Distance Measurement System Based on Visible Light Communications and Ultrasound Emitters

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***Abstract*— Distance estimation is an important task in positioning systems, as it is needed for performing the triangulation process used by location algorithms. Different techniques, such as received signal strength indication (RSSI), time of arrival (ToA), and time difference of arrival (TDoA), can be used to estimate the distance between devices. Cricket indoor positioning systems, designed by MIT, are based on TDoA techniques, and they use a combination of ultrasound and radiofrequency signals. In this paper, a new distance measurement scheme based on Cricket technology, but introducing some modifications, is proposed. In this way, some new advantages are obtained. The radiofrequency signal is substituted by an optical signal, making the system applicable to environments where radio emissions are not suitable. Furthermore, a double-way measurement is also introduced, in order to allow both measurement devices (base station and mobile node) to perform the distance estimation, unlike in Cricket systems, where only one of the devices is able to calculate the distance.**

Keywords-Distance estimation; VLC; time arrival; double measurement.

I. INTRODUCTION

Indoor distance measurement is a challenging problem for many indoor positioning systems, as they make use of location information to offer contextual services [1][2][3]. During the last few years, many different wireless methods based on WiFi, wireless sensor networks, Bluetooth, and Cricket sensors [4] have been suggested. These techniques use specific algorithms to estimate distance from different signal parameters, such as signal strength, and arriving angles or delays. However, these distance-measurement systems either need an additional network infrastructure or have difficulties in obtaining accurate distances because of multipath propagation. Visible Light Communications (VLC) [5][6] takes advantage of the relative high switching speed of LEDs to use the light from lamps not only for lighting but also as a transmission channel. VLC has a set of communication characteristics: low cost, light-speed propagation, and no electromagnetic interference, which reduces some Radio Frequency (RF) technological drawbacks, such as spectrum saturation or interference between systems.

In this paper, a new VLC distance-measurement scheme, based on the Cricket's TDoA paradigm is proposed. It uses an optical signal instead of the Cricket's radiofrequency one in order to avoid the aforementioned radio signal problems. In this way, the system can be used in other environments, such as underwater scenarios, where radiofrequency presents a prohibitively high attenuation. However, optical links require a more complicated alignment, or the use of several optical emitters and receivers. Moreover, by the moment, optical technology presents the lack of broadly accepted and implemented standards, which assure the interoperability between different systems, and only isolated solutions as the one presented in this work are being developed.

On the other hand, the transmission and reception stages have been modified in order to provide distance measurement capability simultaneously to the two devices involved in the process: the base station (or transmitter node in this work) and the mobile node (or receiver node). In Cricket systems, only receiver-node devices are able to estimate distance from the signal emitted by the transmitter node. In the proposed system, the mobile node returns back a new optical signal to the base station, allowing it to perform its own relative distance estimation. As it is needed in traditional Cricket networks, in order to develop a full positioning system, a trilateration structure [7] must be implemented using several of the presented distance meters.

This paper is organized as follows. In Section II, a description of the proposed method for obtaining the distance is presented. Section III presents a proof of concept implemented prototype. In Section IV, a detailed description of the measurements and results are provided. Section V summarizes the obtained conclusions.

II. DISTANCE ESTIMATION METHODS

In this work, VLC and ultrasound links are used in the measurement devices. The optical signals perform the same function than the Radiofrequency ones in Cricket schemes, which is to serve as time reference for measuring the ultrasound signal time delay. The basic scheme of the proposed system is presented in Fig. 1.

As it can be observed, the transmitter node uses an ultrasound transmitter, an optical transmitter and an optical receiver, whilst the receiver node makes use of an ultrasound receiver, an optical receiver and an optical transmitter. In this way, a single acoustic link and two optical links are established. The use of VLC technology is proposed because the aim of this work is to use the illumination fixtures as base stations in indoor positioning systems. Nevertheless, this scheme can be also used with other optical wavelengths (IR e.g.).

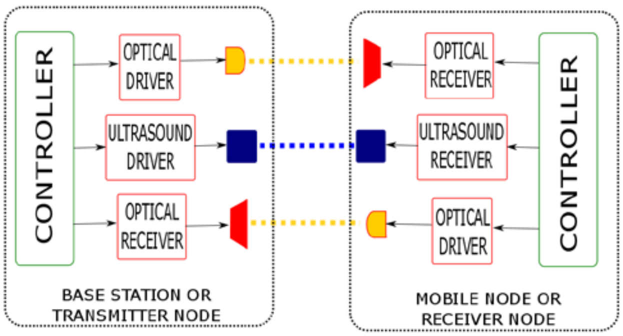

Figure 1. System scheme

In the measurement process, the base station starts sending an optical and an ultrasound signalsynchronously. The mobile node receives the optical signal and waits for the ultrasound signal arrival. As the time for light propagation can be neglected, at least, when compared with acoustic propagation, it can be considered that light is transmitted with zero delay, and the delay between both signals in reaching the receiver node, depends only on the ultrasound propagation. Therefore, the distance from base station to mobile node is proportional to that delay. This procedure is equivalent to the one performed by Cricket systems, except for the use of an optical signal instead of the radiofrequency one for delay reference. In this case, the estimated distance is calculate by (1)

$$D = \frac{t}{\frac{1}{v_S} - \frac{1}{c}} \approx v_S \cdot t \qquad (1)$$

Where D is the distance, t is delay time, c is the speed of light and v_S is the speed of sound. Nonetheless, there are several delay sources that must be considered if an accurate result is intended. The main delay sources are the electric-to-acoustic and acoustic-to-electric transduction times in the acoustic interfaces, and the time delay due to the sequential operation of the microcontroller.The delays produced by this sources are solved by means of an adjustment variable. In order to set and synchronize the LED and the ultrasound pulses in the mobile system, an adjustment variable with a value of 250 microseconds has been used.

This value allows adjusting both the time required for ultrasound transducer operation and the runtime delay in the microcontroller. In this way, the delay time between optical and ultrasound pulse is calculated by (2).

$$\Delta\tau_{LED-US} = (T_{\mu C} - T_{ini}) - \Delta\tau_{adj} \qquad (2)$$

Where the time between the LED and ultrasound pulses, $\Delta\tau_{LED-US}$, is calculated by subtracting to the measured microseconds by the microcontroller $T_{\mu C}$,the start time measurement T_{ini} , and the adjustment variable $\Delta\tau_{adj}$.

At the instant in which the ultrasound signal is received, the mobile node sends back an optical signal, indicating that the ultrasound signal has reached the mobile node. Neglecting again the optical signal propagation delay, the base station is able to estimate the distance from the delay between its optical and ultrasound transmission and the reception of the optical signal from the mobile node (using again (1)). In this way, we obtain distance estimation capability in both devices, increasing the system flexibility. This proposed modification can be easily introduced in Cricket systems by adding an additional radiofrequency signal transmission. Fig. 2 presents the corresponding chronogram.

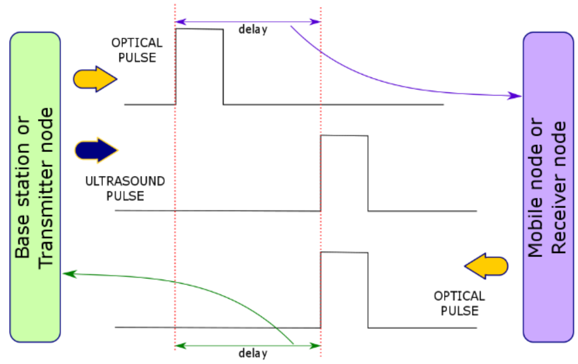

Figure 2. Signals timing for mobile node and base station

It can be seen how the delay values are obtained in the mobile node and in the base station.

III. SYSTEM PROTOTYPE

As a proof of concept, a prototype based on the proposed scheme has been implemented. Fig. 3 depicts the system.

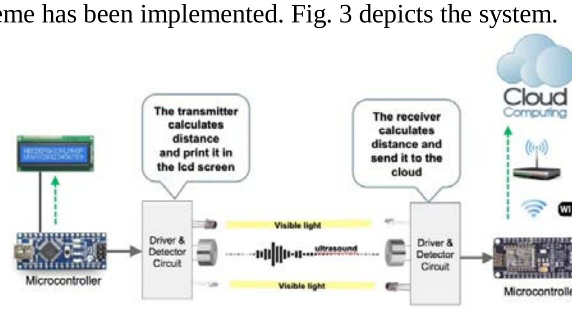

Figure 3. Distance measurement system

This prototype is based on microcontrollers for time measurement and distance calculation. We have used Atmel ATMega328P (Arduino Nano) for base station and NodeMCU (based on ESP8266 chip) for the mobile node. Moreover, the system includes results presentation by means of crystal display (LCD) and a wireless network connection to a cloud server. The measurement process performed by the system is described below

1. The transmitter node sends a light pulse and an ultrasound signal and starts its time counter. Since a MCU is used, both pulses are not sent exactly at the same time and a very small artificial

delay is introduced. This delay presents no jitter and can be easily considered at the receiver side.

2. The optical receiver at the mobile node detects the optical pulse and starts its own time counter. Due to light speed, it can assumed that both time counters start at almost the same time.

3. When the ultrasound signal is detected, the receiver node stops the counter and sends an optical pulse to the transmitter node. In that moment, it can perform the distance calculation from the measured delay. This estimation is stored and published in the web page. Regarding the ultrasound detection, taking into account the behavior of piezoelectric devices, two extra delays due to excitation must be considered. Furthermore, the sound speed is highly affected by temperature, needing the use of a temperature sensor to estimate the local sound speed in order to compensate the propagation-speed error. In order to consider this problem, mobile node includes a temperature sensor and uses this information for calculating the actual sound speed following (3).

$$V_S = 331.5 + 0.60714t\ (m/s) \qquad (3)$$

Where t is the temperature in Celsius degrees.

4. When the transmitter node receives the optical signal, it stops its time counter and proceeds to calculate its relative range. Once more, thanks to light speed, the optical signal can be considered to reach the base station at the same time than the ultrasound signal reach the receiver node. Therefore, both devices obtain the same delay for calculating the distance. Finally, the base station calculates the distance and presents it in the LCD display.

In the next subsections, the devices' main blocks are described and commented.

A. Ultrasound subsystem

The main component of this block is the ultrasound transducer 400ST/R160 from Daventech. This device requires a 40 KHZ signal, which is generated by the microcontroller and a driver circuit, composed mainly by a MAX232 integrated circuit. Fig. 4 shows the emitter's schematic.

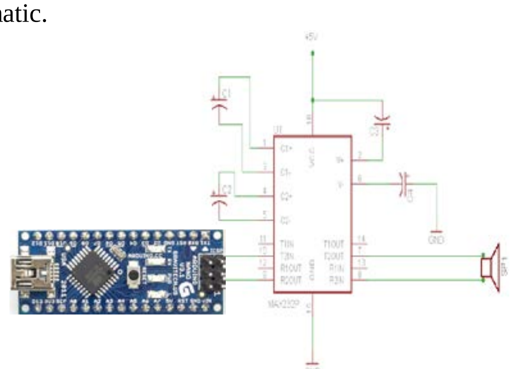

Figure 4. Ultrasound emitter

The ultrasonic wave receiver circuit includes a detector (the same transducer than in the emitter), and a signal amplifier based on CX20106A from Sony, which is connected to the NodeMCU microcontroller, as is shown in Fig. 5.

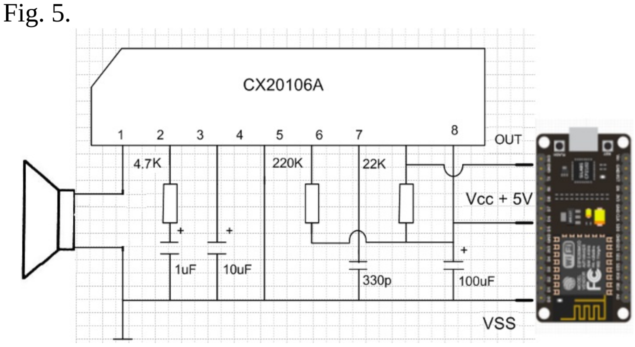

Figure 5. Ultrasound receiver

B. Visible light subsystem

Optical links make use of white LED and phototransistor BPW40 devices as transducers and in this case, simple current drivers and amplified receivers have been implemented.Since the system is a proof of concept, low-gain schemes have been used. Nevertheless, the use of integrated high-gain amplification circuits would improve the performance of a commercial device. Fig. 6 shows the emitter and receiver circuits used in this prototype.

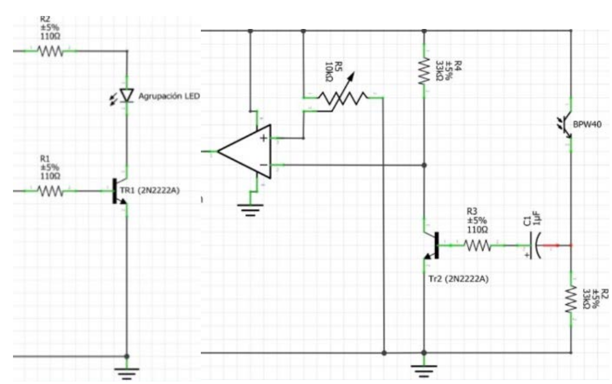

Figure 6. Optical emitter and receiver schemes

Fig. 7 and 8 present the circuits corresponding to the base station system and the mobile node system. As it was explained before, both devices have optical emitter and receiver blocks, whilst the ultrasound block is different: is a transmitter in the base station and a receiver in the mobile node.

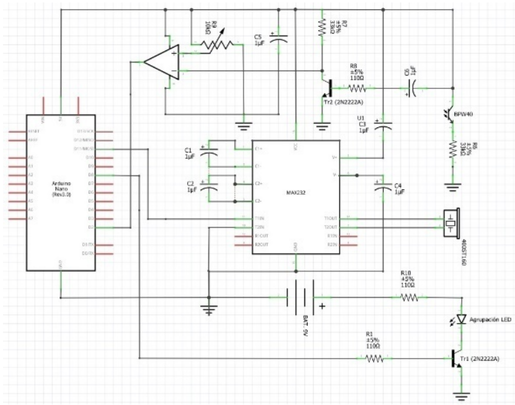

Figure 7. Base station scheme

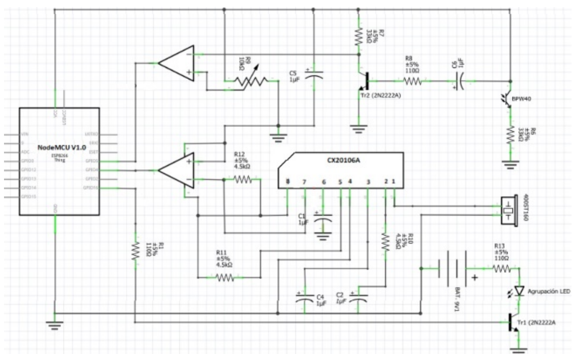

Figure 8. Mobile node scheme

Finally, an actual picture of base station and mobile node is shown in Fig. 9.

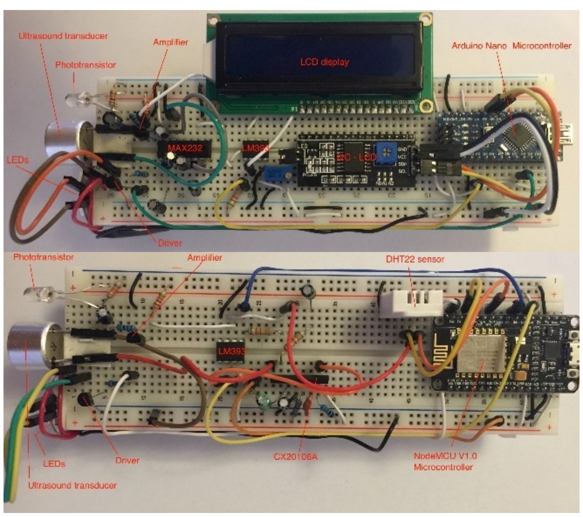

Figure 9. Base station and mobile node scheme

Where it can be appreciated the actual dimmensions and circuitry conplexity of the implemented prototypes.

IV. Results

In this section, experimental results of the implemented proposed system are presented. First, some signals which are used in the process, such as the emitted and received ultrasound signal and the pulse generated for the microcontroller, can be shown in Fig. 10.

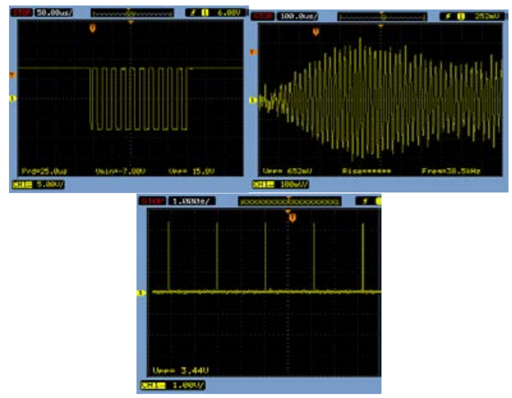

Figure 10. Ultrasound driving signal (left), received ultrasound signal (right) and detected (down) signals.

Note that the received ultrasonic signal is affected by severe multipath distortion. However, since this block acts only as a power indicator, multipath only introduces a delay (which can be estimated and considered in the distance calculation). Furthermore, the received signal is amplified and passed through an open-loop comparator, generating a pulse to serve as input to the microcontroller. Regarding the optical part of the system, the emitted and received pulses are depicted in Fig. 11.

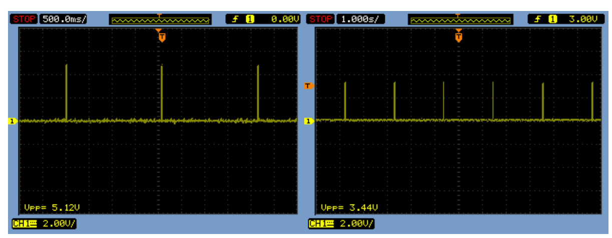

Figure 11. Optical emitted (left) and detected (right) signals.

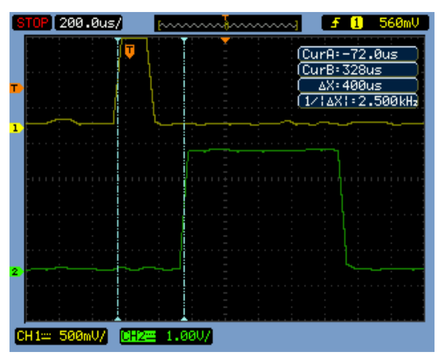

Figure 12. Optical (yellow) and Ultrasound (green) received pulses.

An example of delay measurement is presented in Fig. 12, where the optical and ultrasound pulses received by the

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mobile nodecan be observed.A delay between signals of ΔX= 400 µs is observed. Introducing it in (1), along with the sound speed (0.0343 cm/s), results in an estimated distance of 13.72 cm. Theseresults suggest an interesting high accuracy of the system, since the distance between terminals was set to 14 cm.

In order to test the system performance, different distances were tried. Fig. 13 compares the obtained results in the base station and mobile devicewith the real value.

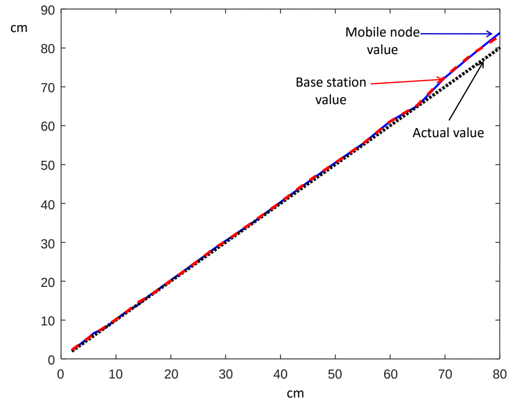

Figure 13. Measured distance values

Finally, Fig. 14 shows the measurement error in both devices.

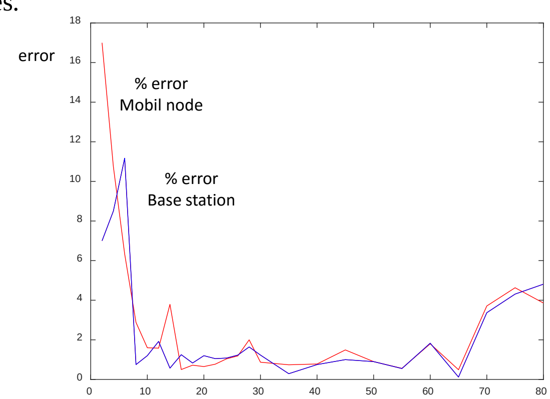

Figure 14. Measures error in base station (left) and mobile node (right).

It can be observed that the error remains below 2% except at the measurement limits of the system, where it is dramatically increased due to low signal strength (long distance) or due to the limited processing speed of the CPU (short distance).

V. CONCLUSIONS

In this work, a new VLC distance-measurement scheme, based on TDoA has been proposed. It is based on Cricket technology but introducing some modifications, which provide several advantages. The main change consists of the substitution of the cricket radiofrequency signal by an optical one.

In this way, the system can be used in new environments not suitable for radiofrequency technology, such as underwater scenarios, where radiofrequency suffers a prohibitively high attenuation.

On the other hand, in the proposed system, the mobile node returns back a new optical signal to the base station for it to perform its own distance estimation. Therefore, the proposed system provides distance measurement capability to both devices involved in the process: the base station and the mobile node. In Cricket systems, only one of the devices is able to calculate the distance, from the signals (radio and ultrasound) emitted by the other. Nevertheless, this technique can be easily incorporated to Cricket modules, just including a new radiofrequency signal.

As a proof of concept, a basic prototype has been implemented. It consists on a base station, which generates optical and ultrasound signals, and a mobile node, which provides the optical signal to the base station. While this prototype has some limitation, such as its short range, results probe that both system devices are able to calculate the distance between them, with similar accuracy (about 2% of error). Therefore, with this implementation, the accuracy and feasibility of the proposed technique is demonstrated.

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