Ultrasonic signal acquisition module for smartphone indoor positioning

Alejandro Lindo, María del Carmen Pérez, Jesús Ureña, David Gualda, Enrique García, J. Manuel Villadangos
Electronics Department, University of Alcala
E-28805, Alcalá de Henares (Madrid), Spain.
{alejandro.lindo, carmen}@depeca.uah.es

***Abstract*—Smartphone capabilities can significantly enhance mobile and context-aware applications that depend on location information. Whereas outdoor Location Based Services (LBS) are highly developed thanks to GPS, indoor LBS still demand a positioning technology that provides accurate location data. In this paper, an ultrasonic signal acquisition module for fine-grained indoor positioning of portable devices, such as smartphones or tablets, is presented. It is based on a microcontroller that digitizes the signals coming from a set of ultrasonic beacons placed on the ceiling and transfers the data acquired through Bluetooth Wireless Technology to the smartphone, for their consequent processing. All ultrasonic beacons emit simultaneously, each one a different Kasami code which is BPSK modulated with a carrier frequency of 40kHz. At the reception, the proposed module, that can coexist with an unlimited number of receivers, digitizes the analog signal captured by an electret microphone and sends it to the smartphone. Then, the smartphone carries out the correlation of the received signal with the emitted codes and obtains its absolute position by hyperbolic trilateration. Test results show that the proposed system can achieve similar accuracies to conventional ultrasonic based local positioning systems, with the advantage of services of a smartphone.**

I. Introduction

The deployment of smartphones and other portable devices will permit numerous advances in location-based services (LBS) and ambient intelligence, allowing a variety of multimedia services and web applications for user interaction or augmented reality. More research and industrial effort is still required to design and build indoor localization systems that can offer similar degree of precision, reliability and cost than the obtained for outdoor environments with the GPS system [1]. Most indoor LBS for smartphones use Radio-Frequency (RF) signals, obtaining the position mainly by means of Received Signal Strength (RSS) methods [2], Time of Arrival (TOA) [3], or Angle of Arrival [4]. Nevertheless, they exhibit meter accuracy levels. On the other hand, Ultrasonic Local Positioning Systems (U-LPS) offer accurate indoor results, achieving sub-centimeter accuracies [5], but demand specialized hardware not available for current smartphones.

Recently, new proposals merge LPS with smartphones obtaining sub-meter accuracy results. In Lok8 [6], a centralized U-LPS is proposed, where the smartphone transmits at 20-22 kHz range, and a set of four ultrasound microphones placed in the environment detect the emissions and send the data gathered to a centrally controlled-service that computes the Time Differences of Arrival (TDOA). On average, Lok8 offers accuracies about 10cm. In [7] we present a first work that offers multiuser positioning and avoid a centralized administration of location. That is, users with their smartphones ascertain their position autonomously. Since current mobile phones are designed to work with frequencies under 22kHz, an external device based on an analog multiplier was designed to translate the high frequency ultrasonic signals emitted by a set of ultrasonic beacons (typically around 40kHz in U-LPS) into a low frequency band (11 kHz) understandable by the smartphone. The output of the analog multiplier was connected to the smartphone using the Jack input as if it was a microphone. The mobile device process the low-band frequency signals and estimates its position by means of hyperbolic trilateration (there is no need of synchronization among emitters and receivers). Real tests show errors below 7 cm in 90% of the evaluated cases, when considering a covering area of $36m^2$. In this work, a new proposal is presented and compared with the former one. An acquisition module based on a microcontroller has been developed to control the acquisition and digitization of the ultrasonic signals emitted by the beacons, the resulting data is send to the smartphone through a wireless protocol for its processing. Note that this solution does not require a frequency down conversion and offers better positioning results. The rest of the paper is organized as follows: Section II describes the U-LPS, then in Section III the proposed implementation for the smartphone processing of the ultrasonic signals coming from the U-LPS is detailed. Real test results can be found in Section IV; and, finally, conclusions are outlined in Section V.

II. General features of the U-LPS

The main features of the U-LPS can be seen in Fig. 1. A set of five beacons are placed on the ceiling, at a height of 3.50m and located into a 0.707m x 0.707m surface. The beacons emit simultaneously and periodically each one a different 1023-length Kasami code. Mutual Access Interferences (MAI) are significantly mitigated due to the good cross-correlation properties of the selected codes. On the other hand, taking into account the frequency response of the ultrasonic transducer [8], a BPSK modulation with central frequency 41.67 kHz and two cycles per modulation symbol has been chosen. Consecutive transmissions are spaced 50ms to mitigate multipath effects.

Then, a non limited number of portable receivers (smartphones, tablets or similar), can compute their positions asynchronously by hyperbolic trilateration. With that purpose, the users have to carry, apart from the smartphone, a dedicated hardware with small dimensions which contains the ultrasound microphone and a microcontroller that manages the acquisition and data sending to the smartphone. Note that Line of Sight (LOS) of at least signals coming from four beacons

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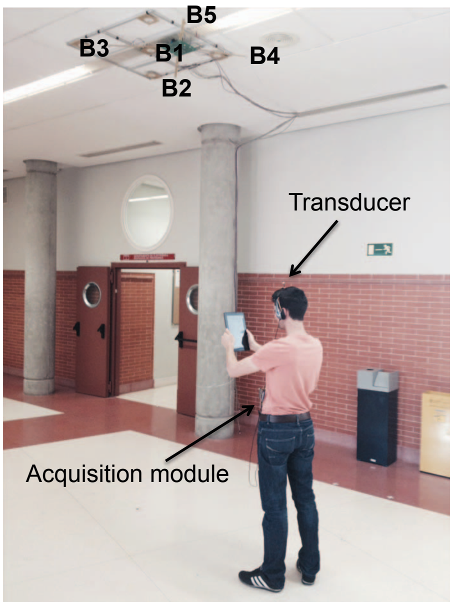

Fig. 1. View of the U-LPS.

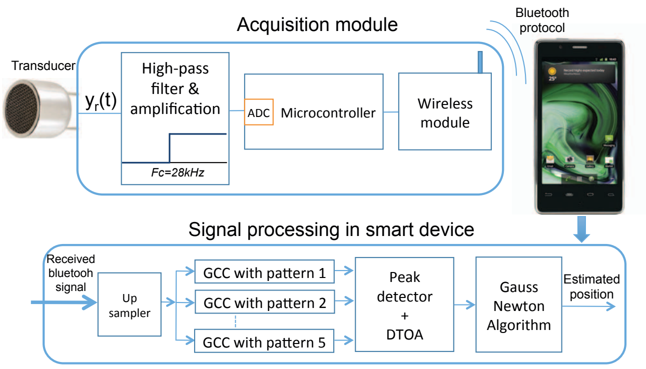

Fig. 2. Block diagram of the proposed ultrasonic signal acquisition module.

are required for good positioning. No wire connections are necessary between the smartphone and the dedicated hardware, which is described in detail in section III. The processing carried out in the smartphone involves firstly an asynchronous demodulation of the incoming signal. Then, the simultaneous generalized cross-correlation (GCC) [9] with all codes emitted by the beacons is performed. The main correlation peak at the output of each GCC indicates the instant of arrival of each corresponding code. The time of arrival of the nearest beacon is subtracted to obtain the TDOAs, and then a Gauss-Newton minimization method is used to compute the position.

III. Implementation of the Proposed Ultrasonic Signal Acquisition Module

A block diagram of the proposed acquisition system is shown in Fig. 2. It consists of three main stages: a reception and conditioning stage; a management module based on a microcontroller that digitizes the incoming signal; and a last stage that receives the data from the previous one and delivers the digital samples through Bluetooth to the portable device.

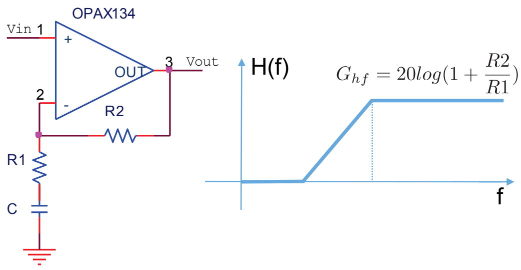

Fig. 3. Non-inverting operational with a capacitor.

An omnidirectional Panasonic WM-61B electret transducer [10] is used as receiver. Then, the conditioning stage allocates the DC component (by means of a non-inverting Operational Amplifier) in the middle of the span of the microcontroller Analog to Digital Converter (ADC) and amplifies the AC component to take full advantages of it. Also, the conditioning stage filters the signal so as to remove the unwanted frequencies under 28kHz. The filtering and amplification are carried out at the same time by means of a non-inverting Operational Amplifier with a capacitor in the inverting $(-)$ input, resulting in a first order filter. Fig. 3 shows the corresponding circuit and its frequency response. Because of the low order of this scheme and therefore, low gradient slope of the transition band, a cascade connection of three stages has been used. The resulting gain can be adjusted thanks to a potentiometer placed in the second one. The integrated circuit chosen for this prototype is the OPA2134 [11]. It includes two single-supply operational amplifiers designed optimally for audio applications which provide low distortion and low noise amplification. Since the design needs four operational amplifiers (one for the DC allocation and three for the AC filtering and amplification), two OPA2134 have been included.

For the transmission stage, a low power class 2 Bluetooth module RN42 by Microchip Technology Inc [12] has been chosen. This device uses a 2.0 version of the standard, is compatible with almost all commercial off-the-shelf smart devices and provides data transfer rates up to 2.1 Mbit/s. The communication between the microcontroller and Bluetooth module is carried out by means of an asynchronous serial protocol (UART).

The microcontroller is probably the most important component and determines the correct operation of the whole system. A NXP LPC1768 mbed [13] with a 100MHz ARM Cortex M3 processor has been used. It is a low-cost and low-consumption microcontroller with a high performance ADC (up to 500kHz of sampling frequency when the 12-bit integrated ADC is used as 10-bit or lower ADC [14]). The electrical characteristics of the ADC are set by default, i.e. the span is fixed between 0 an 3,3V and it can not be modified. As mentioned before, the microcontroller digitizes the analog signal coming from the reception and conditioning stage, and delivers the digital samples to the Bluetooth module through an asynchronous serial protocol (UART). This fact limits the maximum data transfer to 921.6kbps, enough for the purpose of this system. The sampling frequency of the ADC must be as stable as possible in order to ensure the correct processing of the signal in the smart device. For that reason,

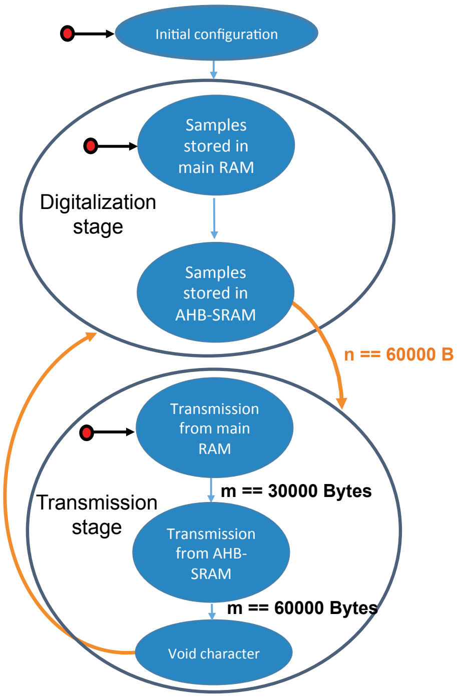

Fig. 4. FSM of the microcontroller, where n indicates the number of Bytes digitalized, and m the number of Bytes transmitted.

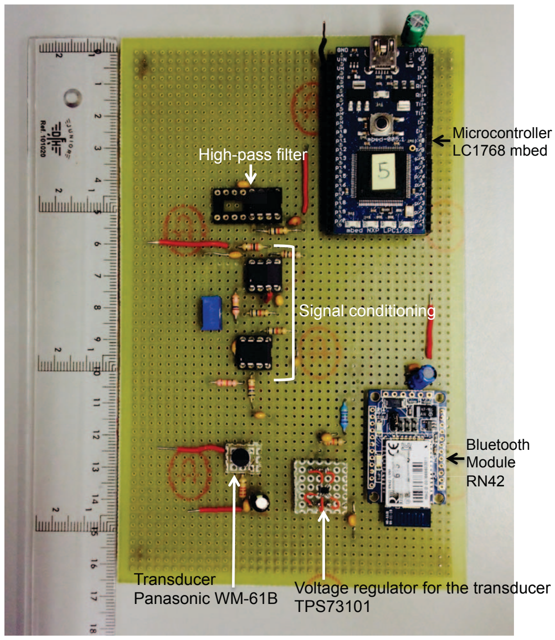

Fig. 5. View of a prototype of the proposed ultrasonic signal acquisition module.

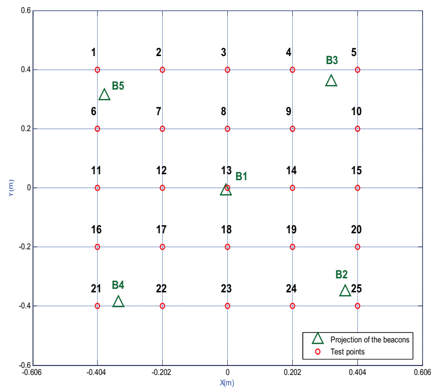

Fig. 6. Test positions and beacon projections in the ground.

and trying to avoid interferences in the digitalization process, the operation of the microcontroller has been divided into two isolated stages. In the first one, the microcontroller digitizes a section of the signal coming from the beacons (called window) with a sampling frequency of 333.33kHz and 8-bit resolution. The resulting samples are stored in the main memory. In the second one, the microcontroller transmits all the samples to the wireless RF module and empties the main memory. Finally, a void character is send to notify the finishing of the cycle to the smartphone/tablet. Then, the process starts again. The length of the stored window must be large enough in order to contain at least one complete transmission of the U-LPS. With the configuration parameters mentioned in section II, the window length must be equal or greater than 150ms, resulting in 50kB after the digitalization process. Since the microcontroller has only 32kB of RAM memory, two additional blocks of 16kB are required, called AHB-SRAM, that are usually used by DMA, USB and Ethernet peripherals. Fig. 4 depicts the Finite State Machine (FSM) that manages the microcontroller, whereas Fig. 5 is a photo of the proposed acquisition module first prototype.

Finally, NXP recommends to carry out an active low pass filtering before introducing the signal into the ADC [15] in order to improve the final results. Therefore, an active low pass filter based on OPA2134 with cut-off frequency at 500kHz has been included. In this first prototype the supply for the microcontroller is obtained from the laptop through the USB port; as well as this, the supply for the rest of the components is obtained from a regulate 3.3v output of the microcontroller.

IV. Results with Real Signals

In order to verify the feasibility of the system, some real experiments have been carried out considering the U-LPS shown in Fig. 1 and a grid over the floor with 25 test positions (see Fig. 6). The Bluetooth signal coming from the proposed acquisition module has been sent to a laptop and then processed using Matlab (see Fig. 2). In the future, the laptop should be replaced by a smartphone or tablet. Before the processing stage, the signal has been resampled from 333.33kHz to 500KHz in order to increase the resolution of the peak detector.

In Fig. 7 the mean error and standard deviation in the x-axis and y-axis are shown for each of the 25 test positions. Positions located close to a specific beacon, such as positions 13 or 21 can be more affected by near-far effect, and offer worst positioning results. Note, however, that standard deviations are below 14 mm in all real tests performed. It can be observed that standard deviations are similar for both axes, meanwhile

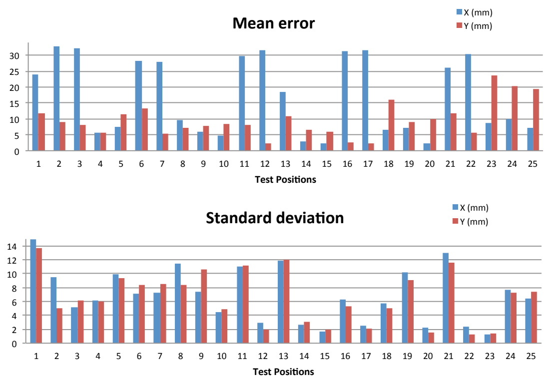

Fig. 7. Mean Values and Standard deviations for each test position.

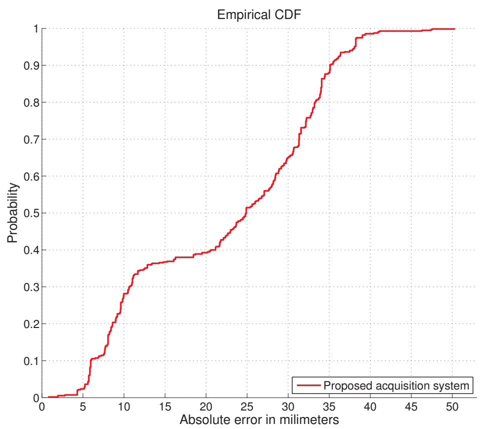

Fig. 8. Empirical CDF for the 25 evaluated test positions.

the mean errors in the x-axis are in some positions higher than in the y-axis, this is mainly due to systematic errors caused during the test setup. Fig. 8 depicts the Cumulative Distribution Function (CDF) considering all evaluated positions. Accuracies below 35mm are obtained in 90% of the cases. If these results are compared with those presented in [7] we found a significant accuracy increase (35mm accuracy levels versus the 100mm of [7]).

Note that, in this work, only one U-LPS has been considered, but the proposed system can be used in extended areas if several U-LPS are operating, each of them covering a particular zone of the total area. In that case, the smartphone odometer can be used in places where there are no ultrasonic signals available, as indicated in [5].

V. Conclusion

An acquisition module that adapts the signals coming from an U-LPS for their processing in smartphones or any other portable devices has been presented and compared with a previous proposal based on an analog multiplier. An external hardware device has been designed, it is based on a ultrasonic microphone and an acquisition system that digitizes the incoming signals from the U-LPS and send them through a Bluetooth wireless protocol to the mobile device. All the processing involved in the reception is carried out in the mobile device, allowing privacy and multi-user positioning. Results with real tests show centimeter-level accuracy (standard deviations below 2 cm in all evaluated test positions).

Acknowledgment

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