Simultaneous and Multi-frequency Driving System of Ultrasonic Sensor Array for Object Recognition

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Abstract: Ultrasonic sensors are widely used in mobile robot applications to recognize external environments, because they are cheap, easy to use, and robust under varying lighting conditions. However, the recognition of objects using a ultrasonic sensor is not so easy due to its characteristics such as narrow beam width and no reflected signal from a inclined object. As one of the alternatives to resolve these problems, use of multiple sensors has been studied. A sequential driving system needs a long measurement time and does not take advantage of multiple sensors. Simultaneous and pulse coding driving system of ultrasonic sensor array cannot measure short distance as the length of the code becomes long. This problem can be resolved by multi-frequency driving of ultrasonic sensors, which allows multi-sensors to be fired simultaneously and adjacent objects to be distinguished. Accordingly, this paper presents a simultaneous and multi-frequency driving system for an ultrasonic sensor array for object recognition. The proposed system is designed and implemented using a DSP and FPGA. A micro-controller board is made using a DSP, Polaroid 6500 ranging modules are modified for firing the multi-frequency signals, and a 5-channel frequency modulated signal generating board is made using a FPGA. To verify the proposed method, experiments were conducted in an environment with overlapping signals, and the flight distances for each sensor were obtained from filtering of the received overlapping signals and calculation of the time-of-flights.

Keywords: Sensor array, Ultrasonic sensor, Mobile robot, Simultaneous driving, Multi-frequency driving

1. INTRODUCTION

Ultrasonic sensors are widely used in mobile robot applications to recognize external environments, because they are cheap, easy to use, and robust under varying lighting conditions. However, the recognition of objects using a ultrasonic sensor is not so easy due to its characteristics such as narrow beam width and no reflected signal from a inclined object[1]-[2]. As one of the alternatives to resolve these problems, multiple sensors system has been studied.

In case of using multiple sensors at the same time, the reflected signals would be superimposed mutually and correct distance measurement is difficult. In conventional systems, to avoid superposition of signals, sensors should be located apart[3] and sensors should be driven sequentially at an enough interval. A pulse coding ultrasonic signal system has been used for simultaneous driving of multi ultrasonic sensor. These systems, however, cannot measure short distance as the length of the code becomes long. In case of using phase modulation for coding of signal, the system becomes complex with respect to the hardware structure because phase modulation and detection hardware is needed additionally. As another approach, an amplitude modulation method has been considered, yet this method is difficult to apply for multi-channel. To resolve these difficulties we have to come up with another method not using coded signal.

Accordingly, in this paper, we propose a simultaneous and multi-frequency driving system of ultrasonic sensors in which each sensor is driven by each different frequency. The proposed system is able to easily discriminate each sensor's own signal by frequency filters even if the received signal is superimposed. In addition, number of pulses of a transmitted signal is reduced, and thus infinitely many ultrasonic sensors can be driven theoretically.

The remainder of this paper is organized as follows. Section 2 describes the properties of a simultaneous and multi-frequency driving system of ultrasonic sensors. Section 3 describes how to obtain the distance of flight to an object from the received signal. Section 4 describes hardware system and interface of the proposed system. Section 5 verifies the proposed system by experimental results. Some conclusions are given in section 6.

2. CONCEPT OF MULTI-ULTRASONIC DRIVING SYSTEMS

To mitigate the limitations of single sensor system, various studies of multi-ultrasonic sensor systems have been performed. The main issue of multi-ultrasonic systems is how to deal with the overlap of received signal.

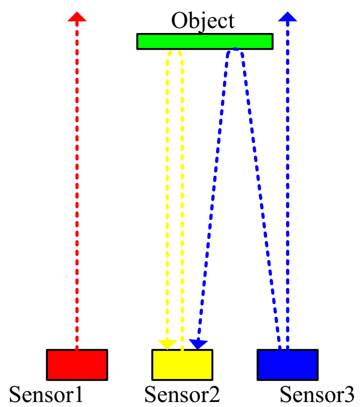

Fig. 1.(a) Example of object environment

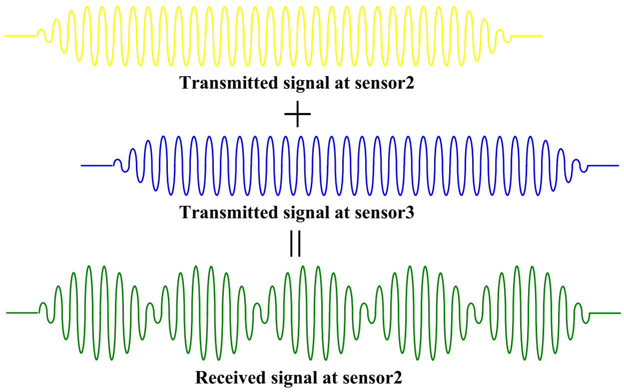

Fig. 1. (b) Overlap of received signal

Fig. 1. Example of simultaneous driving system of ultrasonic array

Fig. 1 represents a typical example of object environment and overlapped signal in simultaneous driving system of ultrasonic array. For a received signal at sensor 2, a transmitted signal from sensor 2 is superposed on a transmitted signal from sensor 3 having time difference. To extract the correct information from the superposed signal, we have to discriminate between two transmitted signals.

2.1 Sequential driving system of ultrasonic array

One method to avoid signal overlapping is sequential driving of ultrasonic array. When a system sequentially drives sensors, overlapped signal with transmitted signal from other sensors not occurs. However, this sequential driving needs a long measurement time according to use of many sensors and does not take advantage of multiple sensors. Furthermore, correct detection of moving object is difficult since transmitting time of each sensor is different. When multi-robot uses ultrasonic sensors in the same space, it may cause a malfunction like that one robot's sensor would receive a signal from the other robot's sensor.

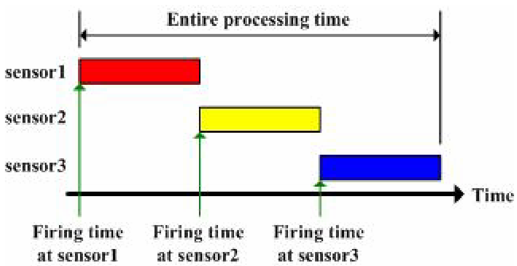

Fig. 2. Timing diagram of sequential driving system

Fig. 2 indicate timing diagram of sequential driving. Each rectangle represents period from firing signal to completing signal process. After sensor 1 completes transmitting, receiving and processing of signal, then sensor 2 is allowed to start firing a signal.

2.2 Simultaneous and coded driving system of ultrasonic array

In the simultaneous and coded driving system of ultrasonic array, the sensor's transmit signals are carried on each specified code which is useful for separation of signals from an overlapped signal to measure correct distances. In conventional researches, several codes such as Pseudo-random codes[6], Golay codes[7]-[8] and Barker codes[9] have been used. A reflected signal from object is put into a matched filter for discrimination of overlapped signal. To separate more accurately, the code length should be long enough. These systems, however, cannot measure short distance as the length of the code becomes long. Plus, the number of simultaneous driving sensors is limited since difficulties in signal processing is increased as the more codes are used.

2.2 Simultaneous and multi-frequency driving system of ultrasonic array

A simultaneous and multi-frequency driving system of ultrasonic array is a newly proposed system in this paper. In this system, each transmit signal of sensors has each different frequency and the system can separate overlapped signals according to frequency response. It is possible to measure shorter distance relatively because the signal length is not limit and, theoretically, infinitely many ultrasonic sensors can be driven as far as the frequency characteristic of the sensor is allowed.

3. MULTI-FREQUENCY SIGNAL PROCESSING

The received signal is processed according to the following steps to obtain the distance to an object:

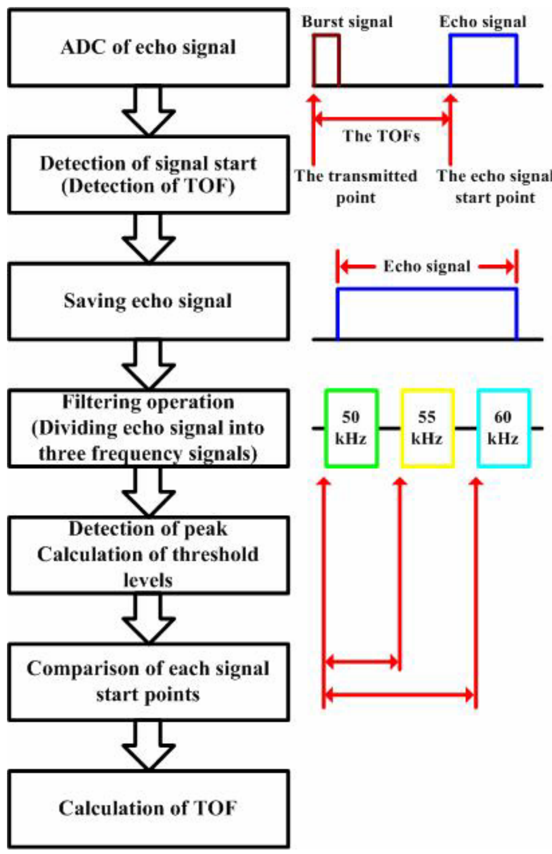

Fig. 3. Diagram of signal processing

3.1 ADC(analog-to-digital conversion) of echo signal

After transmitting ultrasonic waves, a DSP(Digital Signal Processor) convert analog signal received at ultrasonic sensor to digital signal during the interval of 20ms. The sampling time of ADC is 2us and a DSP saves 10000 data in external memory. These data include information of objects within 340cm range from ultrasonic sensor.

3.2 Detection of echo signal's starting point

The starting point of echo signal includes accurate distance information between a sensor and a object. We determine a time instant as the starting point of echo signal when a received echo signal, after burst signal is over, is greater than a certain threshold level. This point will be used to calculate accurate distance later.

3.3 Storing echo signal

The echo signal includes much information of external environments. Because of simultaneous driving, the echo signal could contain overlapped transmitted signals not only from own sensor but also from the others. Only the echo signal is stored during the entire receiving interval and is used for further processing.

3.4 Filtering operation

In this paper, three sensors emit ultrasonic waves having different frequencies with each other. For a received echo signal at each sensor, it should be supposed that three frequencies components are overlapped. To measure the distance between an object and each sensor correctly, each signal with assigned frequencies is needed to be separated from the overlapped echo signal. To resolve such problems, we use digital FIR (Finite Impulse Response) filters. The microprocessor performs the convolution with the echo signal and coefficients of band-pass FIR filter, which were saved in DSP internal memory, and separates signals of three different frequencies from the echo signal.

Digital FIR filters were designed by Matlab. Three digital filters have pass-band frequencies of 50kHz, 55kHz and 60kHz, respectively. Each filter has coefficients of 379 orders..

3.5 Determination of thresholds for filtered signals

Amplitudes of each filtered signal from an object is varying according to the beam width of emitting signals and the distance and the reflection angle between the object and the sensors. Then the peak value of the filtered signals could be also different. To calculate TOF (time-of-flight) of each filtered signal, it is necessary to define a threshold level. However, it is difficult to predetermine one threshold to be adequate for each filtered signal since the filtered signals have different amplitudes and have some distortion. To determine appropriate thresholds, we use the peak value of the filtered signals and each threshold for each signal is set to a fraction of the each peak value.

3.6 Comparison of starting point of filtered signals

The starting points of filtered signals are different according to overlapping time to echo signal. The starting points can be obtained by applying calculated threshold level to each filtered signal. By comparing the start points of each signal, we select firstly received signal for a sensor. Then, we calculate gaps between starting point of a selected signal and starting point of the other signals. These represent gaps of flight distances of each signals.

3.6 Calculation of TOF

The TOF of a firstly received signal is equal to the starting point of the echo signal (SPE). The TOF of the other two signals is calculated by adding the gap value of the starting point of the signal (GSP) to the SPE. The time and distance of flight are calculated using the following equations:

TOF(Time of flight) = (SPE + GSP) * Sampling time (1)

Distance of flight = TOF * speed of ultrasonic wave (2)

4. DEVELOPED HARDWARE SYSTEM

The hardware system consists of a ultrasonic sensor unit, micro-controller unit, and frequency modulated signal generating unit. A diagram of the system is shown below:

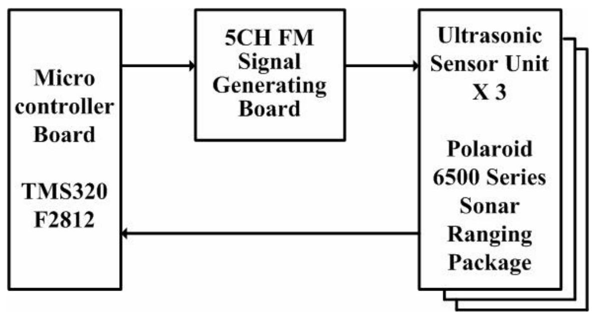

Fig. 4. Diagram of hardware system

4.1 Ultrasonic sensor unit

To drive simultaneously multi-ultrasonic sensors with different frequencies, a sensor is needed to have a wide bandwidth of receiving/transmitting frequency. There is usually one recommended driving range of frequencies for ultrasonic sensor and a ultrasonic sensor has maximal receiving/transmitting sound pressure in that region. The Polaroid 600 series ultrasonic sensor is well met this requirements. The Polaroid 600 series sensor has a fairly flat frequency response from 50kHz to 65kHz[10] as shown in Fig. 5.

Three Polaroid 600 series transducers and three 6500 ranging modules are used in the ultrasonic sensor unit. The Polaroid 600 series transducers act as both transmitters and receivers, while the 6500 ranging modules are used to drive the ultrasonic transducers.

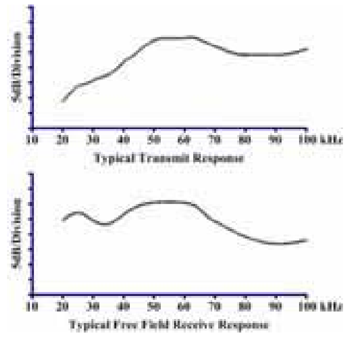

Fig. 5. Freq. response of Polaroid 600 series transducer

The 6500 ranging modules were modified to transmit a frequency-modulated signal, thereby another control unit, a frequency-modulated signal generating board, is required.

4.2 Frequency-modulated signal generating unit

The frequency-modulated signal generating board is made using a Xillinx XCS10XL FPGA. A major function of the frequency-modulated signal generating board is the driving ultrasonic sensor unit according to a given parameters of frequency and the number of pulses which is set by the microcontroller unit.

Fig. 6. Frequency-modulated signal-generating board

4.3 Microcontroller unit

The microcontroller unit consists of one main CPU TMS320F2812, an external memory, a CPLD for control logics and a power input part.

TMS320F2812 is made in Texas Instrument and is DSP chip for control application and is 16-bit microprocessor. The TMS320F2812 sends pulse counts and frequencies of transmitting signals to frequency-modulated signal generating unit to drive ultrasonic sensors. Received signals at sensors are converted to digital signals through ADC channel of DSP and are saved in an external memory. A stored signal data is processed by using digital filters which are implemented in DSP.

The external memory is K6R1016V1D which is made in SAMSUNG electronics and has 64K*16-bit memories. In addition, the CPLD chip is made in ALTERA and is used to decode external memories and other devices.

Fig. 7. Microcontroller board

5. EXPERIMENTAL RESULTS

5.1 Experimental environment

Three ultrasonic sensors were arranged in a line. The frequency of the center sensor is 50kHz, the frequency of the left sensor is 55kHz, and the frequency of the right sensor is 60kHz. The distance between the center of a sensor and the center of the neighbored sensor is 6cm. Like the corner of the wall, two objects is right angled and located 50cm from the center sensor, as shown in Fig. 8.

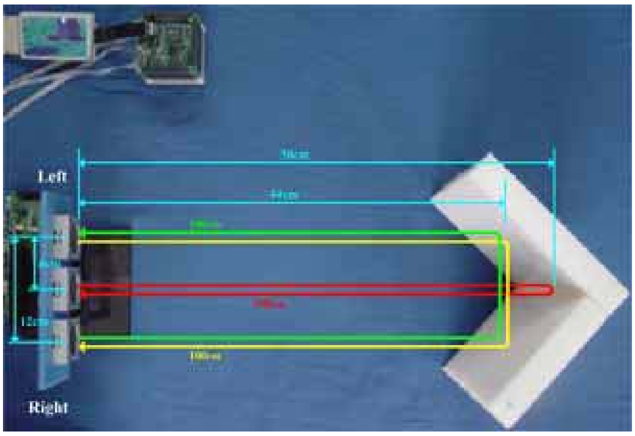

Fig. 8. Experimental environment

5.2 Experimental results

The transmitted ultrasonic waves are reflected from the object and are received at each ultrasonic sensor. The received signals in each sensor are converted to the digital signal and then are saved in memory except of burst signals (during 1.6ms from the beginning of the emitting). Only echo signal of the saved signals in memory is passed to digital filters.

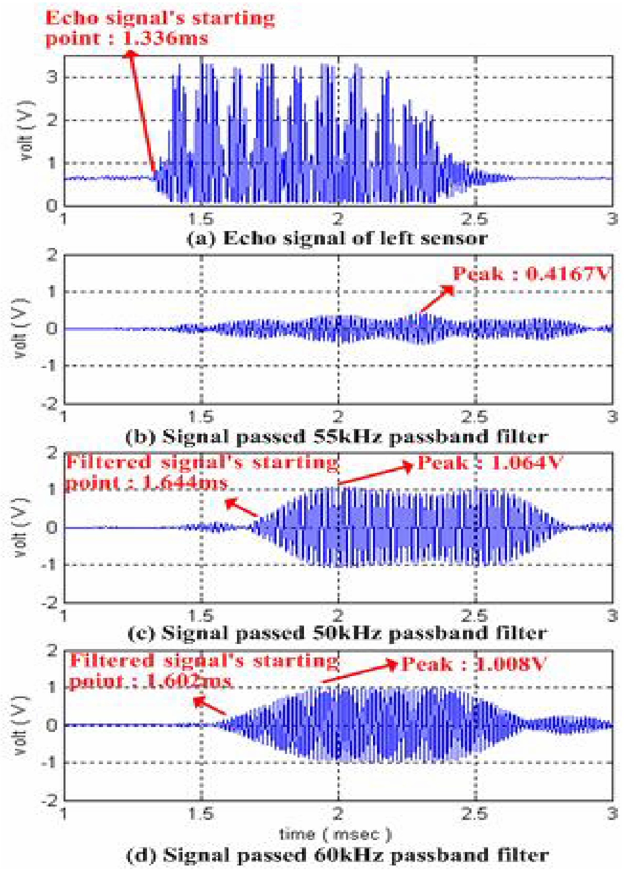

Fig. 9. Signal processing of the left sensor

Fig. 9 shows the received echo signal in the left sensor and signals after filtering. Using the echo signal of Fig. 9 (a), the calculated flight distance was 99.824cm. The peak value of signal in Fig. 9 (b), filtered by 55kHz band-pass filter, was under about 1/2 of the other signals' peak values. Then the 55kHz signal was considered not to be received. The threshold values of signals, filtered by 50kHz and 60kHz band-pass filters as shown in Fig 9 (c)-(d), was calculated to detect the starting points. Since the 60kHz signal started formerly, the flight distance of 60kHz signal is 99.824cm. The difference of starting point of the 50kHz signal and the 60kHz signal was 42us. Therefore, the flight distance of 50kHz signal is 101.252cm.

In the sequel, received signals in the center sensor and the right sensor were processed. The summarized result is shown below.

Table 1 Experimental results

	Left sensor	Center sensor	Right sensor
55kHz	X	101.728cm	99.756cm
50kHz	101.252cm	99.824cm	101.456cm
60kHz	99.824cm	102.612cm	X

By comparing the experimental results in gray cell of Table 1 with the actual distances in Fig. 8, the errors in the left sensor, the center sensor and the right sensor are 0.176cm, 0.176cm and 0.244cm, respectively. With these results, we can infer the shape of the object as well.

In this experimental environment, if a sequential driving method is used, the left sensor and the right sensor can not receive any echo signal and only center sensor can have experimental result of 100cm.

6. CONCLUSION

Now, the systems of using multiple sensors at the same time have been widely studied. However, these systems has limit of time, distance and object. To resolve these problems, we knew how to use frequency.

This paper presented a new system using multi-frequency and digital FIR filters to drive simultaneously ultrasonic array. The proposed system could separate overlapped signals. And it was verified through experiments that the proposed system could mitigate difficulties of the multi ultrasonic sensor system in comparison with the conventional methods. The proposed system will be needed more various methods using information of filtered signals. We expect that the proposed system is useful for various applications of robots.

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