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# FPGA-based Embedded System for Ultrasonic Positioning

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***Abstract*— This paper presents an FPGA-based ultrasonic location system. This system uses low-cost FPGAs and ultrasonic transducers to provide 3-D location to mobile nodes in an indoor environment. Synchronization is reached using the radiofrequency transducers that mobile nodes usually include. FPGAs have been used to sample ultrasonics and radiofrequency inside a custom peripheral which is attached to a MicroBlaze soft-processor. The calculus of the position of the mobile node is accomplished inside this processor.**

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

## I. INTRODUCTION

For many applications, and especially those in which some of their devices have the ability to move (i.e. robots), location is an important issue. If the mobile nodes are deployed in an indoor environment, outdoor location systems, like the well-known GPS or Galileo, are not suitable. On the one hand, indoor context usually needs fine accuracy (in the order of centimeters) and, on the other hand, the coverage of these systems in indoor environments is poor. Indoor location is not only significant for robotics but also for Wireless Sensor Networks (WSN) with mobile nodes, domotics, etc [1-3].

For indoor purposes, many technologies have been used, like image recognition and RFID. The first one is computational expensive and needs cameras, which increases the cost of the system. However, the accuracy that it gets is fine. RFID technology can be used for location if some transmitters are located in known points and the transmitting power is progressively changed. With some tries, the approximately distance between devices can be estimated. However, the accuracy of RFID-based location systems is not enough for many applications.

Ultrasonics-based location is inexpensive and it provides good accuracy. The time of flight of a transmitted ultrasonic signal can be measured in order to get the distance between the transmitter and the receiver of the signal. Ultrasonics is a slow propagation signal (about one million times slower than radiofrequency), so even a low-cost sampler can reach fine accuracy. The time-of-flight can be easily translated into distances knowing the speed of sound. If several distance measurements between a mobile target and different anchor points (points with known locations) are taken, the location of the target can be known using trilateration.

In the past, some ultrasonic-based location systems have been developed. Some systems, like the Bat Ultrasonic Location System [4], have a mesh of receiving anchor points installed at the ceiling, whilst some mobile devices are transmitting. The location of these mobile nodes is computed in an external PC. The MIT Cricket Indoor System [5-6] uses the opposite idea: the anchor points take turns to transmit while the mobile devices receive those transmissions. This system provides room-accuracy but accurate location can be reached with an external PC. The system of Randell and Muller [7-9] also uses transmitting anchor points and receiving mobile nodes and provides fine accuracy

In the present work, a low-cost 3-D indoor location system based on ultrasonics is presented. In this system, signal sampling and the calculus of the position are accomplished in a low-cost FPGA with an embedded soft-core microcontroller. The signal sampling is made with an ad-hoc custom peripheral of the microprocessor, implemented also inside the FPGA. The system does not need any external PC to assist the location, so the location system will be autonomous. This is the main novelty of the proposed system.

The rest of the article is organized as follows: Section 2 explains the trilateration method. Section 3 shows how to estimate distances between anchor points and nodes, and the mathematical expressions of trilateration. Section 4 explains the proposed architecture. Section 5 shows some experiments and their results. Finally, section 6 shows the conclusions of this work.

## II. TRILATERATION

There are two main methods to locate a mobile target in an environment: Triangulation and Trilateration.

Triangulation estimates the position of the target measuring the angles between it and some anchor points, which are well-defined geometrical points. This method is quite expensive because it needs hardware like unidirectional antennas and it uses non-trivial mathematical equations.

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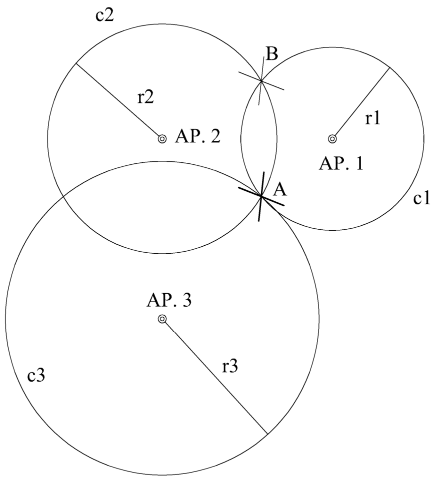

Fig. 1. Trilateration in 2-D space.

Trilateration calculates the position of the target measuring the distances between the target and some anchor points. Low-cost hardware can be used, and the mathematical problem is reduced to calculate the intersection of circumferences or spheres.

In 2-D spaces, trilateration needs 3 distance measurements (r1, r2, r3) to different, and not colinear, anchor points to locate the target. As Fig. 1 shows, that 3 measurements set 3 circumferences (c1, c2, c3) centered in the anchor points locations, and which radiuses are (r1, r2, r3). The first two circumferences intersect at points A and B. The third circumference intersects at just one of those two points (in the example, point A). In other words, the intersection of the three circumferences is where the target stands.

On the other hand, in 3-D spaces, trilateration requires 4 distance estimations (r1, r2, r3, r4) to different anchor points which cannot be coplanar. That estimation uses 4 spheres (s1, s2, s3, s4) centered where the anchor points are and which radiuses are (r1, r2, r3, r4). The Fig. 2 illustrates this problem. The first two spheres intersect at a circumference, c1. A third sphere intersects with c1 at points A and B. The fourth sphere intersects just at one of the points. The target is located in that point, which is the intersection of all spheres.

Using 3 and 4 anchor points for 2-D and 3-D spaces respectively is the general configuration. However, with a proper configuration, we can use just 2 and 3 anchor points, as it will be explained in Section III.

In order to estimate distances between the anchor points and the mobile node, we use the time-of-flight of an ultrasonic signal. However, both the starting time and the arrival time of the emission are needed. Using a fast signal like radiofrequency (RF), we can estimate the time of emission of the ultrasonics, so the receiver will be able to calculate the time-of-flight of the ultrasonics subtracting both times. Usually, robots and the nodes of a WSN already use RF to communication and collaboration purposes, so using RF in location does not imply added costs.

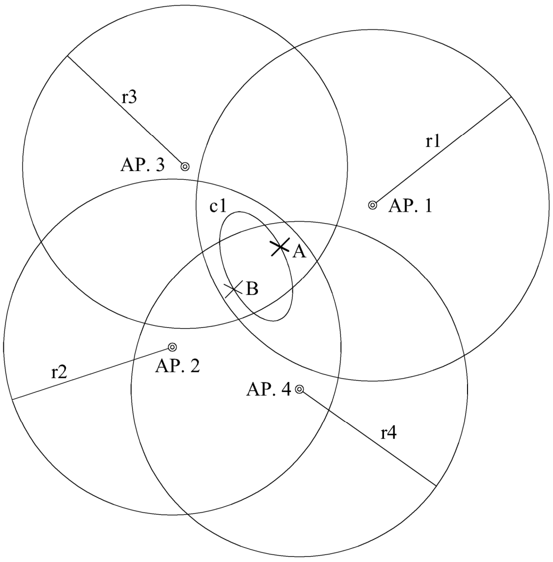

Fig. 2. Trilateration in 3-D space.

## III. LOCATION

As explained, the mobile node needs several distances to well-known points in order to locate itself.

### A. Distance Estimation

The distance between two points can be estimated measuring the time of flight of a signal which is emitted from one point to the other. Ultrasonics are frequently used in indoor positioning because the speed of sound is considerably slow and, consequently, the estimation can be accurate, even with a low-cost sampling system. The speed of radiofrequency is around $3 \cdot 10^8$ m/s, whilst the speed of sound is approximately of $3.4 \cdot 10^2$ m/s, near a million times smaller. For that reason, if a system samples the incoming signals at 100 MHz, and only detects the presence or absence of a signal, the theoretical resolution of the sampler could be up to $3.4 \cdot 10^{-6}$ m (0.0034 mm) with ultrasonics, while the resolution with radio signals is only up to 3 m. However, this resolution of ultrasonics is usually lower due to the frequency of the ultrasonic signal.

Anyhow, the time of flight of a signal can be estimated just if it knows the time when the signal was emitted, so time synchronization is needed. An easy and low-cost way to get synchronization is emitting a radiofrequency signal at the same time. Radio propagation speed is much greater than ultrasonics, so radio can be used as a synchronization method.

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

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

where $t_{US}$ is time of flight of the ultrasonic signal, $v_{us}$ is the speed of sound, which depends on the room temperature, and *offset* is a set of fixed delays that depend on the receiver circuit and that can be empirically measured. The time of flight of ultrasonics ($t_{US}$) 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 synchronization signal ($t_{RF}$) and the time difference between the arrival of both ($t_{diff}$):

$$d_{m-a} = (t_{diff} + t_{RF} - offset) \cdot v_{us} \quad (2)$$

The time of flight of the radio wave ($t_{RF}$) can be considered insignificant due to the speed of light, which is approximately a million times faster than the speed of sound. For that reason, the distance can be estimated just with the time difference:

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

### B. *Trilateration*

The location can be achieved when enough distances to different points are estimated. The configuration proposed in the paper is the location of a mobile device ($x_m$, $y_m$, $z_m$) in a 3-D space with three anchor points placed at (0, 0, 0), (a, 0, 0) and (c, b, 0). Fig. 3 shows this geometrical problem. The mobile node is in the intersection of three spheres centered in the anchor points. When the distances $d_{m-a1}$, $d_{m-a2}$ and $d_{m-a3}$ are measured, there are three equations that must be satisfied:

$$\begin{aligned} d_{m-a1}^2 &= x_m^2 + y_m^2 + z_m^2 \qquad (4) \\ d_{m-a2}^2 &= (x_m - a)^2 + y_m^2 + z_m^2 \\ d_{m-a3}^2 &= (x_m - c)^2 + (y_m - b)^2 + z_m^2 \end{aligned}$$

Solving the equation system, the coordinates $x_m$, $y_m$ and $z_m$ are:

$$\begin{aligned} x_m &= \frac{d_{m-a1}^2 - d_{m-a2}^2 + a^2}{2a} \qquad (5) \\ y_m &= \frac{c^2 + b^2 + d_{m-a1}^2 - d_{m-a3}^2}{2b} - \frac{c}{b} x_m \\ z_m &= \pm\sqrt{d_{m-a1}^2 - x_m^2 - y_m^2} \end{aligned}$$

As three anchor points are used in a 3-D space, there are two solutions. Nonetheless, the anchor points can be deployed close to the ceiling of the room, which is the usual deployment, so just the positive values of the Z axis are considered, and the solution is well-determined. One anchor point can be added in order to remove this restriction. Besides, another anchor point can be used with the intention of adding redundancy to the system and also it can be used to increase the coverage area.

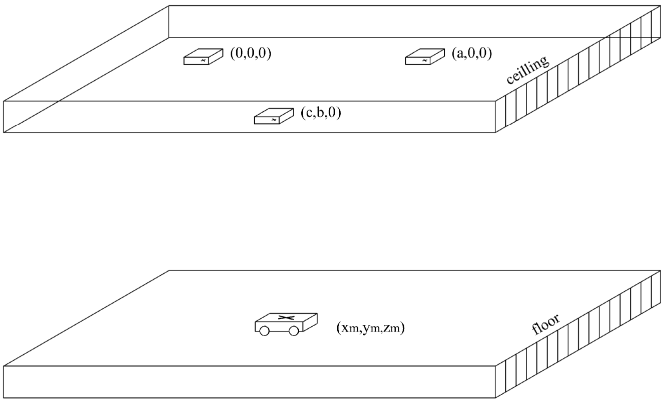

Fig. 3. Trilateration in a 3-D space with three anchor points.

## IV. DESIGN

### A. *Architectural Design*

The location architecture with anchor points can be divided into two categories: Passive Architecture, and Active Architecture. In the active architecture, mobile nodes transmit the necessary signals, whilst the anchor points receive them. The mobile nodes must take turns to transmit, so the number of mobile nodes in the system is critical, because the latency of the location system depends on it. However, this architecture is suitable for nodes which are moving during the location, because just one transmission is needed to locate one mobile node, so all the anchor points receive the emitted signal from exactly the same position.

On the other hand, in a passive architecture anchor points transmit while mobile nodes receive that transmission. Although anchor points must take turns to transmit, the number of anchor points in a coverage area is small and fixed. The mobile nodes don't transmit anything, so any number of mobile nodes can be deployed in the system, making scalable this architecture. The main disadvantage of this architecture is the accuracy with moving nodes. If a node is moving, the distances to the anchor points are taken in slightly different geometric points, so the error of location increases.

Besides, location privacy must be taken into account. In the active architecture, the mobile nodes transmit, and an external device calculates the position of the node. That position must be transmitted back to the node, so any device could read it, threatening the privacy of the node's location. However, in the passive architecture the node doesn't transmit, so the location of the node can be calculated by itself, and no position is broadcasted, preserving the privacy. Location outdoor systems

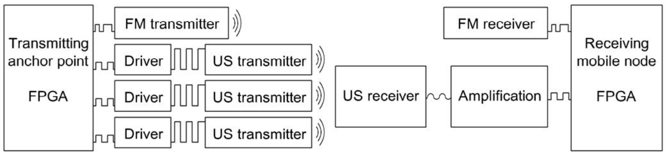

Fig. 4. Architectural design of the indoor location system.

like GPS or the forthcoming Galileo use a passive architecture.

We use a passive architecture because it is scalable and preserves the privacy of the node's location. Both anchor points and mobile nodes are low-cost FPGA-based systems, using the Xilinx Spartan3 family.

The top-level design of the proposed location system is shown in Fig. 4. The transmitting anchor points consist of an FPGA, a radiofrequency transmitter and several ultrasonics transmitters, one per anchor point. Besides a push-pull driver has been added in order to increase the range of ultrasonics powering the transmitters at 20 V. The FPGA that is used is a Xilinx Spartan3 (XC3S200).

The receiving mobile node consists of an FPGA with a radiofrequency receiver, an ultrasonics receiver, and a two-stage amplifier and digitalization circuit. This circuit is shown in [10]. Inside the FPGA, there is a custom peripheral and an embedded processor. The peripheral samples the incoming signals and checks their integrity. The FPGA used in the mobile node is a Xilinx Spartan3A (XC3S400A). Fig. 5 shows the internal design of the receiving FPGA.

An FPGA-based architecture has been used for several reasons. First of all, fine accuracy is needed in the sampling of the signals, because a little error in the time-of-flight estimation implies a big location error. Besides, with an FPGA the sampling of the two incoming signals can be accomplished in parallel, which is also important to reach fine accuracy, and time constraints and the frequency of the signals can be checked while they are being received. Finally, the sampling of the signals is not made in the processor, so the processor free time can be used for other tasks. An architecture based on a simple microcontroller without custom hardware would be less accurate and the design would be more complex.

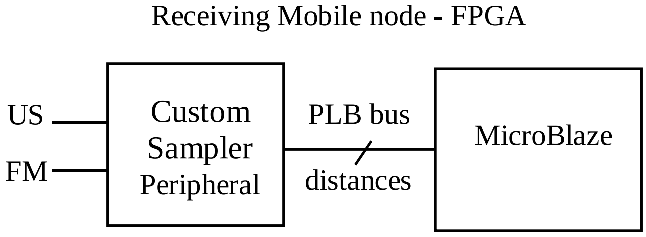

Fig. 5. Internal design of the FPGA-based receiving node.

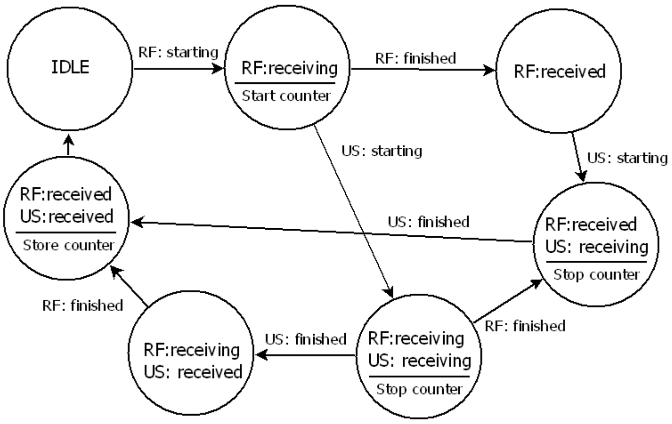

Fig. 6. State Machine of the custom peripheral.

## B. *Custom Peripheral*

The receiving FPGA includes a custom peripheral to sample both signals and it is connected to a MicroBlaze soft-processor, which calculates the position of the mobile node.

The peripheral is based on a state machine. It waits for an incoming FM signal, and it starts a 32-bit counter. This counter stores the difference of arrival times of both signals.

The counter stops when the ultrasonic signal arrives. This difference of time can be translated into distances knowing the speed of sound.

The FM signal should arrive before the ultrasonics one. However, the ultrasonic signal may arrive before the whole radiofrequency signal has finished, because the period of the modulated radiofrequency signal is bigger than the ultrasonics one. The state machine, which is shown in Fig.6, deals with all situations.

Fig. 7 shows an example of the sampling of a location frame. The first signal that arrives is the FM one. This signal consists of 6 Manchester-coded bits: 2 bits to synchronize the clocks of the transmitter and the receiver devices, 3 bits for identification of the transmitting anchor point and 1 stop bit. The peripheral takes the synchronization bits to measure accurately the period of the FM signal.

On the other hand, the ultrasonics is a square signal modulated at 40 kHz. The peripheral checks the integrity of both signals and reads the ID of the anchor point. If a signal doesn't meet the time constraints (8 kHz for FM and 40 kHz

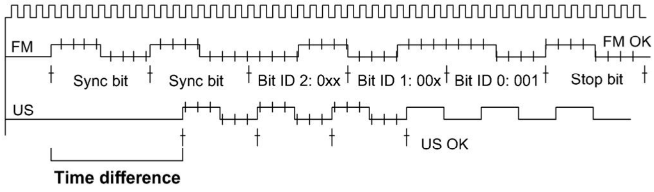

Fig. 7. Example of a complete frame from anchor point 1.

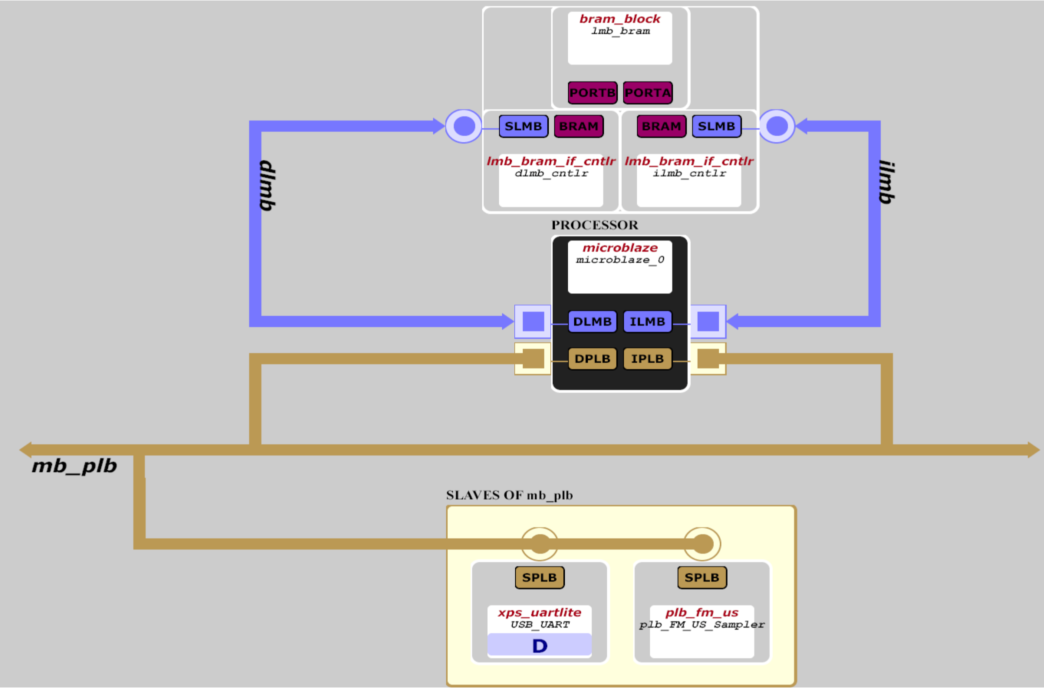

Fig.8: Block diagram of the MicroBlaze processor

for the ultrasonics), the frame is rejected, and the state machine resets.

The time constraints are applied to complete periods instead of semi-periods. Besides, the tolerance of the ultrasonic signal period is bigger because this signal is less reliable than radiofrequency.

If the time constraints are met and, at least, 3 ultrasonic pulses are received, the counter with the time difference of arrivals, expressed in clock cycles, is stored in a 32-bit register, which can be read by the MicroBlaze processor through a PLB bus. With a clock of 100 MHz, the maximum equivalent distance that a register can store is more than $1.4 \cdot 10^4$ meters, which is much more than necessary.

Although the system needs just 3 anchor points to locate in a 3-D space, the design has 3 identification bits so it handles up to 8 anchor points in a coverage area. More bits for identification could be used if necessary.

### *C. Peripheral Interface*

The peripheral is connected to the processor with a PLB bus, as it is shown in Fig. 8. The communication between the processor and the peripheral is accomplished with 8 registers, one per possible anchor point. Each 32-bit register has the last measurement to its corresponding anchor point, expressed in clock cycles.

The peripheral has two external inputs, which are the ultrasonics and the radiofrequency inputs. The clock period of the peripheral must be defined when the peripheral is added to the processor, so it can work with different clock frequencies.

The MicroBlaze processor periodically reads the 8 registers and, if they have changed, calculates the new position of the mobile node. The processor has been added to facilitate the calculus of the location. The registers have the differences of arrival times of the FM and US signals expressed in clock cycles, so a program translates them into distances using equation 3. After translating the registers, the location can be accomplished with equation 5, taking 3 measurements concurrently.

The calculus of the location is not complex so almost all the processor time is free for other purposes like motor control, communication, collaboration with other nodes, or move planning. Therefore, the MicroBlaze processor can be the central unit of the complete mobile node, which can be a node in a WSN, a robot or any other application.

## V. RESULTS

A prototype of the system has been developed in order to check the accuracy of the system. Two experiments have been made: distance estimation and trilateration.

Equation 3 has been used to check the accuracy of the distance estimation. A mobile node has been located at different distances from an anchor point and distance estimation inside an interval between 40 and 300 cm has been checked. 15 measurements have been taken in each point, while the distance between points is 20 cm.

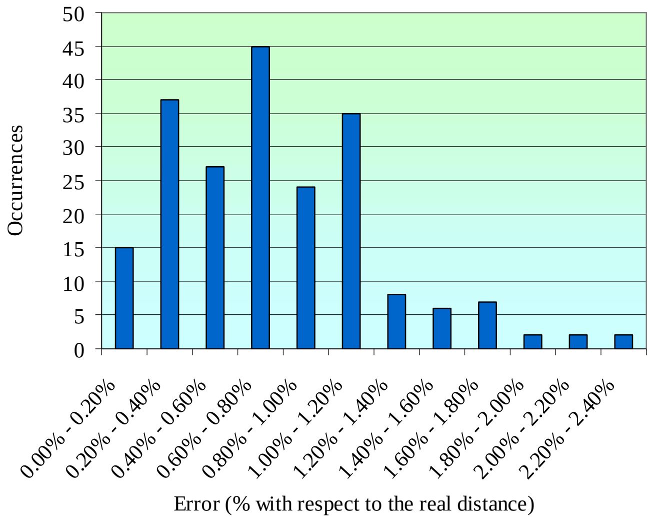

Fig. 9. Histogram of the error in distance estimation.

Fig. 9 shows a histogram with the number of cases inside a specific error interval. More than 70% of the samples get an error lower than 1.00%. The average error is 0.78% while the standard deviation is 0.60%.

3-D trilateration has been tested with three anchor points in points (0,0,0), (1200,0,0) and (0,1800,0) mm. A mobile node has been placed in different points in order to check the accuracy of the system in each one. As Fig. 10 shows, these points are in the positions (n·400, m·400, 2500) mm where $n \in [0,3]$ and $m \in [0,4]$. The average error of the 3-D trilateration system is 43.50 mm while the standard deviation is 51.02 mm.

In order to decrease the error of the system a median filter has been applied. The location is calculated with the medians of three distance estimations to each anchor point. With this filter, the average error of the 3-D location system is 35.02 mm and the standard deviation is 19.27 mm. The standard deviation is much lower because the filter rejects the outliers that may be estimated in the distance measurements.

The locations which are far away from the anchor points present bigger errors, up to 133.70 mm in point (1200,1600) mm. This is due to a geometrical problem. When a mobile node is much further respect to the anchor points, a little error in distance estimation produces a big error in the trilateration because the circumferences intersect at a very different point than the real point. However, if the mobile node is near the anchor points, a little error in the distance estimation produces also a little error in the trilateration, because the circumferences intersect near the real point. More anchor points could be used in order to reduce the distances between anchor points and the mobile nodes.

## VI. CONCLUSIONS

This paper presents an FPGA-based 3-D indoor location system using ultrasonics. The average error of the location

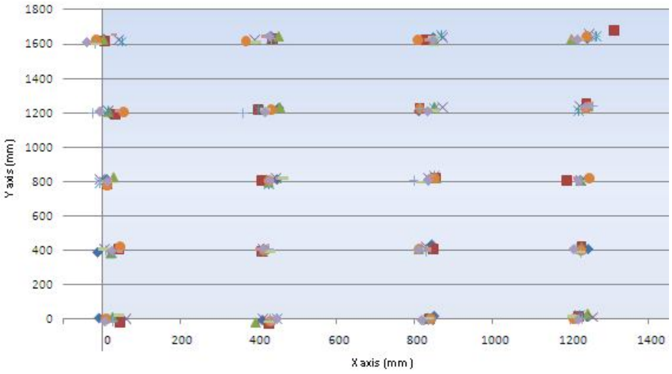

Fig. 10. Results of 3-D trilateration system with the median filter.

system is approximately 3.5 cm, which is appropriate in most indoor applications. A low-cost FPGA provides accurate signal sampling in parallel to the processor execution, so other tasks like mapping and movement control can be executed at the same time. Only 3 emitting anchor points are used to provide location in 3-D, although more points can be used to add redundancy or improve the accuracy of the system.

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