Distance Estimation With a Long-Range Ultrasonic Sensor System

Jarosław Majchrzak, Mateusz Michalski, and Grzegorz Wiczyński

***Abstract*—This paper presents the results of tests conducted with an ultrasonic proximity measurement system (composed of *Polaroid 600* sensors and a Sonar Ranging Module SN28827), which is used in sensory subsystems in many mobile robots. The tests took into account distances ranging from 0.4 to 11 m. The analysis of the obtained measuring results created the basis for selecting a distance estimator that would guarantee the smallest measuring errors in the whole measuring range of the system. The research described was carried out in a closed room at constant environmental conditions so as to eliminate the influence of external factors on the measurement result. Each measuring series was composed of 100 measurements. For the best estimator chosen in such environment, the value of absolute measuring error never exceeded $\pm$ 0.03 m. Histograms that present the scatter of measurement results are also included. The minimal number of measurements necessary to achieve a reliable measurement with the selected distance estimator was determined. It is shown that in order to achieve a relative measuring error smaller than 1% with 0.99 probability there is a need to perform at least seven measurements. A proposition of the distance measuring procedure with the chosen estimator is presented. The analysis described in this paper helps to evaluate the reliability of measurements performed with ultrasonic sensors.**

***Index Terms*—Distance estimator, measurement error, mobile robot, ultrasonic sensor.**

I. Introduction

MEASUREMENT of distances to other objects and obstacles is an important source of information about a robot's surroundings and environment. The kind of control which is based on surroundings information processing is used commonly in robotics at the task planning level, in behavioral navigation, and in unknown terrain exploration.

The ability to gather information about the scene of action, as well as its proper classification and fast, appropriate usage are the basic conditions for robust performance of a mobile robot [1]–[8]. Literature on the use of ultrasonic sensors focuses both on topics related to tests of sonars used in robotics [9]–[11] and on the use of measurement results to create a knowledge base of robot's surroundings. Ultrasonic sensory systems are used to build raster and geometrical maps of the robot's environment [5]–[7], to assist navigation systems [12], [13], and to position the robot in relation to obstacles [14], [15]. Most of the publications do not give information on the issue of distance measuring errors, other ones only analyze it to a limited extent, while it is actually a vital problem as the measurement realized without the knowledge about its error is, in practice, useless.

Paper [9] includes the analysis of measurements' quality for the measuring made with an ultrasonic system which consisted of one transmitter and several receivers. Similarly, in [16], the authors present the Gaussian distribution of measurement results, while obtaining an average distance to objects in the scene using the results collected with ultrasonic sensors and a laser proximity meter. The usage of a geometrical model of a sonar measuring beam to build a raster map of robot's surroundings was presented in [5]. The shape of the characteristics built with the assumed models suggests normal distribution of measuring results. In the case of triangular measurements [7], the accuracy of the final measurement depends on the precision of each of the intermediate measurements. The lack of information about measuring errors complicates the evaluation of the reliability of the final results.

Evaluation of the reliability of the proximity measurements made with ultrasonic systems is, in general, difficult. It is conditioned strongly by the physical properties of an ultrasonic wave propagation [17], [18]. The ultrasonic sensor's measuring errors depend on several factors. The fundamental factors here are the environmental conditions in which the propagation of ultrasonic waves takes place (temperature, humidity, movements of air—among others) [9], [18] and functional conditions which may cause disturbances, like the presence of other active transmitters of acoustic waves of similar frequencies, reflections from other objects (for example, the multi-echo phenomenon for objects of specific shapes). This paper presents the results of tests conducted with the ultrasonic *TRC Proximity Subsystem*, equipped with *Polaroid* sonars of type *600* [19], [20]. Sonars of this type are used in sensory subsystems in many mobile robots [21]. The research described was carried out in a closed room. The wall was used as an obstacle that reflected the ultrasonic beam emitted by the sensor which was installed in such a way that the beam could approach the reflecting surface perpendicularly. For several known distances between the sensor and the wall, a large number of measurements was performed, preserving the constant conditions in each series. The aim of the analysis presented in this paper is to choose the best estimator of a real distance. The selection was made on the basis of measuring error analysis for each available distance estimator. It will be shown that the maximal value of the appropriately chosen number of measurements serves as the

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estimator that guarantees the smallest measuring error. As an alternative estimator the histogram's modal value will be proposed. Moreover, the possibility to decrease the measurement error by taking into account a correction will be presented. The minimal required number of measurements to obtain a result with the assumed reliability level will also be depicted.

The tests were conducted in laboratory conditions. The aim of preserving those conditions is to reduce the influence of external factors to a minimum in order to discover the capabilities of the sensory system itself. The intentional arrangement, with purposeful elimination of disturbances, results in obtaining a reference point useful while developing any target system that will take into account multiple echos, nonperpendicular reflections, and other phenomena present in real-life settings.

The paper ends with a proposition of a distance measuring procedure that guarantees reliable results with an arbitrarily chosen probability level.

Throughout this paper, the following notation will be used.

N Measuring series size.

x_i A single, ith, result of distance measurement between the ultrasonic sensor and an obstacle in a measuring series of size N.

x_r The real, correct distance between the ultrasonic sensor and an obstacle (measured with a ruler with an absolute error $\Delta x_r = \pm 2\%$).

x_m Measured value of the distance between the ultrasonic sensor and an obstacle obtained with a chosen estimator of x_r value.

x_{mc} Measured value x_m with a correction taken into account.

$x_{\mathtt{MIN}}$ Minimal value of measuring series results

$$x_{\mathtt{MIN}} = \min\{x_1, \ldots, x_N\}. \quad (1)$$

$x_{\mathtt{AVG}}$ Average value (arithmetic mean) of the measuring series results,

$$x_{\mathtt{AVG}} = \frac{1}{N}\sum_{i=1}^{N} x_i, \quad (2)$$

$x_{\mathtt{MAX}}$ Maximal value of the measuring series results,

$$x_{\mathtt{MAX}} = \max\{x_1, \ldots, x_N\}. \quad (3)$$

Δ_x Absolute error of x_r distance measurement

$$\Delta_x = x_m - x_r. \quad (4)$$

δ_x Relative error of x_r distance measurement.

$$\delta_x = \frac{\Delta_x}{x_r} \cdot 100\%. \quad (5)$$

$x_{\mathtt{D}}$ Modal value of histogram obtained from a series of x_i measurements.

$\Delta x_{\mathtt{MAX}}$ Presumed allowable difference between the maximal value $x_{\mathtt{MAX}}$ and the value of a single measurement result x_i.

X_m A range of measurements results

$$X_m = \langle x_{\mathtt{MAX}} - \Delta x_{\mathtt{MAX}}; x_{\mathtt{MAX}}\rangle. \quad (6)$$

N_i Minimal size of measuring series in which measurement result x_i with the value in range X_m will occur with probability p_M, $N_i \in \mathbb{N}$.

p_i Probability of the occurrence of a single measurement result x_i with the value in the range X_m, $p_i \in \mathbb{R} : \langle 0.0; 1.0\rangle$.

p_M Probability of the occurrence in a given measurement series N_i of at least one measurement result x_i with the value in range X_m, $p_M \in \mathbb{R} : \langle 0.0; 1.0\rangle$.

P_{k,N_i} Probability according to the Bernoulli binomial formula [22]

$$P_{k,N_i} = \binom{N_i}{k} p_i^k \left(1 - p_i\right)^{N_i - k}. \quad (7)$$

where k Number of the occurrences of the x_i results that belong to the X_m range in an N_i-sized series (assuming $k \le N_i$), $P_{k,N_i} \in \mathbb{R} : \langle 0.0; 1.0\rangle$, $k \in \mathbb{N}$.

II. Ultrasonic Distance Measurement System

A. Short Characteristics of the System

During the tests, an integrated measuring *TRC Proximity Subsystem* [4] was used, which measures distance with 24 ultrasonic sensors. In the measurement system *Motorola* 68HC11 microprocessors are used. Each processor in the system controls eight different ultrasonic sensors. The measuring chain between the processor and each ultrasonic sensor contains a *Texas Instruments'* SN 28827—Sonar Ranging Module [19].

Distance determination is based on the measurement of the time-of-fly of a sonic ping. To measure a distance the transducer creates a sonic ping at a specific frequency (in the case of the Senscomp module, the ping consist of a series of pulses). Then, the ranging module measures the time it takes for a reflected sonic ping to return to the transmitter.

The duration of a measurement conducted by one sonar in a nominal range equals ca. 75 ms. The sonar generates an acoustic wave of frequency of approximately 50 kHz [20]. The total measurement time is extended by electronics latency (i.e., switching of the measurement channel from the transmitter mode to the receiver mode which includes the time needed to cease the membrane vibration), and by the computational processing of the measurement result. A typical relative measurement error given by the manufacturer of the system is 1% [20]. During the tests, the sensory system was mounted on a mobile robot platform. The tests made use of only one measuring chain (out of 24 available). Fig. 1 presents a block diagram of the prepared system configuration. The ultrasonic sensor was placed at some distance, x_r, from an obstacle. The control system performed a series of measurements x_i for every preset distance x_r. The measuring process (the number of measurements in a series, inter-

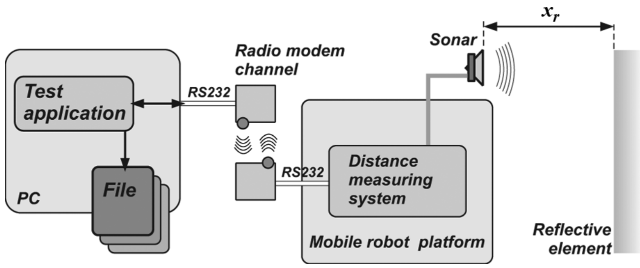


Fig. 1. Measuring system's block diagram.

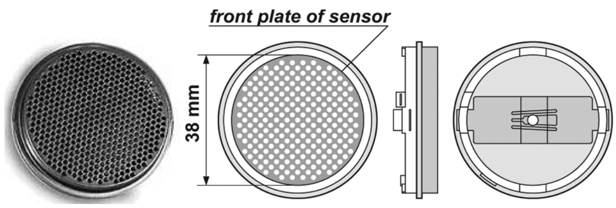


Fig. 2. Simplified view of the ultrasonic sensor—type *600*-series of *SensComp* [20] (formerly known as *Polaroid*).

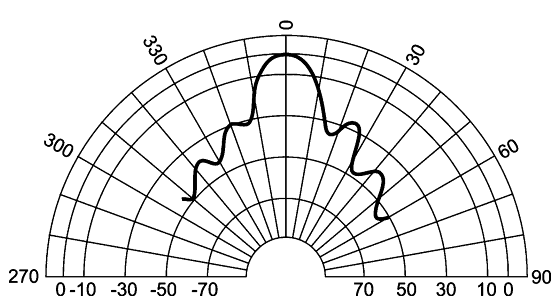


Fig. 3. Typical characteristic of a horizontal section of the measuring beam for a *600*-series Polaroid sensor [20].

vals between consecutive measurements, communication link handling) was controlled with a dedicated software application.

B. Ultrasonic Sensor Description

The tested sensor, a *Polaroid 600*–series model, is composed of two galvanically isolated main parts: a steel case and a circular membrane made of gold foil. In the transmitter mode, the resilient circular membrane generates an ultrasonic beam. The emission is a result of a vehement increase of charge in the capacitor (the phenomenon of electrostriction) formed by the sensor's casing and the circular membrane. In the receiver mode, the circular membrane acts as a mechanical detector of the reflected wave—any displacement of the membrane changes the capacity of the capacitor (an electrostatic phenomenon). Fig. 2 presents a view of the ultrasonic sensor.

The basic properties of the measuring system stem from the characteristics of the ultrasonic sensor used. The sensor is designed to work in the air. In the nominal measurement range of 0.15–10.7 m, the diameter of the ultrasonic beam changes from 0.038 m (the diameter of sensor's active part) to about 2.3 m. Fig. 3 presents a typical characteristics of the type *600*–series transducer.

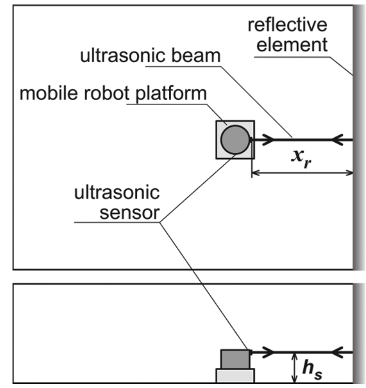


Fig. 4. Measuring sensor placement in the test room.

III. Testbed Description

The selection of the best distance estimator was made on the basis of measuring error analysis. Tests were carried out in a closed (windless), dry room where all the walls, the ceiling, and the floor were flat, with the size of $\mathrm{L} \times \mathrm{W} \times \mathrm{H} = 15.0 \times 5.2 \times 3.2\ \mathrm{m}$. The geometrical properties of the room enabled testing at the whole measuring range of the sensor. The measuring system was placed on a mobile robot platform (which was immobile during the measurements) at the height of $h_s = 0.92\ \mathrm{m}$ (see Fig. 4). During the measurements the following conditions were provided:

1) a series of measurements was carried out in constant geometrical conditions (unchanging surroundings) with one sensor;
2) all series of measurements were carried out in constant atmospheric conditions: constant temperature $(24\ ^\circ\mathrm{C},\ 75.2\ ^\circ\mathrm{F})$, constant relative humidity (ca. 65%), and no air movement (0 m/s).
3) the wall was used as a reflective element; the area of the wall was greater than the front area of the sonar beam (the area of the base of a circular cone formed by the measuring beam) for the selected distances;
4) during each series of measurements the selected sensor was placed steadily against the reflecting surface;
5) the measurements in a series were conducted consecutively one by one, without any additional intervals in between;
6) the number of measurements in a series was set to $N = 100$.

IV. Distance Estimator Selection

For each preset distance between the sensor and the wall (x_r), 100 measurements were performed and recorded. Then, the following characteristic values were derived (all of which are the estimators of x_r): the minimal value $x_{\mathtt{MIN}}$ (1), the arithmetic mean value $x_{\mathtt{AVG}}$ (2) and the maximal value $x_{\mathtt{MAX}}$ (3). For each of these possible estimators, the analysis of measuring errors was conducted. Figs. 5 and 6 present the obtained error values: absolute Δ_x and relative δ_x, respectively, for different distances x_r, which were calculated with (4) and (5).

On this basis, the whole measuring range was divided into several subranges. For the used estimators of the x_r distance, the following subranges were delimited:

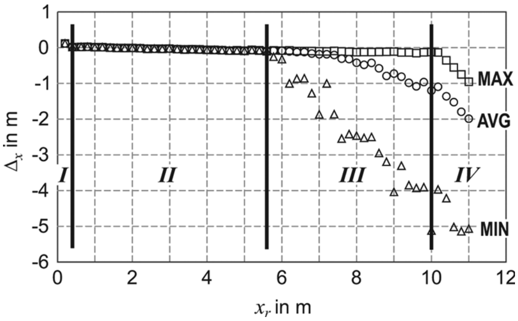


Fig. 5. Absolute distance measuring error Δx for each of the chosen estimators of the x_r distance: $x_{\mathtt{MAX}}$, $x_{\mathtt{AVG}}$, $x_{\mathtt{MIN}}$.

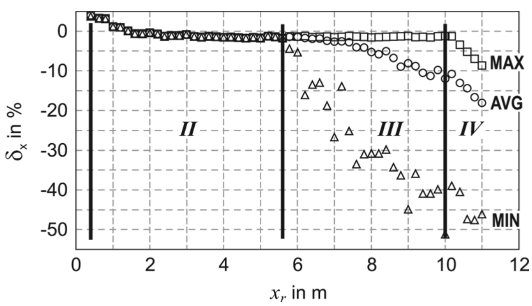


Fig. 6. Relative distance measuring error δ_x for each of the chosen estimators of the x_r distance: $x_{\mathtt{MAX}}$, $x_{\mathtt{AVG}}$, $x_{\mathtt{MIN}}$.

(i) useless (block distance); the area of the predominant influence of the measuring chain switching between transmitter and receiver modes [4], [23], the influence of a so-called near zone (Fresnel zone) in an ultrasonic wave emission [24];
(ii) useful—the basic subrange;
(iii) useful only with the best distance estimator;
(iv) useless.

The subranges (ii) and (iii) belong to the so-called *far zone* (Fraunhofer zone) in ultrasonic wave emission [24]. The choice of the estimator is based on the comparison of the errors in the subrange (iii). In this range, significant differences among the values for a particular estimator are clearly visible. Taking into account the smallest values of errors Δ_x and δ_x, one can state that the best estimator of the x_r distance is the maximal value of measurement results. By this we assume that $x_m = x_{\mathtt{MAX}}$.

However, the choice of the maximal measuring result as the distance estimator is, in general, (except for laboratory conditions) burdened with the risk of obtaining an improper result because of taking into account the value measured with gross error. To reduce the probability of committing such a mistake, some further analysis is proposed based on the histograms that illustrate the scattering of the measuring results. Figs. 7 and 8 present the histograms of x_i distance measurement results for two exemplary x_r values in the subrange (iii).

From the histograms presented in Figs. 7 and 8, one can see that the measurement results x_i are grouped near the modal value, $x_{\mathtt{D}}$. The modal value lies close to both the real distance value x_r and the maximum value $x_{\mathtt{MAX}}$. Therefore, the mode could be chosen as an alternative estimator of the real distance. Fig. 9 gives a view of the relative measuring error δ_x values,

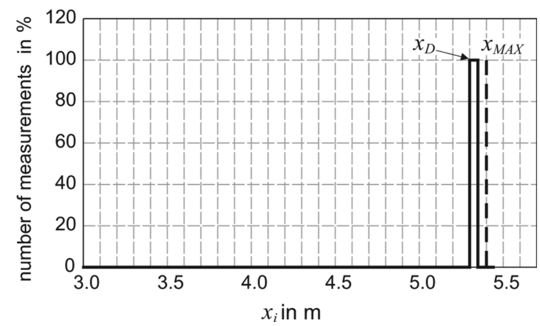


Fig. 7. The histogram of x_i measurement results at $x_r = 5.4$ m.

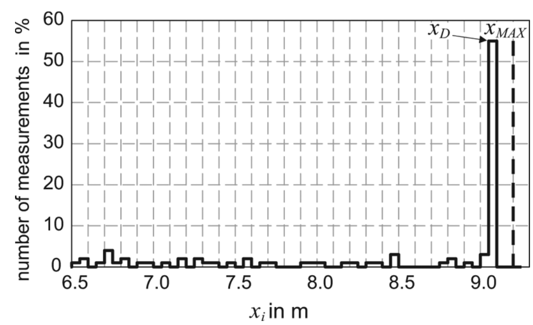


Fig. 8. The histogram of x_i measurement results at $x_r = 9.2$ m.

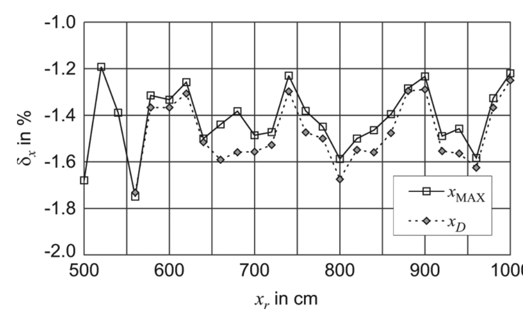
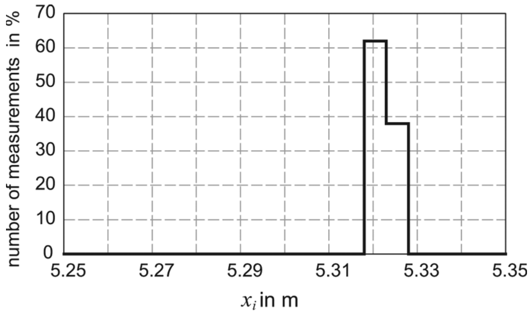


Fig. 9. Relative measuring errors δ_x in the subrange (iii) for the two estimators of the real distance: $x_{\mathtt{MAX}}$ and $x_{\mathtt{D}}$.

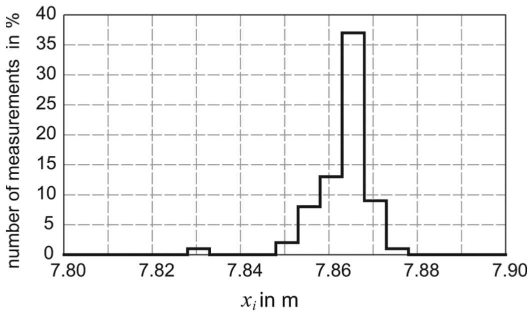
where x_m was substituted first with $x_{\mathtt{MAX}}$ and then with $x_{\mathtt{D}}$ in the subrange (iii) for the two estimators of the real distance: $x_{\mathtt{MAX}}$ and $x_{\mathtt{D}}$ [obtained with (5)].

The usage of $x_{\mathtt{D}}$ as a distance estimator leads to an increase in the values of the relative error δ_x. Nevertheless, such a choice of an estimator could be expedient in the presence of some disturbing factors (which were absent when the test was being conducted). The estimation with the histogram's modal value is less prone to short-timed disturbances than the estimation with the maximal value. The influence of short-timed disruptions results in the occurrence of additional modes, which could be easily eliminated by mutual comparison.

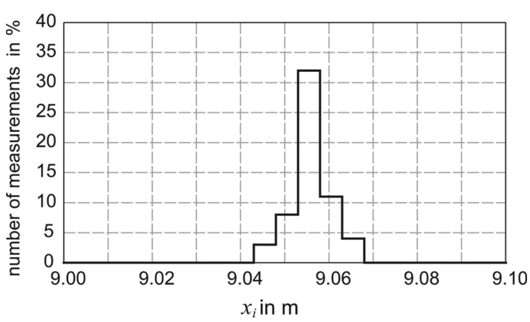
Fig. 10 presents the measurement results' histograms scaled in order to emphasize the values which are closest to the modal value. The results x_i from the subrange (ii) are affected by a smaller dispersion range then those from the subrange (iii). The plotted histograms do not provide any grounds to point out any



(a) The histogram of x_i-series at $x_r = 5.4$ m.



(b) The histogram of x_i-series at $x_r = 8.0$ m.



(c) The histogram of x_i-series at $x_r = 9.2$ m.

Fig. 10. Simplified histograms of x_i measurement results at different x_r distances.

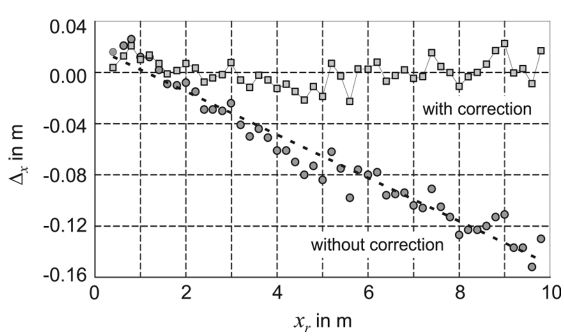


Fig. 11. The plot of the absolute measuring error Δ_x for measurement results without and with correction taken into account.

common distribution that could possibly describe the scatter of x_i values for the presented measurement series.

A. Measured x_m Value Correction

Fig. 11 presents the plot of the absolute measuring error $\Delta_x = f(x_m)$, where $x_m = x_{\mathtt{MAX}}$ (the estimator chosen in the previous section), in the (ii) and (iii) subranges.

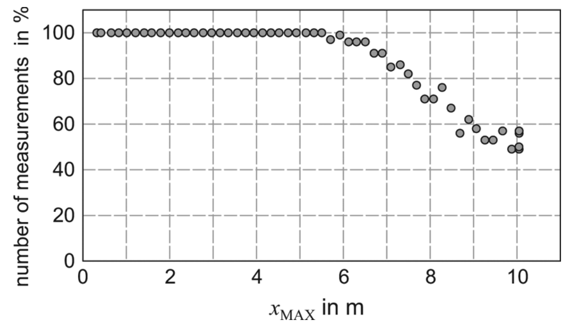


Fig. 12. The number of x_i measurements in a 100-element series that belong to the range X_m for $\Delta x_{\mathtt{MAX}} = 0.01 \cdot x_{\mathtt{MAX}}$.

The $\Delta_x = f(x_m)$ dependence without any correction is nearly linear. Therefore, it is possible to reduce the inaccuracy of the measurements by taking into account the value of correction $\Delta_{\mathrm{cor}}(x_m)$

$$x_{mc} = x_m + \Delta_{\mathrm{cor}}(x_m). \tag{8}$$

The correction's value $\Delta_{\mathrm{cor}}(x_m)$ was derived from the equation obtained with linear regression. With correction $\Delta_{\mathrm{cor}}(x_m)$ taken into account, the values of the absolute errors Δ_x are significantly reduced (see Fig. 11).

B. Minimal Number of Required Measures in a Measuring Series

In the case of the distance estimator mentioned above, the measurement consists in the determination of the maximal value from the series of x_i measurements. In practical applications however, carrying out such a large number of measurements each time the information about the distance to obstacles is needed would be rather problematic and ineffective. Therefore, it is purposeful to determine a minimal number of measurements in a series, N_i, which would guarantee that at least one of measurement results, x_i, belongs to range $\mathrm{X}_m = \langle x_{\mathtt{MAX}} - \Delta x_{\mathtt{MAX}}; x_{\mathtt{MAX}} \rangle$. Fig. 12 presents how many x_i measurement results belong to the range X_m for different x_r distances with presumed $\Delta x_{\mathtt{MAX}} = 0.01 \cdot x_{\mathtt{MAX}}$. The minimal number of values that fall under this range is 52 for a 100-element series at each distance in the whole measuring range. From that the minimal probability of the occurrence of the measurement result x_i that belongs to the $\langle 0.99 x_{\mathtt{MAX}}; x_{\mathtt{MAX}} \rangle$ range is $p_i = 0.52$.

The conditions of this task correspond to the Bernoulli process: a sequence of independent trials (measurements in this case) of the following properties:

- the outcome of each trial can be either of the two possible values: *success* (the measurement result belongs to the delimited range) or *failure* (the measurement result does not belong to the range);
- each trial (measurement) is independent and does not provide any information regarding future outcomes;
- the probability of *success* or *failure* is equal in every trial.

The minimal required number of measurements in a series was derived for the given probability of the occurrence of at least one measurement result x_i belonging to the range X_m, denoted as p_M. The Bernoulli binomial formula [25] was used here (7).

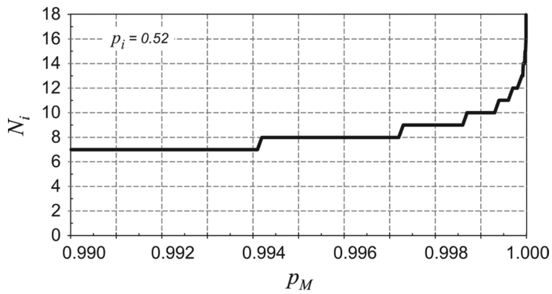


Fig. 13. The minimal required measurements in a series, N_i, for $\Delta x_{\mathtt{MAX}} = 0.01 \cdot x_{\mathtt{MAX}}$ and $p_i = 0.52$.

For the sake of simplicity, calculations were carried out with the use of the opposite event $P_{k,N_i} = (1 - p_M)$ probability (probability that none of the x_i results belongs to the X_m range). With $k = 0$ such probability could be described with the following expression:

$$P_{0,N_i} = (1 - p_M) = \binom{N_i}{0} p_i^0 (1 - p_i)^{N_i} = (1 - p_i)^{N_i}. \quad (9)$$

After a simple transformation, N_i can be found as

$$N_i(p_M, p_i) = \frac{\log(1 - p_M)}{\log(1 - p_i)}. \quad (10)$$

The result of (10) is a rational number, $N_i(p_M, p_i) \in \mathbb{R}$. As N_i in this case is the minimal number of measures, it has to be rounded up to the nearest (greater) natural number. For example, at the distance $x_r = 9.6$ m for $p_M = 0.99$, the minimal necessary number of measurements in a series is $N_i = 7$, and for $p_M = 0.9995$ it is $N_i = 11$ measurements. Fig. 13 presents the plot of (10) for $\Delta x_{\mathtt{MAX}} = 0.01 \cdot x_{\mathtt{MAX}}$ with $p_i = 0.52$.

V. The Proposition of the Measuring Procedure With the Use of the Distance Estimator x_r

The selection of a distance estimator discussed above was based on the measurement results obtained in constant environmental conditions. Clearly, changeable conditions must be taken into consideration when performing regular measurements. Therefore, the following measuring procedure is suggested:

1) determine environmental conditions (temperature, humidity, air movements);
2) perform a large-sized measurement series (e.g., 100 measurements) for distance x_r close to the sonar's maximal measuring range;
3) analyze the results: build the histogram and determine the maximal value $x_{\mathtt{MAX}}$, the modal value $x_{\mathtt{D}}$, and evaluate the scatter of the results;
4) if the scatter is small enough, determine the probability of x_i occurring in the range X_m; otherwise, omit the next steps as the measurement results are not reliable;
5) determine the minimal number of measurements N_i for the assumed probability p_M [according to (10)];
6) if possible, perform additional series of measurements for a smaller distance x_r (e.g., at a half of the sensor's measuring range)—this could enhance the measurement accuracy by taking correction into account [according to (9)];
7) perform regular measurements with the determined minimal number of measurements.

This procedure should be carried out for any significant change in environmental conditions. The procedure is easily applicable to typical measuring systems. Any required changes are limited to software modifications. A longer measuring time results in a possible improvement of measuring accuracy. Using the suggested procedure the user of a sensory system can find the probability of performing a reliable distance measurement with the available equipment. The suggested procedure could be also used as an indirect evaluation of the environmental conditions in which the sonars operate and to eliminate the undesirable situation when the measurements are not reliable.

VI. Summary

This paper presented the results of a research conducted on an ultrasonic distance measurement system. The scatter of the results was observed. From that the conclusion was drawn that the single measurement result does not provide reliable information about the real distance. Further analysis of the collected results led to the following conclusions.

1) When it comes to measuring errors, the best distance estimator is the maximal value $x_{\mathtt{MAX}}$.
2) For the presumed probability p_M the minimal number of measurements N_i was obtained. For example, with the test measurement results and $p_M = 0.99$, $\Delta x_{\mathtt{MAX}} = 0.01 \cdot x_{\mathtt{MAX}}$, the minimal number of measurements N_i is 7.
3) The modal value of the measuring results distribution $x_{\mathtt{D}}$ could be chosen as an alternative estimator of the real distance value x_r. The usage of $x_{\mathtt{D}}$ as a distance estimator leads to greater measuring errors, but such a choice could be a necessity in the presence of strong disturbances.
4) A way to enhance measurement accuracy by taking correction (approximated with a linear function) into account was shown.
5) The scatter of measuring results x_i does not conform to normal distribution.
6) The proposition of measuring procedure which uses the maximal measuring result, $x_{\mathtt{MAX}}$, as the distance estimator was presented. Better measuring accuracy is a strong advantage of this procedure. Longer measuring time, on the other hand, is the main disadvantage of the process.

The proposed measurement procedure could be useful when dealing with problems concerning the reliability of the measurement results obtained with ultrasonic sensors. It could be used as an alternative to other statistics-based methods.

The proposed estimator was chosen on the basis of the error analysis for measurements performed in the range (iii). Nevertheless, the estimator chosen in such a way is also applicable at distances that belong to delimited range (ii) even though in this range the scatter of the results is small, and the problem of proper estimator selection is not critical.

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