Design of an ultrasound-based sensory system for environment inspection robots

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***Abstract*—Many robotic systems rely on infrared sensors, lasers, cameras and/or ultrasonic transducers for perceiving their environment. Most of these sensors can easily determine the distances to the surrounding objects, and even their shape. However, they are often unable to discriminate among different nearby-placed objects, obstacles, materials or surfaces. This paper presents the design and development of a low-cost ultrasonic-based sensory system, which is able to exploit the information contained in the magnitudes of the reflected sound waves. Therefore, the common ultrasonic distance measurement is complemented with the value of the acoustic reflection coefficient of the observed object. The estimated reflection coefficient facilitates the classification of different materials. Experiments are conducted to demonstrate solid performance of the proposed sensory system.**

***Keywords*—Ultrasound; Sensor; Distance; Material; Reflection; Robotics**

I. Introduction

Nowadays, significant effort is put into the development of the robotic systems that are able to autonomously navigate in unknown environments, perceive their surroundings, and determine their location [1]. Autonomous navigation and planning is equally important in the field of mobile robotics (unmanned underwater, ground and aerial vehicles) as in industrial environments [2]. In all autonomous robotics applications, the correct and precise sensing of the environment is of paramount importance. However, accurate measurements often come with great expense, especially when the number of needed sensors increases (e.g. in swarm robotics [3]).

Most of the systems used for non-invasive environment sensing in robotics are based on one of the following types of sensors: optical/photo-sensors (usually infrared), lasers, cameras and ultrasonic transducers. Optical sensors (see e.g. [4]) are very reliable, simple to use, economic, but consequently very sensitive to environmental conditions (rain, fog, dust, etc.). Laser based systems are extremely accurate, but they are often very expensive [5], bulky and power demanding, which is not suitable for larger scale distributed mobile robotics systems. Perceiving the environment using the camera and image processing is very popular [6]. However, in cases of low visibility or a monochromatic environment, the usefulness of a camera is significantly reduced. Ultrasonic transducers are widely used in mobile robotics for distance measurements [7]. Moreover, they are characterized by solid performance and satisfactory accuracy. Ultrasonic transducers can also be used for flow measurements [8], material inspection [9], medical imaging [10], etc., ranging from very inexpensive to extremely expensive off-the-shelf solutions.

A robotic system often needs to discriminate among different types of materials and objects. Low-cost variants of the previously introduced sensors are generally unable to perform these classification tasks. To this end, we design a sensory system which exploits the magnitude of the reflected ultrasonic wave received by the inexpensive transducer to obtain additional information about the environment. The proposed ultrasound-based sensory system is able to discriminate among different observed materials. Experimental results indicate that the system can be used in practical applications.

The paper is organized as follows. Section 2 explains the theoretical foundations upon which the system is designed. The implementation details are given in Section 3. Main experimental results are presented in Section 4, while the conclusion and guidelines for future work are given in the last section.

II. Principles of operation

The main structure of the proposed measurement system is depicted in Fig. 1. The sensory system is based on two piezoelectric ultrasonic transceivers located in close vicinity. They are used to transmit and receive ultrasonic sound waves. The time t elapsed while the sound wave has traveled from the transmitter, reflected from the obstacle, and was picked up by the receiver is used to compute the distance d to the obstacle:

$$d = \frac{1}{2} c t, \qquad (1)$$

where c is the speed of sound in air. The speed c depends on many factors, such as temperature, humidity, density, pressure etc. The relation $c = 331.4 + 0.6T [m/s]$ was used to compute sound speed [11], where T is the ambient temperature.

The magnitude of the reflected sound wave will be different for various obstacles on the same distance. Two parameters

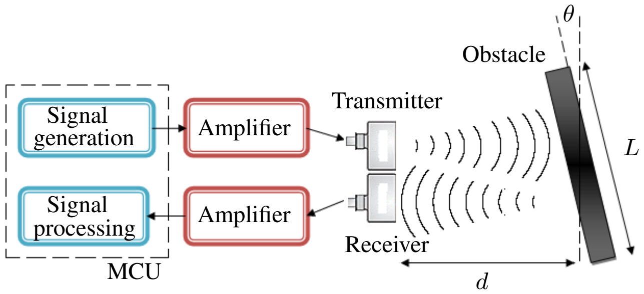


Figure 1. Block diagram of the proposed system.

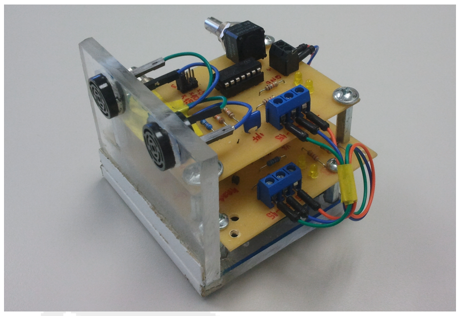


Figure 2. The prototype of the designed sensory system.

mainly affect the magnitude of the reflected wave: the attenuation due to the air absorption, and the attenuation due to the absorption on the obstacle itself.

The magnitude of sound waves in air conforms to Stokes' Law, which states that the amplitude of a plane wave decreases exponentially with distance traveled, at a rate which depends on the dynamic viscosity coefficient of the fluid, the sound frequency, fluid density and the speed of the sound. According to the work presented in [12], this attenuation can be approximated by a constant absorption coefficient (in $[dB/m]$ at a chosen operating point).

When a sound wave hits another medium (obstacle), one part of that wave reflects from the surface, while other passes through. The reflection coefficient R is defined as the ratio of the amplitude of the reflected wave to that of the incident wave. It depends on the densities of the materials, the sound speeds in the air and the obstacle, and the incidence angle.

According to the above, a simplified model that describes the relation between the magnitudes of the transmitted and the received sound waves is given by:

$$A_r = A_0 \cdot R \cdot 10^{-B \cdot 2 \cdot d/10} \Rightarrow R = \frac{A_r}{A_0} 10^{B \cdot 2 \cdot d/10} \quad (2)$$

where A_r and A_0 are the magnitudes of the received and transmitted waves respectively, R is the reflection coefficient of the material ($R \in [0, 1]$), B is the attenuation of the ultrasonic waves in air, and d is the distance between the sensor and the obstacle. According to [12], the value of B should be between $2[dB/m]$ and $5[dB/m]$ depending on temperature, pressure and humidity. A value of $B = 2.4[dB/m]$ was experimentally determined.

III. The Proposed System

A. Hardware design

An assembled prototype of the sensory system is shown in Fig. 2, while the circuit diagram is given in Fig. 3. As it may be seen in Fig. 3, the system is composed from an ultrasonic transmitter/receiver pair, amplifiers, demodulator, and a microcontroller unit for signal generation and processing.

Ultrasonic transmitter and receiver: They are the essential components for producing and acquiring ultrasound. We used A-16PT10 and A-16PR10 as ultrasonic receiver and transmitter respectively. They are characterized by a central frequency of $40[kHz]$, very narrow frequency and directional characteristics, high sensitivity and low cost.

Amplifiers: The system is equipped with one single stage amplifier in the transmitting circuit, and one three-stages amplifier in receiving circuit, both based on TL084 operational amplifier. The latter is chosen for its satisfactory $3[MHz]$ gain-frequency product.

Signal generation and processing: The main processing power comes from the 8-bit Atmel ATmega328 MCU. This microcontroller is chosen for several reasons: it provides solid performance for a reasonable price (16 MIPS, 6x10bit analog channels with 13-260$[\mu s]$ conversion time, 6 PWM channels, etc.) and it has excellent support (ATmega328 is the base for the famous Arduino Uno module). The MCU is used for producing signals for the transmitter, and for processing signals from the receiver. The RS485 bi-directional bus is used for sending results of the processing (distance, reflection coefficient) to a master computer or microcontroller, and receiving calibration and control commands for the sensor module. The processing unit is also equipped with a temperature sensor, which is primarily used for computing the accurate value of the speed of sound.

Signal demodulation: The central frequency of the transmitted and received signal is $40[kHz]$, with the $2[kHz]$ bandwidth, while the sampling frequency of the AD converter of the MCU is set to $6[kHz]$. Therefore, the received signal must be demodulated prior to sampling, otherwise the Nyquist-Shannon sampling theorem would be violated. The simplest possible implementation of the amplitude demodulator is given in Fig. 3 (a rectifier and a low-pass filter).

B. Signal generation and processing

In order to be able to measure the distance and the magnitude of the reflected waves, specific signals are produced and processed by the MCU. These signals are depicted in Fig. 4. A $0.5[ms]$ short bursts of $40[kHz]$ frequency square waves (U_E) are generated by the MCU. The emitted signal on the transmitter is actually a $40[kHz]$ sine wave burst, because the ultrasound transmitter acts like a band-pass filter and eliminates all higher harmonics. Burst are repeated every $20[ms]$, allowing a $50[Hz]$ refresh rate. These time steps are chosen according to the requirements of the system - to be able to measure distance (d) and discriminate objects over 30

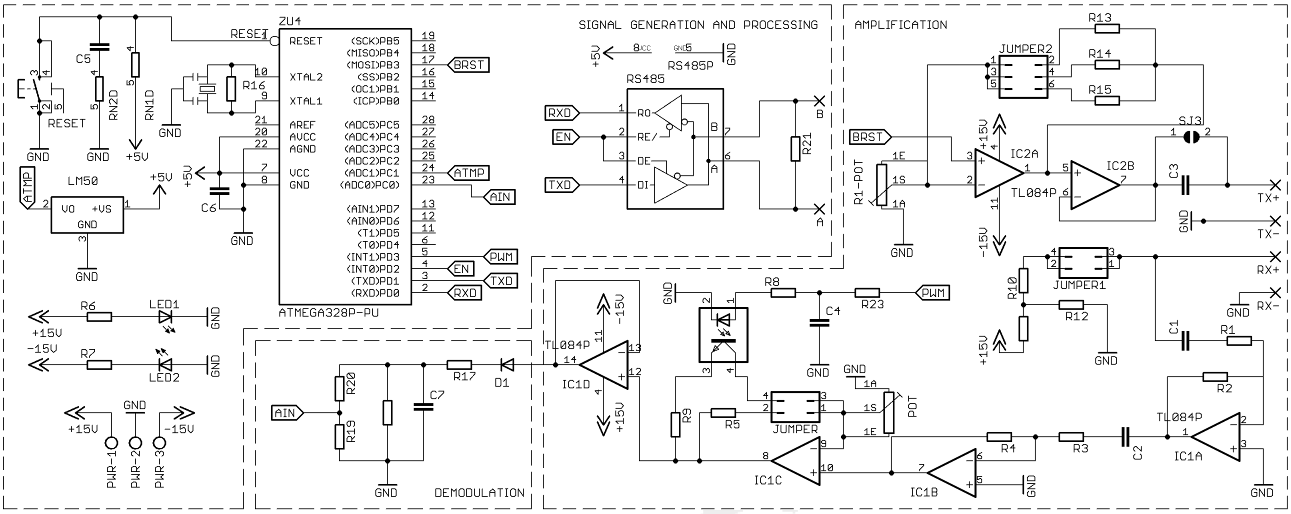


Figure 3. Circuit diagram of the proposed sensory system.

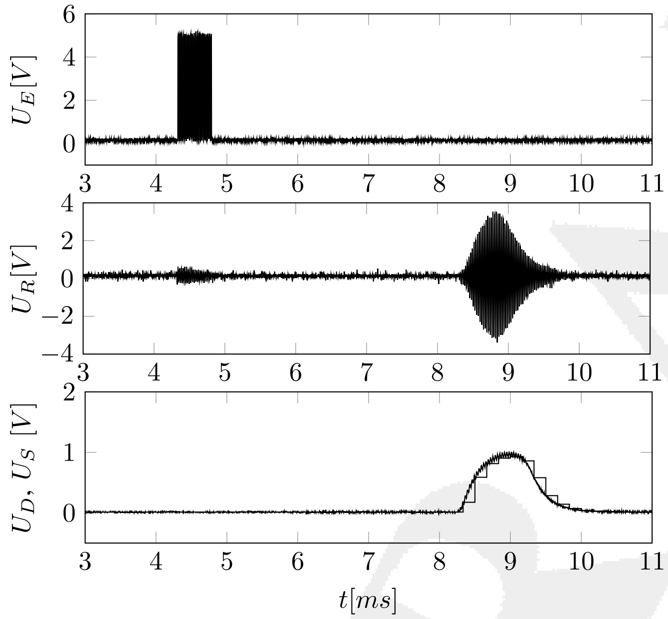


Figure 4. Signal generated by the MCU (U_E), amplified signal received by the ultrasonic receiver (U_R), demodulated signal (U_D) and sampled demodulated signal (U_S) processed by the MCU.

to $300[cm]$ (for which the sound wave travel time is approx. $1.7[ms]$ - $17[ms]$). Therefore, the interaction of the transmitted and received sound wave is prevented, so in a later design one transceiver may be used instead of a transmitter-receiver pair.

The computation of the obstacle distance is conducted using (1). The travel time is measured using the MCU analog comparator and timer.

The computation of the reflected wave's magnitude is more difficult. The received signal is a $40[kHz]$ modulated sine wave whose envelope determines the reflection coefficient of the obstacle. Since the effective sampling rate of the analog signal is $6[kHz]$, the signal U_R needs to be demodulated first. The demodulated signal U_D is then sampled using the MCU analog-to-digital converter, thus the discrete signal U_S is obtained.

In order to estimate the shape/magnitude of the demodulated signal U_D from the sampled signal U_S, a truncated Whittaker-Shannon-Kotelnikov series is used [13]:

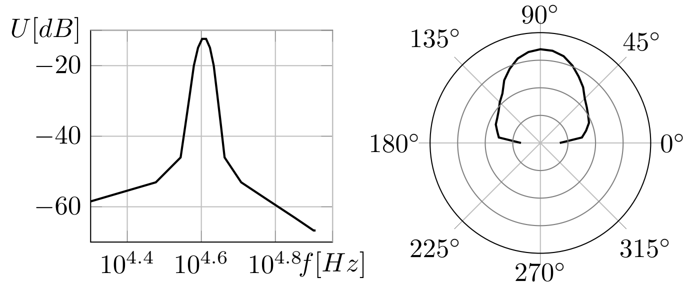
$$\widetilde{U}_D(t) = \sum_{k=-N}^{N} U_S\,(kT)\,sinc(2\omega_C(t-kT)), \qquad (3)$$

where $sinc(t) = sint/t$ for $t \neq 0$ and $sinc(0) = 1$, $2N+1$ is the number of samples, T is the sample period, and ω_C is the bandlimit of the demodulated signal. Series given with (3) converges absolutely and uniformly on **R** if $N \to \infty$ [13]. Since the analyzed signal is bandlimited and time-limited, and the signal U_D satisfies a decay condition [13], the approximation $\widetilde{U}_D$ is highly similar to the original signal U_D. Experiments show that when using $N = 50$ the maximal magnitude of the signal U_D or U_R is estimated from $\widetilde{U}_D$ with the maximal error of 5.6% over full scale range.

IV. Experimental results

The performance of the designed system is investigated using different experimental scenarios. First, the frequency response of the sensory system and its directional characteristic are experimentally determined, and illustrated in Fig. 5a) and 5b). It is clear that the sensor is very directional and acts like a bandpass filter with a $40[kHz]$ central frequency.

Five obstacles made from different materials are used in the experiments. The measured attenuation of the sound waves as a function of obstacle distances are presented in Fig. 6. The reflection coefficient R for different materials may be determined from (2), the estimated reflected wave magnitude A_r and distance d. In order to experimentally determine the reflection coefficients R for different materials, 114 measurements were taken for all materials on various distances. Eighty percent of all measurements were fitted by a probability distribution centered around the expected



a) b)

Figure 5. a) Frequency response, b) directional characteristic of the system.

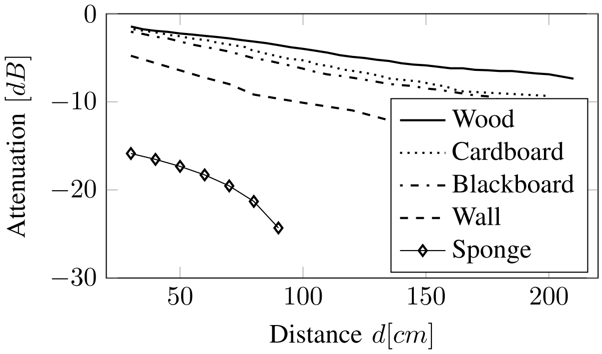


Figure 6. Attenuation of the sound over different obstacles at distance d.

values of the reflection coefficients R, presented in Fig. 7. The determined mean values of the reflection coefficients for different materials are used as inputs to a 1-nearest neighbor classifier to classify the rest of the measurements. The correct classification was achieved in 89.47% of the cases, while the resulting 10.53% classifications assigned the materials into adjunct classes.

As for the magnitude, distance and reflection coefficient measurements, the repeatability of the sensor is rather high, e.g. in one minute of continuous measurement (50 samples per second), fixed distance and surface, the standard deviation of the magnitude measurements is $0.055[V]$. Moreover, the measured voltages/magnitudes are not significantly affected by the dimension of the obstacle L. The reduction of measured voltage is noticeable when the obstacle dimension L falls below $0.1d$.

The main drawback of the proposed sensory system is its sensitivity of the inclination angle θ. Because of the high directivity of the ultrasound, the sensor system works properly if the surface is nearly perpendicular to the sound wave (inclination angle θ smaller than 10 degrees). Outside the defined range, the magnitudes are decreasing almost linearly as inclination angle increases.

V. Conclusion and guidelines for future work

In the paper a design of a inexpensive ultrasound sensory system for obstacle classification is presented. Experimental results showed promising possibilities of the sensor usage in the field of mobile robotics, in tasks of classification, localization and distance measurements. As a part of future work, the system will be redesigned so that only one transceiver is

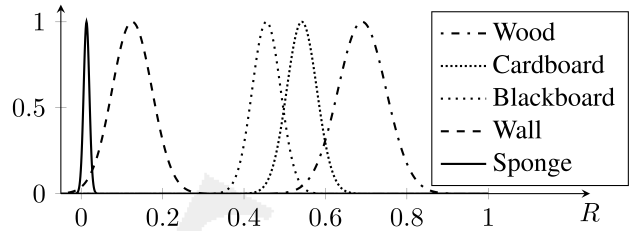


Figure 7. The dispersion of the reflection coefficient R for different materials.

used instead of a sensor pair. This would allow the design of spatially distributed sensor array, that would be able to give an estimation of the inclination angles of the obstacle and compensate the magnitude measurements. Moreover, the developed sensor will be used to produce hybrid 2D structural images, using the fusion of multiple ultrasonic sensor readings and a video camera.

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