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# Development of a practical foolproof system using ultrasonic local positioning

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ABSTRACT

The objective of this research is to develop a prototype for practical foolproof system which can be used in manual assembly processes. For this purpose, a high-performance and low-cost ultrasonic system is proposed to measure 3D positions of an indoor mobile object. Composed of an ultrasonic sender and a receiver, the system employs ultrasonic time-of-flight (TOF) and trilateration to estimate the positions of the object with an accuracy of few centimeters. To calculate three TOFs, ultrasonic signals are processed full-digitally with a low-cost FPGA, which provides high design flexibility keeping both high performance and low noise. Proposed system is autonomous, so there is no need of an external PC and the system development cost becomes low. As an improved thresholding method to calculate the TOFs, this paper proposes a debounce module, designed in the FPGA, to remove the pulse noises generated during the thresholding. The resulting time delay from the debounce is compensated by a microprocessor for calculating actual TOFs. Lastly, the positions of the mobile object are calculated from the TOFs values by trilateration in the microprocessor. In order to remove measurement noises, both moving average filters and Kalman filters are adopted in calculating the TOFs and positions.



## 1. Introduction

Ultrasonic techniques provide an effective solution for applications in many local positioning systems [1–5], where the positioning is based on time-of-flight (TOF) of ultrasonic signal to estimate the distance between a receiver node and a transmitter node. So, the accurate estimation of TOF is a fundamental element, and there are many different methods for calculating the TOF of an acoustic signal. TOF calculation methods are reviewed in detail in [6], and classified into three categories: time-domain method, frequency-domain method, and hybrid method. Because each method has trade-off relationship between performance and cost, limiting factors, such as required performance and implementation cost, should be considered for building the best possible system. Among these, although somewhat inferior in accuracy to the other two, the time-domain method is most widely applied in real-time systems, since its implementation is very simple. Various time-domain approaches have been studied in depth in [7], where four methods of range measurement using ultrasonic echo signal are compared. Among these methods, the cross-correlation method has the best accuracy [8], but a considerable level of signal processing apparatus is required to implement it in real time. As an improved thresholding method [7] proposed sliding-window method that not only has relatively high accuracy, but can be implemented easily. In order to increase the accuracy of the thresholding method, the threshold level should be lowered close to zero, but, in this case, because

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the influence of noise increases, the accuracy can rather degrade. With a window of some period, sliding through an ultrasonic echo signal, the sliding-window method can have robustness to noise spikes, and therefore allow a low threshold level.

On the other hand, ultrasound positioning systems can be classified into two types by their structures – active type and passive type. Among the systems, Bat system [1] has an active structure where a sending node (mobile object: MO) transmits a RF signal and an ultrasonic signal toward an anchor (receiving node). At this time, the position of the MO is calculated by a separate PC. With passive structure, where a MO receives RF and ultrasonic signals from an anchor, MIT Cricket system [2] calculates its position in the MO, but it also needs a PC. With a system consisting of three ultrasound transmission beacons and three ultrasonic sensors, MM Saad et al. have proposed a method where ultrasound start time can be found out, without the RF synchronizing signal, by combining a TOF with an angle-of-arrival (AOA) of ultrasound [3]. This system is rather complicated to be applied in real time. In addition, Constellation system [4] has provided a high accuracy system of sub-centimeter without a PC by combining the ultrasonic positioning with gyroscopes, magnetic sensors, and acceleration measurements, but the development cost is high. Sarissa GmbH has commercialized worker-assistance-system (WAS) [5], a foolproof device that tracks the location of the work's hands by ultrasonic local-positioning-system. Designed so as to be impervious to human incompetence, error, or misuse, foolproof devices are essential in many industrial fields. WAS consists of an anchor having three ultrasonic sensors, a wearable MO on the wrist, and a PC calculating the worker's hand position. The detecting resolution of the WAS is announced sub-centimeter, but its cost is more than 10 thousand of US dollars.

The objective of this research is to develop a prototype for practical wearable foolproof devices which can be used in manual assembly processes. Under this objective, this work proposes a high-performance and low-cost ultrasonic system to measure 3D positions of an indoor MO (in practice, a worker's hand). Compared with the conventional DSP, as it is possible to perform high-speed parallel processing in real-time and easy to reconfigure the system according to the field requirements, FPGA is used in many ultrasound signal processing areas [1,2,9–11,13]. Implemented with a low-cost FPGA (XC3S200A) [12] and microprocessor combination and composed of an ultrasonic sender and a receiver, proposed system employs ultrasound TOF and trilateration [13] to estimate the positions of the MO with an accuracy of few centimeters. To calculate three TOFs, ultrasonic signals are processed full-digitally with pre-processing modules, designed in the FPGA, which provides high design flexibility keeping both high performance and low noise. The proposed system is autonomous, so there is no need of an external PC and the system development cost becomes low. This paper proposes an improved thresholding method for calculating TOFs, which adapts the sliding-window method of [7] for easy application in real-time. Without a sliding-window, the proposed method makes use of a debounce module, designed in a FPGA, for removing the influence of noises during thresholding ultrasonic signals. And, the resulting time delay from the debounce is compensated by a microprocessor when calculating actual TOFs. Consisting of a microprocessor, a RF module, and an ultrasonic transmitter, the MO sends a RF packet and three consecutive ultrasonic chirps, toward a receiver. The receiver processes the chirps in incoming order through three ultrasonic sensors, and calculates three TOFs of the chirps with the differences in arrival times between the radio packet and the three chirps. Lastly, the positions of the MO are calculated from the TOFs values by trilateration. On receiver, all signal processing is handled by a low-cost FPGA module, and the calculations of the TOFs and positions are all carried out by a microprocessor. In order to remove measurement noises, both a moving average filters [14] and Kalman filter [15] are adopted in calculating the TOFs and positions.

This paper is organized as follows. Section 2 presents system configuration and methods for ultrasonic positioning. Section 3 presents designing components modules and their functions in system. Section 4 describes system hardware and discusses test results. Section 5 summarizes the main conclusions of this research.

## 2. Mobile-object (MO) positioning system using ultrasonic waves

### 2.1. System configuration

Fig. 1 shows the configuration of an ultrasonic trajectory positioning system, consisting of an ultrasonic sender (MO) and a receiver (anchor). Consisting of a microprocessor, a 2.4 GHz RF module, and an ultrasonic transmitter, the MO sends a RF packet, and then three consecutive 40 kHz ultrasonic chirps toward a receiver. Fig. 2 shows an ultrasonic driver circuit and its input signals for generating the ultrasonic chirps from the sender. As the ultrasonic driver, SI9988, an H-bridge MOSFET driver IC, is used. With a continuous PWM signal of 40 kHz, the sender-side processor, while subsequently enabling and disabling the driver, generates three ultrasonic chirps. The first chirp is generated in synchronization with a rising edge of a RF timing pulse from the RF module of the sender. When the processor sends a packet toward a receiver via the RF module, the RF timing pulse (RF pulse) is generated. Driver's enable duration is 250 μs and 10 cycles of ultrasonic waves are generated. Then, the driver is disabled during 1110 μs. Therefore, an ultrasonic chirp period (*tu*) takes 1360 μs. In this way, after three ultrasonic chirps are generated, the driver is disabled lastly during 19,200 μs and an ultrasound transmitting cycle (*trf*) is completed. Afterward, transmitting a new packet, the sender enters new chirps generating cycle. With *trf* value of 22,170 μs and an ultrasonic speed of 340 m/s in the air, the first chirp travels about 7.7 m during *trf*, the second chirp travels about 7.1 m during *trf*–*tu*, and the third chirp travels about 6.6 m *trf*–2*tu*. Therefore, an ultrasonic receiver, if it stands within about 6 m from the sender, can sequentially receive the ultrasonic chirps from the sender.