Investigation of Novel Ultrasonic Positioning Method Installed in Sensor Network

Mitsutaka Hikita, Yasushi Hiraizumi, Hiroaki Aoki, Junji Matsuda, and Tomoaki Watanabe
Faculty of Global Engineering, Kogakuin University, Shinjuku-ku, Tokyo 163-8677, Japan

Abstract — A new concept called “Sensor Network” has been proposed with the development of mobile communications system such as cellular phone, radio LAN and Bluetooth. Signals from many sensor nodes spread in a wide area are gathered to a center node by technology similar to that used in mobile communications. Sensor network enables home/office circumstance control, environment monitoring and protection based on the collected data. We proposed a novel ultrasonic positioning method which can be installed in sensor network. This method has also been investigated to be combined with 2.4-GHz ZigBee, which has been regulated by IEEE 802.15.4 as wireless-communications medium for sensor network.

1. INTRODUCTION

Cellular-phone systems have spread all over the world and their technologies continue to be developed during the first half of the twenty-first century. On the other hand outstanding technical innovations have been observed in a sensor area. A new concept called “Sensor Network” has been proposed recently by combining sensor technologies with such mobile communications system as cellular-phone, radio LAN and Bluetooth. In this network system, a lot of sensors distributed in a certain area such as home, office and public places are connected via rather simple private radio communications network. It is thought to have a big impact on our lives and to grow to be a giant industry like the cellular-phone systems. It will also contribute to future ecology, i.e., energy saving and environmental preservation. In our laboratory, we have been studying the sensor network to achieve comfortable living circumstances by home/office sensing and control [1].

In this paper, we proposed a new ultrasonic positioning method which can be installed in the sensor network. Sensor nodes require long-term operation with extremely low-power supply, such as several-year operation with a single battery. However, such conventional ultrasonic positioning methods as a pulse-echo method and a code-division [2] method require high voltage handling capability for the transmitter and complicated signal processing procedures for receiver, respectively. Therefore, their devices can not be included in sensor nodes. Our proposed method can provide not only the low-power consumption but also removal of the complicated signal processing procedures, which overcomes the limitation for use as sensor-node devices [3]. Our method has also been invented based on ZigBee-based sensor network. ZigBee has been regulated by IEEE802.15.4 [4] and ZigBee Alliance as a wireless-communication medium used in low-power and long-term radio systems such as sensor network. We also showed the feasibility of the new method by fundamental experiments compared with those of conventional method. The sensor network including our positioning devices will possibly be applied not only to home/office monitoring but also to care for old people, prevention of crime and watch in hospitals.

2. SENSOR NETWORK BASED ON ZIGBEE

Texas Instrument, one of the most leading semiconductor-IC manufacturing companies, has a vision as shown in Fig. 1 for ZigBee-based sensor network. Almost all office/home controls, i.e., light, temperature/humidity, security/alarm, smoke-detection/alarm and other notifications, are conducted via sensor network. T. I. has a plan to provide semiconductor ICs used in such network systems. Our proposed ultrasonic positioning devices will be installed in sensor nodes together with these developed ICs.

ZigBee has been regulated by IEEE802.15.4 [4] and ZigBee Alliance as a wireless-communication medium for the sensor network. Wireless specifications for ZigBee are shown in Table 1 compared with other recent radio communications media, i.e., Bluetooth and UWB 2.4 GHz, same frequency as Bluetooth, is used, but data rate is 250 Kbps which is about one third of Bluetooth. The number of connectable nodes per one network is 65,535, which is completely different from Bluetooth’s 7
slaves per one master pico-network. Because of these characteristics, sensor-network is the most adequate application for ZigBee.

The protocol structure for ZigBee is shown in Fig. 2, which has almost same layer configuration as Bluetooth or other radio communications systems. The network topology is shown in Fig. 3. Not only conventional star-link type topology for Bluetooth and radio LAN but also new mesh-link type and tree-type topology can be possible for ZigBee, which can achieve 65,535 nodes connected per one network. Other one of the most important features required for ZigBee is the extremely low-power consumption, which provide several-year operation with a single battery.

![Network Monitor](image)

Figure 1: Concept of ZigBee-based sensor network (slightly modified from originals in H.P. of T.I.).

<table>
<thead>
<tr>
<th>System</th>
<th>ZigBee (IEEE802.15.4)</th>
<th>Bluetooth (IEEE802.15.1)</th>
<th>UWB (IEEE802.15.13)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Modulation</td>
<td>2.4 GHz OQPSK/DSSS</td>
<td>2.4 GHz GFSK/FHSS</td>
<td>3.1-10.6 GHz MC0FDM</td>
</tr>
<tr>
<td>Output Data Rate</td>
<td>0 dBM / 250 Kbps</td>
<td>0 dBM / 721 Kbps</td>
<td>-41.3 dBm/MHz</td>
</tr>
<tr>
<td>Number of Nodes</td>
<td>65,535 Nodes / 1 Network</td>
<td>7 Slaves / 1 Master pico-net.</td>
<td></td>
</tr>
<tr>
<td>Application</td>
<td>Sensor network, Home network, Temperature / Light/Air con., Security</td>
<td>PC, Printer, Key board, Audio sets, Hands free</td>
<td></td>
</tr>
</tbody>
</table>

![ZigBee Alliance](image)

Figure 2: Protocol structure for ZigBee.

3. CONVENTIONAL ULTRASONIC MEASURING METHODS

One of the images for sensor network installed in homes and offices is shown in Fig. 4. Many sensor nodes with various sensors will be arranged, where nodes can communicate one another via ZigBee. Sensed signals from all nodes are gathered to a center node. The center node not
only supervises sensor nodes and processes collected data but also sends control signals to other installations. Ultrasonic devices within sensor nodes transmit and receive ultrasonic waves to measure the distances between sensor nodes and reflected objects.

![Network topology for ZigBee](image1)

Figure 3: Network topology for ZigBee. Only star-link type is accepted for Bluetooth and radio LAN. All three link types are possible for ZigBee.

![Image example for sensor network with ultrasonic positioning method](image2)

Figure 4: Image example for sensor network with ultrasonic positioning method.

Two major measuring methods have been used in conventional positioning systems. One is a pulse-echo method, and the other is a code-division method [2]. Assuming two objects as shown in Fig. 5, the pulse-echo method measures time delays between the transmitted and received burst-type ultrasonic pulses as shown in Fig. 6. In this case, the width of received pulses is spread comparatively compared with that of the transmitted pulses, which requires very narrow transmitted pulse to achieve enough space resolution. However, if we keep the same transmitted energy the amplitude of transmitted pulses must be increased with narrowing their width. Therefore, high voltage handling capability is needed for a final stage amplifier in the transmitter, which reveals that adopting this method to sensor nodes is very difficult.

![Measurement model with two objects as well as transmitter and receiver](image3)

Figure 5: Measurement model with two objects as well as transmitter and receiver.

![Transmitted and received ultrasonic pulses for pulse-echo method](image4)

Figure 6: Transmitted and received ultrasonic pulses for pulse-echo method.
The other code-division method uses Binary-phase-shift-keying (BPSK) signals as transmitted ultrasonic waves shown in Fig. 7’s left figures. The $0/\pi$-phase combination is determined based on specific codes, such as Barker, M-sequence, and Gold codes. Output signals from a sliding correlator within the receiver have sharp peaks which correspond to auto-correlation function between the coded signal in received ultrasonic waves and a replica signal, i.e., reverse-order-coded signal, from the receiver. This method provides high space resolution as shown in Fig. 7. However, very high speed digital-signal-processing (DSP) ICs and large memories are necessary to achieve function of the sliding correlator, which also reveals it difficult to adopt this method to sensor nodes.

![Figure 7: Transmitted and received ultrasonic pulses for code-division method. Left figures show specific code and BPSK signals.](image)

4. NOVEL ULTRASONIC POSITIONING METHOD FOR SENSOR NETWORK

ZigBee which uses 2.4 GHz has been regulated by IEEE802.15.4 as one of radio standards for low data-rate communications media such as a sensor network [4]. As a block diagram is shown in Fig. 8(a), the sensor node used in conventional ZigBee system consists of 2.4-GHz VCO (Voltage-Controlled Oscillator) locked to TCXO (Temperature-Compensated Xtal Oscillator, i.e., 13 MHz) and other circuit components. We have proposed a new sensor node structure which is constructed with not only above circuits but also new ultrasonic-positioning devices as shown in Fig. 8(b).

![Figure 8: Block diagram for ZigBee-based sensor node. (a) Conventional node. (b) New node with ultrasonic-positioning devices.](image)

A same model as shown in Fig. 5 which consists of an ultrasonic transmitter, an ultrasonic receiver and two reflecting objects is considered. In general, an ultrasonic transducer has frequency characteristics. Assuming that the transmitted waves from the transducer have a frequency bandwidth from $f_1$ to $f_2$, and have single-peaked characteristics for amplitude and flat characteristics for phase respectively within the bandwidth as shown in Fig. 9(a), the received waves have reduced-amplitude and increased-phase characteristics due to the propagation and the reflection as shown in Fig. 9(b). A transmission function, $G(\omega)$, between the transmitter and the receiver can be obtained by a fraction between the characteristics in Figs. 9(a) and (b). Therefore, the magnitude of $G(\omega)$, $|G(\omega)|$, is calculated as the relative amplitude between Figs. 9(a) and (b). The argument of $G(\omega)$, $\angle G(\omega)$, is given by that in Fig. 9(b) because the phase of the transmitted waves is assumed to be zero. An Inverse Fourier Transform of $G(\omega)$ leads to the impulse response between the transmitter and the receiver. This impulse response includes signals of $\sin(x)/x$-shaped function, as shown in Fig. 10. Center of the each signal of $\sin(x)/x$-shaped function reveals a time delay of traveling ultrasonic waves between the transmitter and the receiver way of the corresponding reflecting object. Thus we can obtain the distance from the transmitter/receiver to the object by multiplying the time delay and wave velocity, i.e., about 340 m/s.
5. EXPERIMENTAL RESULTS

In order to confirm our proposal, we experimentally investigated the method using a simple model shown in Fig. 12. The transmitter and the receiver are arranged about 50 cm apart to each other.
As a comparison, we first measured the same distance by a conventional pulse-echo method with burst type of 40-KHz ultrasonic pulses. Experimental results of the conventional method are shown in Figs. 13(a) and (b), where (a) and (b) show the transmitted and received pulses, respectively. The received pulse is delayed by about 1.5 msec which corresponds to about 50 cm.

Figure 12: Experimental set-up with transmitter and receiver about 50 cm apart to each other.

Figure 13: Experimental results for conventional pulse-echo method. (a) Transmitted pulse. (b) Received pulse.

In the new method, the transmitted and received continuous waves are displayed in an oscilloscope, and measured data of relative amplitudes and phases between them are sent to a PC as shown in Fig. 12. Relative amplitudes and phases are shown in Figs. 14(a) and (b), respectively. From the figures, 3-dB bandwidth of the transducer is about 1.9 KHz, and almost no waves can be transmitted at the outside frequency range of 37.4–43.5 KHz. Impulse response characteristics between the transmitter and the receiver obtained by IFFT procedure on the basis of data in Figs. 14(a) and (b) are shown in Fig. 15. The distance of about 50 cm can be clearly recognized, and the threshold characteristics are better than those obtained by the conventional method. These results confirmed validity of our proposed novel method.

Figure 14: Measured data for proposed method. (a) Amplitude characteristics. (b) Phase characteristics.

Figure 15: Measured distance with proposed method, i.e., IFFT results using Fig. 14’s data.
6. CONCLUSIONS

Sensor network which consists of small-sized radio-communication infrastructures has been inves-
tigated as most promising means to monitor and control home/office circumstances. We proposed
a novel ultrasonic distance measuring method which can be used as ultrasonic positioning installed
in sensor network. We also devised a new sensor node structure which included not only network
functions but also ultrasonic sensing devices. The fundamental experiments with the transmitter
and the receiver facing to each other showed validity of the proposed method as well as possibility
of new network systems including the positioning method.

REFERENCES

1. Home Page of Kogakuin University (http://www.ns.kogakuin.ac.jp/~wwa1022/).
4. IEEE Standard 802.15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY)
   Specifications for Low Rate Wireless Personal Area Networks (LR-WPANs), 2003.