Design and Implementation of a Remotely Configurable Ultrasonic Local Positioning Systems

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Abstract. Local positioning systems based on ultrasounds (ULPS) are a feasible alternative and breakthrough in the development of smart spaces. They are based on the distribution of several beacons in an environment that provide coverage to a certain area in which a receiver processes the ultrasonic transmissions and estimates its position. In many robotic applications this type of systems is used due to its low cost, easy implementation and positioning accuracy in the range of a few centimetres. This accuracy is achieved by using different coding and correlation techniques for ultrasonic signals, with which the times-of-arrival between beacons and receivers are determined. The drawback of these correlation techniques is that they involve an increase in the computational load and in the complexity of the electronics associated with the ultrasonic transducers. In many cases, new techniques are proposed and simulated in literature, but their corresponding experimental validation may become more difficult to deal with, as prototyping and experimental issues are often time and effort consuming. In this work, the design and architecture of the LOCATE-US positioning system has been enhanced and extended, so it can be configured and managed remotely by using a web application. This allows a remote user to set up different configuration parameters of the ultrasonic emissions, which, after validation for safety reasons, are stored in a database hosted on a server. That server checks the database and sends these configurations to each ultrasonic beacon in the ULPS. At the same time, the proposed architecture deals with the experimental acquisitions, by managing some receivers, whose incoming signals are also stored in the server and subsequently sent to the aforementioned remote user. In this way, this user can easily develop and experimentally test new transmission schemes, modulations or encoding techniques, thus validating them remotely, without requiring any prototyping or implementation to obtain preliminary experimental results about the performance of their novel proposal for the ultrasonic transmissions.

Keywords: Ultrasonic Local Positioning Systems (ULPS), Remote Experimental Testbench, Field-Programmable Gate Array (FPGA), Client-Server.

1 Introduction

Local positioning systems (LPS) [1] have had a significant impact on the spreading of smart spaces in recent years. For the development of these systems, different sensory technologies have been taken into account, such as radio-frequency [2][3][4], infrareds [5], or ultrasounds [6][7]. The last ones have managed to achieve accuracies in the range of centimetres, with low cost and complexity. The most common approach to these systems consists in the distribution of beacons in a space, providing a coverage volume that depends on the number of beacons installed. In this volume, one or more receivers can be deployed and, by detecting the ultrasonic transmissions from the beacons, their positions can be estimated. Ultrasonic local positioning systems (ULPS) have certain limitations, such as cross interference when emitting several transducers simultaneously, low bandwidth of transducers, or a reduced coverage area. These limitations can be overcome by encoding ultrasonic signals, where the sequences involved should have suitable auto- and cross-correlation functions with other sequences in the set [8].

The encoding techniques mentioned before, as well as the different modulation schemes necessary to adapt the ultrasonic transmission to the bandwidth available in transducers, always imply a greater complexity in the electronic control systems associated to beacons and receivers in previous ULPSs. For that reason, FPGA (*Field-Programmable Gate Array*) devices have already been used in previous works, as they provide a suitable parallel architecture for this type of applications, where implementations can achieve real-time and computational load requirements [9].

Nevertheless, these tasks dedicated to the implementation and prototyping of any electronic system in general, and particularly of an ULPS, are always time consuming and skills demanding. After coming up with a new modulation or encoding scheme, its experimental verification is not often a straightforward issue. It implies the selection of transducers, the design of a suitable analog front-end (adaptation, amplification and conversion), and, finally, the development of a control digital system, capable of managing several beacons and receivers simultaneously to proceed with the desired ultrasonic transmissions. This significant hurdle may become the reason why some approaches are discarded or not properly tested under real conditions. This paper presents an ULPS that can be configured by a remote user through a web application, available in http://www3.uah.es/locate-us/index.php. The user selects the parameters of the configuration for the ultrasonic transmissions to be carried out, and the server stores them in a database. These parameters or options that can be set up are: sequences to be transmitted and the way in which they are encoded; carrier frequencies; modulation schemes; or number of acquisitions made by receivers. The server schedules the operation of the ULPS, by querying the database where the configurations are stored to recover one of them and sending it to the beacon. After configuring the ultrasonic emissions, the system will proceed to the data acquisition by means of some ultrasonic receivers that are distributed in the coverage region of the ULPS. These data are sent to a cloud, where remote users can access to get and process them. This online demonstrator is actually based on the LOCATE-US positioning system, developed by the GEINTRA-US/RF group from the University of Alcalá [8] [10]. The rest of the document is organized as follows: Section 2 describes the ULPS positioning system that has been used; Section 3 details the architecture proposed for the control of the ULPS system; some experimental results are shown in Section 4; and, finally, conclusions are discussed in Section 5.

2 Overview of the Proposed System

The global system is composed of a local ULPS and a central server (running on a PC) that controls it. As has already been mentioned, the ULPS is a LOCATE-US module. It consists of: an FPGA device, which manages the ultrasonic emissions for each of the five available transducers; and four receivers, which perform the necessary acquisitions. The server has access to the ULPS through a WiFi link, as well as to a database where configurations and users, who have registered, are stored. Fig. 1 shows the block diagram that represents the complete system. Users should make http requests to the central server to access the system. All users must be previously registered in the database in order to use the web application, which they can select the different configuration parameters with.

The server queries the database to obtain the configurations that users have previously registered. With these configurations, the server schedules the operation of the ULPS, giving time slots to the different configurations so they can be tested on the ULPS. For that purpose, it transmits these configurations to the FPGA device available in the ULPS, and deals with the data acquisitions carried out by the receivers. These are connected to the mentioned server by means of an USB link. Another functionality that the server implements is sending emails to users, indicating that their configurations have already been tested and providing the link where the resulting data can be downloaded from the cloud.

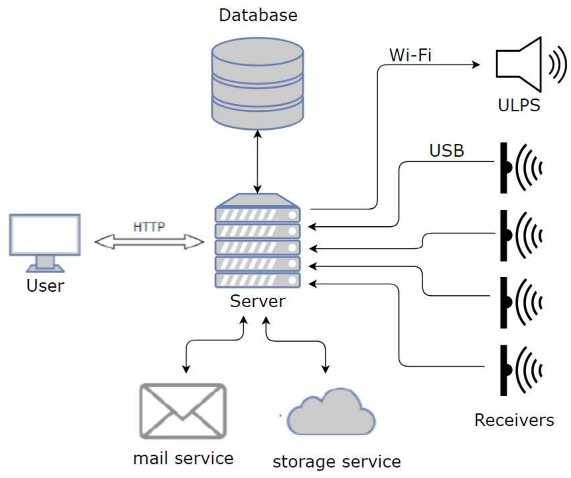


Fig. 1. General block diagram of the proposed system.

In that way, the proposal achieves some specifications that can be summarized next:

- The possibility to remotely establish the configuration parameters of any ultrasonic emission in the beacon, defining modulation schemes, significant frequencies, or encoding sequences.
- Automatic scheduling and planning of different tasks to carry out the uploaded configurations, according to the current system utilization.
- Acquisition of measurements at certain points of interest in the environment, releasing them available in the cloud for the corresponding users.

2.1 ULPS Module

The core of the proposal, together with the aforementioned server, is the LOCATE-US ULPS developed by the GEINTRA-US/RF research group from the University of Alcala [8] [10]. This ULPS consists of a module with five beacons or transducers, geometrically distributed as shown in Fig. 2. The used transducer is Prowave 328ST160 [11], which has an approximated bandwidth of 18kHz centred at a frequency of 40kHz. The beacon is normally installed in the ceiling of the environment to be explored; particularly, in this work it is located at a height h=3.45m. At this point, the beacon module is able to provide a coverage area of around 30m^2 on the ground.

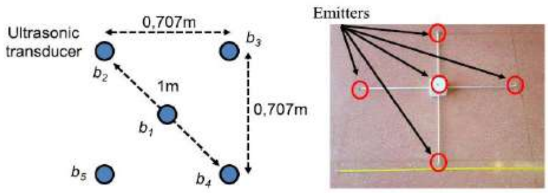


Fig. 2. Geometrical distribution and general view of the beacon module of the LOCATE-US ULPS [10].

The five beacons are managed by an FPGA-based platform, based on the Xilinx xc7z010 device [12]. The FPGA implements the processing datapaths for each one of the beacons in the programmable logic, whereas the ARM processor available in the same die is dedicated to external communications. The FPGA device is also connected to a set of DACs (Digital-Analog Converter), particularly DAC121S101, where the signals to be transmitted by the beacons are converted with a resolution of 12 bits [13]. The analog signal provided by the DAC is amplified with an OPA551 [14] until a range of ± 12Vpp is obtained. It is worth noting that the ARM processor is then in charge of managing the reception of new configurations and download them in the registers and configuration memories for the control of each beacon. This management is done through a WiFi link that is established between the server and the FPGA device.

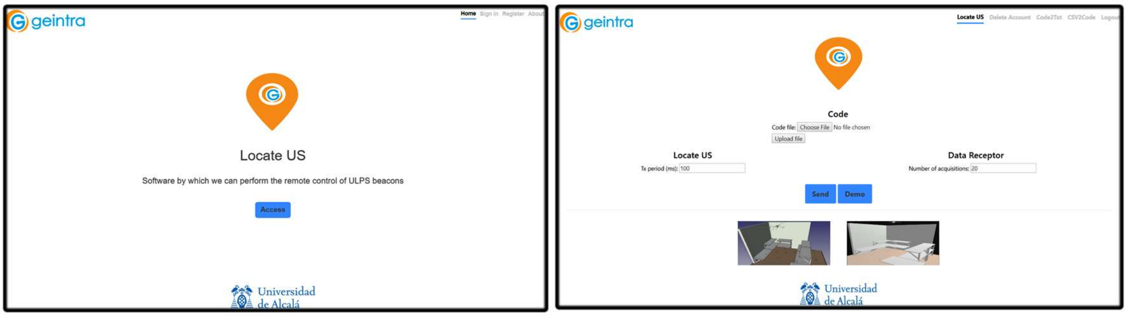
Concerning the ultrasonic receivers, the SPM0204UD5 ultrasonic microphone has been used [15], which is connected to a platform based on an STM32F429 microcontroller; this module carries out the acquisition at a sampling frequency of 100kHz and transmits it to the central server via an USB link.

3 Proposed Architecture

The architecture proposed for the remote control of the ULPS is based on a client-server scheme, where the client is the remote user that makes requests to a server running in a PC. When accessing the online demonstrator, users receive in their browsers the presentation page shown in Fig. 3.a). On this page, it is possible to find a brief description of the system, as well as indications about registration and login in the system. Note that, in order to access the system, users must log in, as only those who have registered before have access. In the registration page, users fill a form with basic information, such as name, email, password, and affiliation. After this page is submitted, these data are sent to the system administrator by email, who finally decides about the registration in the database.

Users can access the main page shown in Fig. 3.b) after having been accepted. This page presents the different parameters that users can modify to set up the ULPS remotely. These parameters are: transmission period, set of samples/emissions to be transmitted, and number of acquisitions that every receiver should perform. The transmission period defines the interval between successive transmissions from every beacon. The set of samples associated to every beacon actually determines the ultrasonic transmissions. Finally, the number of acquisitions defines how many files will be captured for each receiver. Note that receivers operate at a sampling frequency of 100kHz, generating files with a size of 10.000 samples, thus implying an acquisition window with a length of 0.1s. After setting the values for these parameters, users can submit the configuration to the server by clicking the *Send* button and the system will verify the accordance of these parameters (if any of them is incoherent, the system warns the user). They are stored in the system database, and, in turn, will be sent to the FPGA in charge of managing the ULPS to proceed with their configuration.

As an example, the system also provides a demo configuration (by clicking the *Demo* button). In this case, the ultrasonic transmissions are encoded with five 255-bit Kasami sequences [16], one per beacon, with suitable auto- and cross-correlation properties. In addition, a BPSK (Binary Phase Shift Keying) modulation with a carrier frequency f_c=40kHz is used to focus the emission on the bandwidth provided by the transducers. The repetition period of transmissions is configured at 70ms, and a set of 20 acquisitions are selected for each receiver.



(a) (b)

Fig. 3. Presentation page (a) and configuration page (b).

Whether there is any configuration available in the database and ready to be tested, the server schedules the utilization of the ultrasonic beacons over time by each one of these configurations, following the next procedure:

1) Sending the configuration to the FPGA device: the server opens a socket with the FPGA device (responsible for managing the beacons) by means of the WiFi link. In this way, the transmission samples for each beacon are sent, according to the preferences configured by the remote user.

2) Data acquisition by the receivers: the server captures the amplitude values provided by four receivers deployed in the environment, and stores them in text files, classified according to the receiver number, the date and the time of capture. Every file stores 10.000 samples, corresponding to an acquisition window of 0.1ms. As many files are created as the number of acquisitions the remote user has selected in the configuration page. This task is carried out after the previous one, so the beacons are already emitting the desired transmissions when the receivers proceed to acquire.

3) Uploading of acquired files to the cloud: the files that have previously been created are sent to a folder included in an account of any hosting provider in the cloud. Then, an email is sent to the remote user informing where it is possible find the results from their configuration.

Concerning the interval from the instant a configuration is submitted until the results are released available in the cloud, this time interval actually depends on the work load of the system at that moment. Under normal circumstances, with no overload, a response can be obtained in a few minutes.

In the web application described above, different programming languages have been involved. HTML (HyperText Markup Language) language has been used for the presentation of the different forms, whereas the

CSS (Cascading Style Sheets) language has been used to manage their appearance. On the other hand, Javascript is used to verify data registered in the different forms of the application. It is a language that is run on the client side, thus allowing certain improvements in the user interface and dynamic web pages. In the web application presented here, this language is used to manage data entry in different forms and to generate notifications to users. Finally, those tasks performed by the server, cited above, are programmed in PHP (Hypertext Preprocessor). It is a structured programming language that, unlike Javascript that runs in the browser, runs on the server, and the result is sent to a browser as an HTML page. For this reason, PHP allows access to those resources installed in the server, such as a database.

A database created with the PHPMyAdmin software is implemented on the system server as well. It is an open source software that has been designed to manage MySQL databases from a graphical user interface. It is written in PHP and it is compatible with all commonly used operations, such as browsing, creating, altering MySQL databases, tables, fields and indexes. In addition, PHPMyAdmin allows to manage MySQL users and user privileges. This database has been configured at the server. It consists of three tables: *users*, *configuration* and *statistics*. The first two are related to each other by the *user name* field (registered user's email). In the *users* table, all the users who have registered in the web application are stored, which includes the following fields: identifier, name, surname, email, password, a flag indicating when the user is logged in, and another flag that identifies the administrator of the system. The *configuration* table includes all the parameter configurations submitted by remote users. The system adds a new configuration to this table every time a remote user registers a new configuration, and deletes it when it has been tested on the ULPS. Finally, a summary of the users who have logged in and the configurations they have submitted are stored in the *statistics* table.

3.1 Communications with the FPGA Device

As was mentioned above, the server sends the configuration data to the FPGA device [10] by means of a socket based on a WiFi link. These configuration data is organized following the format shown in Table 1.

Table 1. Format of the configuration data sent to the FPGA device.

Content	C	N	Control Register	Frame length	Transmission period	Frames
Size (bytes)	1	1	1	4	1	Variable

C: Command for cancellation of previous configurations.
N: Command to establish a new configuration.
Control: Control register for the operation of the ULPS.
Frame Length: Number of samples in the transmissions to be emitted by each beacon.
Period of repetition transmissions: Period of repetition of successive transmissions.
Frames: Set of samples to be transmitted by every beacon.

The first command is sent to cancel any previous configuration, whereas the second one defines a new configuration characterized by the following parameters: a control register to set the ULPS up; a frame length to define the number of samples for every ultrasonic transmission; the transmission period, which specifies the interval between successive emissions; and finally, the frames or set of samples to be transmitted by every beacon, that's to say, the ultrasonic signal for each beacon.

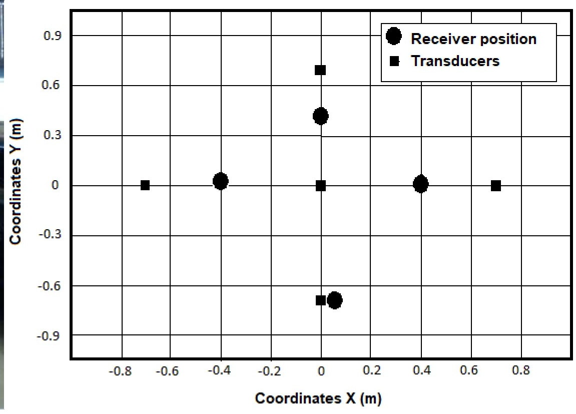
4 Experimental Results

The proposed positioning system has been installed preliminary in a laboratory at the Department of Electronics from the University of Alcala. As is shown in Fig. 4.a), the ULPS is located at a height h=3.45m and the receivers are distributed inside its coverage area, thus allowing the positioning of each one of them. For this paper, tests have been carried out with receivers geometrically distributed as specified in the Fig. 4.b). This figure depicts the vertical projections on the ground (XY plane) of the five beacons available in the ULPS (squared marks), as well as those from four receivers (circles). Furthermore, the web application is available for any remote user at: http://www3.uah.es/locate-us/index.php.

Based on the aforementioned experimental setup, the following configuration has been selected for the ULPS at the website: a repetition period of transmissions equal to 70ms, and a set of 100 acquisitions to be carried out by each receiver. With regard to the set of samples to be transmitted by the beacons and uploaded in the configuration page, they are based on five 255-bit Kasami sequences [16], which have been BPSK modulated at 40kHz to adjust the transmission to the transducers' bandwidth.

After the configuration is submitted, the server sends it to the FPGA device, which is responsible for the corresponding transmission of the desired signals by the beacons. To verify the operation of the system, Fig. 5.a) shows the signal emitted by a transducer, measured at the output of the DAC. It is possible to observe the repetition period of 70ms. Furthermore, Fig. 5.b) plots a zoom of the previous signal, which allows to observe the corresponding BPSK modulation.

(a)

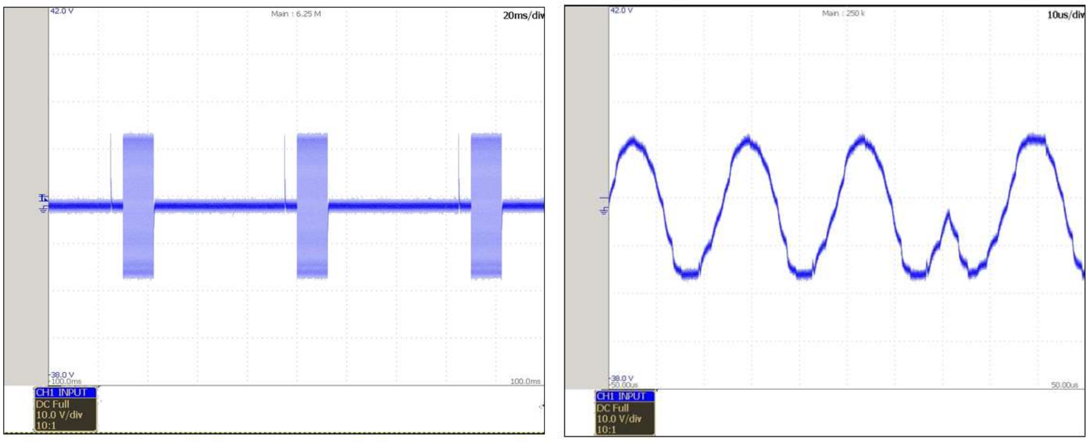


(b)

Fig. 4. Experimental setup detailing the ULPS installation (a); and geometrical projection on the ground of the ULPS and the positions of the four receivers (b).

While the beacons are transmitting the configured emissions, the server manages the receivers, in order to acquire the incoming signals (amplitudes) and stored them in text files suitably labelled. Note that the number of acquisition to be carried out is configured by the web application. When all the acquisition files are available, the server uploads the files to the cloud and sends an email to the remote user indicating the link where they can be downloaded.

For this example, the acquired signals have been processed, firstly demodulated and then correlated with the original five Kasami sequences, by using Matlab©. The resulting correlation functions allow to identity the instant of arrival for the corresponding transmissions, based on the position of the correlation peaks. In that way, the time-differences-of-arrival (DTOA) can be determined and used in a hyperbolic positioning algorithm to estimate the receivers' position, so the performance of the ultrasonic transmissions configured for this test can be evaluated easily and in a real environment, without requiring any hardware development or prototyping. Fig. 6 shows the acquired signal for a certain receiver, whereas Fig. 17 shows the correlation functions for that acquired signal, where the correlation peaks are easily distinguished. Furthermore, peaks for the same transducer are separated 70ms, corresponding to the repetition period configured before.



(a) (b)

Fig. 5. Example of signal transmitted by a transducer with a repetition period of 70ms (a); and zoom of the emitted signal, involving a BPSK modulation (b).

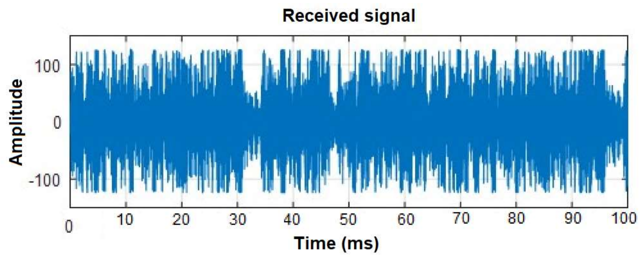


Fig. 6. Signal acquired by the receiver located at the position (x, y) = (0.4m, 0m).

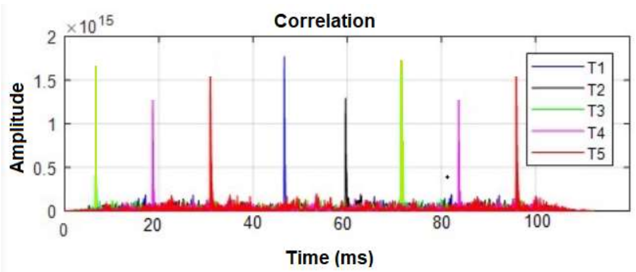


Fig. 7. Correlation functions of the signal acquired at (x, y)=(0.4m, 0m).

As has already been mentioned, and following this example, the position estimates for each receiver can be obtained from the DTOAs, by applying the hyperbolic Gauss-Newton positioning algorithm. Table 2 provides these results, particularly the mean position, the root mean square error (RMSE) and the standard deviation, obtained for a set of a hundred measurements per receiver. Nevertheless, it worth noting that the system presented here just provides the user with the amplitude of the signals acquired by the ultrasonic receivers, without carrying out any type of processing. This processing is actually out of the scope, since the remote user could consider different algorithms depending on the ultrasonic signals configured in the ULPS.

5 Conclusions

This paper presents the design of a remotely configurable ultrasonic local positioning system, which can be managed and set up from a web application. The system has been based on the LOCATE-US LPS, for which a web application has been developed. This allows the ultrasonic transmissions to be configured, so a remote user can modify the type of modulation and its carrier frequency, possible sequences involved in the encoding techniques, repetition periods, medium access techniques, etc. These features imply that the proposal is an useful tool in the design and development of novel processing techniques applied to ultrasonic signals in LPSs, enabling an rapid and easy way of carrying out experimental tests, while avoiding any hard task related to prototyping and electronic design. Experimental tests have successfully verified the feasibility and usefulness of the proposal for the study and development of ultrasonic local positioning systems.

Table 2. Positioning errors (mean value, RMSE and standard deviation) for the receivers considered in the experimental setup.

Receiver's position (m)	Mean position (m)	RMSE (m)	Standard Deviation
(0.4, 0)	(0.42, 0.01)	0.0427	0.0306
(-0.4, 0.05)	(-0.39, 0.06)	0.0124	0.0120
(0, 0.45)	(0.01, 0.5)	0.0492	0.0259
(0.02, -0.7)	(0.01, -0.73)	0.0502	0.0308

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