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Obstacle Arrangement Detection using Multichannel Ultrasonic Sonar for Indoor Mobile Robots

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Abstract: In the last several years, mobile robot systems that perform complicated tasks have been studied. To work in complicated environments, the robot has to avoid collisions with obstacles. Therefore the robot needs to detect the arrangement of any surrounding obstacles. We considered a simple distance estimation algorithm using ultrasonic sonar. Since the algorithm was able to estimate distance accurately, we also attempted stereo reception using two ultrasonic microphones. The stereo reception sonar was able to detect direction of obstacles. In order to make precise measurement, we attempted to use the signal coherence of ultrasonic waves. In order to install small system into mobile robots and to detect any surrounding obstacles, we designed a multi-channel sonar signal processing system using a high-performance embedded microcontroller. This paper describes our ideas for the distance estimation algorithm for ultrasonic sonar and a design for signal processing system using a high-performance microcontroller.

Keywords: Mobile robot, Ultrasonic sonar, Obstacle detection, Signal processing.

1. INTRODUCTION

In recent years, mobile robot systems that achieve complicated tasks such as repairing industrial facilities in hazardous environments have been studied. When robots work in these environments, the possibility of collisions with obstacles or other robots increase. In order to avoid collisions, each robot has to detect the arrangements of circumambient obstacles in the given workspace.

Ultrasonic sonar is one of the most popular obstacle detection systems for mobile robots. Ultrasonic sonar only measures the time period from the ultrasonic pulse emission to the reflected echo reception. This method is called time of flight (TOF) measurement. In an ideal situation, the distance to the reflective object L, is calculated from the time period t and the acoustic velocity V using Eq. (1). The parameter T is the temperature in degrees Celsius in this equation.

$$\begin{aligned} L &= V \times t / 2 \\ V &= 331.5 + 0.60714 \times T \end{aligned} \tag{1}$$

In a real situation, ultrasonic sonar receives many echo signals from different obstacles and needs to analyze these echoes, because it is difficult to detect the leading edge of the ultrasonic pulse. In conventional methods using ultrasonic sonar, the result not exact because its threshold decision mechanism has an incomplete theoretical background. Consequently, if the robot moves into another environment, the threshold value may be less accurate.

Therefore, we considered a distance estimation algorithm using a simple waveform analysis without thresholds [1, 2]. Since the proposed algorithm was able to estimate distances accurately in preparatory experiments, we attempted stereo reception using two ultrasonic microphones [3]. The stereo sonar not only measures distances but also detects the direction of reflective objects. In order to detect distance more accurately, we referred to the coherence of the ultrasonic wave. It is possible to accurately estimate distance if we analyze the receiving wave using coherence.

In order to detect the arrangement of circumambient obstacles, we considered multi-channel ultrasonic sonar that can capture more than two channels in parallel. Eight pairs of ultrasonic emitters and microphones were positioned on the circumference of the robot body facing outward. In order to capture signals, the sampling capability of the signal processing system needs more than twice the frequency of the ultrasonic signal because of the Nyquist-Shannon sampling theorem. We tried to attach implement multi-channel sonar systems onto the microcontrollers and install them onto small mobile robots for experiments.

2. TRUE DISTANCE ESTIMATION USING WAVEFORM ANALYSIS

Conventional ultrasonic sonar measures the time period from an ultrasonic pulse emission to the received echo that exceeds a threshold level. However, since the threshold level of this method has an incomplete theoretical background, the measurement result includes some inaccuracies. Therefore, this method is not appropriate for arrangement detection of circumambient obstacles and for an obstacle map creation. In order to detect the accurate arrangement of obstacles, we considered algorithms that measure distances without thresholds.

2.1 Basic concepts of true distance estimation

Fig. 1 shows a model of ultrasonic pulse reflection. Since an emitted ultrasonic pulse spreads to the corn of the beam to the beam width as shown in Fig. 1, the amplitude of the reflected signal is proportional to the temporal change in the size of the reflective cross section. Consequently, if the sonar measures a period of the echoes maximal amplitude of the echo, it measures the distance of maximum reflective cross section. Therefore, it does not indicate true distance.

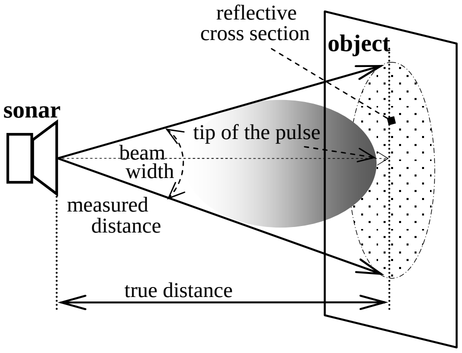

Fig. 1. A model of ultrasonic pulse reflection

The true distance is calculated by measuring the time period between an ultrasonic pulse emission and the tip of the return pulse reception. This is because the tip of the ultrasonic pulse hits and reflects off of the object first, and in turn the tip of the return pulse is received first. Therefore, the true distance is calculated using the received waveform.

2.2 True distance estimation without threshold

In order to estimate true distance, we considered a waveform analyzing algorithm. As previously mentioned we assumed that the amplitude of the reflected echo is proportional linearly to the temporal change in the size of the reflective cross section. We examined the algorithm which measures the arrival time at the tip of the reflected echo under this assumption.

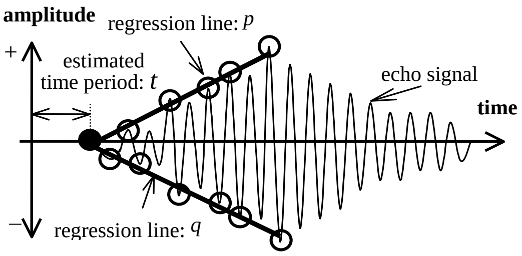

Fig. 2. A model of time period estimation algorithm

Fig. 2 shows a model of time period estimation algorithm. In Fig. 2, the horizontal axis is time and the vertical axis is amplitude. The regression lines *p* and *q* are computed based on the measured data sets using the least-square method. The time coordinates of the intersection of regression lines *p* and *q* shows the estimated time period *t*. The distance is calculated from the estimated time period *t* based on the acoustic velocity *V* using Eq. (1).

In addition, in order to detect distance more accurately, we refer to the coherence of the ultrasonic wave. We use a segment of continuous wave's interval as the transmitter pulse. We compare the received signal with the continuous wave that is used for generating the transmitter pulse.

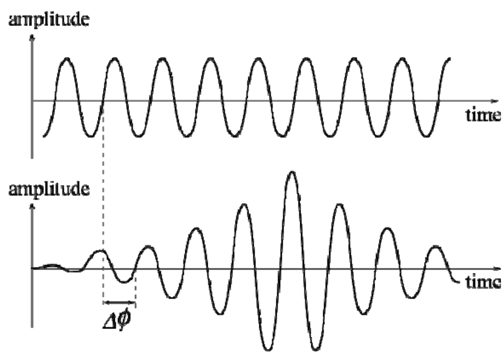

Fig. 3. A model of phase lag detection

Fig. 3 shows a model of phase lag detection. The upward wave pattern in the figure is the continuous source signal. The downward wave pattern is a model of the received signal. When we measured phase difference $\Delta\phi$ from the continuous source signal and the received signal, we considered the method of estimating the distance within less than one wavelength.

3. OBSTACLE ARRANGEMENT DETECTION USING STEREO SONAR

Because stereo sonar receives an echo using multiple microphones simultaneously, the reception time of each microphone of the same echo is different if the object is not in front of the microphones. Since the distance can be calculated using measurement of TOF of an ultrasonic pulse and the direction can be calculated using time difference of arrival (TDOA) of the echo, it is possible to indicate the position using the polar coordinates. Fig. 4 shows a model of stereo reception based on TDOA. In Fig. 4, *S* is an ultrasonic speaker at the center, and M_L, M_R are ultrasonic microphones on both sides. *L* is the shortest diffusion path between the emitter *S* and the reflective target *T*. L_L and L_R are the shortest return paths between the reflective target *T* and microphones *M*x. The position of an object is calculated from L_L and L_R using Eq. (2).

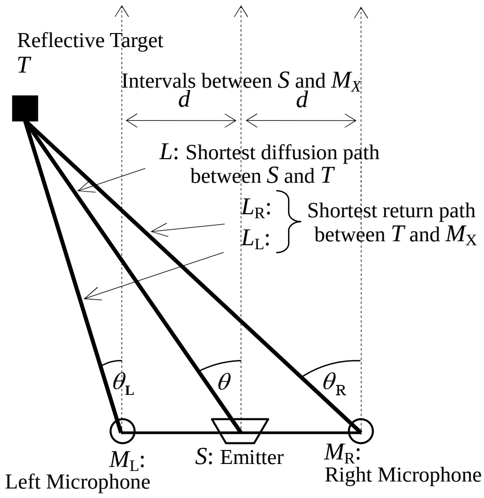

Fig. 4. A model of stereo reception based on TDOA

Value L_L and L_R, θ_L and θ_R alternate their position in this equation when an object is placed on the opposite side.

$$\begin{aligned}
\theta_R &= \arcsin\left(\frac{L_R^{\ 2} - L_L^{\ 2} + 4d^2}{4dL_R}\right) \\
\theta_L &= \arccos\left(\frac{L_R \cos\theta_R}{L_L}\right) \\
\theta &= \arctan\left(\frac{L_L \sin\theta_L + d}{L_L \cos\theta_L}\right) = \arctan\left(\frac{L_R \sin\theta_R - d}{L_R \cos\theta_R}\right) \\
L &= \frac{L_L \cos\theta_L}{\cos\theta} = \frac{L_R \cos\theta_R}{\cos\theta}
\end{aligned} \tag{2}$$

4. A DESIGN OF ULTRASONIC SIGNAL PROCESSING SYSTEM

In order to detect obstacle locations from the ultrasonic echo, we considered the performance of the signal processing system. Table 1 shows the performance of well known embedded high-performance microcontrollers equipped with large size flash memory and static random access memory, high speed multi channel A/D converters and other interfaces.

Table. 1. Performance of embedded controllers

		H8/3069	ADuC7026
CPU	Frequency	25MHz	48MHz
Memory	Capacity	16MByte	512kByte
A/D converter	Channels	8ch	12ch
	Precision	10bit	12bit
	Speed	350ksps	1Msps

Ultrasonic sonar that emits a center frequency of 40 kHz is often used for mobile robot systems. The signal processing system needs a sampling capability that is more than twice the frequency of the signal because of the Nyquist-Shannon sampling theorem. If the integrated multi-channel A/D converters can capture more than 800k samples a second, it can capture 100k samples for 8 channels and process the ultrasonic echo. As seen table 1, ADuC7026 (Analog devices) is appropriate for our needs.

An external bus controller and a memory management unit are built on an FPGA. Fig. 5 shows the system block diagram.

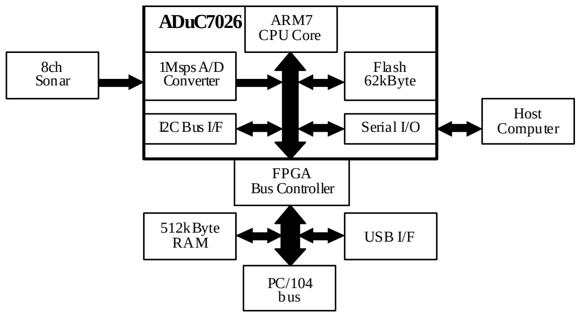

Fig. 5. Block diagram of signal processing system

5. PERFORMANCE CONFIRMATION OF MEASUREMENT ALGORITHMS

As previously mentioned, a true distance estimation algorithm using ultrasonic monaural sonar and an obstacle position detection algorithm using ultrasonic stereo sonar were proposed. A multi-channel signal processing system was also designed. We confirmed the measurement accuracy using the algorithms and the performance of the signal processing system in experiments.

5.1 Examination of A/D converter sampling frequency

In order to obtain ultrasonic wave information efficiently, A/D converter sampling frequencies were examined. We selected the 40kHz ultrasonic pulse. We tested five frequencies: 80ksps, 100ksps, 120ksps, 150ksps and 200ksps. We confirmed the measurement precision in stereo reception of the obstacle at the position of 50cm, 100cm, 150cm and 200cm at each frequency.

Table 2 shows the measurement error for sampling frequency. For sampling frequency more than 100ksps, any sampling frequency was almost the same error rate. Therefore, we adopted a frequency of 100ksps; as it required the least processing.

Table.2.Measurement error of sampling frequency

Target distance	Error distance				
	80ksps	100ksps	120ksps	150ksps	200ksps
500	-24.664	-16.330	-10.240	-17.212	-15.048
1000	-33.300	-21.671	-14.643	-27.085	-20.770
1500	-28.835	-23.967	-15.129	-26.950	-23.127
2000	-36.348	-19.503	-14.947	-29.342	-19.119
Average	-31.729	-20.007	-140042	-25.472	-19.821

Unit: Target distance (mm), Error distance (mm)

5.2 Obstacle position detection using stereo sonar

We examined the performance of ultrasonic stereo reception. In this experiment, ultrasonic transducers (Murata MA40B8R/S, Carrier frequency: 40kHz, Beam width: 50 degrees) were used. The received signals were amplified by a 40kHz tuned FET amplifiers.

Table 3 shows the experimental results derived from ultrasonic stereo sonar. In this table, the positional information is indicated by the distance and the direction, which can be measured using ultrasonic stereo sonar.

Table.3.Measurement results of ultrasonic stereo sonar

	Target 1		Target 2		Target 3	
	Distance	Angle	Distance	Angle	Distance	Angle
Theoretical	715.9	24.8L	1118.0	26.6R	1500.0	0.0
Trigger	701.2	21.6L	1094.4	26.4R	1502.5	2.4L
Error (Trig)	-14.7	-3.2	-23.7	-0.2	2.5	2.4
Burst	701.0	20.5L	1128.3	28.2R	1512.1	0.3L
Error (Burst)	-14.9	-4.2	10.3	1.7	12.2	0.3

Unit: Distance (mm), Angle (degree)

In table 3, the ultrasonic stereo sonar was able to measure distance at an error rate of approximately 2% or less and to measure angles at an error rate of approximately 4.2 or less in the experiments. In the results, the measurement accuracy of the obstacle positions measurement of the obstacle improved as the obstacle was positioned nearer to the center of the range of the stereo sonar.

In order to check the coherence of the received signal, we used a bigger sampling frequency than 100ksps. Our results showed that the coherence of the received signal was uniform.

6. CONCLUSION

We proposed a true distance estimation algorithm using ultrasonic monaural sonar and confirmed the accuracy of the algorithm. In the experiments, approximately error rate of 1% or smaller were achieved using the proposed algorithm.

We also considered an obstacle position estimation algorithm using ultrasonic stereo sonar and confirmed the accuracy of the algorithm. The ultrasonic stereo sonar was able to measure distance at approximately error rate of 2% or smaller and to measure angle at approximately error rate of 4.2 degrees or smaller in the experiments.

We proposed and designed a sonar signal processing system using ADuC7026 micro-controller. We adopted a frequency of 100ksps after testing other sampling frequency and their distance detection precision.

In future work, we will design printed circuit boards (PCBs) of the signal processing system. In order to install it onto small-scale mobile robots for experiments, it will be miniaturized to the PC/104 (90.17×95.89mm) size. When distance detection improves, the angle detection precision improves. Therefore we will try the improvement of distance measurement system that refers to coherence.

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