Real-Time Indoor Localization in Smart Homes Using Ultrasound Technology

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ABSTRACT
Countries around the world are facing an important ageing of their population, leading to medical staff shortages for homecare. With the development of smart homes, cognitively impaired inhabitants could benefit from the help of new adapted technologies in order to assist them in their daily activities. The first step to assisting humans in need comes with the need to detect their position in their home. In this paper, we introduce an innovative use of the ultrasound technology using round-trip time-of-flight (RTOF) based hardware as a mean to measure the position of people in their home. An implementation is described along with an experimentation showing its precision and the promising results in detecting both a static and a moving inhabitant.

Categories and Subject Descriptors
H.1.2 [**User/Machine Systems**], J.3 [**Life and Medical** Sciences]: *Health*.

Keywords
Smart Homes; Ultrasounds; RTOF; Indoor localization; Experimentation;

1. INTRODUCTION
Countries around the world are facing an ever extending life expectancy and falling birthrates [1], leading to several issues including (but not limited to) medical staff shortages for homecare services. With the recent growth of the Internet of Things (IoT) and smart homes, elderly people assistance could benefit from new technologies to improve quality of life. A smart home aims to help its resident in its daily life by assisting him performing specific tasks. In the case of people suffering from cognitive impairment (e.g. Alzheimer's disease) this would mean assisting them in activities in order to improve their autonomy and to ensure their security.

With improvements in the domains of ambient intelligence and emerging concepts for the use in connected environments, new solutions could be developed to help elderly people live in their own house without the need for any personal medical staff. This challenge can be overcome by studying the concept of human activity recognition (HAR). Its goal is to use raw output data from a wide array of sensors disposed in the person's environment and to associate them with activities actually performed by the resident. Recognizing activities as they happen is a key step in order to provide assistance to a frail or cognitively impaired inhabitant.

PETRA '16, June 29-July 01, 2016, Corfu Island, Greece

DOI: http://dx.doi.org/10.1145/2910674.2910718

In HAR, one of the most critical step towards assistance is being able to accurately locate people in the environment and follow their path. In order to do so, one must use raw data (e.g. signal strength from antennas, line of sight) and infer the most precise position possible from it. Several technologies have already been implemented in the past for indoor localization, such as radio-frequency identification (RFID), Bluetooth, ultrasounds or WLAN, each with their strengths and weaknesses.

In this paper, we propose to use ultrasounds as a positioning technology with an innovative implementation based on Round-Trip Time-of-Flight (RTOF), and use the information provided by our sensors to determine the position of individuals present in the environment. This method allows us to develop a low cost solution while remaining precise enough to compete with existing systems. This paper is organized as follows. Section 2 presents an overview of notable technologies used in the domain of indoor localization along with their strengths and limitations. Section 3 introduces the specificities and needs one must consider when developing an ultrasound-based positioning technology, particularly when implementing a RTOF architecture. Section 4 describes our prototype and the experimentation we designed to determine the viability of this technology, along with its results. Finally, section 5 briefly concludes and give an overview of our future work.

2. RELATED WORKS
In this section we overview notable works [2-12] and technologies related to our work on indoor localization. First we exhibit a list of most used technologies in the domain of indoor localization, regardless of the environment they are used in. In a second time we describe the technologies used in the specific domain of smart homes. Finally, we talk about the use of ultrasounds as an indoor localization technique and the different known implementation methods.

2.1 Notable Indoor Localization Technologies
Technologies used for positioning around the world are numerous and vary both in size and cost, but also in their precision and difficulty to actually deploy them. However, when trying to locate people or items in a closed environment, different factors have to be considered: radio wave based technologies suffer from wall penetration problems, which either stops the signal or causes interferences. Cost and scalability is another factor to be

considered: indoor systems work on a much lower scale and thus need smaller and more precise hardware.

2.1.1 Bluetooth (IEEE 802.15)

Bluetooth is a wireless protocol operating in the 2.4GHz ISM band. It has a shorter range than other wireless protocols, such as WLAN (IEEE 802.11), but can provide signal using small size tags with unique IDs used for localization. It has been observed [2] that Bluetooth performed better, in most cases, than WLAN with the same number of bases. Several commercial implementations of this technology already exist [3] such as Topaz and BLPA.

2.1.2 RFID

RFID can be used in two different ways: actively and passively. In a comparable environment, active RFID tags are much more effective than passive tags thanks to the use of an internal power source. Implementation by Hekimian-Williams et al. [4] achieves an accuracy to the millimeter. On the other hand, despite a decreased accuracy, passive RFID tags are powered by the emitting antenna, making them smaller and cheaper.

RFID localization systems have already been the object of an implementation [6] and will therefore not be further discussed in this paper.

2.1.3 WLAN (IEEE 802.11)

WLAN, commonly known as Wi-Fi, imposed itself as a technology of choice for midrange wireless communication. The signal range varies with the norm used, the most common (802.11 b/g) having a theoretical range of 100m. It is now widely used by the general public to connect to the internet at home and through public hotspots. For the same reasons, this technology is also implemented in most enterprise locations. Most portable devices (computers, smartphones) now have embedded Wi-Fi antennas and can be used to localize a person. Liu et al. reports [3] a precision varying from 1m to 5.4m when used on its own, depending on the solution used. When implemented in pair with an ultrasound solution, it's precision can be greatly improved to 2-15cm.

2.1.4 Ultrasounds

Ultrasounds are sound waves with frequencies higher than the upper audible limit of human hearing. Therefore, they can be used without disturbing people in the vicinity. Several methods exist to measure distances using ultrasounds: Received Signal Strengths (RSS); Time of Arrival (TOA); Time Difference of Arrival (TDOA); and Round-Trip Time-of-Flight (RTOF). RSS, TOA and TDOA all require separate emitters and receivers. They are the most used and measure the distance using either the attenuation of the signal strength, or the Time-of-Flight (TOF) in the case of synchronized emitters and receivers. RTOF on the other hand only needs one transceiver, acting as both a transmitter and a receiver. Whenever a sound is emitted, it will bounce off the first object on its path and return to the source. The distance is then derived from the velocity of the radio signal in the air and the travel time. This implementation has the advantages of being small, precise and easy to implement as a part of a cost-effective infrastructure.

2.2 Localization Technologies Used in Smart Homes

Although any of the previously introduced technologies could theoretically work in a smart home, only RFID implementations have been thoroughly studied in such environments, experimented and published in previous papers. Two major implementations of this technology exist. First is the RFID snapshots concept, introduced by Vorst et al. [7] using one Ultra-High Frequency RFID reader and a collection of passive RFID tags placed in the environment. Instead of measuring the distance to the tags by using the signal attenuation, the reader infers its position from the known identifiers of the surrounding tags. After a training phase, the system is able to track a moving entity with a precision of 50cm. To contrast with this system, the second implantation [5, 6] uses fixed RFID readers at various positions in the environment to detect moving objects bearing a passive RFID tag. This is done by using an elliptical trilateration with filters. In contrary to the concept introduced previously, RFID readers used here are able to measure the signal intensity and bearing returned from the passive tags.

2.3 Use of Ultrasounds for Indoor Localization

While the use of ultrasounds as a part of a smart home's architecture has not been active research-wise, the technology has been widely documented over the years for general indoor localization.

One of the earliest implementations [12] uses a system based on the Active Badge [8] architecture. An employee wears a device emitting ultrasounds, which are detected by an array of receivers deployed in some of all areas of a company. A similar implementation by Priyantha et al. [9] called Cricket literally inverts how the system works by fixing ultrasonic transmitters on the ceiling and to have both wireless and ultrasonic receivers in an embed device carried by an employee. Additionally, they are able to measure the bearing of the mobile device by comparing differences in distances estimates.

One other well-known implementation is the WALRUS (Wireless Acoustic Location with Room-Level Resolution using Ultrasound) system [10]. WALRUS uses existing hardware already fitted with Wi-Fi connectivity and a standard microphone able to capture ultrasounds (21 KHz). Such hardware is common nowadays in laptops, tablets and smartphones. Speakers are placed in every room to broadcast an ultrasound signal. A client software is used on a PDA (or a smartphone nowadays) to listen to ultrasounds via the device's microphone, and informs the server through Wi-Fi whichever signal is detected, allowing for positioning.

Another method of implementation called TELIAMADE [11] consists of an array of ultrasound-emitting devices as described in the Active Badge [8] and Active Bat [12] implementations and the use of a ZigBee-based solution. A device carried by the mobile object or person detects ultrasounds and uses the ZigBee protocol for communication. Distance is measured with a Time-of-Flight estimation; several of them are then used to measure a precise position. A precision of 9.6mm is reported for TELIAMADE.

All of the previous implementations have one point in common: they require two different pieces of hardware to send and receive ultrasound signals. Equipping moving objects or personnel with such devices is no problem in most cases but becomes one in the case of smart homes. The goal of our system is to enable people detection without the need to wear any new device. This can be achieved by using a RTOF architecture instead of one-way signals (TOF, RSS, TOA, and TDOA). It is used in our implementation because of its ease of use and low cost. RTOF has flaws such as a lower tolerance for interferences and the need to intelligently position all the sensors.

3. NEEDS FOR REAL-TIME RTOF LOCALIZATION WITH ULTRASOUNDS

Real-time localization forces to take a few constraints into account. Data should be steady and continuous, and any calculation should be done efficiently to avoid unnecessary delays in position measuring. In this section we exhibit the constraints we addressed in the development of our solution.

Ultrasounds are very prone to interferences that could be caused by both ambient noise and sounds, or by the way sound from other ultrasound sensors propagate through the air after bouncing off an obstacle. To avoid false positives and smoothen up the signal, one should consider using a filtering algorithm. Mode and Median filter both are adequate candidates as they do require little computing power and are fast to execute. However, the number of input values directly influences calculation time and it must be tweaked accordingly.

After the filtering step, data (namely the distance to the obstacle) must be transferred to be treated. In the case of real-time localization, transfer should be fast and reliable.

After the transfer of data from the ultrasound sensors to the treatment unit (i.e. a computer running the client application), the position of an obstructing object can be measured. In the case of close sensors or large objects however, multiple detections could actually represent a same entity (e.g. one person obstructing multiple sensors). To address this issue, detected positions must be normalized to potentially merge positions together when applicable.

4. EXPERIMENTATION

4.1 Experimental Area

In order to determine the precision of our implementation, we used the cutting-edge smart home infrastructure of the LIARA laboratory. This prototyping area has been developed to simulate a standard home environment with different areas representing a kitchen, a bathroom, a bedroom and a living room. A wide array of sensors has been implemented and experimented in the laboratory over the years, including RFID antennas [5, 6], pressure plates and infrared (IR). All of these technologies are integrated and used by researchers working on HAR.

Figure 1. LIARA's smart home environment

In this experiment, we focused our efforts on several key points: determine the precision of our ultrasound sensors, have a precise localization system, and being able to follow someone's path. In order to achieve these goals, we tested our prototype in the bedroom area of our laboratory which is 2.28 meters large and 4.19 meters long.

4.2 Prototype

4.2.1 Hardware

As stated in our introduction, one of our goal was to implement a cost-effective solution while staying competitive with other indoor localization solutions. In order to achieve this, we decided to develop our own architecture instead of using existing ultrasound positioning solutions.

We opted for MB1010 sensors from MaxSonar for their durability, their ability to both send and receive ultrasounds, and their compatibility with recent microcontrollers. They have a maximum range of 6.45 meters and a resolution of 2.5 centimeters. The produced beam has the shape of an elongated water drop (i.e. widens at first, then goes in a straight line) with a maximum width of 28 centimeters.

Sensors are managed by multiple Photon microcontrollers built by Particle. The advantages of this device are its wireless connectivity, allowing data from sensors to be transferred easily, and an ease of programming similar to the popular Arduino microcontrollers. It has an embedded 1MB flash memory and 128KB of RAM, is compatible with 802.11b/g/n Wi-Fi, and has 18 GPIO ports (including 6 analog and 7 digital pins). Each one of them can simultaneously control 6 ultrasound sensors.

Sensors and the microcontrollers are connected via regular Ethernet cables.

4.2.2 Software

The downside of creating a custom home-made solution is the lack of software which would allow even basic experimentation of our architecture. The first step was to develop a new firmware for the microcontroller in order to get data from the connected ultrasound sensors. Every 50 milliseconds, the values are read and filtered using a median filter on the last 8 values to remove random signal drops. It is then sent to connected clients using the UDP protocol. This firmware is also responsible for the Wi-Fi connectivity.

We also developed a graphical user interface in order to receive and visualize data sent by the different microcontrollers, identified through their IP address on the network. It is also responsible for the calculation of positions by triangulation. After a short configuration, the user is able to see the different sensors present in the room, their state (i.e. the distance measured) and the position of any detected object. It is also possible to display raw data if needed.

4.3 Experiments on Localization

In order to accurately determine the precision of our system, we decided to carry out two different tests. The first one focuses on determining whether using multiple sensors still produces results loyal to the reality or not. The second one is used to measure the ability of our system to accurately track a moving entity (e.g. a person).

4.3.1 Static object

In order to determine the precision at which we are able to measure the position of a static object, we chose four reference places where an average person would have to stand. Measured positions are then compared to these reference positions. The distance between both of these positions are calculated as a precision factor.

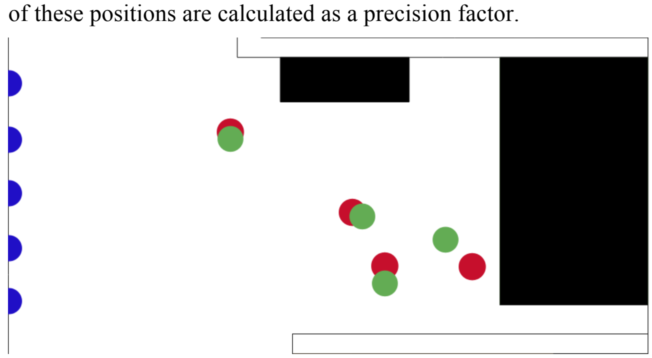

Figure 2. Comparison between real locations (red) and measured locations (green). Ultrasound sensors are shown in blue. Black areas represent furniture.

In our experiment, the least precise position we measured (bottom two dots on Figure 2) was 28 centimeters away from the theoretical point, whereas the most precise position we measured was only 5 centimeters away from its real emplacement. These results are very encouraging: detecting the position of a person with multiple sensors necessarily provokes a drop in the precision, but we are still able to deduce position with a relatively small deviation from reality.

4.3.2 *Moving entity*

The case of moving entities adds a new constraint, which is the refreshment time of the input data. The higher this rate is, the lower the precision of the measurements are. In this test, we asked a person to walk at a normal pace through the testing area twice (once in both directions), the start and end points being out of detection range. The walking speed is of approximately 3 kilometers per hour.

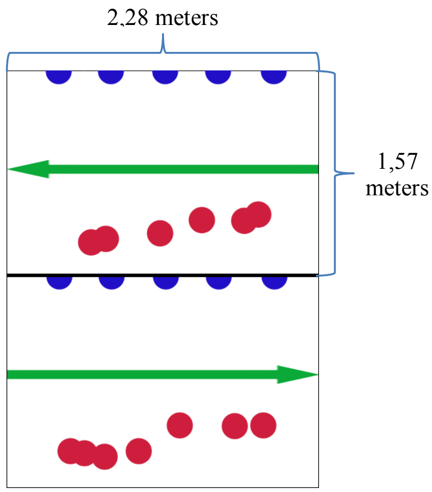

Figure 3. Detected positions (red dots) while moving through the test area (green arrow). Blue dots represent the ultrasound sensors

In our experiment, we were able to follow a walking person by detecting a succession of positions and associating them with the same logical entity. This allowed us to compare the planned trajectory (i.e. a straight line) with the detected path (see Figure 3). Only one false-positive (not illustrated in Figure 3) has been detected in the entirety of the test and is most likely the result of interferences which could be filtered out. We can see that in both cases, the measured positions are very similar and are very close to the actual path of the person walking through the test area. Just like our previous test, these results are very encouraging and show our ability to measure the position of one person moving in a room.

5. CONCLUSION

In this paper we described an innovative use of the ultrasounds as a way to locate people in an indoor environment. We demonstrated that, despite its disadvantages in terms of sensibility to interferences, RTOF-compatible hardware could be used in for the detection of moving persons with a more than satisfying precision. Moreover, this implementation allows indoor tracking without the need for people to carry any device contrary to any other solution. In a case of HAR applied to cognitively impaired people, this system would allow patients to free themselves from any additional locating device that could be an annoying addition to other needs linked to their illness.

Despite encouraging results, several aspects of our implementation could be enhanced. First, sensors must be placed in our whole laboratory in order to validate our model in a complete environment. Our second improvement axis would be to programmatically add the ability to sequentially trigger some sensors. This would allow the placement of additional sensors without the fear of interferences, and therefore increasing the precision of our positioning algorithms.

6. ACKNOWLEDGEMENTS

The authors would like to thank their main financial sponsors: The Natural Sciences and Engineering Research Council of Canada and the Canadian Foundation for Innovation.

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