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Broadband acoustic local positioning system for mobile devices with multiple access interference cancellation

Teodoro Aguilera[a,*], Fernando Seco[b], Fernando J. Álvarez[a], Antonio Jiménez[b]

[a] Sensory Systems Research Group (GISS), University of Extremadura, E-06006 Badajoz, Spain
[b] Localization and Exploration for Intelligent Systems Group (LOPSI), Centre for Automation and Robotics (CSIC-UPM), Ctra. de Campo Real km 0.200, E-28500 Arganda del Rey (Madrid), Spain

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ABSTRACT

This paper presents an Acoustic Local Positioning System (ALPS) suitable for indoor localization of mobile devices, based on the transmission of high frequency Code Division Multiple Access (CDMA) audio signals from a fixed beacon network to a tablet computer. The system permits positioning of the device (and the user carrying it) within a few centimeters, which is accurate enough for most location-based applications. It also implements a CDMA scheme for localization, including compensation for the limited transmission frequency band of the sensors which causes Intersymbol Interference (ISI), as well as Multiple Access Interference (MAI) between the different beacons. Signal reception, processing and estimation of position all take place within the tablet, operating at real time and with an update rate of 2 Hz. Experimental results show that the MAI/ISI compensation algorithm increase both the system's robustness (availability ⩾90%) and accuracy (errors ⩽10 cm) under adverse circumstances such as near-far effect or noisy conditions.

1. Introduction and related works

From the appearance of the first Local Positioning Systems (LPS) for indoor environments to the present time many technological solutions have been proposed [1–3]. Nowadays, the local positioning in indoor environments with mobile devices such as smartphones and tablets is becoming increasingly relevant. Some applications of LPS are the location, tracking and guidance of people in indoor environments, as well as new ways of interacting with the objects in their surroundings. Especially noteworthy are Location Based Services (LBS) apps which are based upon knowledge of the users location to provide them relevant information about their environment.

Currently, mobile smart devices are equipped with a large number of built-in sensors which offer various possibilities in the design of a LPS. In that sense, Pedestrian Dead Reckoning (PDR) systems [4] make use of these sensors (accelerometer, gyroscope and magnetometer) to obtain accuracies (errors respect to the final position) of about 10% of the total walked distance. To improve these results other authors propose adding extra inertial sensors carried by the user [5] or including Map-Matching techniques [6].

Of particular relevance today are location systems based on Radio Frequency (RF) since most mobile devices incorporate this technology off-the-shelf. Their positioning technique is based on the measurement of the Received Signal Strength (RSS), either from Wireless Personal Area Network (WPAN) such as Bluetooth [7], Bluetooth Low Energy (BLE) [8] and Ultra Wide Band (UWB) [9], or from Wireless Local Area Network (WLAN) such as WiFi [10] transceivers. Because of the complex propagation of RF signals indoors, RSS measurements are subject to large variability in this kind of environments, resulting in typical positioning errors between one and a few meters. This poor accuracy has been enhanced by fusing RSS measurements with the information provided by the remaining mobile sensors such as the accelerometer [11], accelerometer and the magnetometer [12], gyroscope [13], magnetometer and the gyroscope [14], barometer [15] or even using all of them [16].

On the other hand there are some LPS, as the one proposed in this work, that benefit from the low propagation speed of sound in air to achieve centimeter accuracy by measuring the Time-of-Arrival (ToA) of acoustic signals [17]. These Acoustic Local Positioning Systems (ALPS) can be easily implemented in portable devices since most of them are equipped with audio recording/emitting hardware off-the-shelf, although this hardware is not prepared to work in the medium or high frequency ultrasonic range. The frequency response of mobile devices' microphones and speakers is always below 22 kHz and their audio acquisition sampling rates are not higher than 96 kHz.

One of the first works appearing in literature, called *Beep* [18], and

* Corresponding author.
E-mail address: teoaguibe@unex.es (T. Aguilera).

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a later evolution of this work [19], propose a centralized LPS where a Personal Digital Assistant (PDA) emitted short ultrasonic pulses that were detected by an array of six microphones, connected through a WLAN with a central process unit. These systems achieved positioning accuracies below 70 cm in 90% of cases, improving to 40 cm in positions away from walls and corners. A similar system was proposed in [20,21], where a smartphone was used to emit short 21.5 kHz pulses detected by an array of four microphones. This centralized system achieved errors below 10 cm by minimizing a positioning cost function. A different proposal was carried out in the *BeepBeep* ranging system [22], in this work the authors developed a two-way sensing technique to estimate the relative distance between a PDA and a smartphone. By measuring the ToA of chirp signals with frequencies between 2 and 6 kHz emitted by these devices, this system achieved positioning errors of 5 cm for distances below 4 m. Later, several works benefited from the *BeepBeep* ranging technique to develop different relative indoor positioning systems among smartphones and tablets [23,24], reporting average positioning errors between 10 and 30 cm. The main constraint of all these systems is their low update rate and low multi-user capability, in order to avoid signal collisions.

The current signal processing capabilities of smart mobile devices [25] allow for more efficient Code Division Multiple Access (CDMA) based systems, in which all signals can be emitted at the same time. The advantages of the CDMA scheme are well known and have been widely used in the design of general-purpose Ultrasonic Local Positioning System (ULPS) [26]. Also works like [27,28] have demonstrated the viability of using spread spectrum audible signals in a general-purpose ALPS using a set of four pseudorandom noise sequences and obtaining errors below 10 cm for 95% of measurements in a testing area of $6\times7\ m^2$. Unfortunately, the use of longer and simultaneous emissions in CDMA schemes comes hand in hand with the appearance of phenomena such as Multiple Access Interference (MAI) and Inter Symbol Interference (ISI) [29]. Due to the above mentioned audio system limitations, the implementation of a CDMA-ALPS with mobile devices either requires the use of an ultrasonic external acquisition system [30] or the emission of audible signals [31]. In this latter work, the authors presented a CDMA-ALPS for mobile devices using audible signals. This system was based on the use of four 255-bit Kasami codes, BPSK modulated at 20 kHz, which were acquired and match-filtered directly by an iPad in order to calculate its own position by means of multilateration. This system was evaluated in a $5.5\times5.75\ m^2$ positioning area obtaining errors below 10 cm for 70% of measurements at testing points free of MAI, ISI or multipath. These errors increased up to 90 cm at locations where these phenomena appear.

This work presents a new CDMA-ALPS which performs indoor localization of smartphones and tablets providing robust ToA estimations by using a MAI/ISI compensation algorithm. The system is based on the prototype presented by the authors in [31], where a similar architecture was proposed. However, this prototype lacked of several design aspects and signal processing tasks that severely reduced its performance, making it useless in a practical situation. The main improvements included in this evolution can be summarized as follows:

- Beacon locations are now determined using a metaheuristic search, in order to minimize the mean Position Dilution of Precision (PDOP) [32] in the entire location area.
- The temporal and spectral features of the emissions have been modified to reduce the effects of multipath and Doppler shift, as well as to minimize the losses caused by the receiver's microphone. These modifications are explained in detail in Section 2.2.
- A new algorithm has been implemented to avoid ambiguity between signals belonging to consecutive emissions.
- A MAI/ISI compensation algorithm has been implemented, completely redesigning the programming flow of the algorithm previously developed for a general purpose computer [29].

The next section of this paper presents a complete description of the ALPS, including design aspects, physical properties of the transducers and electronics, CDMA processing algorithms and programming. Section 4 contains the experimental evaluation of the positioning system, paying special attention to its performance with respect to MAI outliers rejection and noise addition. In Section 5 these results are discussed and further improvements of the system are pointed out. Finally, the most important conclusions of this work are drawn in Section 6.

2. Description of the acoustic local positioning system

The description of the ALPS proposed in this work is depicted in Fig. 1. As shown, Fig. 1(a) displays a picture of the location scenario where four acoustic emitting beacons are placed in a restricted volume inside of a box-shaped room, whose dimensions are detailed in Fig. 1(b). These beacons are close to the wall which is farthest from the entrance to the room and with their acoustic axis arranged perpendicular to it, thus allowing optimal signal reception to those users facing this wall. This configuration is particularly useful for certain types of LBS such as those designed to provide information to the visitors of a museum whose exhibits are shown in a single wall, as long as there are no occlusions of the direct propagation path.

On the other hand, Fig. 1 (c) depicts the PDOP values generated from the optimal beacons distribution obtained with the help of a Genetic Algorithm (GA). This algorithm was programmed to minimize the average PDOP value on the whole location area at 1.1 ± 0.2 meters height, starting with an initial population of 50 real-coded random emplacements for the beacons inside the beacon's location volume (see Fig. 1 (b)). A single-point crossover probability of 0.7 and mutation rate of 0.01 were defined, together with a tournament selection method, to meet a fitness stability convergence criteria within hundred generations.

The beacons are synchronized between themselves to emit four encoded acoustic signals that are detected with an unknown time base from the receiver (an iPad). The iPad identifies the received signals by correlation and obtains the Time-Differences-of-Arrival (TDoAs) between a reference beacon and the remaining ones. Finally, from these TDoAs the iPad computes its position by using multilateration.

The following subsections provide detailed information about the most relevant aspects of this ALPS, namely, the emitting and receiver transducers and their associated electronics, the acoustic positioning signals, the CDMA signal processing method for ToA estimation, the positioning algorithm, and the real time implementation of these algorithms in the iOS mobile platform.

2.1. Emitter and receiver architecture

The emission architecture is illustrated with the help of Fig. 2. The coded signals are synthesized using a Virtex 5 FPGA-based board [33], which has been programmed to simultaneously generate pseudorandom emissions every 80 ms. These digital signals are passed through two double digital-to-analog converter modules (Digilent PmodDA2 [34]), and then high-pass filtered to remove the DC offset.

Finally, they are fed to a pair of two-channel audio amplifiers (Philips TDA8920BTH [35]) powered with a DC source in order to drive a set of four speakers, see Fig. 3(a). Fig. 3(b), and (c) show respectively the acoustic directivity pattern and frequency response of the speakers, as provided by the manufacturer (Visaton CP13 [36]).

As stated before, the receiver module of the ALPS proposed in this work is an iOS device, particulary we have used a third generation iPad [37]. The acoustic signal containing the positioning codes emitted by the beacons is detected by the built-microphone of this device and then processed by its internal processor (A8X). Fig. 3 (d) shows the frequency response of this microphone, experimentally obtained in our laboratory (blue dots).