Testing of a Reliability of SRF02 Ultrasonic Detectors

Martin Pospisilik, Pavel Varacha, Pavel Bartonik, Josef Vorisek, Petr Neumann

Abstract— In various applications the proximity measurement is employed, using different methods. One of the contactless proximity measurements is based on ultrasonic detectors that utilize a time difference between sending and receiving of ultrasonic burst that has been reflected from the obstacle. Because the proper operation of ultrasonic detectors depends on many physical issues, several measurement errors may occur. The purpose of this paper is to present how SRF02 detectors may be used in anti-collision system of a small airship and what quality of the data gained from these detectors can be expected. The authors of the paper made several measurements to prove the reliability of these detectors and summed the gained experience in the text of this paper.

Keywords— Distance Measurement, Ultrasonic Detectors, Measurement Error, Autonomous Airship

I. Introduction

FOR a long time airships seemed to be outdone but now they are experiencing a considerable renascence. Basically, the following constructions can be distinguished:

- big ones for outdoor operation
- small ones for indoor operation.

The authors of this paper focused their attention to the small ones for indoor operation, as there are several interesting aspect at solving the task of its controlling.

A. *Project of Autonomous Monitoring System*

Let us focus on the small ones that are capable of indoor operation and can be used for several purposes. They are good for advertisement because they attract the attention. But this is not our goal. We want to employ their physical advantages, mainly their capability to float in the air with minimal power consumption. Modern Li-Ion accumulators are advantageous to power small engines that move the airship, but do not have to have sufficient power to hold it in the air with all the equipment.

The airship operating at the Faculty of Applied Informatics is a custom-made modeller product that is capable to bear up to 650 g of load. Equipped with an RC controller, it can be driven like an aeromodel, whilst the design of autonomous controlling unit is in progress. The bladder is filled with helium, making the model operation rather expensive. Because the helium molecule is very small and tends to leak through the material of the bladder, the nominal volume of 2.7 m3 of the bladder must be checked weekly. The material of the bladder is a special foil made for airships, having a small weight per area unit in order not to decrease the load capability of the airship.

The goal of the project is to develop such kind of controlling system that would be light enough to be carried by the airship and would be able to drive the airship automatically in order it could avoid obstacles. Such automatically driven airship should carry a web camera streaming the picture to the local area network. It can also bear other appliances, for example radio signal strength meter, thermometer, moisture measurer, etc.

The photography of the airship that is prepared to bear with all the equipment of the Autonomous Monitoring System is depicted at Fig. 1.

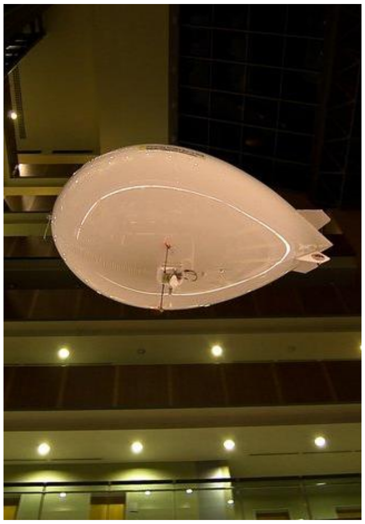

Fig. 1 – Airship for the Autonomous Monitoring System

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B. *Obstacles Detection by Ultrasonic Detectors*

The autonomous controlling system, integrated on a single board employing a single microcontroller, enables the capability of automatic obstacles detection. This detection is based on a set of ultrasonic detectors the operating conditions of which are discussed in this paper, as well as their reliability.

Although the controlling of the airship is primarily intended to be based on the combination of inertial controlling and utilizing of a set of RFID tags that defines the trajectory, the obstacles detection prevent the indoor operating airship from accidental collisions with obstacles that can randomly occur in the operating area. Therefore it is necessary to develop an operational anti-collision system that will increase the operability of the Autonomous Monitoring System.

II. OBSTACLES DETECTION

Avoiding the obstacles is supposed to be assured by a set of 9 ultrasonic detectors. These detectors are connected to a microcontroller via I2C bus. The microcontroller periodically requests data from these detectors in a form of a number, representing the distance between the appropriate detector and the detected obstacle. The measurement is taken at a frequency of about 40 kHz.

The ultrasonic detectors are directional, concentrating the radiated energy in a cone beam in front of their actuators. However, within the space angle inside the beam the ultrasonic detector can be considered as a source of spherical waves that are to be described by the following equation:

$$x = \frac{A_0}{r}\cos\left[\omega\left(t-\frac{r}{c}\right)\right] \qquad (1)$$

Where:

x - instant displacement [m],
A_0 - displacement amplitude [m],
ω - angular frequency [rad/s],
c - wave propagation speed [m/s],
r - distance from the source [m],
t - time [s].

A. *Physical Issues*

There are several disadvantages arising from the ultrasonic distance meters utilization. First of all, the sound velocity in the air differs according to the elevation and to the temperature. It can also be affected by the atmospheric pressure variations. Secondly, accurate clock source must be employed in the ultrasonic distance meter because the distance (length) is generally a function of sound velocity and time. Considering the air to be an ideal gas, the following equation can be applied in order to determine the measured distance l_m:

$$l_m = \frac{\sqrt{\kappa\frac{p_{g0}}{\rho_{g0}}}\left(1+\frac{\gamma_g\cdot t_g}{2}\right)}{2}\cdot T \quad [m] \qquad (2)$$

Where:

κ - Poisson's constant,
ρ_{g0} - gas (air) density at 0°C (273.15 K) $[\mathrm{kg}\cdot\mathrm{m}^{-3}]$,
p_{g0} - gas (air) pressure at 0°C (273.15 K) [Pa],
γ_g - coefficient of the gas (air) thermal expansiveness $[\mathrm{m}\cdot\mathrm{K}^{-1}]$,
t_g - air temperature [K],
T - time period between the sent and the received signal [s].

A partial compensation of the measurement error caused by the changes of the above mentioned parameters can be established when there is also an accurate temperature measurement. The following approximation can be established. Considering the zero elevation and typical air pressure and density, the equation (1) can be approximated by the following one:

$$l_m = \frac{331.51+0.607t_g}{2}\cdot T \quad [m] \qquad (3)$$

According to (2) it can be deduced that once the temperature changed by 25 °C, the measurement error increases by 5 %.

Other problems occurring with method of measurement are caused by the shape of the emitted signal. In a plane, instead of an ideal straight line, the energy of the emitted signal is in front of the transmitter displaced according to Fig. 2. In practice this leads to the effect depicted in Fig. 3. In case the detector does not form a right angle with the measured surface, the shortest way of the emitted and received signal is not the expected red line, but the blue line, being placed at the border of the transmitting diagram. The situation can be analysed by employing the Sine theorem. If supposed the transmitting angle of the ultrasonic distance meter is α and the angle between the detector orientation and the measured surface is β, then a triangle consisting of the red and blue lines and part of the surface (black) can be identified. From the triangle theory the angles inside the triangle are $\alpha/2$, β and $\gamma = 180 - (\beta+\alpha/2)$. When the Sine theorem is applied, the equation (3) can be used to estimate the distance that was really measured. However, this is only a rough approximation, not considering the real shape of the emitted acoustical signal. Moreover, the approximation is valid only if $\gamma = 180 - (\beta+\alpha/2) > 90°$. Otherwise the measurement will be correct.

$$l_{real} = l_m\cdot\frac{\sin\left(180-\frac{\alpha}{2}-\beta\right)}{\sin(\beta)} \; [m] \qquad (4)$$

In Fig. 4 practical issues arising from equation (3) are depicted. On the x-axis the angle between the detector plane and the surface is considered, on the y-axis the estimated error according to (3) is depicted for ultrasonic detectors of different radiation angles (10°, 20° and 40°). It is obvious that detectors with wider radiation angles allow to measure in wider angle with almost no error (± 10°), but once the critical angle is overpassed, the error increases rapidly. Advanced detectors employ a complex algorithm that allows, by changing the irradiation power, change the shape of the emitted signal and consequently obtain better accuracy when the measurement is processed under various angles. Another disadvantage that must be considered at the orientation system of the airship is the fact that the performance of the ultrasonic detectors is dependent on the attenuation of the signal caused by the structure of the measured material. Almost all materials reflect the sound properly but the surface geometry of some of them may cause the reflections are directed not back to the receiver, but in other direction. Therefore poor performance may be observed if the obstacles are including cylindrical or conical surface. In addition, the 40 kHz sound waves are only 8.5 mm long so corrugated or perforated surfaces can cause high attenuation of the sound.

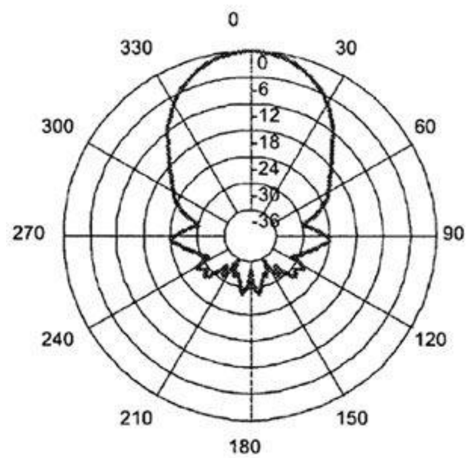

Fig. 2 – Typical ultrasonic transmitter radiation diagram [2]

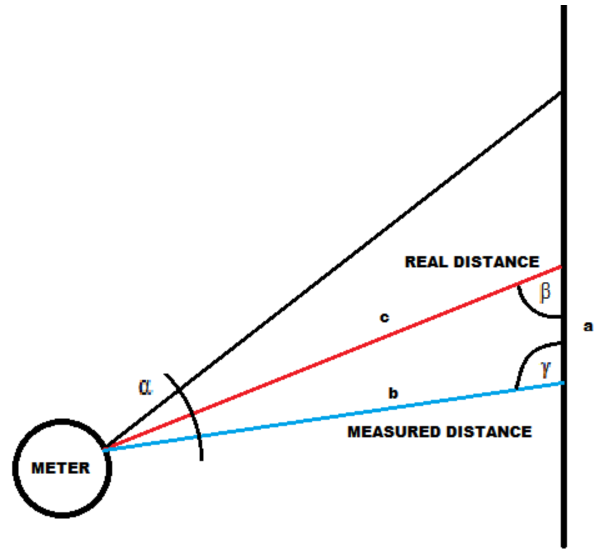

Fig. 3 – Measurement error caused by non-perpendicular reflection Mathematical Equations

B. Detectors Utilized for Obstacle Detection

For the purpose of the obstacles detection SRF02 [2] detectors are employed. They utilize a single transducer driven by a separated microcontroller mounted at the bottom of their PCB. The construction of SRF02 is depicted below. The detectors were driven by the Ultrasonic detectors kit described in [1]. The kit controls up to 9 detectors being connected via I2C bus. The microcontroller embedded in the kit controls the time delay between the activation of the detectors in order

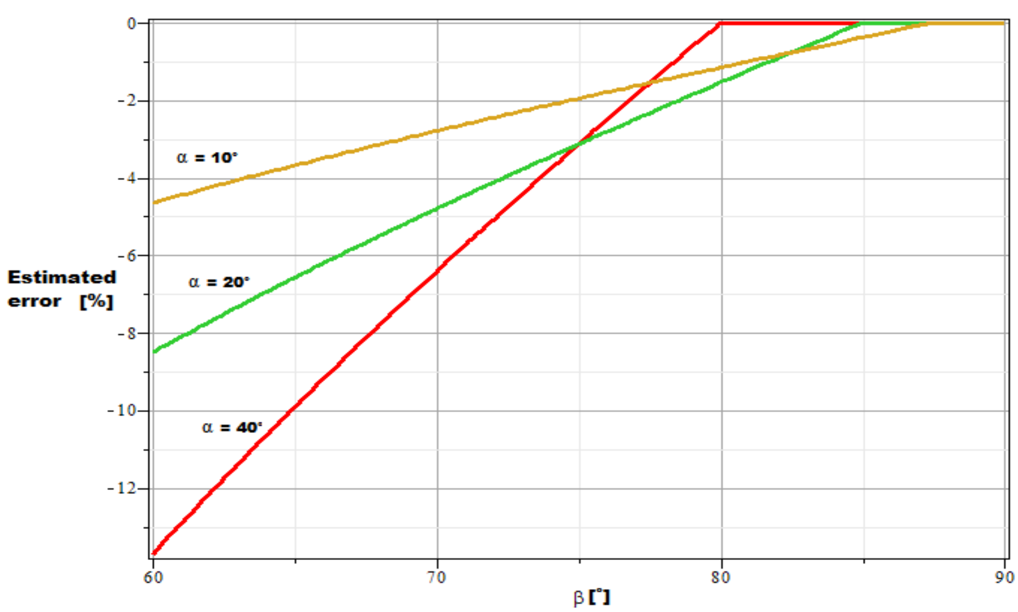

Fig. 4 – Error caused by the mutual geometry of the measured object and the surface of the obstacle (computed in mathematical software, see text).

false measurements were suppressed. It also drives a display on which the distances from the obstacles detected by each of the detectors are displayed.

Fig. 4 – SRF02 construction [2]

In order the parasitic reflections were eliminated, the detector operates in so called burst mode. When the central airship's controlling unit sends request to measure the distance from any object in front of the detector, it transmits 8 cycles of 40 kHz burst and waits for the first response from the space around.

C. Controlling Module for the Detectors

The obstacles detection module employs a set of ultrasonic detectors displaced around the airship's bladder. Each of the detectors communicates by means of I2C bus which allows the constructer to change the number of the detectors as needed. The maximum number of the detectors is determined by the address space of the bus.

In order to prove the operation of the obstacles detector a hardware module has been created, utilizing the Atmel ATtiny2312 microcontroller. This module permanently communicates with 9 ultrasonic detectors displaced on the canopy-shaped surface and displays the distances of the prospective obstacles to each of the ultrasonic detectors. Moreover, a set of LEDs is implemented to indicate that the pre-set "distance threshold" is trespassed. This feature can be utilized for a simple decision whether the obstacle is close enough or not.

The module for obstacles detection was also employed in measuring of accuracy and reliability of the ultrasonic detectors; different obstacles in different distances and under different angles were detected and the measured distances were compared to the really measured ones.

1) Hardware

The physical construction of the module is realized on 3 different printed circuit boards. A functional block diagram as well as a diagram describing connection of all the hardware parts is depicted at the following figures.

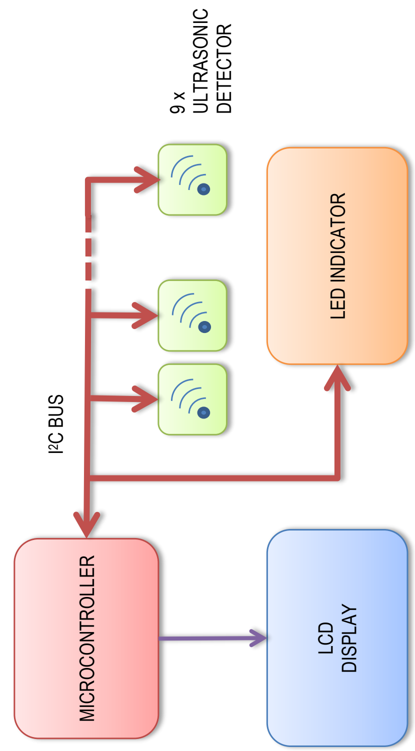

Fig. 5 – Functional block diagram of the ultrasonic detectors' controlling module

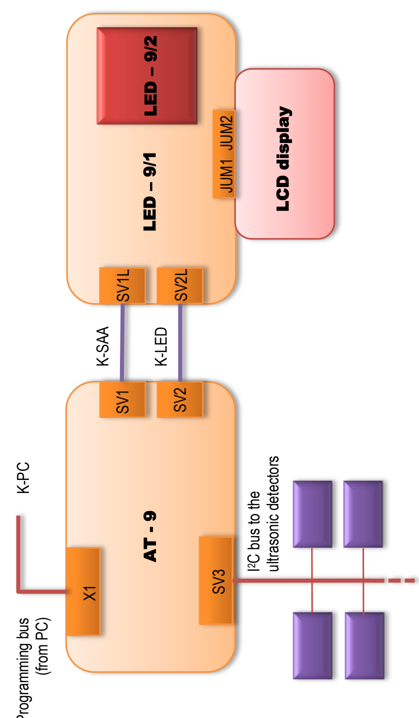

Fig. 6 – Physical arrangement of the module for controlling of the set of ultrasonic detectors

The blocks depicted in Fig. 6 are as described in Table 1.

Table 1 – HW blocks of Controlling Module for the Detectors

PCB No.	Description
AT-9	Motherboard with MCU
LED-9/1	Decoder for LEDs driving
LED-9/2	Matrix of LEDs
LCD	Autonomous LCD Display

2) *Principle of operation*

The principle of operation consists in cyclic sending of requests to the connected ultrasonic detectors. Each of the detectors sends back information on the distance from an obstacle that has been measured at the moment. The measured distances are displayed at the LCD display and by means of a LED matrix. If a preset minimum distance is not met, an indication by the proper LED is given and a black rectangle occurs at the LCD display near to the number of the relevant detector.

3) *Software*

The software implemented in the Module for obstacles detection was created in ATMEL AVR Studio integrated development environment with the aid of program libraries.

From the perspective of the user no adjustment of the module is required. The threshold of the obstacle proximity is set to 99 cm. The indication LEDs are bound to the addresses of the particular ultrasonic detectors. If any detector detects an obstacle being closer than 99 cm, the indication LED appropriate to its address is lit. Because all detectors are connected to the same bus and distinguished by means of the unique address, their commutation does not influence the appropriate led to be lit. Also the values displayed on the LCD display are related to the specific detectors.

The program runs in a loop as follows: the ultrasonic detectors are addressed successively, being asked to return the information on the distance to the pertinent obstacle in front of them. In a period a set of numbers is collected. On the basis of this set the displaying units are driven. If any detector indicates an obstacle being closer than 99 cm, the appropriate LED is lit and close to the measured distance a black rectangle is displayed on the display.

On the basis of the data gained and processed by the Module for obstacles detection the conclusions can be drawn in order to make a decision on the flight direction of the Autonomous monitoring system.

D. *Practical Consequences*

On the basis of the above mentioned issues, the following practical consequences arise from the use of the ultrasonic detectors:

- The obstacles may seem invisible to the detector when they attenuate the ultrasonic waves unduly.
- The obstacles may seem invisible to the detector when their reflecting area is too small.
- The obstacles may seem closer than they are in case they are not in the correct angle to the ultrasonic beam.
- Without calibration the accuracy of the measurement is affected by the air temperature.

Therefore several measurements were taken on SFR02 detectors in order to prove their reliability in practice. The results of the measurements are described in the following chapter. The influence of temperature to the measurement was neglected because as stated above, in air the measurement error is approximately 1 % per 5 °C.

III. PRACTICAL EXPERIENCE WITH THE DETECTORS

The testing of the detectors' behavior was processed in two different blocks. The gained experience is described the following subchapters.

A. *Measurement Block 1*

The set of ultrasonic detectors SRF02 for obstacles detection was utilized in several tasks arranged in order the accuracy and reliability of the ultrasonic detectors was proven. The purpose of these tasks was to claim the appropriateness of the ultrasonic detectors for obstacles detection the accuracy of which is, considering the utilization of this method by the Autonomous monitoring system, critical. By these tests it has been confirmed that in most cases the ultrasonic detectors are accurate and reliable enough to be employed for detecting the obstacles around the airship of the Autonomous monitoring system.

In accordance to the theory described in the theoretical part of this paper, the accuracy of the detection was affected by the ineligible width of the transmitted ultrasonic beam and the receiving characteristics of the ultrasonic detectors (see Fig. 2). However, when the inaccuracy of this type was observed, the measured distance was usually shorter than the real one, which does not affect the obstacles detection. The only consequence of such inaccuracies is that the obstacle is detected sooner or that spurious obstacle is detected. The above mentioned inaccuracies occur in the following cases:

a) the obstacle is not perpendicular to the axis of the ultrasonic beam,
b) there are other obstacles around the ultrasonic detector than the one to which the detector is directed being on the periphery of the ultrasonic beam, causing spurious reflections of the ultrasonic signal.

Whereas the above mentioned inaccuracies do not have a negative influence to the obstacles detection, unfortunately, there exist rare cases in which the detectors fail. The fail of the detectors occur when the surface of the obstacle attenuates the ultrasonic signal considerably or when the surface of the obstacle is too small in comparison with the transmitted ultrasonic beam width. Then the following problems can occur:

a) the range of the detector is decreased,
b) the detector does not detect the obstacle at all.

The results of the measurements obtained by the Module for obstacles detection are as follows:

a) metal column with a diameter of 75 mm was detected at a distance of 3.5 m,
b) paper box of dimensions 22 x 25 x 25 cm was detected at a distance up to 6 m,

c) aluminium foil coated target of dimensions 10 x 10 cm was detected at a distance of 5.16 m,
d) aluminium foil coated target of dimensions 20 x 20 cm was detected at a distance of 6.51 m,
e) wooden stick with a diameter of 12 mm was not detected at all, presumably due to scattering of the sound beam into the surroundings.

The inaccuracy of all the above mentioned measurements was lower than ± 2 cm.

Because in the area, in which the operation of the Autonomous monitoring system is supposed, there are several sound-absorbing sidings operating on the principle of Helmholtz resonators, the ultrasonic detectors were also tested on detecting these surfaces. The sound-absorbing sidings consist of performed plates, employing sound-absorbing material in the perforations. The sound absorption is efficient especially at high frequencies, making the ultrasonic detection difficult. The results obtained when detecting the sound-absorbing sidings were fluctuating according to the angle between the beam and the surface and the point on the surface at which the ultrasonic beam was aimed to. When aimed between the perforations, the ultrasonic detectors operated satisfactorily, having the maximum operating range decreased only. When aimed directly to the perforation, the detectors failed. However it is assumed that the detectors can detect the sound-absorbing surfaces with good reliability due to the fact that the Autonomous monitoring system is moving against their surface, resulting in the acoustic beam angle and position variation in time. Therefore it is expected that some of the reflections from the surface will be detected properly.

In the text below the results of more systematic accuracy measurements are provided. The accuracy of the distance measurement was proven by measuring the distance from a flat wall and from a wooden column under various angles (60°, 90° and 120°). Unfortunately, the format of the provided graphs is fixed and the appropriate functions cannot be distinguished by any other sign that by their colour. However, it is obvious from the graphs which line is which.

The results obtained at measuring the distance from the flat wall are depicted in Fig. 7. The real distance measured manually is displayed on the x-axis while the distance measured by the ultrasonic detectors is depicted in the y-axis. The green line represents the ideally linear relationship between the results of both measurements. The blue line represents the results obtained when the acoustic beam was perpendicular to the wall while the red line represents the results when the acoustic beam clutched with the wall the angle of 120° or 60° respectively (the results for 60° and 120° were identical). It is obvious that for distances higher than 0.4 m and perpendicular acoustic beam to the measured surface the results delivered by the ultrasonic detectors are greatly close to the ideal characteristics while provided the acoustic beam is not perpendicular to the measured surface, the results show a considerable error. For 30° difference from the right angle the error caused by the reflection of the lateral sections of the acoustic beam is approximately – 10 %. The consequence of this phenomenon results in the fact that large flat areas, like walls etc., may be detected as closer than they really are. However, this is not considered as a malfunction of the obstacle detection system.

Other measurements were processed with a wooden column having a rectangular cross-section of approximately 0.24 x 0.6 m. The results are depicted in Fig. 8. The same angles as in the previous measurement were applied. Also the graph elements are formatted in the same way as those depicted at Fig. 7. In this measurement the results were greatly accurate for all applied angles between the detectors and the measured object. This is a consequence of the fact that the area of the object's surface is limited, not allowing reflections of the lateral sections of the acoustic beam.

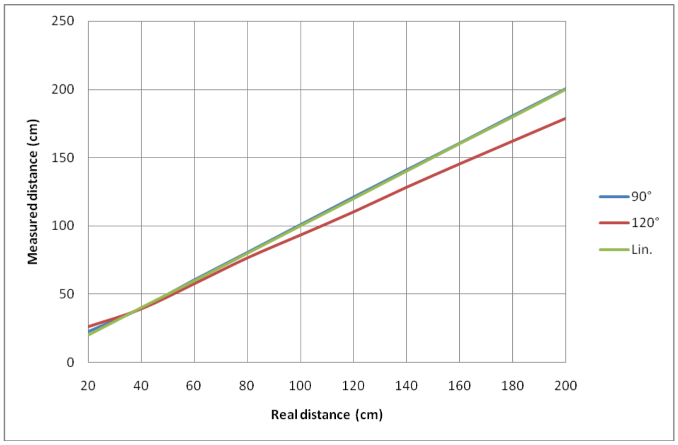

Fig. 7 – Distance from the flat wall measurement results (see text above)

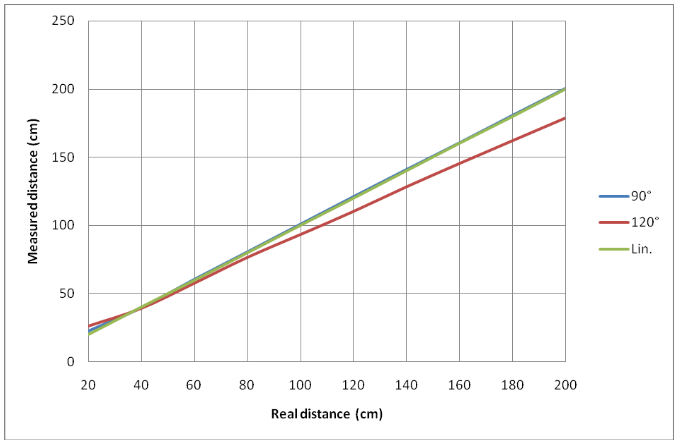

Fig. 8 – Distance from the wooden column measurement results (see text above)

B. *Measurement Block 2*

In order their reliability of obstacles detection was proved, a set of measurements were taken, employing different obstacle shapes and angles. The results are depicted in the following figures.

1) *Obstacles Perpendicular to the Detector*

First measurements were taken perpendicular to the obstacle at different distances, using different obstacle materials and shapes. Under these conditions the influence of the measurement angle is eliminated, showing the basic accuracy of the detector. The obstacles were as follows:

- 20 x 20 cm flat wooden surface,
- 5 x 5 cm flat wooden surface,
- 20 x 20 cm flat surface covered with aluminum foil,
- 5 x 5 cm flat surface covered with aluminum foil.

Each measurement was processed 10 times and average values were taken in account. The results obtained for the above specified obstacles are enlisted in graphs below.

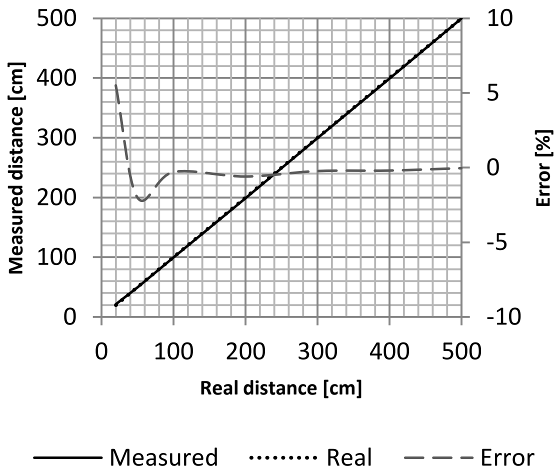

Fig. 9 – Results gained for 20 x 20 cm wooden surface

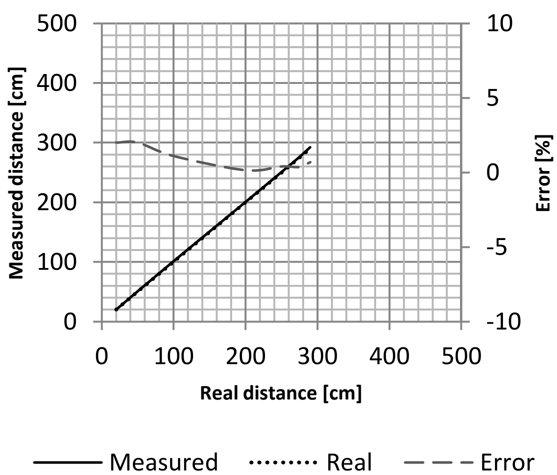

Fig. 10 – Results obtained for 5 x 5 cm wooden surface (for distances above 290 cm the obstacle was undetectable)

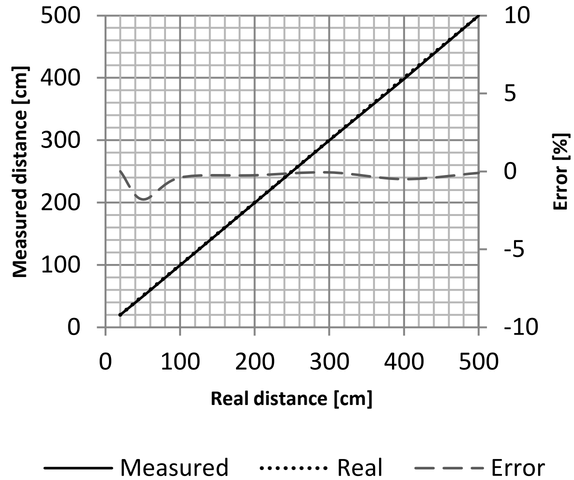

Fig. 11 – Results obtained for 20 x 20 cm flat surface covered with aluminium foil

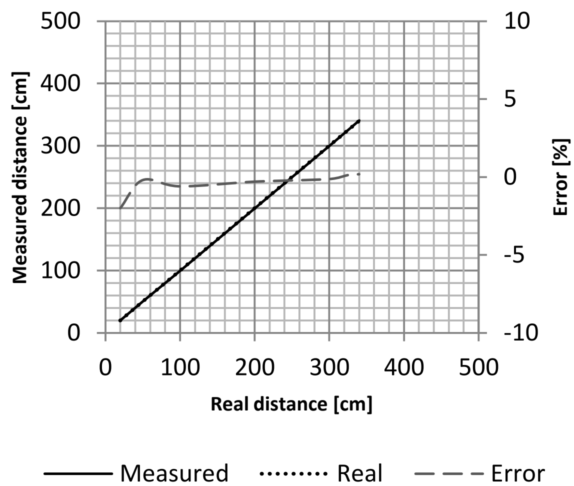

Fig. 12 – Results obtained for 5 x 5 cm flat surface covered with aluminium foil (for distances above 340 cm the obstacle was undetectable)

2) Obstacles Not Perpendicular to the Detector

For these measurements flat wooden wall were employed, inclined in 60 and 75 degrees relative to the detector's beam axis. Each measurement was processed 10 times and average values were taken in account. The results obtained for the above specified obstacles are enlisted in graphs below. Each graph consists of three lines. The dotted line shows how the ideal detector response should look like while the solid line represents the measured values. The dashed line represents percentage expression of the measurement error.

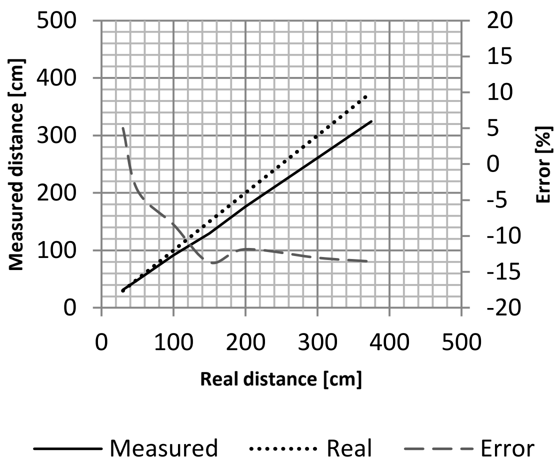

Fig. 13 – Results gained for distance measurement from a wall inclined in 60 ° (120 °) to the axis of the detector's beam

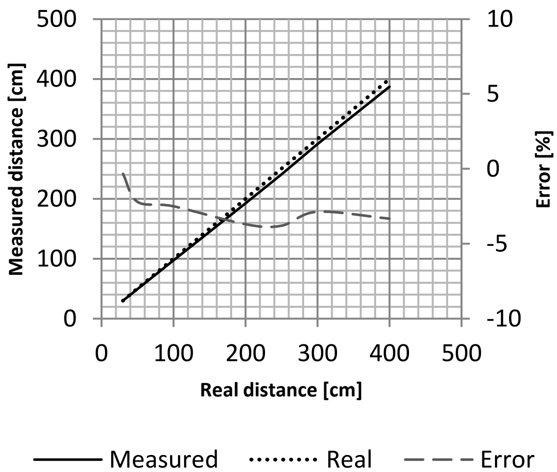

Fig. 14 - Results gained for distance measurement from a wall inclined in 75 ° (105 °) to the axis of the detector's beam

IV. Conclusion

This paper deals with the issue of ultrasonic detectors SRF02 application for obstacles around small autonomous airship recognition. It is crucial to detect the obstacles in distances from 50 to 200 cm and under different angles. The results that were obtained by the measurement are depicted in graphs above. By these measurements it was proven that:

- For obstacles perpendicular to the detector the measurement error is lower than ± 2.5 % at the air temperatures from 20 to 25 °C. For higher temperatures, additive error of + 1 % per 5 °C should be taken in account and vice versa for lower temperatures.
- The relative measurement error is not affected by the surface of the obstacle unless the ultrasonic beam attenuation is so high that the detector is unable to detect the obstacle at all. This is applicable also to small object that do not provide sufficient reflection.
- If the obstacle's surface is not perpendicular to the beam's axis, the measurement error rapidly increases. This is applicable for surface declination higher than 15 °. For declinations around 30 ° the relative error is approximately –13 %, which roughly corresponds with the graph depicted in Fig. 3 for beam angle α = 40 °. It also roughly corresponds with the typical radiation diagram depicted in Fig. 2.
- According to the experiences gained from the ultrasonic detectors' reliability measurements it can be stated that the set of SRF02 detectors is suitable to be applied for obstacles detection around the autonomously operating small airship under the following conditions:
- There are only obstacles that embody sufficient reflection area (no wires, string, etc.).
- The safety distance is set to at least 75 cm in order there was sufficient space for negative measurement errors caused by the declination of the obstacle's surface relative to the detector's beam.
- The safety distance is set to no more than 150 cm in order small and/or poorly reflecting surfaces could be detected properly.

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