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# Using ANT communications for node synchronization and timing in a wireless ultrasonic ranging system

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**Abstract—** Indoor localization and tracking of persons and assets for gaming, augmented reality, medical monitoring, training, security, and inventory is an emerging technology. Localization can be computed from multiple distance measurements between reference beacons and sensors. Low cost, small, light, tiny-battery or even batteryless operated sensors are required. Ranging can be carried out by measuring the time of flight of an ultrasonic chirp traveling from an emitting beacon to receiving sensors. That requires a tight synchronization between the beacon and the sensors. In this work, we present a ranging system based on miniature commercial modules featuring ANT WPAN communication plus onboard microprocessor. A protocol is developed for microseconds synchronization and accurate onboard ranging computations are carried out through ultrasonic signal cross-correlation. The sensor privately computes its own range. The ranging system is composed of a synchronizing unit, a beacon emitting ultrasonic chirps, and a battery-operated distance sensor. The sensor shows low average power consumption (less than 22 mW) and a ranging accuracy of about 1.8 mm for distances up to 2.5 m, under stable environmental conditions.

**Index Terms—**ANT standard, ANT synchronization, cross-correlation technique, ultrasonic ranging.

## I. INTRODUCTION

Distributed and pervasive computing, location aware applications, augmented reality (AR) are undisputed emerging technologies requiring indoor localization services. Navigating in a mall, finding a path in a large hospital or airport, but also offering support for automated surveillance systems, cleaning and maintenance vehicles, are some of the uses of a localization system that can operate inside a building with sufficient degree of positioning accuracy. Different applications require various levels of accuracy positions and refresh rates. Home or office room level location services, with centimeter accuracy at few hertz refresh rate, are expected to pave the way for new applications. For example, knowledge of a person's trajectory during his home moves allows early symptoms discovery of neuromotor diseases such as Parkinson's, or early warning of dangerous situations such as falls or seizures [1-2].

Among other locating methods, trilateration has been proven feasible in indoor environments. Trilateration geometrically combines range measurements between three reference emitters and a sensor whose position you want to know. The critical point of such method is the availability of a technology to perform with sufficient speed, accuracy and reliability the required range measurements. In addition, there are significant constraints on sensor cost, size, and power consumption.

This work aims to present a ranging system showing sufficient accuracy for the room level applications described, and for many others. 3D location with a few centimeters accuracy in a common size room requires millimeter accuracy ranging. To date, millimeter ranging methods and related systems that are at the same time miniaturized and battery operated are still missing [3-16].

The proposed system accurately measures the time of flight (*ToF*) of an ultrasonic chirp traveling from an emitter to a sensor equipped with a microphone [17]. The system aims to demonstrate a novel architecture based on ANT [18] able to synchronize receiver and transmitter with microsecond lag, essential in measuring the *ToF* with the required millimeter accuracy. It copes with the reduced amount of available power supply, as concerning small and wearable sensors, and allows coexistence of multiple sensors.

Section II describes the system architecture and the operating principle with focus on ANT communication features for system synchronization, Section III presents and discusses the system realization and the experimental results; finally, in Section IV, the conclusions are drawn.

## II. SYSTEM ARCHITECTURE AND OPERATION

The distance between the reference point and the sensor is estimated by measuring the *ToF* of an ultrasonic chirp traveling from an emitter placed in reference point to a receiver located in the sensor. The *ToF* of a signal traveling between an emitter and a sensor is calculated by subtracting the emission time from the arrival time. A ranging accuracy of few millimeters requires the emitter and

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receiver timers synchronized with a few microseconds jitter.

This high level of synchronization can be achieved by using an *ad hoc* RF channel. However, if we desire to take advantage, in terms of hardware and software, of existing and well-developed communication standards such as Bluetooth, ANT or WiFi, some difficulties arise. As well known, synchronizing two devices using sync messages with this kind of protocols is practically unfeasible. ANT and other similar standards do not allow knowing a priori the exact delay between the time of a specific message transmission and the time of its reception by the listener. In fact, it is necessary to wait for the physical medium to be free from other transmissions (medium access control layer). The duration of this specific activity is not monitored by standard protocols and shows uncertainty of the order of hundreds of microseconds.

On the other hand, the Broadcast-Reference Synchronization technique [19] involves a sender sending a broadcast message to a multiplicity of receivers that receive the message at the same time. Noticeably, the broadcast message is only used to synchronize a set of receivers with one another.

In light of these considerations, a novel architecture is proposed: a Master acts as message sender while a Beacon, which emits ultrasonic signals, and multiple Sensors act as message receivers (see Fig. 1). Here, for the sake of simplicity, we will consider a single sensor. However, the same observations apply to an arbitrarily large number of sensors.

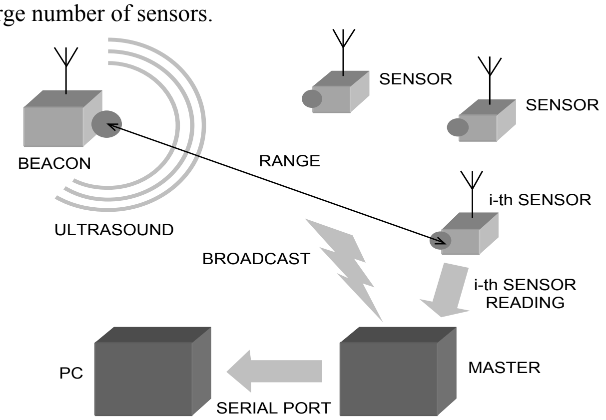


Fig. 1. Ultrasonic ranging system architecture: Master, Beacon, and Sensors. The Master broadcast message synchronizes the Beacon ultrasound emission and the Sensors' ultrasound recording.

The Master, featuring ANT, sends a Broadcast RF message to the Beacon and the Sensor. Once the physical transmission has been accomplished, the reception by Beacon and Sensor takes place at about the same time, with a difference of few ns among them. Experimental tests show however a time difference or jitter up to 3 μs between the two reception times. This jitter includes in fact all the internal processes.

Beacon and Sensor can therefore synchronize their timers based on the received Broadcast message with a discrepancy less than 3 μs, a sufficient precision for the proposed applications (assuming a sound speed of 343 m/s, 3 μs correspond to a ranging uncertainty up to 1.03 mm). This holds for any number of slaves listening to the same broadcast message. To allow the communication with multiple Sensors, a specific address is assigned to each one in the spatial region where the system operates, according to ANT standard. Considering a positioning system built on this ranging system with multiple beacons, a specific address is assigned to each one and fired in sequence according to specific Master's messages.

The Master emits a Broadcast message every time a distance measurement is requested. As a result, the Sensor and the Beacon on-board timers start at the same time, with the said maximum discrepancy of 3 μs. The Beacon sends out the ultrasonic signal at the synchronization message reception, after a constant duration delay $\Delta t_{TX\text{-}DELAY}$ due to the management of the interrupt-based operations in its onboard processor.

The ultrasonic signal, which travels along the line of sight (LOS) between Beacon and Sensor, is received by the Sensor and therein processed to get the actual $t_{ARRIVAL}$ arrival time (see Fig. 2), according to the onboard timer. Knowing that the ultrasonic signal started with the known delay $\Delta t_{TX\text{-}DELAY}$ with respect to the reset of the timers, the $ToF = t_{ARRIVAL}\text{-}\Delta t_{TX\text{-}DELAY}$ is derived by subtraction.

Cross-correlation based methods show high accuracy and, in general, good acoustical noise immunity in estimating the $t_{ARRIVAL}$. When using digital cross-correlation techniques, the received acoustical signal is properly sampled and analog-to-digital converted. The resulting numerical array of samples $S$ is cross-correlated with the digital reference signal $R$, previously stored in the memory of the Sensor processor.

The maximum of the cross-correlation indicates the point in time where $S$ and $R$ are best aligned. The lag $\tau$, or inter-signals displacement, corresponding to the cross-correlation peak is proportional to the $ToF$. By estimating the sound speed as:

$$c_{air} = 331.5\sqrt{1+\frac{T}{273.15}}\ , \tag{1}$$

where $c_{air}$ (m/s) is the speed of sound in air and $T$ (°C) is the ambient temperature, the range $R$ between Beacon and Sensor is computed as follows:

$$R = \frac{\tau_{MAX}\cdot c_{air}}{F_S} - R_{DELAY}\ , \tag{2}$$

where $\tau_{MAX}$ is the lag corresponding to the cross-correlation peak, $F_S$ (1/s) is the signal sampling frequency, and $R_{DELAY}$ (m) is a constant taking into account the range offset due to the sum of all the deterministic system delays.

The Sensor employs $\Delta t_{WINDOW}$ in listening and recording the incoming signal, $\Delta t_{ONBOARD\_COMPUTATION}$ to detect from the recorded signal the $t_{ARRIVAL}$, then it waits for the message from the Master requiring the range just computed, in accordance with the ANT protocol (see Fig. 2). Until now, only the Sensor is aware of its presence and of its ranging data, and its "privacy" is guaranteed, just like in the Global Positioning System (GPS). However, in our system a further step is executed, whenever the Master requires knowing the Sensor's ranging data. In presence of multiple Sensors, after triggering the measurement process in parallel for all Sensors, the Master carries out an individual polling. At the time $t_{SENSOR\_i\_READING}$ the Master sends a "read request" to the i-th Sensor. Finally, the $\Delta t_{RANGING}$ time sums up the $\Delta t_{RECEPTION\_WINDOW}$, the $\Delta t_{ONBOARD\_COMPUTATION}$, and the time that $N$ Sensors employ to communicate the estimated values to the Master, taking into account that they communicate data to the Master in sequence. The Master gathers the distance measurements from the Sensors and passes them to a digital board (a PC in our system), for further processing and data display.

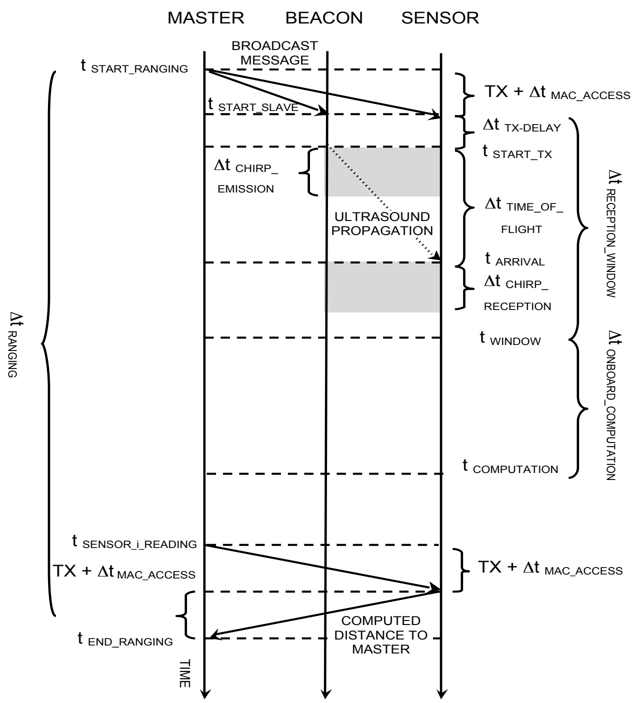


Fig. 2. Ranging process timing.

Estimating the ToF through the cross-correlation peak allows for distance measurement accuracy of the order of the current space sampling (i.e. the distance covered by the ultrasound during the time sampling interval), which can be made much smaller than the ultrasound wavelength. If the signal $R$ is a chirp, the cross-correlation peak is easily detectable. In practice, we can achieve a resolution up to the order of a tenth of the employed wavelength. In addition, cross-correlation greatly increases the SNR, provided they are uncorrelated. A known drawback is that the cross-correlation peak associated with the true chirp travelling delay is not always the highest peak. In some cases, in fact, a number of signals coming from indirect paths can combine to produce a higher peak than the one associated with the direct path signal. A search mechanism can be applied to find the earliest true arriving cross-correlation peak [20].

## III. SYSTEM REALIZATION AND EXPERIMENTAL RESULTS

The Master consists of a N5 module (Dynastream Innovations, Cochrane, Alberta, Canada) connected to a PC via UART/USB interface. The N5 includes a chip nRF51422 (Nordic Semiconductor ASA, Oslo, Norway), equipped with a 16 MHz ARM Cortex M0 processor, and a radio that supports 2.4 GHz communication protocols ANT or Bluetooth.

The Beacon is also composed of a N5 module and of a microcontroller PIC16F1704 (Microchip Technology Inc., Chandler, AZ, USA), for the ultrasonic chirp storage and output through the built-in 8-bit DAC. A linear up-chirp in the bandwidth 30-50 kHz is employed. The chirp signal is composed of 512 samples at 239 kSamples/s Hanning windowed to avoid audible "clicking", with a total duration of about 2.14 ms. The chirp is amplified and fed to a Class AB MOSFET power amplifier; the chirp signal level is further raised to 150 $V_{peak}$ with a signal voltage elevator realized using the miniaturized 1:100 coil transformer LPR6235-752S (Coilcraft, Glasgow, UK). The capacitive transducer is properly polarized by 200 V DC bias obtained employing one ultra-miniature DC to HV DC Converter Q02-5-R (EMCO High Voltage Corp., Sutter Creek, CA, USA). The ultrasonic transducer is the Series 7000 Electrostatic Transducer (SensComp Inc., Livonia, MI, USA).

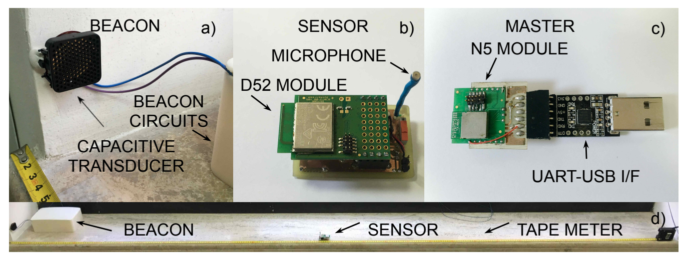


Fig. 3. (a) Beacon composed of N5, PIC16F1704, preamplifier, Power Amplifier, voltage elevator, polarization circuitry, and SensComp Series 7000 capacitive transducer; (b) Sensor including mic, signal conditioning, D52 module and lithium-ion battery (c) Master including N5 module and UART/USB interface; (d) Experimental setup, where the Sensor is moved along the tape meter.

The Sensor is equipped with a D52 module (Dynastream Innovations, Cochrane, Alberta, Canada) built around the nRF52832 chip (Nordic Semiconductor ASA, Oslo, Norway), which includes a 12-bit ADC set at 200 kSamples/s and features a 64 MHz ARM Cortex M4, all powered by a rechargeable lithium-ion battery. The Sensor includes a miniature microphone FG-6163 (Knowles Acoustics, Itasca, Illinois, USA) with length and diameter 2.6 mm, acoustical receiving window diameter 0.79 mm, which is amplified and filtered by a linear circuitry with no AGC [17] based on OPA2835 (Texas Instruments Inc., Dallas, Texas, USA).

We considered a ranging system operating in an average house or office room of 4×4×3 $m^3$, where the emitter is placed on the ceiling center, so that a maximum range of 2.5 m is sufficient for the complete room coverage. The Sensor is moved along a straight line in steps of 10 cm. Ground-truth values were carefully measured using a tape meter. To evaluate reliability, each position measurement was repeated 100 times. No abnormalities were observed and no outliers were eliminated. Experiments were carried out in a normal office room with SNR 30 dB at the farthest point of the measured path, including reflections from surrounding surfaces, as it is possible to see in Fig. 3.d. In Fig. 4.a the experimental results of a single ranging operation are plotted by arbitrarily taking the tenth element from a set of 100 measurements for each position. The standard deviation computed on the entire set per each position is everywhere below 0.8 mm (Fig. 4.b). Fig. 4.c shows the cumulative distribution function (CDF) of the data of Fig. 4.a. During the experiments, the sound velocity was assumed to be constant at 344 m/s (T = 21.1 °C). The ranges estimated by the system are in good agreement with the ones measured using the tape meter, with maximum error below 1.8 mm and standard deviation less than 0.8 mm. Uncertainty is mainly due to synchronization jitter, which is range independent, and secondarily to system time sampling and manual measurement limitations.

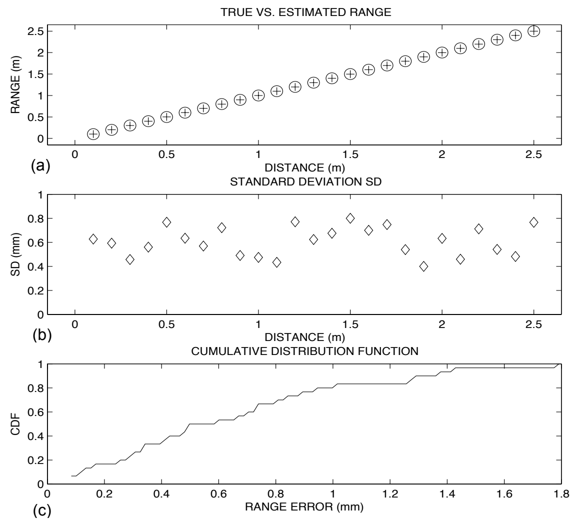


Fig. 4. (a) experimental ranging results (cross) compared to true distances (circle); (b) data set standard deviation (SD); (c) CDF of the data showed in (a).

$\Delta t_{WINDOW}$ was 10.2 ms and $\Delta t_{ONBOARD\_COMPUTATION}$ 241 ms. A ranging rate of 2 Hz has been achieved, actually limited by the computational power of the D52 processor. The measured average sensor power consumption was about 21.7 mW.

## IV. CONCLUSION

An ultrasonic ranging system has been proposed and demonstrated. Its novel architecture allows beacon-sensor synchronization through ANT and the onboard cross-correlation computation, using a small battery. Experimental ranging accuracy is about 1.8 mm within a range of 2.5 m, adequate to cover an average office room. The achieved ranging rate of 2 Hz is limited by the computational power of the specific module used. Ultrasound frequencies in the range 30-50 kHz, allow commercial and low cost ultrasound components. The system is fully scalable in terms of number of sensors and beacons. The sensors can be in perspective realized as miniature System on Chip. Very promising applications include location-aware IoT smart devices, augmented reality, gaming consoles, gestural interfaces, domotics, etc.

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