SERBIAN JOURNAL OF ELECTRICAL ENGINEERING
Vol. 6, No. 3, December 2009, 427 - 437

UDK: 681.586:007.52]:531.718

Calibration of Ultrasonic Sensors of a Mobile Robot*

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Abstract: The paper discusses a mobile robot localization. Due to cost and simplicity of signal processing, the ultrasonic sensors are very suitable for this application. However, their nonlinear characteristics requires thorough calibrating procedure in order to achieve reliable readings from the obstacles around the robot. Here we describe SMR400 ultrasonic sensor and its calibration procedure. The suggested calibration procedure was tested through a number of experiments, and the results are presented in this paper.

Keywords: Ultrasonic sensors, Sonar sensors, Mobile robot, Calibration, Signal processing, SMR400.

1 Introduction

Mobile robots can autonomously move or change their position and/or orientation in space, which is the main difference compared to stationary industrial robots. Namely, they can move freely between obstacles and their location is limited by the operating autonomy, controller ability to solve complex navigation problems as well as sensors to feel and understand environment.

Mobile robots should recognize surrounding on their own, to consider the task and to make the appropriate decisions to execute the task. Recognizing the working area in any situation includes knowledge of mobile robot's position, facilities and objects. For these tasks different sensor systems can be used along with appropriate signal processing algorithms. The simplest sensor system includes simple tactile sensors – limit switches mounted on a mechanical bumper that detects a collision with an obstacle like a wall, other robot, human leg, etc. Information processing from these sensors is effortless, but the contact between the robot and the environment is required, and the direction of the impact force is unknown. On the other hand, the most complex sensor system,

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*Award for the best paper presented in Section *Electronics*, at Conference ETRAN 2009, June 15-19, Vrnjačka Banja, Serbia.

stereo vision, requires a high processing power for image processing in real time, while in this case a physical contact with objects in the workspace is not necessary.

Somewhere in the middle of the scale of complexity regarding processing sensor signals and their use, are the ultrasonic sonar. Today they are irreplaceable because of both, its cost and its simplicity of signal processing [4].

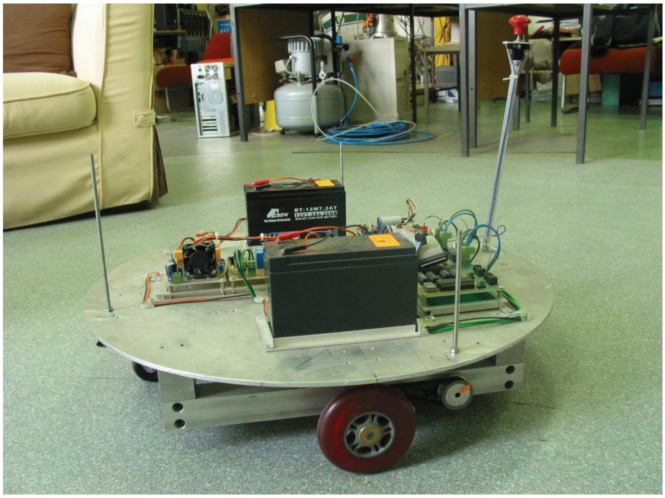

Fig. 1 – *Mobile Robot* SMR-1.

This paper describes the ultrasonic sensor SMR400 along with accompanying measurement procedure and instrumentation. The procedure of calibration is straightforward and requires only a factorial displacement of a standard obstacle. Obtained results from independent measurement are compared against sonar data and standard statistical compilation of the data gives the estimate of how good five sensors of the same type are good to measure the distance to the obstacle in working area. The experiments are carried out on the mobile robot SMR-1, shown in Fig. 1. The results of the proposed calibration procedures are represented, as well as the beam pattern of the sensor regarding the obstacle of a thick stick type.

2 Construction of the Mobile Robot SMR-1

The mobile robot SMR-1 equipped with five ultrasonic sensors in frontal quadrant was done is a laboratory robot designed to study human-robot interaction in both, contact and non-contact ways. Axis rotations of driving wheels are fixed and coaxial, and each wheel has independent drive. The movement of the mobile robot is based on the concept of the differential rotation. That is, depending on the mutual relations between speed drive wheels, the robot might travel forward or backward, it might curve or turn in place. To achieve static stability the two extra wheels, castors, are added to the two-wheel drive. These extra wheels are compliant in the sense that it doesn't restrict the orientation achieved by driving wheels [3]. However, ability to move brings us to another problem: how to make sure the robot will not hit obstacles around it, which is the simplest way of interacting with environment?

The mobile robot control system is designed in such a way that it consists of multi-functional, hierarchically organized units, shown in Fig. 2, that can handle both, control and sensorics of the robot. In the case of distributed hierarchical control, the main controller is at the highest hierarchical and strategic level, which is responsible for the global execution of the tasks. It receives information from the subordinate levels, makes relevant decisions about the execution of the task, and forwards them to tactical-level controllers.

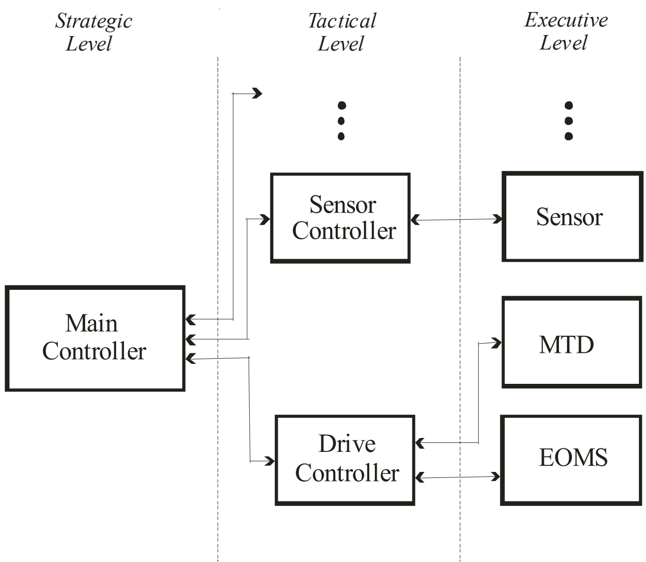

Fig. 2 – *The architecture of the mobile robot's control system, drive and sensor controller.* MTD *is managing transmission devices,* EOMS *is encoder-odometry measuring system* [3].

Usually, there are two types of the control systems at the tactical level: sensor controllers and drive controllers. The drive controller takes care of appropriate functioning of a drive group. It directs and supervises the work of the drive motors, and monitors the current position of the robot [3]. Sensor controllers are designed for independent processing of information from the sensors, as well as for their control and management. The main reasons are that they have to be fast, reliable, and should include lots of data not only for calibration purposes but complex data structures needed to understand what is the obstacle the robot is interacting with, through sensor fusion of various sensoric information.

Because of the specific nature of sensor issues controllers, for practical realization embedded microcontroller systems will be used. This solution will compromise the cost of such systems to the performance in selected tasks. Considering the variety of sensors in terms of type of the data and ways of their processing, we chose low-cost microcontroller with enough processing power and with enough memory, having in mind that almost any commercial microcontroller can handle sonar readings [3].

The following section describes the functioning principles of ultrasonic sensors, showing one way of its application on the mobile robot.

3 The Principle of the Ultrasonic Sensors

Ultrasound is mechanical oscillation that spreads in an elastic environment (solid, liquid or gas), whose frequency is higher than 20 kHz, which is the limit of hearing of human ear. Considering the fact that ultrasound is a mechanical wave, the laws of propagation, refraction and absorption can be applied to ultrasound, also. Based on these laws and on the analogy with living organisms the various devices for measuring distance can be contracted. There are several ways in which the ultrasonic sonar can measure the distance to an object, but they are all based on the same principle. Ultrasound, broadcasted from transmitter, spreads in the surrounding area. When ultrasound wave reaches the object from which we want to measure the distance, one part of the wave is absorbed while the other one is reflected. One part will be reflected back to the transmitter, where it can be detected using one or more receivers. The distance can be determined, for example, by measuring the phase difference between sent and received waves, or by measuring the receiving time difference of the two receivers that are placed on well-known positions in the space. However, the simplest way to measure a distance is by measuring the time-of-flight. The sensor SRM400 described in this paper uses this principle [4].

The device itself consists of the source of ultrasound S, the receiver R and accompanying electronics for signal processing. It is important to note that the SRM400 source and receiver are implemented in a form of a single transceiver, Fig. 3. They are presented separately for easier illustration of functioning of ultrasonic sensors [4].

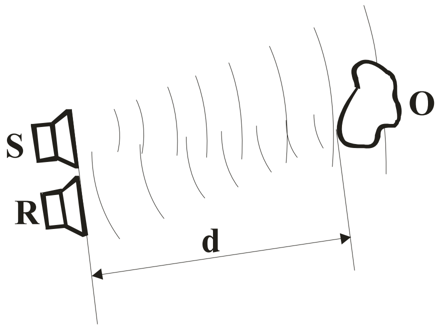

Fig. 3 – *The principle of sonar with the flight-over timing.*

Source S in a short time interval, transmits the ultrasonic wave in the surrounding area. One part of the wave is reflected from the object O and detected at the receiver R. The object is located on the unknown distance d from the sonar. The sonar can measure the time (t) from the moment the wave is broadcast until his detection in the receiver, and this interval is called the flight-over time. Since the ultrasound travels through the environment with the final, well-known speed v, it is possible to determine the unknown distance according to the expression:

$$d = \frac{vt}{2}, \tag{1}$$

where 2 in the denominator stands for the fact that ultrasonic wave crosses over the distance d twice, first as a direct wave and the second time as the reflected one. The speed of ultra-sound waves, , through different media is different and depends on the medium density, temperature, pressure, etc. For the air, speed of ultrasound is in the range of 330 to 345 m/s, depending on temperature, humidity, atmospheric pressure, altitude and so on. During the measurements, it was considered that the speed of ultrasound is constant in an environment where the mobile robot moves, or on location where measurements are performed [4].

4 SRM400

SMR 400 is a sensor for ultrasound measurement of distance used by the specialized IC for measuring distances, PW-0268. The appearance of this sensor is shown in Fig. 4. Operating voltage of this circuit is from 6 to 10 V DC, and the operating frequency may be available in a wide band, up to 250 kHz. It has variable R/C oscillator that compensates for the deviation of the resonant frequency converter due to temperature changes. It also has an adjustable system clock that allows the control of number of sent impulses, slope of amplifier's variable gain and pulse repetition frequency. Size of the chip is 29×18 mm (L×W) [1].

Table 1
Specification.

SRM400	
Operation voltage	6 – 10 V DC
Operation current	< 20 mA for 10 V DC
Pre-Amplifier	14 dB
2^{nd} Stage Amplifier	30 dB
Bandpass filter - Fc	38 kHz
Bandwidth:	20 kHz
Insertion loss:	1 dB
Measuring distance	25 – 150 cm

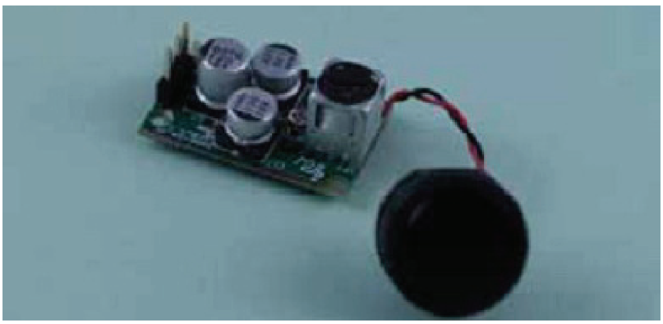

Fig. 4 – *The* SRM400 *sensor.*

Bidirectional I/O pin simplifies the control functions for broadcasting and receiving a pulse echo. After receiving the signal to start the measurement, management electronics generates an electrical signal at a frequency of 40 kHz. This amplifies the signal's voltage up to 130 V range in order to excite the transducer. The transducer generates the ultrasonic wave that is spread in the surrounding space. After wave generation, the transducers membrane electrically brakes, and then switches to receive mode for the reflected wave. This procedure is necessary to prevent the residual oscillation of the transducer's membrane to be interpreted as false receiving of the reflected signal after the sent wave. However, the minimum distance that can be measured, is limited in this way, that is, it must be long enough, so that the flight-over time is longer than the time needed for membrane braking. Since the ultrasonic wave spreads in surrounding space, its strength decreases inversely proportional to the square of the path of the distance traveled. Also, only a small part of the original wave is reflected from the object. Therefore, the receiver of the sonar should have a very large amplifier gain that can be digitally controlled. Control electronic increases gain in time, in order to compensate the wave attenuation with distance. The distance that sonar can measure is in the range from 25 to 150 cm according to the specification, although in practice it is shown that the distance may be greater. The distance without some greater errors, can be even measured up to 250 cm [1, 4].

5 The Procedure and Results of Calibration of Ultrasonic Sensors

The experiment shown in Fig. 5 describes the calibration procedure. As an object whose distance is measured, a metal rod of 50 mm in diameter and about 1 m height is used. This object is also used to test angular sensitivity of the sensor. The object is placed on different distances from the sensor in one same direction, as shown in Fig. 5. The sensor is placed on the robot and fixed in the direction of the longitudinal central axis [5].

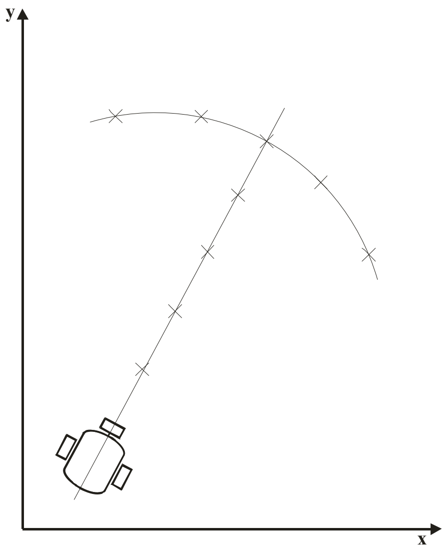

Fig. 5 – *Sketch of calibration situation.*
The × mark stands for a measurement position.
We take ten different distances and five different angular displacements from the main robot axis.

At each distance, which is taken arbitrarily, first the real distance from mobile robot is measured. After that, the distance is measured using the ultrasonic sensor. The measurements are done on the interval from 25 to 150 cm, with an arbitrary step and five readings per position. In MATLAB the processing of these measurements is carried out using the formula:

$$x = Xk_1 - k_2\,, \qquad (2)$$

where [4]:

x - calculated distance,

X - the sensor readings,

k_1, k_2 - calibration coefficients of a constant matrices k, which are used for leveling the sensor readings and absorption of resolution errors which may occur because of different ultrasound speeds and offset. Offset is the result of time needed for processing the signal in sonar and in the microcontroller.

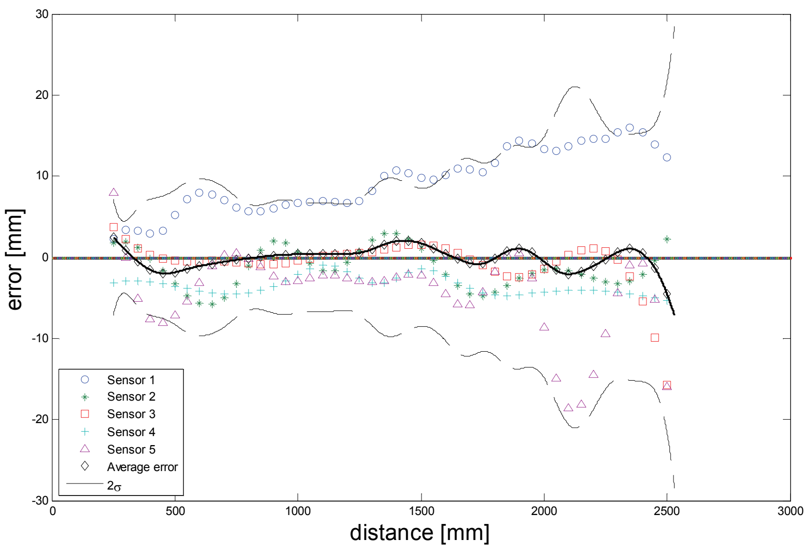

Fig. 6 – *Deviations in calculating the distance from the five sensors and their average estimates. A curved line limits the area which will contain* 95% *of the value of* error().

The measurement is done on the 25 to 250 cm range, with an arbitrary step size, according to Fig. 5, where the operator places the target close to an equidistant positions from minimum to maximum distance. For each distance we took five measurements for each one of five sensors used in this experiment. Approximately ten target placements are used per each sensor, but always different across the five sensors. Our main goal here was to design an average calibration table for the SMR400 sensors so that each direction of the robot will be equally treated when estimating the target locations from it. The raw measurements happen to be very consistent even though we were expecting errors due to sensor manipulation by operator and minor imperfections in the measurement setup.

The raw data were compiled using standard MATLAB functions: **`Spline`**, **`Linspace`** and **`Ppval`**. The procedure followed several important steps: re-sampling, interpolation on a pre specified grid, averaging across each five sensors, and it ends up with calculating mean and standard deviation across each five sensors. All the data from interpolation on the grid are shown on Fig. 6.

As it can be observed from interpolated data on equidistant grid of 25cm, three sensors are quite regular responses, close to zero error, mostly less than 5 mm, while two of them are diverging around 10 mm, especially at distances longer than 2 m. We averaged the five measurements at each of the node to arrive at mean value and its standard deviation. These two data gives shows how the obstacle would be seen at specified range regardless of which one of the sensors is engaged. It can be observed that the error is higher at the shortest and at the longest distances while standard deviation is much higher at the far end of measurement range. For all five sensors, on average, we can estimate that the error of locating the object is 7 ± 15 mm (2σ) for the whole operating range.

Even though the calibration shows somewhat higher error, one should notice that in mobile robotics extremely precise obstacle or navigation sensors are not necessary. Therefore we accept these results as reasonably well. This mobile robot with this calibration scheme of sonar sensors, at this stage of development, fully meets the needs such as positioning and mapping the surrounding space. Additional calibrations are left for the final phase of development of the mobile robot SMR-1 [2].

In addition to these results an additional experiment was done in one of the sensors. That experiment was aiming to determine the angle range within which sensor maintained its function. This is determined by the beam pattern of ultrasonic transducers. The experiment consisted of placing the object at a fixed distance of 880 mm, and displacing it on different angles with respect to the main axis of the sensor, i.e. the central direction of propagation of ultrasonic waves. Angle change step was arbitrary adopted, depending on the obtained results. The results of these measurements are shown in Fig. 7.

Relatively good results are observed gain for the angles between –30° to 30°, which can be seen in Fig. 7. Considering these angles, average error is 20 mm, which can not be neglected, but this is not so bad, considering 880 mm distance (2.8%). However if we focus on angle range from –10° to 10°, the data show quite well distance readings and errors could be ignored.

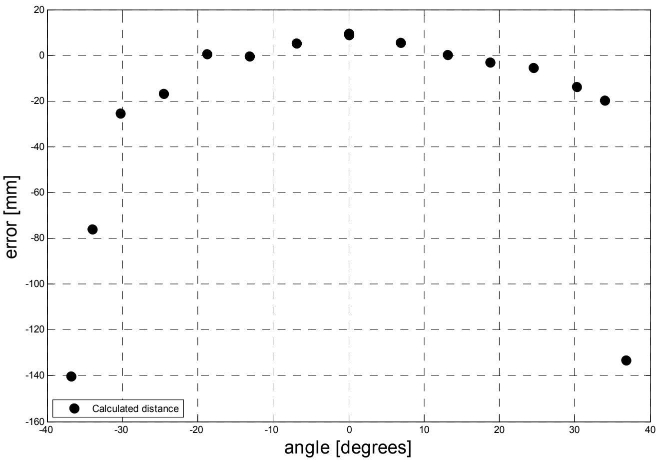

Fig. 7 – *Beam pattern of ultrasonic sensors.*

6 Conclusion

Mobile robots are named after ability to move in the specified working area. For them to move, and to perform set tasks, it is necessary to solve the problem of their localization and positioning. Ultrasonic sensors are used in that purpose. This paper described calibration of ultrasonic sensor SRM400, that are mounted on a mobile robot SRM1 to locate obstacles and measure their distances. Experiments with these sensors are performed to examine their opportunities in terms of distance measurements and angle of measurement.

Using distance measurements performed by five sensors of the same type, universal calibration factor is gained to calibrate the next sensor. Thus avoids future measurements and specific calibrations for every sensor, with minor impact on the accuracy.

The results of calibration were satisfactory. Measured distances are processed in MATLAB, and in mobile robot microcontroller. Achieved accuracy is entirely acceptable given the dimensions of the robot and within the measuring range.

Sonar beam pattern are also experimentally recorded, necessary for further process of defining and validating algorithms for detection and localization of objects in the workspace of robots.

These results shows that the sensor system placed on robot might have a role to create images of whole environment in the main microcontroller. Based on it, the mobile robot will always know its position and the position of objects around it. So it can be expected that the robot will carry out the set tasks by safely moving in its workspace.

These theoretical and experimental results are part of a wider research whose final goal is that of building a reliable and efficient algorithm for localization of objects in the workspace of robots, as well as localization of the robot in the workspace. Such algorithms are essential for the functioning of autonomous mobile robots.

7 Acknowledgement

Milan Rašić (1972-2007)

Mobile robot SMR-1 mentioned in this paper was designed by **MSc Milan Rašić**, in Laboratory of robotics in Faculty of Electronics in Niš. Unfortunately, after a short illness, Milan Rašić passed away. This paper uses some results of his experimentation on the calibration of the SMR-1 robot.

8 References

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