D_{t-a2} + 10 mm	
	x_t	y_t	x_t	y_t	x_t	y_t
D_{t-a1} – 10 mm	0.0	-10.3	-20.5	-5.4	-41.2	-0.8
D_{t-a1}	20.5	-5.4	0.0	0.0	-20.7	5.0
D_{t-a1} + 10 mm	41.2	-0.8	20.7	5.0	0.0	10.3

affects more the location estimation than the distance measurement.

Fig. 8 shows that the error in x axis is greater than in y axis. This difference of error is due to the geometrical configuration when the mobile node has a distance to the wall greater than the distance between anchor points, and therefore the angle to both anchor points is very different to 90º, which is the optimal. Table I shows the error in x and y axis when the distances d_{t-a1} and d_{t-a2} are skewed ± 10 mm. In these examples, the anchor points are in (0, 0) mm and (500, 0) mm respectively, and the mobile node is in (250, 250) mm and (250, 1000) mm. The table shows that, in the position (250, 250) mm, which has a 90º angle to the anchor points, the maximum x-axis error is 14.1 mm and the maximum y-axis error is 14.4 mm. However, if the mobile node is in (250, 1000) mm, which has a 28º angle to the anchor points, the maximum x-axis error is 41.2 mm whereas the maximum y-axis error is 10.3 mm.

VI. CONCLUSIONS

This paper presents a low cost indoor location system implemented in an FPGA that can be used in mobile WSN as well as in robotics, domotics, etc. The location of a mobile receiver is inferred measuring the time-of-flight of ultrasonics with the support of radiofrequency for synchronization purposes. The achieved precision is suitable for many applications whilst the cost of the system is reasonably low. Using only two anchor points for 2-D location, the installation effort and costs of the system are reduced. If 3-D location is intended, three anchor points would be necessary. Besides, the location system could be implemented in an 8-bit processor to reduce costs even more.

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