INVITED PAPER

Acoustic Local Positioning With Encoded Emission Beacons

This paper describes the acoustic local positioning systems employing encoded emission beacons and presents the results based on a testbed of mobile robot navigation.

By Jesús Ureña, *Senior Member IEEE*, Álvaro Hernández, *Senior Member IEEE*, J. Jesús García, *Member IEEE*, José M. Villadangos, M. Carmen Pérez, *Member IEEE*, David Gualda, Fernando J. Álvarez, *Senior Member IEEE*, and Teodoro Aguilera

ABSTRACT | Acoustic local positioning systems (ALPSs) are an interesting alternative for indoor positioning due to certain advantages over other approaches, including their relatively high accuracy, low cost, and room-level signal propagation. Centimeter-level or fine-grained indoor positioning can be an asset for robot navigation, guiding a person to, for instance, a particular piece in a museum or to a specific product in a shop, targeted advertising, or augmented reality. In airborne system applications, acoustic positioning can be based on using opportunistic signals or sounds produced by the person or object to be located (e.g., noise from appliances or the speech from a speaker) or from encoded emission beacons (or anchors) specifically designed for this purpose. This work presents a review of the different challenges that designers of systems based on encoded emission beacons must address in order to achieve suitable performance. At low-level processing, the waveform design (coding and modulation) and the processing of the received signal are key factors to address such drawbacks as multipath propagation, multiple-access interference, near-far effect, or Doppler shifting. With regards to high-level system design, the issues to be addressed are related to the distribution of beacons, ease of deployment, and calibration and positioning algorithms, including the possible fusion of information obtained from maps and onboard sensors. Apart from theoretical discussions, this work also includes the description of an ALPS that was implemented, installed in a large area and tested for mobile robot navigation. In addition to practical interest for real applications, airborne ALPSs can also be used as an excellent platform to test complex algorithms (taking advantage of the low sampling frequency required), which can be subsequently adapted for other positioning systems, such as underwater acoustic systems or ultrawideband radio-frequency (UWB RF) systems.

KEYWORDS | Acoustic local positioning system (ALPS); beacon deployment and calibration; indoor positioning; positioning algorithms; ultrasonic signals

I. INTRODUCTION

In recent years, there has been an increasing demand for proven technologies that provide services based on the position of people, mobile robots (MRs), or other objects across large indoor areas in buildings and surrounding outdoor spaces. For instance, location-aware applications, pervasive computing, and augmented reality require positioning data. In contrast to the high degree of implementation in the global positioning system (GPS) outdoors, there is no consolidated technology operating at the same level indoors.

Positioning technologies are usually classified according to the accuracy and the coverage area that can be achieved in the applications in which they are used [1]. Effective local positioning systems (LPSs) can be divided into five main categories: optical-based, mechanical-based, magnetic-based, acoustic-based and RF-based systems.

Manuscript received July 25, 2017; revised March 14, 2018; accepted March 23, 2018. Date of publication May 7, 2018; date of current version May 24, 2018. This work was supported by the Spanish Ministry of Economy and Competitiveness (TARSIUS project, ref. TIN2015- 71564-C4[1-R&4-R], and SOC-PLC project, ref. TEC2015-64835-C3-2-R). *(Corresponding author: Jesús Ureña.)*

J. Ureña, A. Hernández, J. J. García, J. M. Villadangos, M. C. Pérez, and **D. Gualda** are with the Electronics Department, University of Alcalá, E-28805 Alcalá de Henares, Madrid, Spain (e-mail: jesus.urena@uah.es).

F. J. Álvarez and **T. Aguilera** are with the Sensory Systems Research Group, University of Extremadura, E-06006 Badajoz, Spain (e-mail: fafranco@unex.es).

Digital Object Identifier: 10.1109/JPROC.2018.2819938

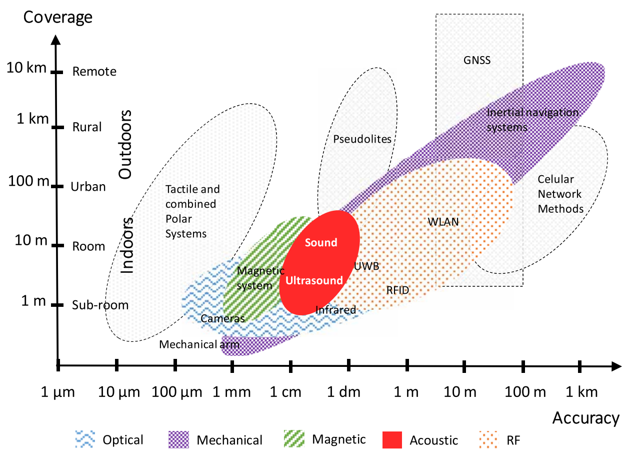

Fig. 1. ***Accuracy and coverage of acoustic systems for other technologies. (Adapted from [1] and [7].)***

As an initial comparison, Fig. 1 shows the coverage range and accuracy that can be achieved with each technology.

Optical-based systems include those that use vision or infrared sensors. Currently, the use of these systems is booming in dedicated applications with high accuracy, motivated by the enhancement of the sensory performance from cameras (including range measurement in 3-D cameras), the increase in the transmission data rate, the improvement of the computational capacity, and the high degree of development from the image processing algorithms. In [2], there is a classification of these types of systems according to the way in which they obtain the reference information used to carry out the positioning.

The most used mechanical-based systems are those based on inertial measurement units (IMUs). These units are composed of three-axis acceleration and inclination sensors, which enable successive positions to be obtained from the variations of velocities and directions. The main problem of these relative positioning systems is that the noise is cumulative; thus, they must be normally used in combination with other absolute positioning systems [3]. However, as there is no need of any special change in the infrastructure, these systems can also be used as transition systems between zones covered by other positioning technologies.

Magnetic-based systems make use of artificial or natural magnetic fields to obtain the position, usually considering the absolute magnetic field value or its variations. With artificial fields, the coverage areas are constrained to the places in which permanent or induced magnets are installed, whereas in the case of using natural magnetic fields, the coverage area is global [4]. Positioning with this technology is always prone to disturbances provoked by changes in the environment (e.g., furniture and people) that affect the magnetic field.

RF-based systems are currently the most used in positioning systems because they take advantage of installed communications infrastructure. As mentioned in [1], any radio signal can be used for indoor positioning at any frequency, signal range, or protocol (e.g., WIFI, BLE, RFID UWB, and LTE). Nevertheless, performance levels and applicability greatly vary depending on factors such as the use of, for example, preexisting reference infrastructure, signal ranges, and power levels. The main methods used with RF can be based on signal strength fingerprinting (several meters of accuracy with important precalibration efforts) or distance-based factors (where time-of-flight measurements face harsh environments for indoor signal propagation).

Finally, acoustic-based systems, which we will address hereinafter, use sound or ultrasound to estimate the position and, depending on the application, the pose of an object or a person (in general, the target). As seen in Fig. 1, this type of technology can achieve accuracies of approximately 1 cm with coverage distances up to tens of meters. To measure distances with acoustic signals, the most used methods are time-of-flight (ToF) [5], time-difference-of-flight (TDoF), or phase coherence [6].

ToF is an absolute method and measures the time that the acoustic signal takes to travel from a transmitter to a receiver. Using ToF, the distances can be computed with the speed of sound. Conversely, phase coherence measures the relative difference of phase between two acoustic sine waves. One of the measures reaches the receiver from a transmitter at an unknown distance, whereas the other arrives from a transmitter at a certain reference point. If the difference of distances traveled by both signals is less than one wavelength, the system can obtain the position of the unknown source. Table 1 summarizes the major advantages and drawbacks of using acoustic systems [6].

Independent of the range measurement method used, an ALPS derives the target position after obtaining several distances between the target to be positioned and a set of beacons distributed around the environment at known positions. Two different alternatives can be used: 1) beacons working as emitters and a receiver attached to every target to be positioned (in this case, there is no limitation on the number of receivers, and each one can obtain its position independently of the rest, thus maintaining privacy); and 2) beacons working as receivers and an emitter attached to every target to be positioned. In this case, the number of emitters is limited by the capacity of the transmission channel, and the distances are first obtained by the beacon infrastructure, and thus privacy is not guaranteed. In both approaches, the channel is shared by different emitter–receiver links; therefore, a type of medium-access control technique must be provided.

Table 1 Advantages and Drawbacks of Acoustic Positioning Systems

METHOD	ADVANTAGES	DRAWBACKS
ToF, TDoF or Coherence systems	– High accuracy and low latency – Multiple user tracking – Electromagnetic interference immunity – Low cost	– Low update rate – Considerable channel multipath and fading variation over time – Time-varying accuracy, (cumulative error over time in coherence systems)

As an example, in [8], a room-level accuracy ALPS is presented that covers ranges of more than 10 m. ALPS consists of a set of transmitters (tags) to be worn by humans or attached to objects whose positions are required. In this case, a set of receivers is installed on the ceiling or walls of each room. The system uses a carrier sense multiple-access (CSMA) protocol; thus, each emitter must find a free channel before attempting to transmit. The low propagation speed of ultrasonic signals implies that the system needs a long repetition interval per user, and that compromises the maximum throughput achieved (less than 0.5 positions per second and per room).

Other approaches, adapted from communications and radar systems, have also been used in ALPSs and reported in the literature. In [9], Segers *et al.* compare the performance of direct sequence spread spectrum (DSSS) and frequency hopping spread spectrum (FHSS). These methods are more noise resistant compared to non-spread-spectrum techniques (e.g., simple narrowband pulses). DSSS uses a signal carrier on which an orthogonal spreading code is modulated together with the data, resulting in a signal being spread around the carrier. On the other hand, the FHSS method uses a carrier that switches between a set of frequencies by following a pattern given by an orthogonal code. DSSS is likely to be more resistant to white noise, while FHSS is more resistant to in-band noise.

Other particular applications of advanced modulators have been proposed, including a discrete multitone modulation [29] and a filter bank-based multicarrier modulation [26].

Additionally, waveforms derived from chirps, changing the starting frequencies and chirp rates, have also been used to provide multiple access to ALPSs [10]. This work reports a very low interference, while it is possible to exploit the full bandwidth for each waveform.

The system presented in this paper uses direct sequence code division multiple access (DS-CDMA) for multiuser environments. The encoding of ultrasonic signals can be based on different types of binary sequences: Barker, Golay, Gold, Kasami, M-complementary sets of sequences (CSSs) or loosely synchronized codes [11]–[13].

In ALPS, when absolute distances between the target and the beacons are obtained (for instance, if the system measures ToFs), the positioning algorithm used is spherical trilateration [14]. It is necessary to provide a type of synchronization between the beacons and the target. Typically, this synchronization is easily achieved using an additional radio-frequency (RF) link between the tag and the beacons because of the difference of propagation speeds of electromagnetic and acoustic waves.

Although this synchronization can be avoided using TDoF, it requires an additional beacon. In this case, only the beacons must remain synchronized, and one of them works as the reference beacon. As the system measures differences of distances, the positioning algorithm is based on hyperbolic multilateration that provides a lower accuracy compared to the spherical case [15].

Thus, this paper presents different techniques and algorithms currently used in ALPS that involve all the signal and data processing levels. Apart from some theoretical discussions (most of them referenced to allow the reader to find a more detailed explanation if needed), this work also includes the description of an ALPS that was actually implemented, installed in a large area and tested for mobile robot navigation. In addition to its practical interest for real applications, airborne ALPSs use similar procedures to other positioning technologies and can be an excellent platform to test complex algorithms (taking advantage of the low sampling frequency required and the easy deployment). The methods tested with ALPSs can be adapted later for other positioning systems, such as underwater acoustic systems or ultrawideband (UWB) RF systems.

Besides the similarities in some of the techniques used for RF-based systems and ALPSs, there are also clear differences that are highlighted along this paper. In this way, different aspects for comparison are considered, such as wave propagation (acoustic waves in air are confined in closed spaces); indoor multipath effect (with reverberation and specular reflections); Doppler shift (not negligible); or the expected types of noise and interferences (flat in-band or impulsive); as well as particular implementation issues (frequency of the electronic equipment involved, utilization of antennas or transducers, etc.).

The rest of the paper is organized as follows. Section II addresses the introduction of ALPSs and is focused on their use with smart portable devices. Section III describes low-level processing techniques applied to acoustic transmitters. Section IV is devoted to high-level algorithms involved in positioning tasks, calibration, and data fusion. Section V explains a practical case of an ALPS implementation. Finally, the study's conclusions are presented in Section VI.

II. ALPS WITH SMART PORTABLE DEVICES

Portable devices, such as smartphones or tablets, offer myriad possibilities for the development of location-based services (LBSs), which has led to further research efforts on positioning and tracking systems. Outdoor LBSs have greatly expanded in recent years thanks to the reliable positioning provided by global navigation satellite systems (GNSS), which achieve accuracies in the range of several meters. Unfortunately, these services perform poorly in indoor environments, and there is no alternative technology sufficiently mature to solve the indoor fine-grained positioning on mobile devices. Conversely, people spend almost 90% of their time in indoor environments [16]. Furthermore, most people in advanced economies own a smartphone or a tablet; Pushter [17] reports that 72% of adults in the United States possess these devices, a percentage that increases up to 92% if only people aged 18–29 are considered. Similar percentages can be found in several European countries. This explains the great efforts and investments that are currently being made in the development of accurate indoor positioning technologies for mobile devices. If compared with other options based on custom hardware, such as conventional local positioning systems (LPSs), the use of smartphones or other mobile devices enhances LBS possibilities, allowing user interaction, augmented reality applications, a wide array of multimedia services or social networking that can enrich the user experience based on location. Examples of applications include building navigation (in, for instance, airports, hospitals, factories, and malls), augmented reality for cultural tourism, gaming, points of interest, and movement patterns to offer targeted advertising or customized services [18].

Existing systems mainly use RF-based methods, or more recently, acoustic signals, for indoor mobile device positioning [19], [20]. In general, accuracies obtained with RF-based systems are in the range of meters, whereas acoustic systems reach centimeter or even subcentimeter accuracies [21]. Nevertheless, conventional ultrasonic LPSs (ULPSs) require special-purpose speakers, microphones, and acquisition hardware (typically operating at approximately 40 kHz for this type of application), which are not compatible with current mobile devices.

Recently, there have been proposals that try to merge the advantages of ULPSs with the variety of services and applications that mobile devices can offer. One of the first proposals was the "BeepBeep" system [22] that uses audible acoustic signals, without the aid of external infrastructure apart from the basic hardware included in COTS mobile phones. It is basically a software solution for relative positioning of two mobile devices: each one emits, in turn, a simple linear chirp signal (bandlimited to 2–6 kHz), records its own emission and the one from the other device, computes the difference in samples, and exchanges the elapsed time with the other device to subtract them and obtain the time the sound takes to travel between both devices.

Nevertheless, the obtained accuracies significantly worsen for distances longer than 5 m in indoor environments, mainly because of the multipath problem. On the other hand, sound signals can be annoying for users, and many applications demand absolute positioning instead of positioning relative to another mobile device. Another proposal that overcomes some of these drawbacks is the LOK8 system [18]. It consists of a centralized system in which the mobile phone to be located transmits a very short designed signal at 21.5 kHz; then, a set of four microphones placed at known positions detects the incoming signals from the mobile phone and sends the measured times to a personal computer (PC) that runs an asynchronous multilateration algorithm based on TDoF. This results in a 7×7 m room showing accuracies reaching 10 cm. However, centralized systems present some concerns about how the user location information is managed, which becomes more critical when the positioning systems are installed in public areas [23]. Therefore, the current trend in this type of application is the design of privacy-oriented systems, in which the device to be located, and not a central unit, controls and computes its own position. This is the case for the ALPS system in [19], the winner of the 2015 Microsoft Indoor Localization Competition—IPSN. It is a privacy-oriented system based on the installation of standard speakers in the environment, which simultaneously transmit a chirp modulated signal with frequency sweeping from 19 to 23 kHz, immediately above the human hearing frequency range but still detectable by commercial mobile devices. To allow multiple-access transmissions, authors use pulse compression techniques based on Hamming codes, also obtaining tight timing resolution and high robustness to noise. Authors report an accuracy below 10 cm in 95% of the cases in a 20×20 m indoor area (this error increases up to 31 cm in the IPSN scenario). The ultrasonic data gathered by the mobile phone are sent through a wireless link to a main computer for processing. A similar approach, but with all the processing tasks performed in the mobile device, is presented in [24] for an aided tour navigation application in a museum. In this work, four speakers, controlled by a field-programmable gate array (FPGA) central unit board, are placed at known positions of the environment. They simultaneously emit four different Kasami codes every 50 ms, which have been previously binary phase-shift keying (BPSK) modulated at 20 kHz. Then, a nonlimited number of mobile devices (iOS devices in [24]) capture 75.5 ms of the incoming signals at a 48-kHz sampling rate. Tests in a laboratory of $5.75 \times 5.50 \times 3$ m show errors that range from 3 cm in the best cases to 90 cm in user positions adversely affected by multipath or near–far effects. Likewise, Lopes *et al.* [20] present a wireless sensor network infrastructure of synchronized acoustic beacons. The previous systems cope with the maximum sampling rate of commercially available smartphones at 44.1 kHz by emitting signals with frequencies just above the audible human range (typically from 18 to 22 kHz). Nevertheless, the available bandwidth to transmit encoded signals is quite narrow, which decreases the signal quality, and audible artifacts can appear. The limitation caused by working just above the human hearing range must be further analyzed in these cases to avoid potential annoyance to users. The first study with users of different ages was carried out in [7].

The LOCATE-US system, presented in [25], is a low-cost ALPS for mobile devices in which the incoming signals are not directly captured by the mobile device but rather by an attached acquisition module [26], [27], thus mitigating the aforementioned frequency constraints.

Cross correlation between the transmitted and received signals is commonly used in LPSs to maximize the signal-to-noise ratio (SNR) at the output of the correlator. The development of mobile communications in recent years and the interest of large companies has boosted the promotion of new encoding schemes and modulations [28], [29].

The measurement range of a single ALPS is limited. Thus, an application in which the user moves freely in a large indoor environment will require the use of several ALPSs to cover the entire analysis area. The use of complementary metal–oxide–semiconductor (CDMA) techniques allows us to assign a set of codes to every ALPS that identifies them, avoiding problems in areas of common coverage. To reduce costs, it is possible to use a particular deployment of different technologies: the acoustic beacons (ALPS) are installed only in critical zones where centimeter positioning is required, such as entrances or exits, whereas in zones where the positioning does not need to be as accurate, the inertial sensors of the mobile phone or even RF signals from the environment can be used to obtain a coarse-grained positioning. The drift errors from the inertial sensors are corrected when the mobile device reaches one of the ALPS coverage areas. Several examples of applications combining several technologies can be observed in [18], [24], and [30].

III. LOW-LEVEL PROCESSING IN ALPS

For the sake of clarity, the different algorithms and techniques involved in ALPS have been classified into two different processing levels. Fig. 2 summarizes this classification. This section addresses all the processing techniques used at the last stages before the emissions of the beacons and at the first stages after the signal reception at the receivers.

A. Narrowband Versus Broadband Systems

The first ALPS proposals, dating from the late 1990s and early 2000s, were based on the emission of short and constant-frequency ultrasonic pulses whose arrival was detected by following a simple amplitude or energy thresholding procedure [14], [31], [32]. This approach significantly reduced the complexity of both the emitter and receiver acoustic modules but at the expense of providing a limited ranging precision (some tens of centimeters) with high sensitivity to in-band noise. Indoor acoustic noise has different sources, both airborne and structure-borne, but most of its energy concentrates in the low-frequency sonic range ($f < 8$ kHz). In the high-frequency sonic and low-frequency ultrasonic bands (15 kHz $< f <$ 100 kHz) the power spectral density estimate for this background noise typically exhibits a flat pattern with peaks at certain frequencies that characterize a particular environment. These peaks are generated by cooling fans, pneumatic tools, fluorescent lamp chokes, and damaged plugs, among other phenomena, and they can severely affect the correct performance of narrowband ALPS. Fig. 3(a) shows an example of indoor acoustic noise acquired for 5 s with a broadband ultrasonic microphone [33] in a 30-m^2 research laboratory under typical working conditions. More than 90% of the energy represented in this figure falls within the low-frequency sonic range, and only 8.5% of this energy corresponds to the high-frequency sonic and low-frequency ultrasonic bands. Furthermore, the amplitude histogram of this high-frequency noise commonly fits a zero-mean Gaussian distribution as the one shown in Fig. 3(b).

In addition to the in-band noise, special attention has to be paid in the design of narrowband ALPS to avoid interference between different emitters, either by making use of time-multiplexing strategies [31] or by developing specific algorithms [32].

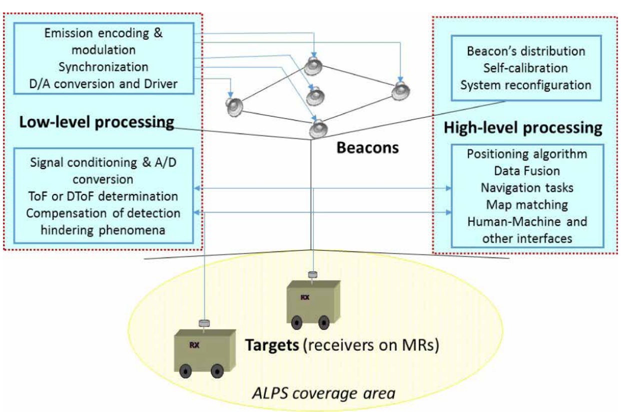

Fig. 2. ***Example of ALPS with a classification of the algorithms and tasks into low-level and high-level processing.***

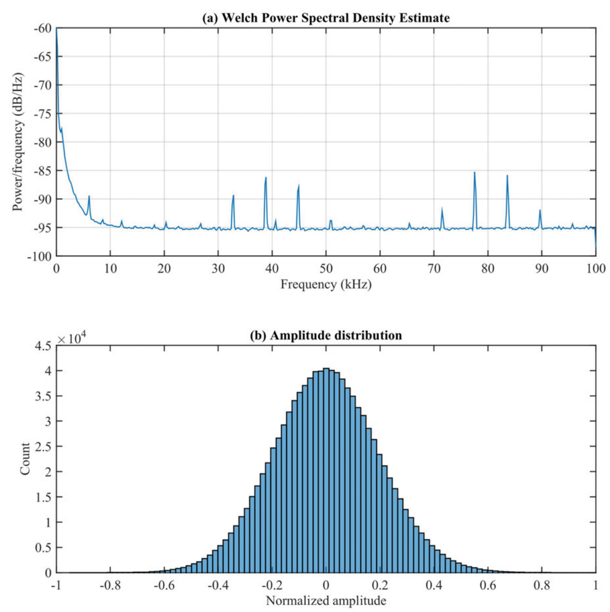

Fig. 3. ***Example of indoor acoustic noise acquired for 5 s at a sampling frequency of 200 kHz in a 30-m^2 research laboratory. (a) Power spectral density estimate. (b) Amplitude histogram of the high-frequency components ($f > 15$ kHz).***

To overcome these limitations, broadband signals extensively used in radar systems were soon incorporated in a new generation of ALPSs [11], [12], [34]. As is well known from signal detection theory, the precision of a one-way range measurement in an additive white Gaussian noise (AWGN) channel is given by [35]

$$\delta r \geq \frac{c}{B_{\mathrm{rms}} \cdot \sqrt{\mathrm{SNR}}} \tag{1}$$

where c is the signal propagation speed, SNR is the signal-to-noise ratio at the output of the receiver, and B_{rms} is the effective or root-mean-square (rms) bandwidth. Equation (1) indicates that to achieve a lower bound for the precision in the range measurement, a minimum value is required for the bandwidth-SNR product. Fig. 4 shows the relation between these two magnitudes for different values of the range precision.

From Fig. 4, it can be observed that by assuming a reference value of 6 dB for the SNR, a theoretical precision of 1 cm can be achieved with a signal bandwidth of 17 kHz. This bandwidth can be increased by shortening the duration of a continuous frequency pulse, but then the amplitude of the signal should be increased to keep constant the signal energy E appearing in the denominator of (1). There is actually a physical limit for this amplitude imposed by both real transducers and electronics. An alternative is to modulate the original waveform to extend its bandwidth while maintaining a constant energy and use a matched filter in the receiver to detect this signal. This technique is known as pulse compression in radar theory [36] or spread spectrum modulation in communications theory [37]. The use of a matched filter in the demodulation process also ensures the maximization of the output SNR, thus solving the high sensitivity of narrowband systems in the presence of in-band noise. The third shortcoming of these systems identified above, namely, interference between different emissions, can be addressed by choosing an appropriate modulation of the emissions or by a suitable selection of sequences, as detailed below.

B. CDMA-Based Systems

There have been mainly two alternatives to modulate the emitted waveform with the aim of increasing its effective bandwidth. The first one is based on linear frequency modulation (LFM), where the frequency of a pulsed waveform is linearly increased from f_1 to f_2 over the duration of the pulse. This is, for example, the strategy followed in [34], where an ALPS based on four transmitters sequentially emitting 1-ms-long LFM pulses was proposed. A time-multiplexing strategy was employed in this case to avoid interference between different emissions.

The second option to increase the effective bandwidth is based on binary phase coding, where a long pulse is divided into N subpulses whose phase is selected to be either 0 or π radians according to the bits of a certain code. If this code is a pseudorandom (PR) sequence, the waveform approximates a noise-modulated signal with a delta-like autocorrelation function. Fig. 5(a) shows the power spectral density of one of these broadband emissions with $N = 255$

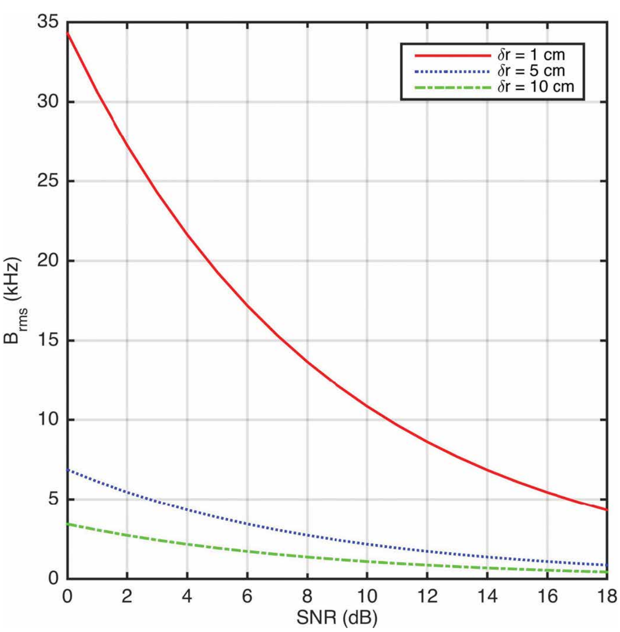

Fig. 4. ***Relation between effective bandwidth and SNR for different values of the range measurement precision.***

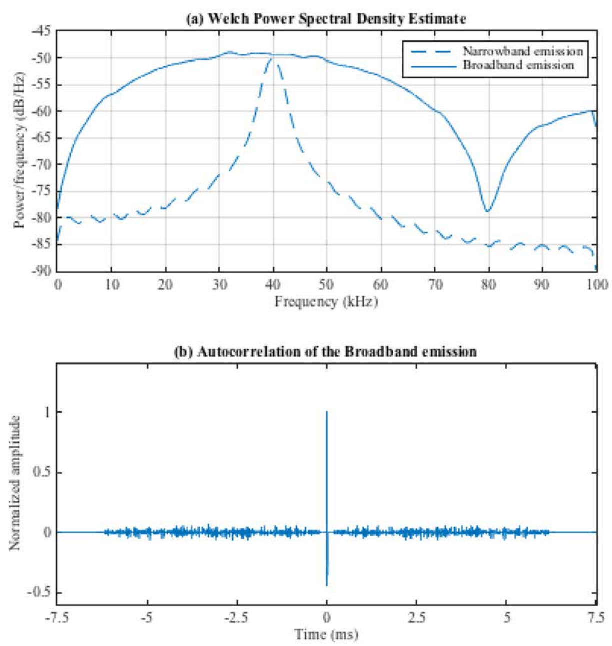

Fig. 5. ***(a) Power spectral density of a narrowband emission (20 cycles of a 40-kHz tone) and a broadband emission (a 40-kHz pulse BPSK modulated with a 255-b PR sequence). (b) Autocorrelation of the broadband emission.***

and a pulse frequency of 40 kHz ($B_{\mathrm{rms}}\approx 16.2$ kHz), together with the spectral density of a typical narrowband emission formed by 20 cycles of a 40-kHz tone ($B_{\mathrm{rms}}\approx 3.6$ kHz). Fig. 5(b) shows the delta-like autocorrelation function of the broadband emission. The main advantage of this approach is that different sequences from the same family can be generated with nearly null cross-correlation properties, thus allowing the simultaneous emission of different emitters with very low interference among them. This technique for sharing the transmission channel among several users by assigning them different modulating PR codes is known in communications theory as code division multiple access (CDMA). To date, several CDMA-based ALPSs have already been designed that propose the use of different sequences, such as Gold [12], Kasami [11], LS [13], or CSS [38]. In these systems, the receiver's matched filter can be designed as a straightforward digital correlator matched to the modulated waveform [12]. To reduce the hardware implementation complexity, several works propose the cascade combination of two correlators: one matched to the subpulse waveform and the other based on an efficient architecture matched to the binary code [38], [39]. These efficient architectures reduce the total number of arithmetic elements required to perform the correlation of an N-bit sequence from $O(N)$ to $O(\log_2 N)$, thus allowing the actual implementation of a real-time operating system in a hardware platform.

In most CDMA-based systems, the time delay of the received signal is measured when the autocorrelation peak exceeds a certain threshold, improving the precision of the range measurements between one and two orders of magnitude with respect to that of narrowband systems. Additionally, robustness to in-band noise is significantly improved thanks to the process gain provided by the matched filtering detection, which is proportional to the length of the emitted codes. Unfortunately, the use of simultaneous encoded emissions aggravates the pernicious effect of other phenomena that may hinder signal detection. Some of these phenomena are described below.

C. Detection Hindering Phenomena

There are three detection hindering phenomena that have been studied in the context of broadband ALPS, namely, intersymbol and multiple-access interference, multipath propagation, and Doppler shift. Although it is out of the scope of this work to present a comprehensive description of the different solutions proposed in the literature, it is worth mentioning the main effect that these phenomena may have on the system performance.

The signal received $r(t)$ in a broadband ALPS with N emitters can be expressed as

$$r(t) = \sum_{j=1}^{N} A_j \cdot \left(h_j * g_j\right)(t - t_j) + n(t) \tag{2}$$

where $g_j(t)$ are the modulated coded signals; t_j and A_j are the ToFs and amplitudes of the signals to be estimated; $n(t)$ represents the noise; and index j runs from 1 to N. The effect of the acoustic channel on the signal is introduced in the convolution term $h_j(t)$. This represents the channel impulse response, *a priori* unknown. The output of the conventional receiver is formed by correlating $r(t)$ with all signal codes. For the kth beacon

$$R_{rg_k}(t) = A_k \cdot \underbrace{\left(h_k * R_{g_k g_k}\right)(t - t_k)}_{ISI_k} + \underbrace{\sum_{j\neq k} A_j \cdot \left(h_j * R_{g_k g_j}\right)(t - t_k)}_{MAI_k} + \eta(t) \tag{3}$$

where $R_{g_k g_j}(t)$ is the cross correlation of codes $g_k(t)$ and $g_j(t)$. As (3) outlines, there are two effects that deteriorate the estimation of the ToFs: intersymbol interference (ISI), where the limited bandwidth of the acoustic channel lowers the correlation peaks and degrades the signal detection and ranging; and multiple-access interference (MAI) among all the emitted codes, in which larger amplitude signals impede the detection of weaker signals emitted simultaneously. Combined, both effects can lead to large deviations of the ToF estimates from their true values, notably decreasing the percentage of measurements whose error is below the outlier threshold (system availability) and increasing the mean error of these valid measurements. This effect can be compensated for by using recursive subtractive techniques, such as the parallel interference cancellation algorithm developed in [40], to increase the system availability from less than 50% to more than 90% in critical locations. Needless to say, this improvement is achieved at the expense of increasing the receiver complexity and thus the time required to compute a new position estimate. A minimum update rate of 2 Hz has been reported by Aguilera *et al.* [40], which seems to be high enough to perform the real-time tracking of moving persons. MAI might also be avoided by using another multiple access technique such as time-division multiple access (TDMA), since each emitter has its own slot of time to use the channel. The problem with this technique is the slow positioning rate achieved, mainly due to the low speed of acoustic waves. Nevertheless, an intermediate option between TDMA and CDMA (T-CDMA) has been proposed in [41]. The idea is to insert a certain delay between emissions to mitigate the superposition of signals while retaining CDMA separation (as some superposition of signals in the channel persists).

On the other hand, the multipath propagation has also been identified as a main cause of degradation in the performance of broadband ALPS. The effect of this phenomenon is critical near room walls and corners, where the strongly reflected signals interfere with line-of-sight (LOS) emissions and deteriorate the ideal correlation properties of these emissions. As a direct consequence of this deterioration, the largest correlation peaks obtained by matched filtering at the receiver do not always correspond to the instant of arrival of the LOS emissions. Multipath problems in ALPSs are mainly caused by multiple specular reflections that are rapidly attenuated in air. This phenomenon gives rise to typical room impulse responses where a first pattern of early reflections is followed by a late-field reverberant tail. Since the pattern of early reflections is basically a sparse channel whose number of coefficients with nonnegligible magnitude is much lower than the total number of coefficients, a matching pursuit algorithm can be used as a low complexity approximation to the maximum-likelihood solution to estimate the LOS–TOF. Indoor multipath acoustic and RF propagation exhibit similar relative delay spread, with typical rms values of some tens of milliseconds in the acoustic case and some tens of nanoseconds for RF signals. In both cases, the delay spread corresponds to a wave propagation distance of some tens of meters. Nevertheless, similarities seem to end there. Experimental work on indoor multipath RF propagation [42] has demonstrated that, in this type of environment, RF rays generally arrive in clusters whose arrival times can be modeled as a Poisson process with some fixed rate Λ. Within each cluster, subsequent rays also arrive according to a Poisson process with another fixed rate $\lambda \gg \Lambda$. The first of these clusters comprises the direct ray, which can propagate both through open space and likely some other obstacles. Subsequent clusters result from reflections in metalized structures and scattering from other elements [42], [43].

Acoustic impedance of air is much lower than the impedance of all building materials and other obstacles that can be found in a typical indoor environment. Consequently, acoustic waves propagating in air are almost perfectly reflected by these materials with zero phase shift [44]. This phenomenon gives rise to typical room impulse responses where the direct ray, which can only propagate through open space (LOS emission), is followed by a first pattern of early reflections, and finally by a late-field reverberant tail. This response is represented in Fig. 6(a) for a room with highly reflective walls. Since the pattern of early reflections is basically a sparse channel whose number of coefficients with nonnegligible magnitude is much lower than the total number of coefficients [see Fig. 6(b)], a matching pursuit algorithm can be used as a low complexity approximation to the maximum-likelihood solution to estimate the LOS–TOF. This multipath cancellation technique has proven to notably decrease the mean positioning error measured under strong multipath conditions in a CDMA-based ALPS where a 16-kHz sonic carrier was modulated with 63-b Kasami sequences [45], as well as in a T-CDMA-based ALPS where a 41.67-kHz ultrasonic carrier was modulated with 255-b Kasami sequences [42].

Finally, the low speed of sound in air that allows high-resolution positioning is also the cause of a new difficulty in broadband systems. As some authors have pointed out [45], [48], the Doppler shift caused by the user's movement in the acoustic encoded signal could make it

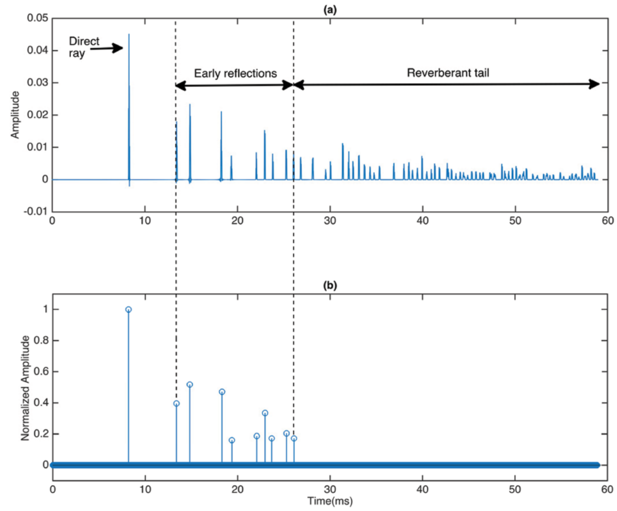

Fig. 6. ***(a) Acoustic impulse response of a room with highly reflective walls. (b) Equivalent ten-coefficient sparse channel model.***

completely unrecognizable to the receiver. Doppler shift is likely the detection hindering phenomenon where larger differences can be found between acoustic and RF-based local positioning systems. Assuming a static emitter, the relative change of frequency caused by a moving receiver is given by

$$\frac{\Delta f}{f_0} = \frac{v_r}{c} \tag{4}$$

where v_r is the velocity of the receiver relative to the emitter; and c is the signal propagation speed in air (about $3.43 \cdot 10^2$ m/s in acoustic systems and $2.997 \cdot 10^8$ m/s in RF systems). As can be deduced from (4), a fast moving person ($v_r = 2.5$ m/s) would cause a $8.3 \cdot 10^{-7}$% relative change of frequency in a RF-based system (20 Hz in a 2.4-GHz WiFi carrier), whereas this relative change would be 0.73% in an acoustic system (292 Hz in a 40-kHz ultrasonic carrier).

A straightforward solution to this problem would be to replace the single correlator at the receiver with a bank of them, each one matched to different frequency-shifted versions of the code to be detected. However, this simple implementation would require a very high operating frequency at the receiver if a fine Doppler resolution Δv_r is required. In [49], Álvarez *et al.* propose, as an alternative solution, the use of a multirate filter bank to compensate for the Doppler shift caused by the receiver's movement. This receiver is represented in Fig. 7 for a bank of $K = 7$ matched filters and five different codes, where the interpolation factor Q is determined by the Doppler resolution as

$$Q = \frac{c}{\Delta v_r} \tag{5}$$

This receiver notably improved the detection rate of broadband signals (with a 40-kHz carrier modulated with 255-Kasami sequences), which were acquired by the receiver

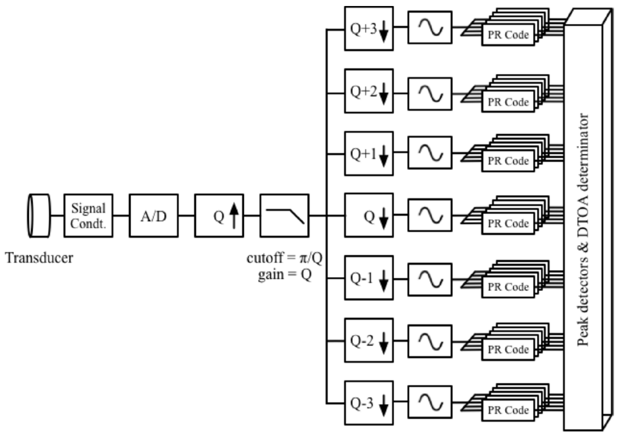

Fig. 7. ***Block diagram of the Doppler-tolerant receiver proposed in [49].***

when moving in a horizontal plane with linear velocities of up to 6.82 m/s.

A different approach to compensate for this phenomenon consists in using intrinsically Doppler-resilient polyphase codes to modulate the emissions of the ALPS. A polyphase code with L elements can be described as

$$\{s_i\} = \{e^{j\varphi_i}\} = \{\cos\varphi_i + j\sin\varphi_i\}, \qquad i \in \{1,\ldots,L\} \tag{6}$$

where $\varphi_i \neq \{0, \pi\} \forall i$. In [50], this interesting alternative was explored by using a metaheuristic search to find an optimal set of phases φ_i for the encoded emissions of an ALPS. This search tried to minimize a fitness function where the sum of two terms where considered: a first one assessing the autocorrelation and cross-correlation properties of the nonshifted unmodulated signals; and a second one computing the autocorrelation properties of the Doppler shifted modulated emissions. Unfortunately, the experimental results of this work were limited by the bandwidth constraints of current acoustic transducers.

IV. HIGH-LEVEL PROCESSING

From a high-level processing point of view, there are several issues that should also be considered when designing an ALPS, namely, distribution of beacons, positioning algorithms, integration of relative positioning systems, calibration algorithms, and the integration of map-matching techniques. This section addresses the key points for each one.

A. Distribution of Beacons

The determination of the number of beacons that compose an ALPS and their distribution is one of the first tasks to be carried out, since the cost and the accuracy of the system depend on this distribution. In addition to the coverage area and the cost, one of the most common metrics used to select the number and distribution of the beacons is the optimization of the propagation of measurement uncertainties to the position estimation error [51]. The influence of the beacon geometry on the position computation is known as dilution of precision (DOP) [52] or position dilution of precision (PDOP) if we consider only variances of coordinates. An estimation of the PDOP can be obtained as

$$\mathrm{PDOP} \approx \frac{\sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}}{\sigma_m} \tag{7}$$

where σ_x^2, σ_y^2, and σ_z^2 are the position variances in X, Y, and Z, respectively, and σ_m is the standard deviation in the distance measurements. Therefore, a suitable geometry for an ALPS structure should provide low PDOP values along the coverage area, thus creating a system with lower positioning uncertainties.

Another important factor in determining the structure of an ALPS is the reduced coverage range of the acoustic beacons (few meters). At times, the emitters are placed as close to each other as possible to cover a common positioning space with similar influence of all the beacons (although, in this case, the PDOP could not be optimal).

The use of metaheuristic optimization methods, such as genetic algorithms (GAs) [53], is one of the most extensive procedures for determining the number of beacons and the placement strategy based on the PDOP optimization, considering some restrictions such as the minimum distance among them. GAs are proposed in [54]–[56] to solve the sensor placement problem, and in the particular case of acoustic signals, one of the first studies was reported in [57] and, more recently, in [45].

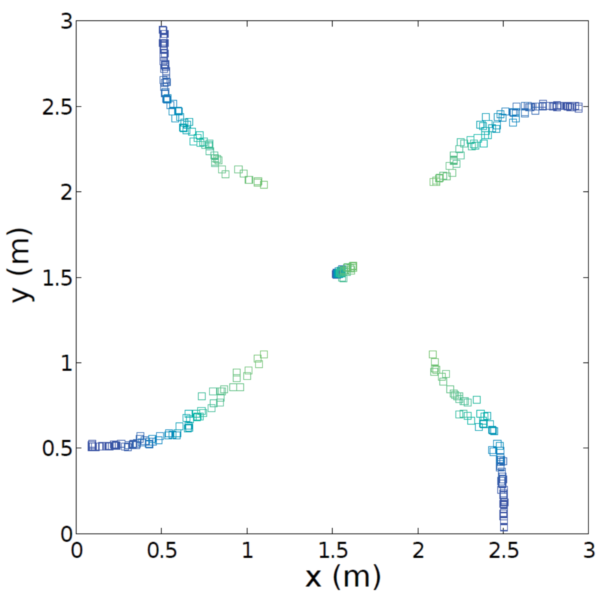

Fig. 8. ***Study of the optimal placement of five beacons according to a multiobjective optimization based on CRLB (five points of the different clusters with the same color correspond to a possible structure) [59].***

Furthermore, the optimal placement of the beacons can be addressed from an analytical point of view. In [58], a study is shown that discusses the influence of several parameters, including the geometry, on the accuracy of the position. Another work of optimal sensor placement [59] applies multiobjective optimization based on the Cramer–Rao low bound (CRLB) to estimate the location of several beacons. Fig. 8 shows an example of this study for the case of five beacons without geometrical constraints; the best distribution of this beacons is a square structure with four beacons at the corners and another one placed at the center.

This square structure was used from the beginning in our works related to ALPSs [60], since it is compact and portable if the distances between beacons are not too large. A similar structure has been recently proposed in [61]. In these cases, the main advantage is that all the beacons have the same orientation and a similar coverage area, and at the receiver, the acoustic powers coming from the different beacons are similar.

B. Positioning Algorithms

The main objective of a positioning system is to obtain the position of a target inside a coordinate reference. This position is commonly estimated by solving a nonlinear system of equations derived from the ranging measurements. There are different techniques depending on the nature of the observations. The most used for acoustic positioning are the ToF and the TDoF.

As mentioned in the Introduction, ToF is based on measuring the time between the signal emission of an active beacon and the reception in the target (that can be a system carrying another receiving beacon or a microphone). This method requires synchronization between the emitter and the receiver, as this is required to know exactly when the emitter starts to emit the signal. After obtaining a set of ToFs, they can be converted into distances using the propagation velocity of sound.

TDoF [62] is the ranging technique used when there is no synchronization between the emitters and the receiver. It is based on the differences of time between the receptions of two or more different emissions, using one of them as a reference. Then, the time differences are converted into differences of distances.

When a minimum set of distances or differences of distances is available (at least three for 3-D positioning in a hemispace), the position can be obtained by solving the corresponding system of equations (based on either trilateration or multilateration, i.e., either spherical or hyperbolic positioning, respectively). There are several approaches: the minimization of a cost function, directly through geometric methods, or Bayesian filtering.

Geometric methods are based on the linearization of the equation system in order to find a closed solution [63]–[65]. The problem of these methods is that they can be very sensitive to noise in some positioning areas. Other geometric methods address this problem using the Cayley–Menger bideterminant described in [66]. An example of this method for spherical trilateration is shown in [67] and for the hyperbolic multilateration case in [68].

In other approaches, the position is solved by iterating until a minimum is found for a cost function related to the positioning of a target. One of the most used numeric solvers is Gauss–Newton (GN). Some examples of this strategy can be found in [69] and [70]. Note that it is crucial to provide an adequate initialization for this type of algorithm in order to facilitate its convergence toward a suitable solution. A summary of the mathematical methods for indoor positioning is shown in [71], whereas [68] compares the GN implementation with a geometric method based on the Cayley–Menger bideterminant. The study shows that the GN method is more accurate (centimeter resolution) than the geometric one but with a higher computational cost. Fig. 9 shows a grid of real estimated positions on the floor of a room with five beacons placed on the ceiling (the projections on the floor are also shown in Fig. 7), comparing the performance of both methods. At each point, a set of 50 measurements was performed. As can be observed, the Cayley–Menger method presents a performance similar to the GN method. It is worth noting that the receiver has been positioned on the grid by hand, and both methods obtain the same positions.

Section IV-C describes some known Bayesian methods, since these techniques are also used to integrate measurements acquired by different sensors.

C. Integration of Relative Positioning

In many cases, ALPSs are used as an absolute positioning method for MRs or people; that is, they provide their positions in a global map. MRs use their internal odometer to estimate at a high rate their position and orientation

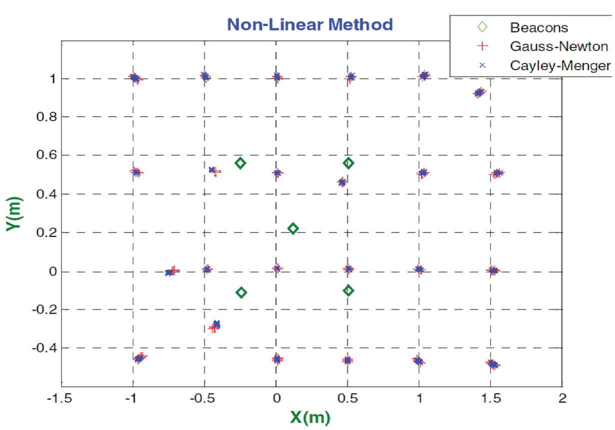

Fig. 9. ***Grid of estimated positions using Cayley-Menger and GN algorithms [68].***

(relative to the initial state) by integrating the number of rotations in their axes. A person can also wear an inertial measurement unit (IMU) with accelerometers and gyroscopes to achieve the same goal, thus obtaining their relative position and orientation. These relative measurements can be very accurate in short integration times, but they also involve cumulative errors. The combination of absolute and relative positioning systems is a good way to achieve high rates of positioning while avoiding cumulative errors. There are several techniques for merging both positioning systems [72]. For instance, Bayesian methods use statistical distributions to estimate the MR position from a set of measurements [73], dealing with the uncertainty associated with real measurements and with the possibility of adding the *a priori* knowledge of the positioning system (map information, physical constraints, etc.).

Common approaches are based on the extended Kalman filter (EKF), which is optimal for Gaussian noise, as well as several variants: the ensemble Kalman filter (EnKF) uses a Monte Carlo method to predict the statistical errors [74], and the unscented Kalman filter (UKF) [75] uses an estimator for non-Gaussian errors.

The work in [76] presents the implementation of an ALPS that allows a mobile robot to navigate in an extensive area using an H-infinite filter to combine the position measurements provided by the odometer and the ALPS. If the robot is in an area where the ALPS is not available, the H-infinite filter only uses the odometer information, and when it reaches an area covered by the ALPS, the absolute position improves the MR position and cancels the odometer cumulative noise.

See, for instance, the case in Fig. 10, where an MR with an odometer onboard is inside the coverage area of an ALPS.

The position estimation is often represented in the discrete space state as

$$\mathbf{X}_k = f(\mathbf{X}_{k-1}, \Delta d_{odo}, \Delta\theta_{odo}) + \mathbf{w}_k \quad (8)$$

$$\mathbf{Z}_k = h(\mathbf{X}_k) + \mathbf{v}_k \quad (9)$$

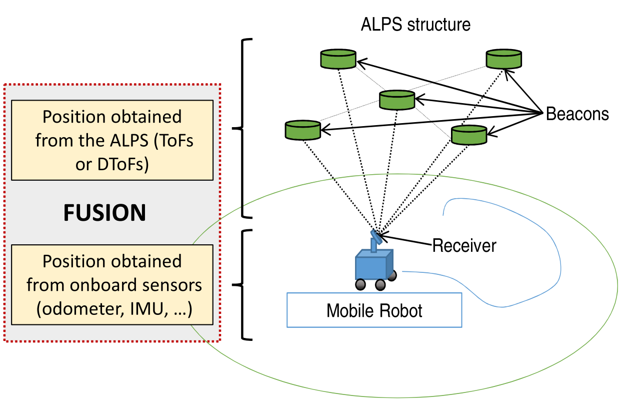

Fig. 10. ***Diagram of a fusion algorithm when an MR is inside the coverage area of an ALPS.***

where $\mathbf{X}_k$ is the state vector at instant k (usually the target position and its orientation); $f(\mathbf{X}_{k-1}, \Delta d_{odo}, \Delta\theta_{odo})$ represents the relationship between the previous and the current state (that is, $\mathbf{X}_{k-1}$ and $\mathbf{X}_k$) obtained from the onboard sensors and/or a movement model that give the increments of distance and angle ($\Delta d_{odo}, \Delta\theta_{odo}$); $h(\mathbf{X}_k)$ represents the relationship between the state vector $\mathbf{X}_k$ and the ALPS measurements $\mathbf{Z}_k$; and $\mathbf{w}_k$ and $\mathbf{v}_k$ are noise matrices related to the process and measurement equations. The estimated state vector $\hat{\mathbf{X}}_k$ and its covariance matrix $\hat{\mathbf{P}}_k$ can be updated using a filter that combines all the information, as the diagram in Fig. 11 shows. The most referenced methods are the EKF [77], the UKF [75], the H-infinity filter (H-∞) [78], and the particle filter (PF) [79]. Some examples of these methods in ALPSs can be found in [76] and [80].

As an example of the application of these Bayesian techniques to estimate the position of a target while it is moving using the ALPS measurements and the information of the sensors (increments of distance and angle between iterations), Fig. 12 shows a real experiment based on [76] inside a building with some ALPSs. An MR describes a trajectory through the environment with the ALSPs obtaining two estimated trajectories: using only the odometer (red line), and the fusion with the ALPSs information carried out by an H-∞ filter (black line); the areas in green represent the ALPS positioning in the coverage areas before integration.

D. Calibration Algorithms

Another important aspect for the deployment and use of ALPSs is the search for optimal zones to install the beacons. This positioning implies a tradeoff between coverage area (taking into account a minimum number of beacons at each positioning point); LOSs between emitters and receivers; minimization of effects such as interference, multipath, and near–far issues; good geometric configuration (to minimize the PDOP); and cost (minimum number of beacons). The complexity of this task is solved by using meta-heuristic algorithms that provide better results than regular lattices [54].

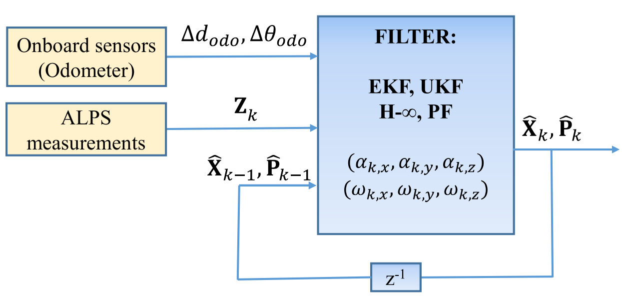

Fig. 11. ***Diagram of the fusion method for absolute and relative positioning.***

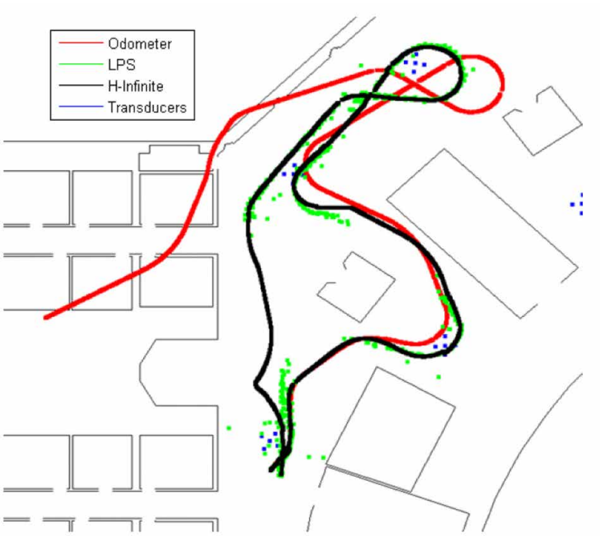

Fig. 12. ***Estimated trajectories of an MR comparing the odometer (red line) and the fusion with the ALPSs information (green points) by an H-∞ filter (final trajectory in black line); the blue points are the projections of the beacons [76].***

After the beacons are installed in the environment, it is important to know the precise coordinates for every beacon (with respect to the global coordinate origin). These coordinates are obtained from a calibration process that can be manual, semiautomatic, or automatic (also self-calibration). Handmade calibration processes usually take a long time and require several people carrying out measurements. Self-calibration techniques are very interesting [81] because they allow the system to automatically compute the position of the beacons.

One method to facilitate the calibration is the use of inverse positioning to determine the positions of the beacons. This process is based on capturing several measures at known test positions in the environment and then obtaining the estimates of the beacon positions by using a positioning algorithm in an inverse manner [81]–[83]. The drawback of this method is that it is necessary to accurately know the coordinates of a high number of measurement test points.

Another approach is the use of iterative methods. The work in [84] presents a method in which the positions of the beacons are estimated by mixing known and unknown test points and applying a Levenberg–Marquardt minimization algorithm. However, this approach requires a high number of iterations in order to achieve an accurate result. Other proposals use an MR to estimate the position of the beacons while the MR is navigating inside the ALPS coverage area, merging the odometry information with the measured distances [85]. This method was extended to more than one ALPS [86], showing in this case that the error in the beacon position estimates is accumulatively increased, and thus, only a limited number of ULPS can be calibrated in the same process.

E. Integration of Map-Matching Techniques

In some occasions, when a target is navigating along indoor environments, some position estimates can be out of the possible geometric boundaries (i.e., the estimate of a target position is behind a wall). Recent solutions in the field of RF positioning [87], [88] have incorporated the information from the building map as a constraint. In the case of using a PF, a new stage is added where the particles that are out of the possible estimates are eliminated. Gualda *et al.* [89] present a solution based on a constrained EKF for acoustic positioning that improve the results of the PF approach in terms of computational efficiency.

Another advantage of using mapping constraints is the reduction of the number of sensors needed to cover a positioning area, since the position of the target can be limited to a graph (i.e., a line placed in the middle of a corridor). The work in [90] studies the positioning based on graph information that evaluates the behavior of an ALPS for a different number of beacons.

Additionally, the map information can be used as well when calibrating the position of the beacons in an ALPS. For instance, in [91], a proposal that estimates the position of beacons in a map is presented. In this case, the user inserts several distances from the beacons to the surrounding walls as well as other easily obtained heuristic information such as the approximated region where the beacons are located (that can be roughly drawn on a map) and the approximated direction of measurement from the beacons to the walls.

V. IMPLEMENTATION AND APPLICATIONS

From an implementation point of view, previous works have already addressed the challenges coming not only from the positioning issue but also from the sensory technology used in the ToF or TDoF determination, often presenting similar constraints and issues. In this sense, the authors have already been involved in the real-time implementation of several LPSs based on different technologies, such as radio frequency [92], infrareds [93], ultrasounds [60], IMU-based approaches [94], or fusion of GPS/RF/ULPS [95].

The design of any acoustic positioning system involves two different modules: the emitters (beacons) and the receivers. For the sake of clarity, hereinafter, it is considered that the beacons are fixed at certain positions where they can transmit the acoustic waves; on the other hand, the receiver is mobile and often portable. It is worth noting that this approach could be swapped, thus having a mobile and portable transmitter, whereas the beacons would acquire those emissions. In this case, similar algorithms and methods can be applied to estimate the transmitters' positions, although different considerations should be taken into account with regard to the real-time implementation of the signal processing. Note that the portable device, more constrained than beacons from a computational point of view, should run those tasks corresponding to the transmitter.

With regard to RF-based developments, it is important to remark that the key difference is on the propagation speed for both technologies. Since the ultrasonic one is much lower, any aspect involved in the design of the corresponding ALPS becomes much more affordable. In this way, the influence of any clock imperfection, such as drifts, on the final performance can be considered even negligible. Note that typical carrier frequencies in the ultrasonic transmissions are in the range of tens of kilohertz, whereas common clock frequencies in the digital processing systems in charge of managing the ultrasonic signals are in the range of megahertz. Furthermore, this difference in terms of magnitude also implies an advantage when, in an extended ALPS formed by multiple ultrasonic beacons to cover a larger area, it is possible to use an RF or infrared link to synchronize all the transmissions without a further consideration about possible delays in the synchronization link, since they are again negligible.

Another relevant aspect, compared to RF-based systems, is noise. Ultrasonic systems are often affected by different types of noise, not only white Gaussian one, but also impulsive among others. As has been already mentioned, it is worth noting that, whereas those types of noise present a higher impact on the audible band, the ultrasonic band is much less aggressive in most scenarios, except maybe from some industrial environments. This is the reason why most previous works usually consider only white Gaussian noise in common ultrasonic channels. Furthermore, the correlation-based processing described here for ultrasonic signals is indeed a suitable method to reject noise in general terms.

The fact that ALPSs' last element is actually a certain ultrasonic transducer implies a big difference compared to RF-based approaches, where antennas are the typical element at this level, often providing a further complexity. Concerning the ultrasonic transducers, the aperture beam, the sensitivity (related to the achieved range), and the available bandwidth (with a nearly flat response in the region of interest) are the significant features, which will be described next.

A. Design of a Beacon Unit

In this case, a single ALPS is the module formed by the acoustic emitters or beacons as well as by all the electronic equipment necessary to achieve the desired behavior in the corresponding transmission. The design of this module implies a set of requirements [96], which can be summarized as follows.

- The first issue to be considered is the selection of the acoustic transducer. Three main aspects should be observed at this point. In this regard, the acoustic power and the radiation pattern (aperture beam) will define the final coverage area achieved by the ALPS. Furthermore, the transducer response should also be analyzed, particularly whether the ultrasonic transmission involves advanced encoding and/or modulation schemes, since they can require specific bandwidths and linearity properties.
- A second issue is the method used by the transducer to access and share the channel. A simultaneous or a multiplexed access protocol has different consequences on the design decisions, which must be evaluated.
- As previously mentioned, the bandwidth available in the final beacon unit is a key feature, since it may significantly determine not only the range of sequences and modulations that can be applied but also the final performance of the whole system in terms of precision, possible simultaneous emissions, or noise immunity.
- A last detail to be considered is the synchronization issue. This is closely related to the positioning algorithm later implemented. If a spherical positioning algorithm is involved, it is necessary to provide a synchronization link between the beacons and the receiver to achieve a common time frame. On the other hand, hyperbolic algorithms allow this synchronization link to be avoided, although the emitting beacons still need to have the same time reference in order to properly estimate the TDoFs.

According to the parameters that should be taken into consideration in the final design, the electronic system managing the beacons can achieve a significant complexity, mainly due to the encoding and modulation schemes selected in the implementation. Note that the computational load may include correlations, modulations, filtering, or fast Fourier transforms (FFTs). Furthermore, the sequences involved in the encoding could be either binary, multilevel, or even complex, thus increasing the complexity in real-time hardware architectures.

In most ALPSs, it is possible to identify four key blocks [96]: the acoustic transducers, the amplification stage, the analog-to-digital (AD) converters, and the electronic system in charge of managing the transmission carried out by the beacons available in the ALPS. With regard to the design of this electronic system, it is possible to distinguish two major trends: one based on general-purpose processors and another based on FPGA devices [97]. The first one provides a simple and straightforward way to control beacons in an ALPS, with short development times. Nevertheless, this approach often becomes unsuitable when advanced solutions are proposed in the acoustic signal processing. As an example, it cannot often afford simultaneous access techniques with synchronous and accurately simultaneous access to several beacons; also, multicarrier modulations cannot be dealt with. Generally, these proposals achieve a limit when massive and parallel data processing is necessary. At this point, recent Systems-on-Chip (SoCs), based on

FPGAs, allow designers to integrate the processor's advantages, thanks to the SoC placed in the same die (typically an ARM architecture), with the flexibility and parallelism from the configurable logic in the FPGA device [98], [99].

As a case study, this last part is dedicated to the description of the LOCATE-US beacon unit developed by the GEINTRA-US/RF group from the University of Alcalá, Spain [100]. In this particular case, the beacon is based on an ultrasonic transducer. This unit was designed keeping in mind that it could be adapted to any possible approach for the signal processing involved in an ALPS. It proposes a flexible architecture where a memory bank is connected to each ultrasonic transducer. This bank memory can be used to store the samples corresponding to any transmission, no matter the type of encoding or the modulation scheme considered. The architecture is based on an FPGA device consisting of an ARM processor plus some specific advanced peripherals in charge of managing the ultrasonic emissions. Fig. 13 shows its block diagram. It is worth noting that the system can be adapted to any type of modulation (e.g., BPSK, FSK, and multicarrier modulations) [26] as well as to any type of sequence (e.g., binary, multilevel, and complex) [101].

Compared to other processor-based approaches, such as those with general purpose processors, digital signal processors, or even microcontrollers, the main advantage of using a FPGA-based architecture is the capability to address several ultrasonic transducers in a simultaneous and parallel way. In this case, the system must manage at least five digital-to-analog converters (DACs), connected to the corresponding transducers. They are set at a sampling frequency of f_s=500 kHz, which implies that a new sample must be provided to every DAC every 2 μs. This type of parallelism and synchronization level in many channels at the same time is feasible and more addressable if the implementation is carried out on an FPGA device. Furthermore, this proposal is flexible enough to be adapted to any modulation scheme or sequence involved by saving the signals to be emitted in the memory banks available in the platform. This flexibility is possible thanks to the proposed FPGA-based architecture, but it will be not so easy in a processor-based solution, where changing the modulation scheme would imply modifying the source code run by the processor.

At this point, it is important to note that this design is actually the first FPGA-based prototype to validate the architecture and its functionality. At a later commercialization stage, the architecture can be migrated to an application-specific integrated circuit (ASIC) solution, where further considerations, such as power consumption or miniaturization, should be considered.

The system consists of five ultrasonic beacons, placed at the ceiling, in a 70.7 × 70.7 cm square providing a coverage area of approximately 30 m^2 for a height h=3 m. Fig. 14 shows two versions of the LOCATE-US beacon unit with different geometric configurations. The difference is that in the second version, the transducers are not coplanar, so the system can also be applied to 3-D positioning.

The transducers are hardware synchronized and emit simultaneously or sequentially at a certain millisecond rate (depending on the length of the code and the modulation scheme). A schematic representation of these types of emissions can be observed in Fig. 15. In one case, the emissions of all beacons are simultaneous every 20 ms (the separation at the receiver is performed by code, CDMA). In the other case, there is a different slot of time for each emission, although some interferences can still be produced

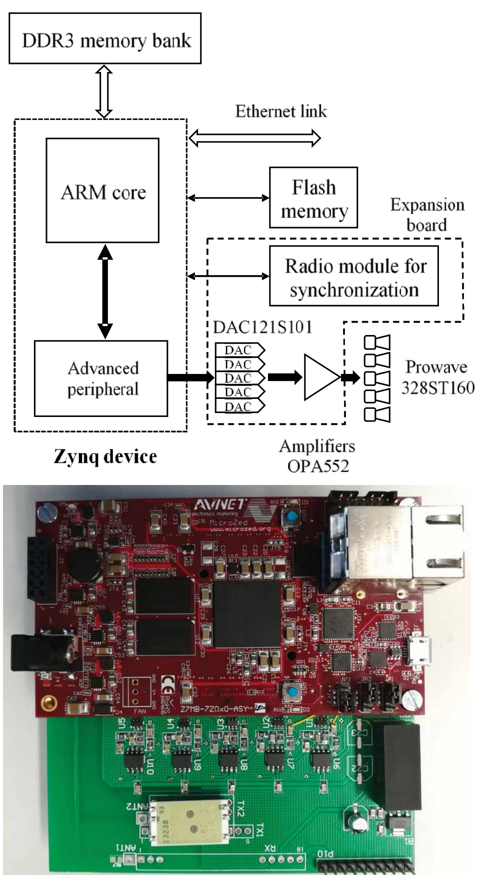

Fig. 13. ***Block diagram (up) and general view (down) of the ALPS unit designed to control five acoustic beacons, based on a Microzed board, for LOCATE-US, developed by the GEINTRA-US/RF group, University of Alcalá [100].***

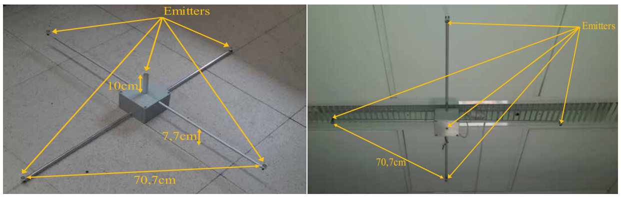

Fig. 14. ***View of the LOCATE-US beacon unit: version for 2-D positioning (left); version more suitable for 3-D positioning (right) since the transducers are not coplanar.***

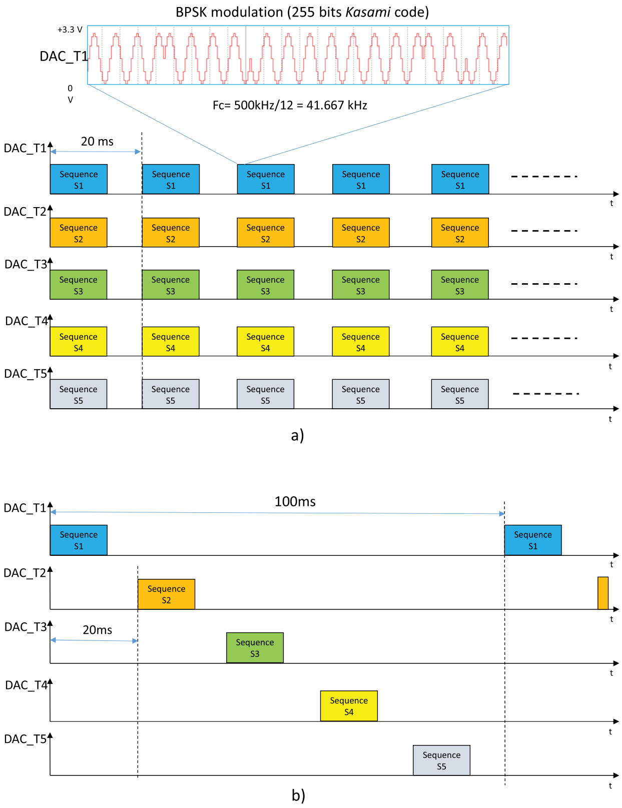

Fig. 15. ***Two schemes of beacon transmissions. (a) CDMA with simultaneous emissions every 20 ms. (b) T-CDMA with a certain separation in the emissions (period of 100 ms).***

due to partial superposition of signals in the channel (the separation at the receiver is carried out by time and by code, T-CDMA). Both schemes permit an emission encoding with a 255-b Kasami sequence, BPSK modulated with a symbol composed of two cycles of a sine carrier at a frequency f_c=41.67 kHz. The sampling frequency is f_s=500 kHz, thus giving an oversampling of f_s/f_c=12.

After each period of emission (20 ms for CDMA and 100 ms for T-CDMA), a nonlimited number of portable receivers (smartphones, tablets, or similar) can compute their position autonomously by hyperbolic trilateration. As an advantage, this system does not require synchronization between the beacons and the receivers. If spherical trilateration is required or multiple beacon units need to be synchronized to provide greater coverage, an RF module synchronism indicates the instant of transmission to the receivers and/or to the rest of slave ALPSs.

The 328ST160 transducers used have enough bandwidth for different types of acoustic signal modulations [102]. The transducer frequency response is defined by a flat region between two resonant frequencies (34 and 47 kHz), so the modulation carrier frequency has been approximately centered between both, thus obtaining a bandwidth of approximately 12 kHz and a nearly constant phase response. This phase linearity is a key aspect, especially when applying a BPSK modulation and correlation techniques, and, consequently, ultrasonic transducers should provide this feature for the desired bandwidth in these cases.

B. Design of a Receiver

One important aspect to be noted from the very beginning is that the design of a receiver is not directly related to the design of the beacons in an ALPS. It is clear that some aspects have to be common in both cases, such as frequencies of interest, bandwidths, or sequences employed. Nevertheless, after these general issues, the receiver can follow its own development so long as it meets certain compliance requirements.

Fig. 16 depicts a general scheme with the basic blocks included in a possible receiver. The ultrasonic transducer should be selected by keeping in mind three features: suitable frequency response and compatibility with the beacons; enough bandwidth to recover the transmitted signal; and enough sensitivity and aperture beam to ensure a certain coverage area.

Concerning the preamplification stage, the receiver should be designed with the same considerations, trying to avoid any saturation or nonlinear effect coming from nondesired frequency components out of the range of interest, thereby occasionally implying filtering.

Finally, after acquiring the preamplified signal, the computing platform should be capable of processing the ultrasonic transmission, demodulating the signal and then correlating it with the emitted sequences to determine the ToFs or the TDoFs, whether or not there is a synchronization link with the beacons. This is likely the most computationally expensive point of the design, since the complexity of operations can easily increase depending on the selected schemes and sequences, whereas some real-time requirements can arise according to certain applications. The need of having available these ToFs/TDoFs at a certain rate has an influence on the type of architecture that can be proposed for the implementation of the receiver signal processing. Again, most restrictive applications are prone to require parallel approaches, such as those based on FPGA devices. Nevertheless, if the timing constraints are not as demanding, processor-based solutions can also offer an alternative, which is often cheaper and with a shorter development time, for the receiver design.

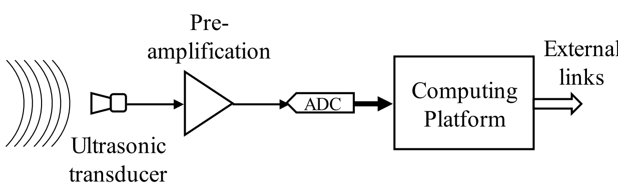

Fig. 16. ***General scheme in the design of a receiver for an ALPS.***

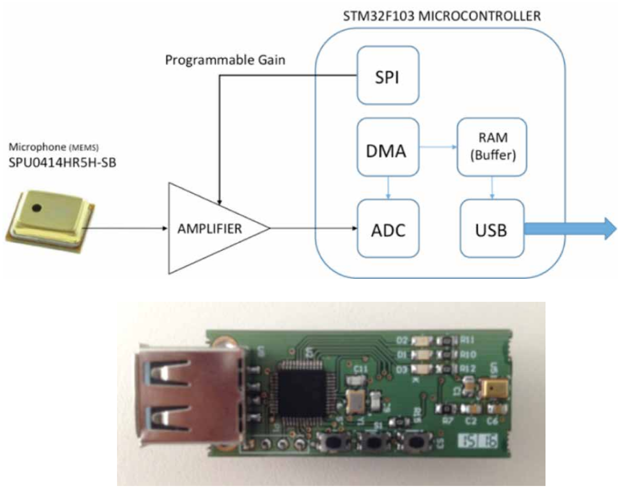

Fig. 17. ***Block diagram (up) and general view (down) of a receiver based in Cortex-M3 microcontroller for LOCATE-US, developed by the GEINTRAUS/RF group, University of Alcalá [13].***

For the LOCATE-US ALPS in the case study, the receiver architecture was based on a low-cost Cortex M3 microcontroller STM32F103 (see Fig. 17) [13]. The microcontroller includes a microelectromechanical system (MEMS) microphone, a high-bandwidth amplifier and an internally configurable high-pass filter (SPU0414HR5H-S). A programmable gain amplifier allows for dynamically adjusting the level of the received signal at the input of the analog-to-digital converter (ADC).

An important feature in the receiver module is the size of the acquisition buffer, which is constrained by the size of the internal memory available in the microcontroller. This parameter, together with the sampling frequency, influences the acquisition time necessary to obtain a position. To shorten this time, it is possible to reduce the emission time for the sequences or the multiplexing time, depending on the transmission scheme used (see Fig. 15), as well as the sampling frequency by downsampling by a factor N, even if resolution can be degraded in the ToF or TDoF determination. This affects the positioning error of the receiver, particularly in the case of hyperbolic multilateration (when synchronism between emitters and receiver is avoided). Note that a sampling frequency of 100 kHz, with a downsampling factor of 5, provides suitable results, as will be described later. The necessary buffer in the CDMA scheme with 255-b Kasami sequences (two cycles per symbol) for an emission period of 20 ms should be at least 2000 samples long in order to guarantee at least one sampling period. On the other hand, in T-CDMA, this value is multiplied by the number of transducers if the multiplexing time is equal to the emission period in CDMA. The main advantage provided by the T-CDMA scheme is that the MAI effect is discarded; furthermore, the algorithm of the DToF determination is less complex since the transducer emissions are always sorted

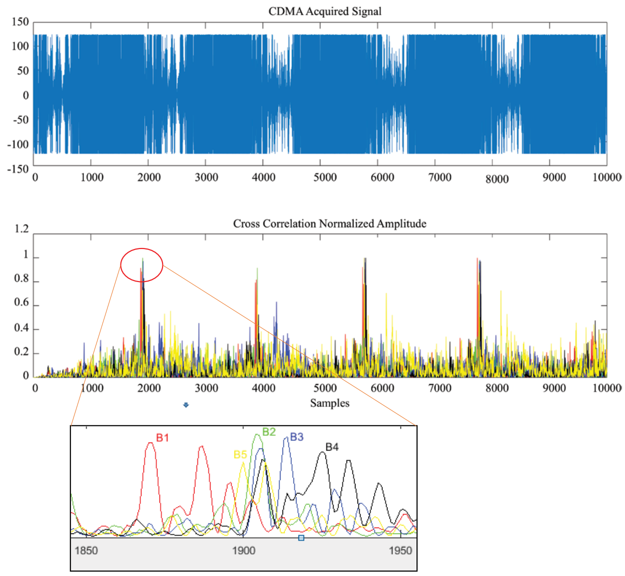

Fig. 18. ***CDMA scheme: received signal (top); correlated signal for each beacon (B1-B5) (middle); and detail of the correlated signals (bottom).***

after performing the correlation of the received signal with the corresponding codes or patterns assigned.

Figs. 18 and 19 show the results for the signal received from the five beacons (B1–B5) and the correlations obtained in the CDMA and T-CDMA schemes, respectively. When obtaining these results, the receiver has been placed below the central beacon at a distance of 3 m. It is possible to observe that the overlapping effect in CDMA, coming from the simultaneous emissions of the transducers, can degrade the peaks in the correlation functions due to the MAI effect. This effect has much less influence in T-CDMA because the overlapping of the signals, as they are in different slots of time, is less probable with the geometric configuration used.

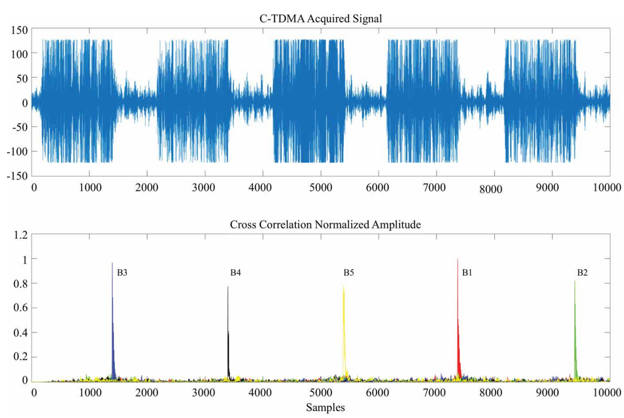

Fig. 19. ***T-CDMA scheme: received signal (top) and correlated signal for each beacon (B1-B5) (bottom).***

Note that some overlapping at the receiver is still acceptable, as CDMA is also used.

C. Experimental Results

With regard to the experimental results, the LOCATE-US ALPS has allowed a complete set of tests to be obtained in order to verify the different mentioned approaches, not only in low-level but also in high-level processing. As an example, for the configuration presented in Fig. 20 (with a single ALPS installed in the ceiling), a microphone has been placed at a grid of points on the floor. The emitted signals (following the T-CDMA scheme) have been encoded with a 255-b Kasami sequence and BPSK modulated with two periods of a sine carrier at 41.67 kHz, which has been sampled at 500 kHz in the receiver. Afterwards, the position is estimated with a Gauss–Newton hyperbolic multilateration algorithm.

Fig. 21 shows the cloud of points obtained after 100 trials at each point. Note that the errors depend on the position of the microphone due to the different PDOP and to the different propagation paths followed by the acoustic waves.

A quantization of the error for these measurements can be derived from the cumulative distribution function (CDF) representations plotted in Fig. 22. For the most centered test points (P6, P7, P10, and P11), the error is always below 15 cm. Considering all of the points, the error is below 20 cm for 90% of the cases and never higher than 30 cm. It is worth noting that these results have been obtained for an ALPS with beacons very close to each other using TDoF with a relatively high common coverage area. These results have been obtained using the T-CDMA scheme; when using only CDMA to increase the measurement rate, one of the more adverse effects is that the number of outliers increases. As an example, the work in [100] addresses this problem by fusing the results of the positioning system with

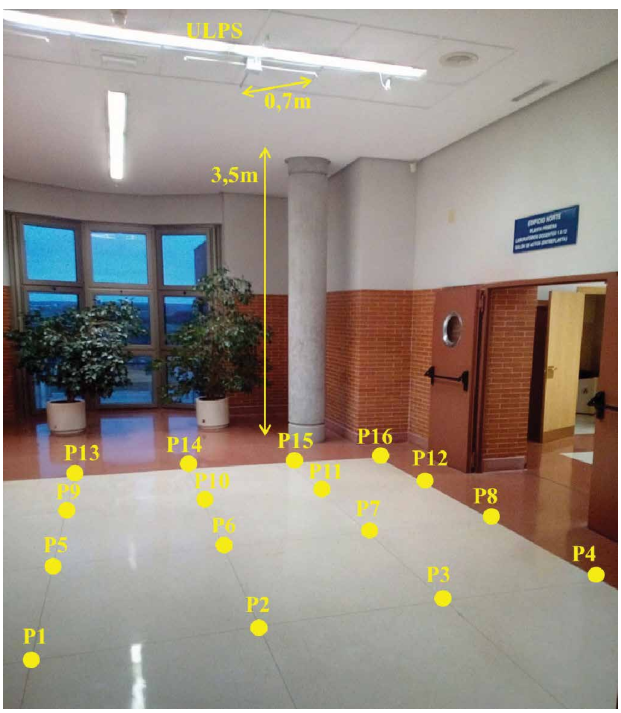

Fig. 20. ***Configuration of a single ALPS (LOCATE-US) installed on the ceiling and a grid of points to take measurements on the floor.***

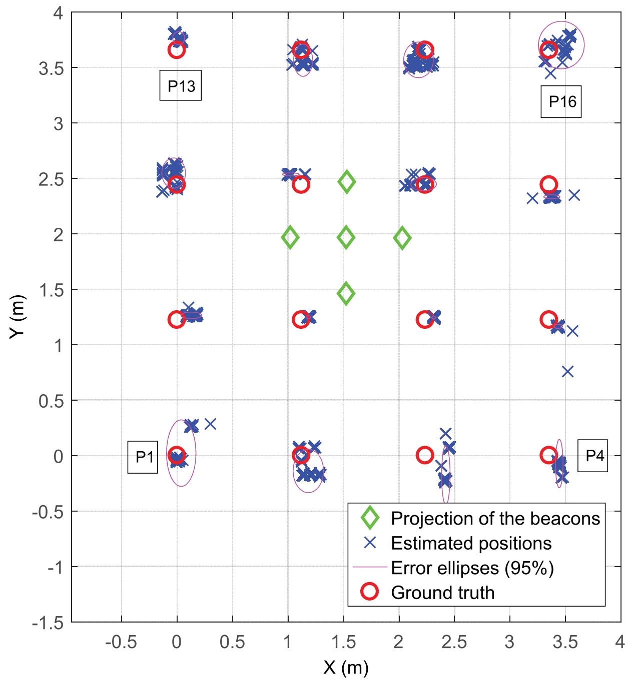

Fig. 21. ***Cloud of points around the ground truth and error ellipses for 100 trials at each test point.***

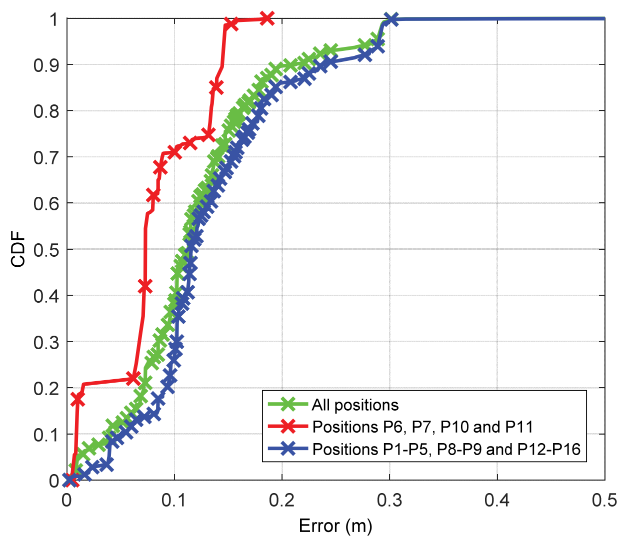

Fig. 22. ***Cumulative distribution functions (CDFs) for the trials shown in Fig. 21.***

an EKF, which uses the CDMA scheme, with the odometer of an MR.

Other tests have been performed with similar ULPSs. In [103], the influence of the sequence encoding involved in the acoustic transmission is analyzed for different types of sequences (Kasami and LS codes) and how they can be helpful in mitigating some adverse effects such as multipath or near–far effects. The low-level processing is further studied in [104] and [105], where the positioning results in adverse environmental conditions can be improved by implementing a generalized cross correlation together with a PATH filter instead of a classical matched filter version. This approach results in significantly better performance for multipath environments.

However, concerning high-level processing, in [106], an experimental scenario is described where multiple LOCATE-US ALPSs have been deployed in a large environment to provide a noncontinuous coverage area. The proposal applies an H-infinite filter to merge information, not only from ALPS measurements but also from the odometer system onboard the robot. This test shows the feasibility of covering extensive areas with multiple ALPSs by choosing a suitable beacon distribution and an appropriate merging method for the positioning algorithm in high-level processing. Finally, an example of a simultaneous calibration and navigation process for a large environment with multiple ALPSs can be observed in [107]. Note that the beacon positions are not known *a priori*, and the robot employs the first positions in its navigation (where errors from the odometer are still reduced) to estimate the beacon positions. Afterwards, these estimates for the beacons are used in a common positioning algorithm to follow the robot trajectory

VI. DISCUSSION AND CONCLUSION

Today, there is an increasing demand for a proven technology with a certain accuracy, to provide services based on position of people, mobile robots, or other objects across large indoor areas, as well as in GNSS-denied outdoor environments. In contrast to the high implementation degree of the GNSS systems outdoors, there is no consolidated technology or LPS operating at the same level of performance indoors. Practical systems integrate and merge information obtained by using different positioning technologies (optical, mechanical, magnetic, RF based, or acoustic) and strategies (trilateration, triangulation, fingerprinting, integration in inertial systems, etc.).

ALPSs are an interesting alternative for indoor positioning. Compared to other approaches, they have some advantages, such as a relatively high accuracy, low cost, and room-level signal propagation.

In the common case of using time (difference) of arrival of acoustic (sonic or ultrasonic) signals between emitters (usually in the infrastructure) and receivers (normally on the node to be positioned), problems faced are well known by researchers and designers working with RF-based systems: multipath propagation, near–far effect, Doppler shift, or proper distribution of beacons.

Nevertheless, there are also important differences to consider. The main difference is on the wave propagation speed for both technologies, which makes acoustic systems much more affordable and manageable with lower frequency processing systems. Another aspect to take into account is the wave propagation, since acoustic waves in air are confined in closed spaces with specular reflections on most of the indoor man-made walls and objects. For acoustic systems, the typical room impulse response includes a LOS path, followed by a first pattern of early reflections and, afterwards, by a late-field reverberant tail with negligible amplitudes. Doppler shift is likely the phenomenon with larger differences between acoustic and RF-based local positioning systems, due to the different wave propagation speeds. For an acoustic system, a receiver that moves at velocities higher than 2–3m/s can experience adverse effects in the received signal processing.

The type of noise encountered in the high-frequency sonic and low-frequency ultrasonic bands, i.e., between 15 and 100 kHz, has a power spectral density estimate with a flat pattern and peaks at certain frequencies that characterize a particular environment (due to cooling fans, pneumatic tools, fluorescent lamp chokes, etc.).

Another important issue is related to the type of emitters and receivers used: antennas for RF-based systems and transducers (microphones and speakers) for ALPSs. In this last case, aperture beam pattern, sound pressure level and sensitivity, and available bandwidth are significant features to consider.

This research described the different challenges facing the design of an acoustic local positioning system in order to achieve suitable performance. The description of this design process has been focused on both low-level and high-level signal processing. In the first case, the waveform conformation (coding and modulation) and the processing of the received signal involve significant issues in order to address drawbacks, such as multipath conditions, multiple-access interference, near–far effects, or Doppler shifting. Conversely, high-level processing is often related to the distribution of beacons, easy deployment, and calibration and positioning algorithms, including the possible fusion of information obtained from, for example, maps and onboard sensors. In both cases, this work provides a complete review of previous works as well as some theoretical discussions with regard to the mentioned topics. Furthermore, the description of the LOCATE-US ALPS system, developed by the GEINTRA-US/RF group (University of Alcalá), has been briefly included, together with experimental results in extended coverage areas and tests for mobile robot navigation.

REFERENCES

[1] R. Mautz, "Indoor positioning technologies," M.S. thesis, Dept. Civil, Environ. Geomatic Eng., Inst. Geodesy Photogramm., ETH Zurich, Zürich, Switzerland, 2012.

[2] R. Mautz and S. Tilch, "Survey of optical indoor positioning systems," in *Proc. Int. Conf. Indoor Positioning Indoor Navigat. (IPIN)*, 2011, pp. 1–7.

[3] A. R. J. Ruiz, F. S. Granja, J. C. Honorato, and J. I. Rosas, "Pedestrian indoor navigation by aiding a foot-mounted IMU with RFID signal strength measurements," in *Proc. Int. Conf. Indoor Positioning Indoor Navigat. (IPIN)*, Sep. 2010, pp. 1–7.

[4] J. Haverinen and A. Kemppainen, "Global indoor self-localization based on the ambient magnetic field," *Robot. Autonom. Syst.*, vol. 57, no. 10, pp. 1028–1035, 2009.

[5] A. R. J. Ruiz and F. Seco, "Precise localisation of archaeological findings with a new ultrasonic 3D positioning sensor," *Sens. Actuators A, Phys.*, vols. 123–124, pp. 224–233, Sep. 2005.

[6] Y. Cheng, X. Wang, T. Caelli, and B. Moran, "Target tracking and localization with ambiguous phase measurements of sensor networks," in *Proc. IEEE Int. Conf. Acoust. Speech Signal Process. (ICASSP)*, May 2011, pp. 4048–4051.

[7] S. I. Lopes, "In search of reliable centimeter-level indoor positioning. A smartphone-based approach," M.S. thesis, Univ. Aveiro, 2014. [Online]. Available: http://ria.ua.pt/bitstream/10773/14100/1/in%20search%20of%20reliable%20centimeter-level%20indoor%20positioning.pdf

[8] S. Holm, "Airborne ultrasound data communications: The core of an indoor positioning system," in *Proc. IEEE Ultrason. Symp.*, Sep. 2005, pp. 1801–1804.

[9] L. Segers, J. Tiete, A. Braeken, and A. Touhafi, "Ultrasonic multiple-access ranging system using spread spectrum and MEMS technology for indoor localization," *Sensors*, vol. 14, pp. 3172–3187, 2014.

[10] M. O. Khyam, L. Xinde, S. S. Ge, and R. M. Pickering, "Multiple access chirp-based ultrasonic positioning," *IEEE Trans. Instrum. Meas.*, vol. 66, no. 12, pp. 3126–3137, Dec. 2017.

[11] J. Ureña, M. Mazo, J. J. García, Á. Hernández, and E. Bueno, "Correlation detector based on a FPGA for ultrasonic sensors," *Microprocess. Microsyst.*, vol. 23, no. 1, pp. 25–33 1999.

[12] M. Hazas and A. Ward, "A novel broadband ultrasonic location system," in *Proc. UbiComp Ubiquitous Comput.*, 2002, pp. 264–280, 2002.

[13] M. C. Pérez *et al.*, "Ultrasonic beacon-based local positioning system using loosely synchronous codes," in *Proc. IEEE Int. Symp. Intell. Signal Process. (WISP)*, Oct. 2007, pp. 1–6.

[14] A. Ward, A. Jones, and A. Hopper, "A new location technique for the active office," *IEEE Pers. Commun.*, vol. 4, no. 5, pp. 42–47, Oct. 1997.

[15] M. Deffenbaugh, J. G. Bellingham, and H. Schmidt, "The relationship between spherical and hyperbolic positioning," in *Proc. MTS/IEEE Prospects 21st Century OCEANS*, vol. 96. Sep. 1996, pp. 590–595.

[16] L. K. Wang and M. H. S. Wang, *Handbook of Environmental Engineering*. New York, NY, USA: Springer-Verlag, 2016.

[17] J. Pushter, *Smartphone Ownership and Internet Usage Continues to Climb in Emerging Economies*. Washington, DC, USA: Pew Research Center, 2016.

[18] V. Filonenko, C. Cullen, and J. Carswell, "Indoor positioning for smartphones using asynchronous ultrasound trilateration," *ISPRS Int. J. Geo-Inf.*, 2013.

[19] P. Lazik and A. Rowe, "Indoor pseudo-ranging of mobile devices using ultrasonic chirps," in *Proc. 10th ACM Conf. Embedded Netw. Sensor Syst.*, 2012, pp. 99–112.

[20] S. I. Lopes, J. M. N. Vieira, J. Reis, and D. Albuquerque, "Accurate smartphone indoor positioning using WSN infraestructure and non-invasive audio for TDoA estimation," *Pervasive Mobile Comput.*, 2014, pp. 1–18.

[21] J. C. Prieto *et al.*, "Performance evaluation of 3D-LOCUS advanced acoustic LPS," *IEEE Trans. Instrum. Meas.*, vol. 58, no. 8, pp. 2385–2395, Aug. 2009.

[22] C. Peng, G. Shen, Y. Zhang, Y. Li, and K. Tan, "BeepBeep: A high accuracy acoustic ranging system using COTS mobile devices," in *Proc. 5th Int. Conf. Embedded Netw. Sensor Syst.*, 2007, pp. 1–14.

[23] M. Langheinrich, "Privacy by design-principles of privacy aware ubiquitous systems," in *Proc. UbiComp Ubiquitous Comput.*, 2001, pp. 273–291.

[24] T. Aguilera, J. A. Paredes, F. J Álvarez, J. I. Suárez, and A. Hernández, "Acoustic local positioning system using an iOS device," in *Proc. Int. Conf. Indoor Positioning Indoor Navigat.*, 2013, pp. 1–5.

[25] E. Díaz *et al.*, "Ultrasonic indoor positioning for smart environments: A mobile application," in *Proc. Experim. Int. Conf. (EXP.AT)*, 2017.

[26] A. Lindo, E. García, J. Ureña, M. C. Pérez, and A. Hernández, "Multiband waveform design for an ultrasonic indoor positioning system," *IEEE Sensors J.*, vol. 15, no. 12, pp. 7190–7199, Dec. 2015.

[27] M. C. Pérez *et al.*, "Android application for indoor positioning of mobile devices using ultrasonic signals," in *Proc. Int. Conf. Indoor Positioning Indoor Navigat. (IPIN)*, 2016.

[28] D. F. Albuquerque, J. M. Vieira, I. Lopes, C. A. C. Bastos, and P. J. S. G. Ferreira, "OFDM pulse design with low PAPR for ultrasonic location positioning systems," in *Proc. Int. Conf. Indoor Positioning Indoor Navigat.*, 2013, pp. 34–35.

[29] E. García, J. Ureña, A. Hernández, and F. Nombela, "Discrete multitone modulation for ultrasonic indoor positioning systems," in *Proc. Int. Conf. Indoor Positioning Indoor Navigat.*, 2015, pp. 1–4.

[30] W. Kang, S. Nam, Y. Han, and S. Lee, "Improved heading estimation for smartphone-based indoor positioning systems," in *Proc. IEEE 23rd Int. Symp. Pers. Indoor Mobile Radio Commun. (PIMRC)*, 2012, pp. 2449–2453.

[31] E. Foxlin, M. Harrington, and G. Pfeifer, "Constellation: A wide -range wireless motion-tracking system for augmented reality and virtual set applications," in *Proc. SIGGRAPH*, 1998.

[32] N. B. Priyantha, A. Chakraborty, and H. Balakrishnan, "The cricket location-support system," in *Proc. 6th Annu. Int. Conf. Mobile Comput. Netw. (MobiCom)*, 2000, pp. 32–43.

[33] GRAS Sound & Vibration, 40BE-FV, *Prepolarized Free-Field Microphone, Product Specification*, 2018.

[34] M. R. McCarthy and H. L. Muller, "RF free ultrasonic positioning," in *Proc. 7th IEEE Int. Symp. Wearable Comput.*, Oct. 2003, pp. 79–85.

[35] S. M. Kay, *Fundamentals of Statistical Signal Processing: Estimation Theory* (Signal Processing Series). Englewood Cliffs, NJ, USA: Prentice-Hall, 1993.

[36] M. I. Skolnik, *Introduction to Radar Systems*. New York, NY, USA: McGraw-Hill, 2001.

[37] J. G. Proakis and M. Salehi, *Communication Systems Engineering*, 2nd ed. Englewood Cliffs, NJ, USA: Prentice-Hall, 2002.

[38] M. C. P. Rubio *et al.*, "Correlator implementation for orthogonal CSS used in an ultrasonic LPS," *IEEE Sensors J.*, vol. 12, no. 9, pp. 2807–2816, Sep. 2012.

[39] M. C. Pérez *et al.*, "Very efficient correlator for loosely synchronised codes," *Electron. Lett.*, vol. 46, no. 16, pp. 1127–1129, Aug. 2010.

[40] T. Aguilera *et al.*, "Broadband acoustic local positioning system for mobile devices with multiple access interference cancellation," *Measurement*, vol. 116, pp. 483–494, 2017.

[41] J. M. Villadangos *et al.*, "Measuring time-of-flight in an ultrasonic LPS system using generalized cross-correlation," *Sensors*, vol. 11, pp. 10326–10342, 2011.

[42] A. M. Saleh and R. A. Valenzuela, "A statistical model for indoor multipath propagation," *IEEE J. Sel. Areas Commun.*, vol. SAC-5, no. 2, pp. 128–137, Feb. 1987.

[43] M. Cheffena, "Industrial indoor multipath propagation—A physical-statistical approach," in *Proc. 25th IEEE Int. Symp. Pers. Indoor Mobile Radio Commun. (PIMRC)*, Mar. 2014, pp. 68–72.

[44] D. T. Blackstock, *Fundamentals of Physical Acoustics*. Hoboken, NJ, USA: Wiley, 2000.

[45] F. J Álvarez, T. Aguilera, and R. López-Valcarce., "CDMA-based acoustic local positioning system for portable devices with multipath cancellation," *Digital Signal Process.*, vol. 62, pp. 38–51, Mar. 2017.

[46] T. Aguilera *et al.*, "Multipath compensation algorithm for TDMA-based ultrasonic local positioning systems," *IEEE Trans. Instrum. Meas.*, to be published.

[47] M. Alloulah and M. Hazas, "An efficient CDMA core for indoor acoustic position sensing," in *Proc. Int. Conf. Indoor Positioning Indoor Navigat. (IPIN)*, 2010.

[48] J. A. Paredes, T. Aguilera, F. J. Álvarez, J. Lozano, and J. Morera, "Analysis of Doppler effect on the pulse compression of different codes emitted by an ultrasonic LPS," *Sensors*, vol. 11, pp. 10765–10784, 2011.

[49] F. J. Álvarez, A. Hernández, J A. Moreno, M. C. Pérez, J Ureña, and C. De Marziani, "Doppler-tolerant receiver for an ultrasonic LPS based on Kasami sequences," *Sens. Actuators A, Phys.*, vol. 189, pp. 238–253, 2013.

[50] J. A. Paredes, T. Aguilera, F. J. Álvarez, J. A. Fernández, and J. Morera, "New pseudo-orthogonal family of polyphase codes to improve Doppler resilience," in *Proc. Int. Conf. Indoor Positioning Indoor Navigat.*, 2013.

[51] R. Kaune, "Accuracy studies for TDOA and TOA localization," in *Proc. Int. Conf. Inf. Fusion*, 2012, pp. 408–415.

[52] R. B. Langley, "Dilution of precision," *GPS World*, vol. 10, no. 5, pp. 52–59, 1999.

[53] J. H. Holland, *Adaption in Natural and Artificial Systems*. Ann Arbor, MI, USA: Univ. Michigan Press, 1975.

[54] J. O. Roa, A. R. Jiménez, F. Seco, J. C. Prieto, and J. L. Ealo, "Optimal placement of sensors for trilateration: Regular lattices vs meta-heuristic solutions," in *Proc. 11th Int. Conf. Comput. Aided Syst. Theory (EUROCAST)*, 2007, pp. 780–787.

[55] M. Laguna, J. O. Roa, A. R. Jiménez, and F. Seco, "Diversified local search for the optimal layout of beacons in an indoor positioning system," *IIE Trans.*, vol. 41, no. 3, pp. 247–259, 2009.

[56] T. Leune, T. Wehs, M. Janssen, C. Koch, and G. von Colln, "Optimization of wireless locating in complex environments by placement of anchor nodes with evolutionary algorithms," in *Proc. IEEE 18th Conf. Emerg. Technol. Factory Autom. (ETFA)*, 2013.

[57] P. K. Ray and A. Mahajan, "A genetic algorithm-based approach to calculate the optimal configuration of ultrasonic sensors in a 3D position estimation system," *Robot. Autom. Syst.*, vol. 41, no. 4, pp. 165–177, 2002.

[58] Y. Shen and M. Z. Win, "Fundamental limits of wideband localization—Part I: A general framework," *IEEE Trans. Inf. Theory*, vol. 56, no. 10, pp. 4956–4980, Oct. 2010.

[59] F. Domingo, "Sensor resource management with evolutionary algorithms applied to indoor positioning," Ph.D. dissertation, Univ. Alcalá, Alcalá de Henares, Spain, 2016. [Online]. Available: https://dspace.uah.es/dspace/bitstream/handle/10017/29265/Thesis%20Francisco%20Domingo%20P%C3%A9rez.pdf?sequence=1

[60] J. Ureña *et al.*, "Advanced sensorial system for an acoustic LPS," *Microprocess. Microsyst.*, vol. 31, no. 6, pp. 393–401, Sep. 2007.

[61] J. Li, G. Han, C. Zhu, and G. Sun, "An indoor ultrasonic positioning system based on TOA for Internet of Things," *Mobile Inf. Syst.*, vol. 2016, pp. 1–10, 2016.

[62] J. Delosme, M. Morf, and B. Friedlander, "Source location from time differences of arrival: Identifiability and estimation," in *Proc. IEEE Int. Conf. Acoust. Speech Signal Process. (ICASSP)*, 1980.

[63] W. Navidi, W. S. Murphy, and W. Hereman, "Statistical methods in surveying by trilateration," *Comput. Stat. Data Anal.*, vol. 27, no. 2, pp. 209–227, 1998.

[64] J. J. Caffery, "A new approach to the geometry of TOA location," in *Proc. 52nd Veh. Technol. Conf. Fall (IEEE VTS Fall VTC)*, 2000.

[65] S. C. Nardone and M. L. Graham, "A closed-form solution to bearings-only target motion analysis," *IEEE J. Ocean. Eng.*, vol. 22, no. 1, pp. 168–178, Jan. 1997.

[66] D. M. Y. Sommerville, *An Introduction to the Geometry of N Dimensions*, vol. 2. London, U.K.: Methuen Publishing, 1929.

[67] F. Thomas and L. Ros, "Revisiting trilateration for robot localization," *IEEE Trans. Robot.*, vol. 21, no. 1, pp. 93–101, Feb. 2005.

[68] D. Ruiz *et al.*, "New iterative algorithm for hyperbolic positioning used in an ultrasonic local positioning system," in *Proc. IEEE Conf. Emerg. Technol. Factory Autom. (ETFA)*, 2009.

[69] X. Li and A. Scaglione, "Convergence and applications of a gossip-based gauss-newton algorithm," *IEEE Trans. Signal Process.*, vol. 61, no. 21, pp. 5231–5246, Nov. 2013.

[70] L. Duc-Hung, P. Cong-Kha, N. Thi Thien Trang, and B. Trong Tu, "Parameter extraction and optimization using Levenberg-Marquardt algorithm," in *Proc. 4th Int. Conf. Commun. Electron. (ICCE)*, 2012.

[71] F. Seco, A. R. Jimenez, C. Prieto, J. Roa, and K. Koutsou, "A survey of mathematical methods for indoor localization," in *Proc. IEEE Int. Symp. Intell. Signal Process.*, 2009.

[72] L. Kleeman, "Advanced sonar and odometry error modeling for simultaneous localization and map building," in *Proc. Intell. Robots Syst. (IROS)*, vol. 1. 2003, pp. 699–704.

[73] D. Fox, J. Hightower, L. Liao, D. Schulz, and G. Borrello, "Bayesian filters for location estimation," *IEEE Pervasive Comput.*, vol. 2, no. 3, pp. 24–33, Mar. 2003.

[74] G. Evensen, "The ensemble Kalman filter: Theoretical formulation and practical implementation," *Ocean Dyn.*, vol. 53, no. 4, pp. 343–367, Nov. 2003.

[75] E. A. Wan and R. van der Merwe, "The unscented Kalman filter for nonlinear estimation," in *Proc. IEEE Adapt. Syst. Signal Process. Commun. Control Symp. (AS-SPCC)*, 2000, pp. 153–158.

[76] D. Ruiz, E. García, J. Ureña, D. de Diego, D. Gualda, and J. C. García, "Extensive Ultrasonic Local Positioning System for navigating with mobile robots," in *Proc. 10th Workshop Positioning Navigat. Commun. (WPNC)*, 2013, pp. 1–6.

[77] H. Cox, "On the estimation of state variables and parameters for noisy dynamic systems," *IEEE Trans. Autom. Control*, vol. 9, no. 1, pp. 5–12, Jan. 1964.

[78] D. Simon, "A game theory approach to constrained minimax state estimation," *IEEE Trans. Signal Process.*, vol. 54, no. 2, pp. 405–412, Feb. 2006.

[79] J. S. Liu and R. Chen, "Sequential montecarlo methods for dynamic systems," *J. Amer. Stat. Assoc.*, vol. 93, no. 443, pp. 1032–1044, 1998.

[80] D. Gualda, J. Ureña, J. García, and A. Lindo, "Locally-referenced ultrasonic-LPS for localization and navigation," *Sensors*, vol. 14, no. 11, pp. 21750–21769, 2014.

[81] A. Mahajan and F. Figueroa, "An Automatic Self Installation and Calibration Method for a 3D Position Sensing System using Ultrasonics," *Robot. Autom. Syst.*, vol. 28, no. 4, pp. 281–294, 1999.

[82] F. D. Ruiz *et al.*, "Optimal test-point positions for calibrating an ultrasonic LPS system," in *Proc. 13th IEEE Int. Conf. Emerg. Technol. Factory Autom. (ETFA)*, 2009.

[83] A. Nishitani, Y. Nishida, T. Hori, and H. Mizoguchi, "Portable ultrasonic 3D tag system based on a quick calibration method," in *Proc. IEEE Int. Conf. Syst. Man Cybern.*, 2004, pp. 1561–1568.

[84] P. Duff and H. Muller, "Autocalibration algorithm for ultrasonic location systems," in *Proc. 7th IEEE Int. Symp. Wearable Comput.*, 2003.

[85] J. Ureña *et al.*, "LPS self-calibration method using a mobile robot," in *Proc. IEEE Int. Instrum. Meas. Technol. Conf. (IMTC)*, 2011, pp. 1–6.

[86] D. Gualda, "Simultaneous calibration of ultrasonic local positioning systems and mobile robot navigation," Ph.D. dissertation, Dept. Electronics, Univ. Alcalá, Alcalá de Henares, Spain, 2016.

[87] F. Zampella, A. R. J. Ruiz, and F. S. Granja, "Indoor positioning using efficient map matching, RSS measurements, and an improved motion model," *IEEE Trans. Veh. Technol.*, vol. 64, no. 4, pp. 1304–1317, Apr. 2015.

[88] J. Pinchin, C. Hide, and T. Moore, "A particle filter approach to indoor navigation using a foot mounted intertial navigation system and heuristic heading information," in *Proc. Int. Conf. Indoor Positioning Indoor Navigat. (IPIN)*, 2012, pp. 13–15.

[89] D. Gualda, J. U. Ureña, and E. García, "Partially constrained extended Kalman filter for navigation including mapping information," *IEEE Sensors J.*, vol. 16, no. 24, pp. 9036–9046, Dec. 2016.

[90] D. Gualda, J. Urena, J. C. Garcia, J. Alcala, and A. N. Miyadaira, "Reduction of ultrasonic indoor localization infrastructure based on the use of graph information," in *Proc. Int. Conf. Indoor Positioning Indoor Navigat. (IPIN)*, 2016.

[91] D. Gualda, J. Ureña, J. C. Garcia, J. Alcala, and A. N. Miyadaira, "Calibration of beacons for indoor environments based on a map-matching technique," in *Proc. Int. Conf. Indoor Positioning Indoor Navigat. (IPIN)*, 2016.

[92] E. García, P. Poudereux, A. Hernández, J. J. García, and J. Ureña, "DS-UWB indoor positioning system implementation based on FPGAs," *Sens. Actuators A, Phys.*, vol. 201, pp. 172–181, Oct. 2013.

[93] E. M. Gorostiza, J. L. L. Galilea, F. J. M. Meca, D. S. Monzú, F. E. Zapata, and L. P. Puerto, "Infrared sensor system for mobile-robot positioning in intelligent spaces," *Sensors*, vol. 11, no. 5, pp. 5416–5438, Mar. 2011.

[94] E. M. Diaz, "Inertial pocket navigation system: Unaided 3D positioning," *Sensors*, vol. 15, no. 4, pp. 9156–9178, 2015.

[95] A. Bahillo, T. Aguilera, F. J. Álvarez, and A. Perallos, "WAY: Seamless positioning using a smart device," *Wireless Pers. Commun.*, vol. 90, no. 2, pp. 1–19, 2016.

[96] F. Ijaz, H. K. Yang, A. W. Ahmad, and C. Lee, "Indoor positioning: A review of indoor ultrasonic positioning systems," in *Proc. 15th Int. Conf. Adv. Communi. Technol. (ICACT)*, 2013, pp. 1146–1150.

[97] J. Rabaey, "Reconfigurable processing: The solution to low-power programmable DSP," in *Proc. 22nd IEEE Int. Conf. Acoust. Speech Signal Process. (ICASSP)*, 1997, pp. 275–278.

[98] S. Knapp, "Field configurable system on chip devices architecture," in *Proc. 22nd IEEE Custom Integr. Circuits Conf. (CICC)*, 2000, pp. 155–158.

[99] J. Becker, N. Libeau, T. Pionteck, and M. Glesner, "Efficient mapping of pre-synthesized IP-cores onto dynamically reconfigurable array architectures," in *Proc. 11th Int. Conf. Field-Programm. Logic Appl. (FPL)*, 2001, pp. 584–589.

[100] Á. Hernández *et al.*, "FPGA-based architecture for managing ultrasonic beacons in a local positioning system," *IEEE Trans. Instrum. Meas.*, vol. 66, no. 8, pp. 1954–1964, Aug. 2017.

[101] E. García, J. A. Paredes, F. J. Álvarez, M. C. Pérez, and J. J. García, "Spreading sequences in active sensing: A review," *Signal Process.*, vol. 106, pp. 88–105, Jan. 2015.

[102] *Pro-Wave Electronics Corporation, Air Ultrasonic Ceramic Transducers 328ST/R160, Product Specification*, 2005.

[103] (2009). *GEINTRA-US/RF, Ultrasonic Indoor Positioning System*. [Online]. Available: https://www.youtube.com/watch?v=d_ddYMlOp7g

[104] (2013). *GEINTRA-US/RF, Ultrasonic LPS Using Generalized Cross-Correlation*. [Online]. Available: https://www.youtube.com/watch?v=JO2yzZkLQK4

[105] (2013). *GEINTRA-US/RF, Ultrasonic Positioning Using GCC-PATH Filter*. [Online]. Available: https://www.youtube.com/watch?v=Wd20FHN7QM4

[106] (2013). *GEINTRA-US/RF, Multiple Ultrasonic Local Positioning Systems*. [Online]. Available: https://www.youtube.com/watch?v=HVT9j5uEaq8

[107] (2016). *GEINTRA-US/RF, ALPS Self-Calibration*. [Online]. Available: https://youtu.be/fstIf9jzKsM

ABOUT THE AUTHORS

Jesús Ureña (Senior Member, IEEE) received the B.S. degree in electronics engineering and the M.S. degree in telecommunications engineering from Universidad Politécnica de Madrid, Madrid, Spain, in 1986 and 1992, respectively, and the Ph.D. degree in telecommunications from the Universidad de Alcalá, Alcalá de Henares, Spain, in 1998.

Since 1986, he has been with the Department of Electronics, University of Alcalá, currently as a Professor. He has collaborated in several educational and research projects in the area of electronic control and sensorial systems for mobile robots and wheelchairs and in the area of electronic distributed systems for railways. His current research interests are in the areas of ultrasonic signal processing, local positioning systems (LPSs) and activity monitoring, and sensory systems for railway safety.

Álvaro Hernández (Senior Member, IEEE) received the Ph.D. degree from the University of Alcalá, Alcalá de Henares, Spain, and Blaise Pascal University, AubiŁre, France, in 2003.

He is currently an Associate Professor of Digital Systems and Electronic Design at the Electronics Department, University of Alcalá. His research areas are multisensor integration, electronic systems for mobile robots, and digital and embedded systems.

J. Jesús García (Member, IEEE) received the B.Sc. degree in electronic engineering from the University of Alcalá, Alcalá de Henares, Spain, in 1992, the M.Sc. degree from the Polytechnic University of Valencia, Valencia, Spain, in 1999, and the Ph.D. degree (with distinction) from the University of Alcalá in 2006.

Currently, he is an Associate Professor of Digital and Analog Electronic at the Electronics Department, University of Alcalá. His research areas are multisensor integration, local positioning systems, and biomedical signal processing.

José M. Villadangos received the Ph.D. degree from the University of Alcalá, Alcalá de Henares, Spain, in 2013.

He is currently an Associate Professor of Electronic Digital Systems at the Electronics Department, University of Alcalá. His current research interests include multisensor integration, electronic systems for mobile robots, digital and embedded systems, low-level ultrasonic signal processing, and local positioning systems.

M. Carmen Pérez (Member, IEEE) received the M.S. degree in electronics engineering and the Ph.D. degree from the University of Alcalá, Alcalá de Henares, Spain, in 2004 and 2009, respectively.

Currently, she is an Associate Professor at the Electronics Department, University of Alcalá. Since 2003, she has collaborated on several research projects in the areas of sequence design, low-level ultrasonic signal processing, and computing architectures.

David Gualda received the B.S. degree in electronics systems and the M.Sc. degree in advanced electronics system from the University of Alcalá, Alcalá de Henares, Spain, in 2009 and 2011, respectively, and the Ph.D. degree in electronics from the University of Alcalá, Alcalá de Henares, Spain, in 2016.

He is currently at the Department of Electronics, University of Alcalá, with a Postdoctoral Research Contract. His main research interests are in the areas of ultrasonic indoor location, signal processing, and information fusion.

Fernando J. Álvarez (Senior Member, IEEE) received the Physics degree from the University of Sevilla, Sevilla, Spain, in 1998, the Electronic Engineering degree from the University of Extremadura, Badajoz, Spain, in 2012, the M.S. degree in signal theory and communications from the University of Vigo, Vigo, Spain, in 2014, and the Ph.D. degree in electronics from the University of Alcalá, Spain, in 2006.

In 2008, he was a postdoctoral "José Castillejo" Fellow in the Intelligent Sensors Laboratory, Yale University, New Haven, CT, USA. Currently, he is an Associate Professor of Digital Electronics at the Department of Electrical Engineering, Electronics and Automation, University of Extremadura, where he is also Head of the Sensory Systems Group. His research interests include local positioning systems, acoustic signal processing, and embedded computing.

Teodoro Aguilera received the Physics degree and the Ph.D. degree in electronics from the University of Extremadura, Badajoz, Spain, in 2011 and 2016, respectively.

He was an Assistant Professor of Automation for three years at the Department of Electrical Engineering, Electronics and Automation, University of Extremadura, where currently, he is a research member of the Sensory Systems Group. His work is focused on the design of acoustic local positioning systems (ALPSs) based on mobile devices.