Journal of Physics: Conference Series

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To cite this article: V A Zhmud *et al* 2018 *J. Phys.: Conf. Ser.* **1015** 032189

IOP Conf. Series: Journal of Physics: Conf. Series **1015** (2018) 032189 doi:10.1088/1742-6596/1015/3/032189

Application of ultrasonic sensor for measuring distances in robotics

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Abstract. Ultrasonic sensors allow us to equip robots with a means of perceiving surrounding objects, an alternative to technical vision. Humanoid robots, like robots of other types, are, first, equipped with sensory systems similar to the senses of a human. However, this approach is not enough. All possible types and kinds of sensors should be used, including those that are similar to those of other animals and creations (in particular, echolocation in dolphins and bats), as well as sensors that have no analogues in the wild. This paper discusses the main issues that arise when working with the HC-SR04 ultrasound rangefinder based on the STM32VLDISCOVERY evaluation board. The characteristics of similar modules for comparison are given. A subroutine for working with the sensor is given.

1. Introduction

Robotic devices are very relevant and various. The development of such devices is important also for training of the future engineers and scientist. It is very important for students to be able to develope robots independently, beginning from simple robots, using cheap sensors and driving devices [1–8]. This demands the use of modern methods resulting from the developments in the field of automatics and in various relative fields of knowledge, such as identification, techniques for measuring, and others.

Most robots require accurate information about the location of surrounding objects. Optical sensors (including laser sensors and sensors based on the stereoscopic effect with the help of two or more photo or video cameras with additional illumination or without it) are most effective for this purpose, as well as sound locators and electromagnetic locators. Electromagnetic location is most effective at large distances to objects and if the objects are electrically conductive. For the perception of closely located objects, ultrasound location and optical sensors are most suitable. This article is devoted to ultrasonic sensors.

2. Principle of Operation and Selection of Sensors

The principle of the ultrasonic rangefinders is to measure the time during which that signal propagates at the distance from the transmitter to the receiver. The propagation speed of the signal is known. The ultrasonic range finder HC-SR04 is considered in this paper.

The sensor consists of a transmitter that generates ultrasonic waves, a receiver that perceives the echo, and auxiliary nodes for normal operation of the module.

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The ultrasonic rangefinder HC-SR04 is shown in Figure 1, where the transmitter and the receiver are designated as T and R, respectively. The rangefinder generates sound waves at a frequency of 40 *kHz*. The sound waves reflects from the object and returns to the receiver, the sensor gives the information about the time, which was demanded to sound waves for propagation from the sensor to the object and back. This process can be clearly seen in Figure 2.

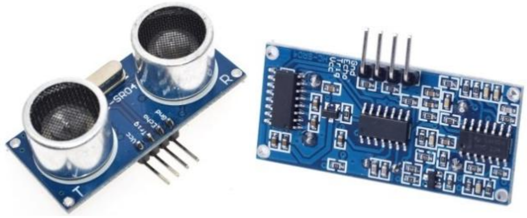

Figure 1. Ultrasound rangefinder HC-SR04

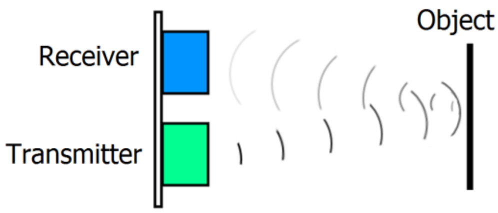

Figure 2. Movement of the ultrasonic signal from the transmitter to the receiver

The ultrasonic signal is propagated by a wave directed at an angle of 30°. The direction of propagation of the ultrasonic signal from the transmitter is shown in Figure 3. The most effective measuring angle is 15°. External objects falling under this measurement angle interfere with the determination of the distance to the desired object.

The readings of the ultrasound range finders are not affected by sunlight or the color of objects, as is the case with infrared sensors. The ultrasonic wave is reflected from almost any surface, even transparent, but it can be difficult to determine the distance to fluffy or small objects. In addition, the readings are affected by the angle of incidence of the wave. If the sensor is directed perpendicular to the object, the measurements will be most accurate. In addition, if, the angle of incidence is too large, then the wave, reflected from the object, does not enter the receiver, which will lead to an incorrect measurement.

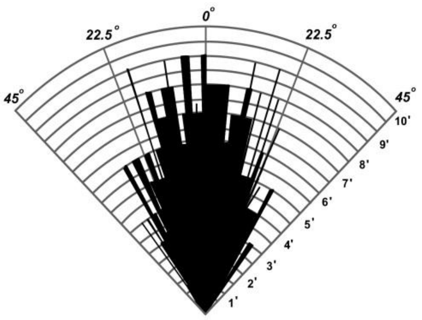

Figure 3. The ultrasonic wave pattern

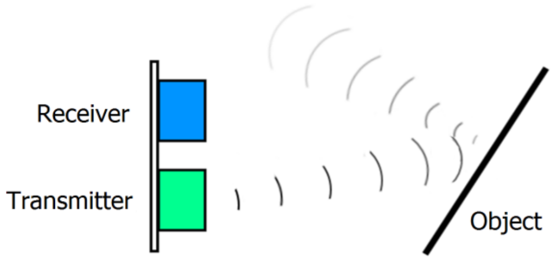

Figure 4. Movement of the ultrasonic wave from the transmitter to the receiver at an angle

Next, let us calculate the distance from the sensor to the object. The sensor itself does not count anything on its own, but only gives an impulse of certain duration. All calculations must be made by the microcontroller.

3. Practical Relations and the Accuracy of Measurement Obtained

Calculation of the distance is based on the obtained time. It is calculated using the following relationship:

$$S = vt;\ t = T/2 \Rightarrow S = vT/2\ . \quad (1)$$

Here, υ is speed of sound (≈ 340 *m/s*); t is time of motion of the wave from the sensor to the object; T is time of motion of the wave from the sensor to the object and back.

Division by two is necessary because the signal passes the distance to the object and back, then when only the distance to the object is required. This paper uses a timer to measure the duration of a signal. The timer is adjusted so that 1 digit is 0.000001 s. Therefore, the equation will look like this:

$$S = vT / 2 \Rightarrow S = vT_{im} \cdot 10^{-6} / 2. \quad (2)$$

Here, T_{im} is the number of timer counts in microseconds.

The final equation will look like this:

$$S = 340 \cdot T_{im} 10^{-6} / 2 = 170 T_{im} / 10^{6}. \quad (3)$$

In order to represent this distance in centimeters, it is necessary to multiply it by 100:

$$S_{cm} = 17 T_{im} / 10^{3}. \quad (4)$$

As a result, using one simple equation, the distance to the object in centimeters can be calculated.

$$S_{cm} = 0.017 \cdot T_{im}. \quad (5)$$

However, the microcontroller does not provide operations on floating-point numbers. Therefore, to calculate the distance, it is necessary to use equation (4). Alternatively, the division can be replaced by the multiplication by the reciprocal value:

$$S_{cm} = T_{im} / 58.8 , \quad (6)$$

The User Guide [11] has similar equation; however, the value of denominator in it is 58.

The above formulas are sufficient for a correct measurement of the distance, but if there is a need to improve the accuracy of the measurement, it is necessary to take into account a number of factors.

First, it is desirable to take into account the ambient temperature in which the measurements are made. This is because the speed of sound in gases increases with increasing temperature. With an increase in air temperature by 1°C, the speed of sound in it increases by 0.6 *m/s*. The graph of the dependence of the speed of sound on temperature is shown in Figure 5, and Table 1 shows some values. To be able to quickly adapt to changing ambient temperature, it is necessary to add a temperature sensor to the measurement system and to use the results of its measurements. Some rangefinders have inbuilt temperature sensors.

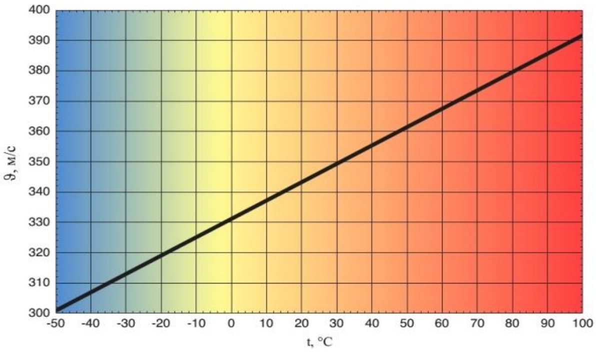

Figure 5. Dependence of sound velocity on temperature

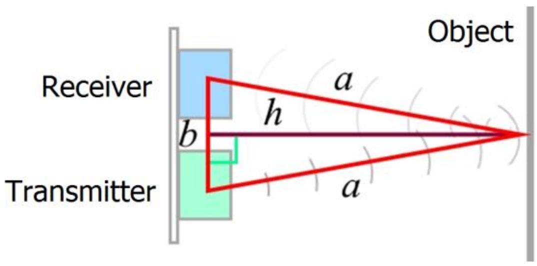

Figure 6. Geometric representation of sound wave propagation

Table 1. Speed of sound at a certain temperature

t, °C	-20	-10	0	10	20	30
υ, m/s	318.8	325.1	331.5	337.3	343.1	348.9

Secondly, it is necessary to take into account the propagation path of the signal. From the geometric point of view, finding the distance from the sensor to the object of measurement is the finding of the height of an isosceles triangle *h* (Figure 6). Here the length *a* should be calculated with the help of equation (5) or (6). To find the height *h* let us turn to the Pythagorean theorem:

$$h^2 = a^2 - (b/2)^2 \tag{7}$$

Here, *h* is the distance from the sensor to the object (the height of an isosceles triangle); *a* is the distance traveled by the sound wave from the transmitter to the object or from the object to the receiver (the triangle side); *b* is distance from the transmitter to the receiver (base), for HC-SR04 *b* = 3 *cm*.

Because base *b* is rather small, it will have a significant influence at small values of *a*, in other words, when measuring small distances. For an example, let us take for *h* the minimum and maximum possible distance of the sensor measurement, this is 2 *cm* and 400 *cm*.

For *h* = 2 *cm*:

$$a = \sqrt{2^2 + 3^2/4} = \sqrt{4 + 2.25} = 2.5$$

For *h* = 400 *cm*:

$$a = \sqrt{400^2 + 3^2/4} = \sqrt{160000 + 2.25} = 400.0028$$

Based on the calculations, there are the following: when measuring the real 2 *cm* to the object, the sensor will show 2.92 *cm* (46% error), and when measuring 400 *cm*, the error is only 0.0015%. To compensate for this error, the distance found by formula (6) must be transformed into a real one:

$$S_{hcm} = \sqrt{S_{cm}{}^2 - 2.25}\,,$$

Hence, the measuring error is 0.3 *mm*.

4. Connecting of Ultrasonic Distance to the microcontroller STM32

To get started, one should familiarize oneself with the characteristics of this module:

- Supply voltage +5 *V*;
- Consumption in silent mode 2 *mA*;
- Consumption at work of 15 *mA*;
- Measurement range from 2 to 400 *cm*;
- Effective measuring angle 15°;
- The dimensions are 45×20×15 *mm*.

The board has 4 outputs:

- *V*cc - power supply +5 *V*;
- Gnd - "earth";
- Trig - to start the sensor;
- *Echo* - to obtain the measurement results.

When the connection is done, one should take into account that the microcontroller these findings must maintain the ability to work with 5*V* levels [11]. In the documentation, this output is marked as *FT*.

The sensor operates as follows:

Initially, the "*Echo*" and "*Trig*" outputs are set to "0". In order to start the measurement process, it is necessary to send a "*Trig*" output, a pulse with duration of 10 *μs*. Repeat measurement can be done no earlier than 50 *ms*. After that, the transmitter receives 8 short pulses to generate an ultrasonic wave. After the generation of a series of sound waves, the output "*Echo*" is set to "1". After reflecting a series of waves from the object and returning to the receiver, the output of "*Echo*" is set to "0". The result is a pulse, the duration of which is equal to the time spent on passing the sound from the sensor to the object and back. The duration of this pulse lies in the range from 118 *μs* to 24 *ms*. Knowing this time one can determine the distance. In Figure 7, a timing chart of the range finder signals is shown.

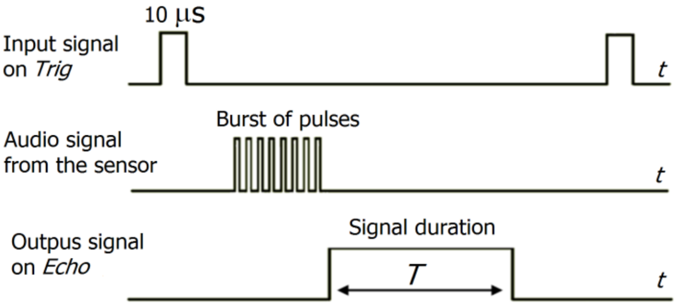

Figure 7. Timing chart of the range finder signals

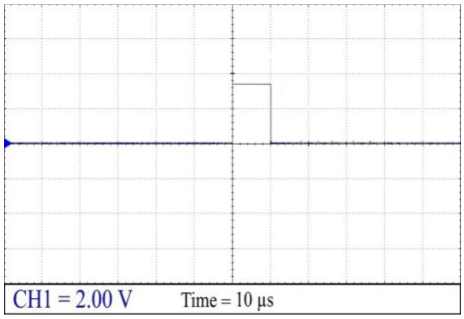

Figure 8. The signal supplied by the microcontroller to the input "*Trig*"

The user can calculate the pulse width from the output "*Echo*" using STM32 in various ways. In this paper, let us propose a method of measuring with the help of a timer, without interrupts. To do this, one must configure one of the timer channels in capture mode. In this mode, the timer records the duration of the input pulse in cycles in the counting register.

To generate the triggering signal to "*Trig*", the developer must configure any other contact to be output. The adjusted output forms a pulse with duration of 10 *μs*.

In this example, the authors used the STM32VLDISCOVERY evaluation board based on the STM32F100RBT6B microcontroller using the SPL library. To work with the rangefinder, the first TIM4 timer channel was used. The code is given below.

To verify that the sensor is working correctly, consider the oscillograms of real signals from the module. The pulse that triggers the sensor is shown in *Fig*. 8.

To test this, one calculates the theoretical value of time and compare it with the real signal from the sensor. Based on the equation (1), one calculates the pulse duration, when measuring distances of 30 *cm* and 100 *cm*.

$$S = vT/2 \Rightarrow T = 2S/v. \tag{8}$$

At 30 *cm*: $T = 2\cdot 0.3/340 = 1764\cdot 10^{-6}$ = 1764 *μs*. At 100 *cm*: $T = 2\cdot 1/340 = 5882\cdot 10^{-6}$ = 5882 *μs*.

Fig. 9 and 10 show the actual duration of the pulses, when measuring distances of 30 *cm* and 100 *cm* and compare it with the theoretical. Also it shows the trace change in pulse width from the output "*Echo*", depending on the distance measured.

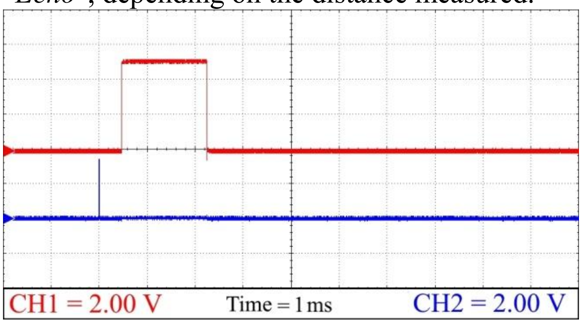

Figure 9. The signal at the output "*Echo*" with a duration proportional to the distance of 30 *cm* (red) and the signal at the input "*Trig*" (blue)

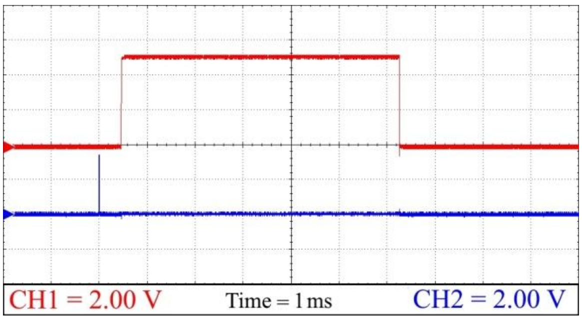

Figure 10. The signal at the output "*Echo*" with a length proportional to the distance of 100 *cm* (red) and the signal at the input "*Trig*" (blue)

Figure 11 clearly shows the operation of the sensor, from the moment the trigger pulse is applied, until the generation of a series of ultrasonic waves and the formation of a time pulse. As can be seen, the real picture of the signals is similar to the signals in *Fig*. 6, from the documentation.

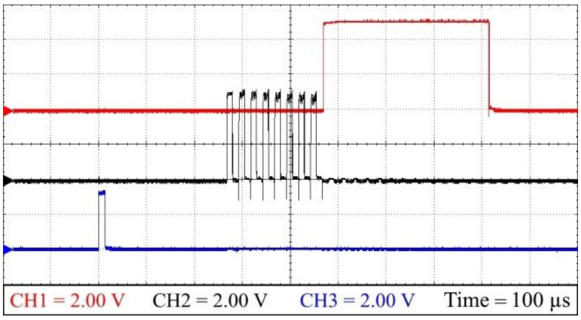

Figure 11. View of three signals taken from the input "*Trig*" (blue), from the module when generating a sound signal (black) and from the output "*Echo*" (red)

5. Similar Devices, Accessories and Additional Periphery

In addition to HC-SR04, there are other ultrasonic sensors. However, their differences are insignificant. Each, equipped with a transmitter and receiver, have an identical measurement principle, the physical dimensions of the devices are almost identical. Various parameters are such as: the maximum possible measurement distance, accuracy. Some sensors support specialized interfaces for pairing them with microcontrollers. Let us consider some of them.

Ultrasonic sensor HY-SRF05 (see Figure 12), a more expensive improved model, compared to HC-SR04. The main difference, according to the manufacturer, is the maximum possible measurement distance of -450 cm. In addition, one more "*OUT*" pin was added to the board; however, the functionality of this "output" could not be established.

The ultrasonic sensor US-015 (see Figure 13), according to the manufacturer, performs measurements with greater accuracy than HC-SR04. In addition, the price of this device is slightly higher, because the sensor was less popular. In connection with the non-distribution of the module, it is difficult to establish the genuine characteristics of the device. For example, the accuracy in different sources is indicated as 0.1 *mm* or 0.3 *mm*. Pin arrangements are exactly the same as for HC-SR04. The similarity of the characteristics of the sensors makes them interchangeable.

Figure 12. Ultrasound range finder HY-SRF05

Figure 13. Ultrasound range finder US-015

The following sensor URM37 provides the connectivity on a variety of interfaces: Serial or PWM, TTL or RS232. Also, different modes of operation are provided: determination of the distance on request or permanent scanning. In addition, a temperature sensor is installed on the board, which is used to correct the readings of the rangemeter, as discussed earlier, the sound speed at different ambient temperatures is different.

In addition to the considered sensors, there are specialized modules that, working in conjunction with an ultrasonic rangefinder, expand the functionality of the system. For example, module RCW 0012 (see Figure 15) independently performs all necessary calculations, thereby losing the need to connect the microcontroller STM32 or any other. In addition, the built-in three-digit seven-segment indicator allows one to immediately display the distance to the object in centimeters. The board is

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based on the microcontroller STC 11 f-04e. There is a 4-pin connector on the board, in which an ultrasonic module is installed.

Another module that can perform these tasks is DYP-ME008. In parallel, the developers released their own ultrasonic sensor DYP-ME007, suggesting their joint work. A bundle of these two devices is shown in Figure 16. A comparison of the characteristics of these ultrasonic sensors and some others is given below, in Table 2.

The *Octasonic* 8 x HC-SR04 *Ultrasonic Breakout Board* (see Figure 17), which is a private development of the *"Super Awesome Robots!"*, allows the use of several ultrasonic sensors simultaneously (meaning in one system). The developer suggests using his device as an unusual synthesizer.

The next important question is the fixing of the module on the robot, because ultrasonic rangefinder is often used as a "sight" of robots. For these purposes, there are specialized cases available. To provide the possibility of turning the ultrasonic module, there are fasteners for connection with the servo drive.

Figure 14. Ultrasound range finder URM37

Figure 15. Module RCW 0012

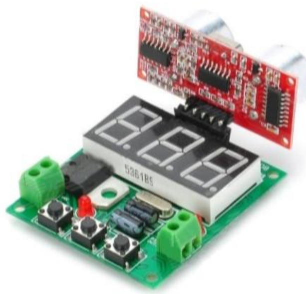

Figure 16. Module DYP-ME008 and ultrasonic rangefinder DYP-ME007

Figure 17. Module *Octasonic* 8 x HC-SR04 *Ultrasonic Breakout Board*

Figure 18. Mounts for ultrasound module

Table 2. Comparative table of characteristics of ultrasonic sensors

	HC-SR04	**HY-SRF05**	**US-015**	**US-100**	**URM37**	**GH-311**	**DYP-ME007**
Supply voltage, V	+5	+5	+5	+5	+5	+5	+5
Consumption in silent mode, *mA*	2	2	2,2	2	-	-	-
Consumption at work, *mA*	15	15	20	15	20	-	15
Measurement range, *cm*	2 - 400	2 - 450	2 - 400	2 - 450	4-500	2 - 300	2 - 500
Effective measuring angle, *gradus*	15	15	15	15	15	15	15
Ultrasound frequency, *kHz*	40	40	40	40	40	40	40
Accuracy, *mm*	0,3	0,3	0,1 +1%	0,1	1	-	0,3
Dimensions, *mm*	45×20×15	44×20×14	45×20×12	44×26×14	51×22×22	46×20×18	45×20×15
Average price for the end of 2017, *rubles*	≈ 50	≈ 70	≈ 80	≈ 155	≈ 1000	≈ 520	≈ 240

Notes: Some characteristics of the sensors from different open sources may vary; references to the sources used are given in the LITERATURE section; "-" means unknown parameters;

6. Conclusions

Ultrasonic rangefinder HC-SR04 is a good and cheap module for measuring distance, in comparison with its analogues.

The measurement process is fairly simple and straightforward, and the interface between the sensor and the microcontroller does not require specialized interfaces.

The accuracy of measurements is influenced by many factors that should be considered. This is the ambient temperature, the propagation path of the signal, the angle of incidence of the wave, the shape and size of the object. However, even taking into account all the errors, it was not possible to achieve the accuracy stated by the developer.

If one needs the most accurate measurements, one should use laser rangefinders. And ultrasound is better suited, for example, as motion sensors at short distances or as a vision of a robot, to find objects around them.

There are modules that are designed specifically for ultrasonic sensors. Using these modules allows one to work with sensors without connecting to the microcontroller, because it can independently perform calculations and display results.

When using any sensors, it is necessary to remember the general rules for their selection and application [9–20].

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