The Influence of Drive Unit on Measurement Error of Ultrasonic Sensor in Multi-rotor Flying Robot

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Abstract:
The article describes the impact of the drive units on the data obtained from ultrasonic sensors. These sensors are mounted on the multi-rotor flying robot. In experiments, previously designed ultrasonic sensor was used. On purpose of this study special testbed, consisted of a dynamometer and manipulator from KUKA company was created. In the research the influence of the location of the drive unit on the aforementioned sensor was measured. For this purpose, the sensor was placed in front, behind and in the line of the rotating propeller. The obtained results allowed to identify places where there are the least interference from the drive units that affect the ultrasonic sensor. Thanks to this, the results of measurements of the obstacles distance from a flying robot were improved.

Keywords: *quadrocopter, sonar, ultrasound, navigation*

1. Introduction

One of the key issues that goes along with autonomous robots is an obtainment of an environmental information, [2]. For this purpose a various systems such as video-based scanners or laser can be used. However many of these systems are not suitable for the on board implementation in the flying robot. Often ideas of the use of precision and heavy equipment are dropped. Instead of this, smaller, but less accurate sensors are utilized. An alternative may be creation of system based on several subsystems [3]. The fusion of such subsystems helps to minimize measurement errors, as well as reduces of the impact of environmental conditions on the received data. Through this method, similar or even better results than the use of one precision and heavy sensor can be obtained. In development of one of the most common measurement systems, ultrasonic sonar are used [1]. Their compact, yet lightweight design, provides a large flexibility for installation and does not increase weight of the flying robot platform. Compared to infrared sensors their major advantage is the insensitivity to natural light. Ultrasonic sensors are used to determine the distance to flat obstacles such as walls and floors. Many research groups who works on flying multi-rotors platforms are not aware of the consequences of location of the ultrasonic sensor. The place where sensors are mounted on board of the robot is as important as obtainment not disturbed data. In general, the sensors are mounted in places where it will be convenient to measure the workspace, regardless of distance to power units. This article presents the results of experiments to determine the most preferred locations for installation of ultrasonic sonar on board of the flying robot. This leads to improvement of the measurements obtained from them.

Sensors work in the different areas, that is why the study had to be divided into several cases. The overall aim was to establish a convenient location for ultrasonic sensors which measure the distance from walls and obstacles located around the robot. In all cases of the experiment the sensor was mounted in the plane parallel to the axis of rotation (Fig. 1).

Fig. 1. Sensor in a plane parallel to the axis of rotation of the propeller

Experiment was carried out in special room, where walls and obstacles were in safe distance from the sensors (could not catch the reflected signal from the barriers). Testbed (Fig. 2) was equipped with dynamometer (Fig. 3) and the manipulator from KUKA company (Fig. 4). Location of the sensor was changed by the manipulator's tip position.

2. The Ultrasonic Sensor

For experiments purpose, special ultrasonic sonar was designed and constructed with an idea to fit on board multi-rotor flying robot. This sensor is characterized by small dimensions (25x25 mm) and low weight (8g). To minimize the amount of robot's on-board wiring, the sensor communicates with the control PCB using the I2C interface. This approach minimizes the amount of lines to four, as well as allows for parallel connection of sensors. Each sensor has the operational amplifier, whose task is to strengthen the received pulses from the transmitter/receiver ultrasonic part. For processing

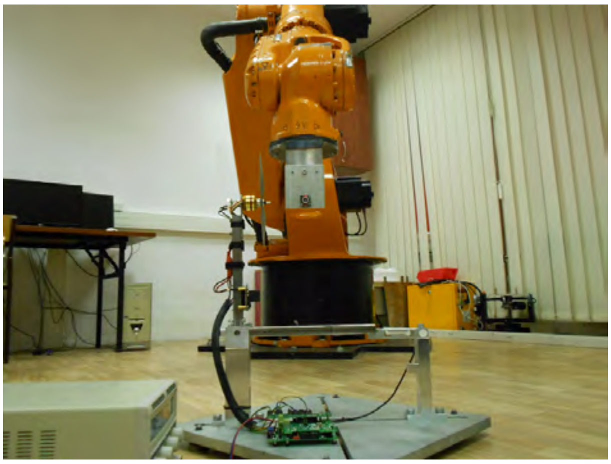

Fig. 2. *Testbed*

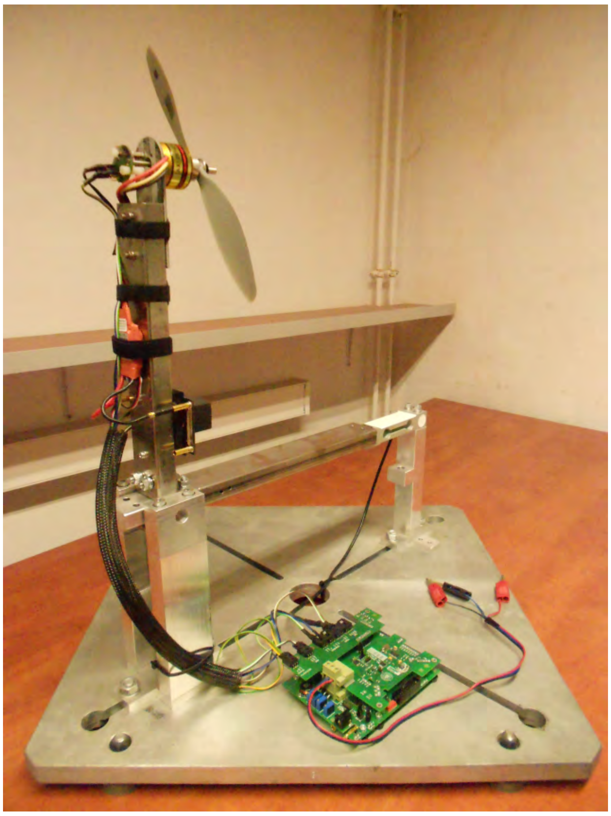

Fig. 3. *Dynamometer with drive unit and the propeller*

the received data 8bit CPU (AVR) was used.

In the first phase, processor via an ultrasonic transmitter sends a packet consisting of 10 pulses and activates the timer. The packet is delivered via a mechanical wave. When it encounters an obstacle in its path, the pulse returns back to the transmitter and then it is processed by the measuring system. At this point, the aforementioned processor latches the input timer and counts the measured time. On the basis of the conversion by the formula 1 the distance from the encountered obstacles is obtained (where v is the speed of sound at a given temperature, and t is the total time of flight of measurement beam to the obstacle and back). Befor the experiment, sensor was calibrated. Standard deviations of measurements for different distances were shown in Fig. 5. As it can be seen, sensor was designed in such a way, that it cannot be used to search of walls in range up to 20 cm. On the other hand, this sensor is perfectly good while using in a range above 20 cm and up to 60 cm. During normal operation it achieves error less than 0.5 cm (standard deviation calculated for tested sets of data).

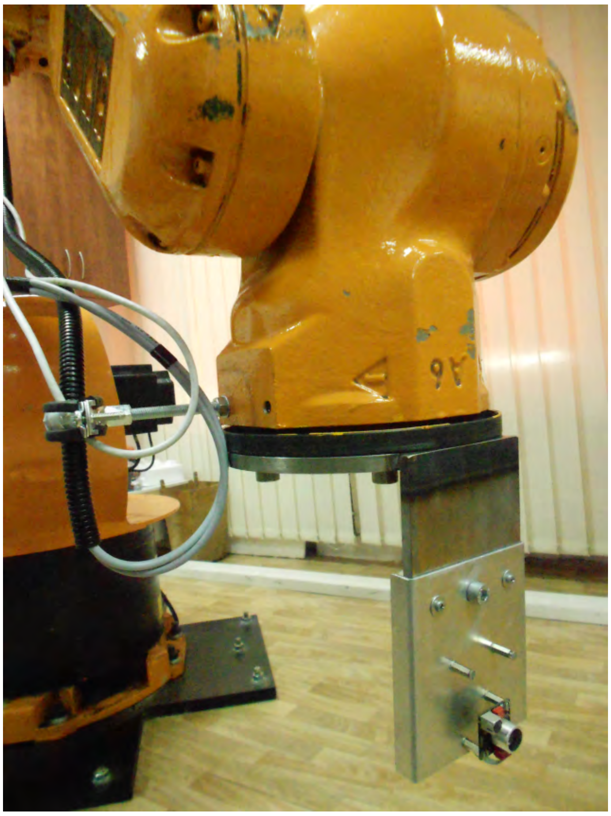

Fig. 4. *Ultrasonic sensor on the KUKA robot*

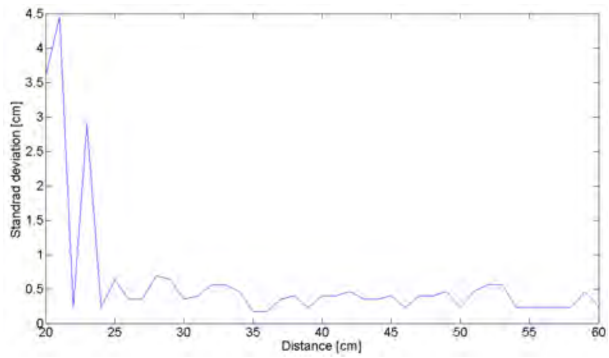

Fig. 5. *Ultrasonic sensor - standard deviation*

$$l = \frac{v \cdot t}{2} \tag{1}$$

$$v = 331.5\sqrt{\frac{1+\theta}{273.15}}\,\frac{\mathrm{m}}{\mathrm{s}} \tag{2}$$

The speed of sound at a given temperature is calculated from the formula 2, where θ is the temperature of the air (in °C) during the test and $331.5\frac{m}{s}$ is the speed of sound at 0°C.

3. Measurement of the Distance from the Wall

3.1. Testbed Specification

Before testing appropriate sensor was calibrated. The study was performed by using a dynamometer (in order to test the drive and the propeller) and KUKA manipulator (model KR 500 570-2 PA). It was decided to use the manipulator because of the ability to simple and accurate move the sensor (mounted permanently to the tip of the manipulator) in 3D space relative to a stationary motor. The experiment was carried out as "enter how many" places where the ultrasonic sensor could be mounted in.

3.2. Experiment Description

The study refers to the determination of the impact of the air stream generated by the robot's drive unit on sonar distance measurement error. The study was divided into two parts. The first included the investigation of the effect of air flow on measurement error when the position of ultrasonic sensor was changed in relative to the drive location. In the second part, angular speed (duty cycle of the PWM control signal) of power unit was subjected to change. During tests, the sensor was placed in several different places on planes B, C, D, E and F (Fig. 6 and 7). The planes were

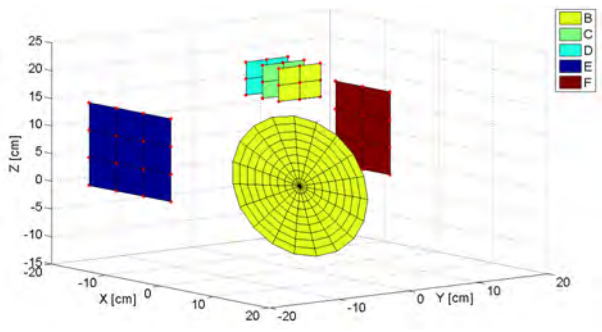

Fig. 6. *Planes on which sensor was placed*

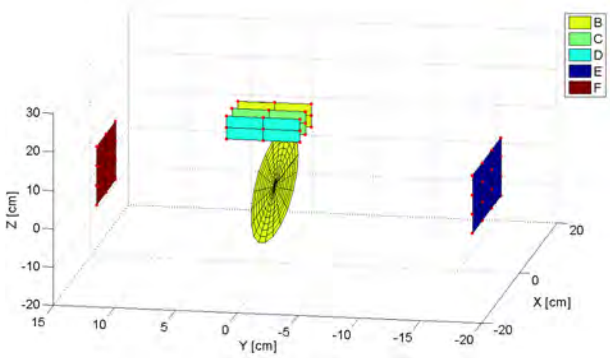

Fig. 7. *Planes on which sensor was placed (different perspective)*

marked with color and the location at which measurements were collected are marked with red points. Also in Fig. 6 concentric circles that lie on a different plane can be seen. It is the position of the drive unit and propeller, which during tests, accelerated the air flow. Each point for which measurements were collected can be represented as follows:

- in plane B: $x = \{0, ..., 0\}$, $y = \{-3, 0, 3\}$, $z = \{15.7, 18.7, 21.7\}$,
- in plane C: $x = \{3, ..., 3\}$, $y = \{-3, 0, 3\}$, $z = \{15.7, 18.7, 21.7\}$,
- in plane D: $x = \{6, ..., 6\}$, $y = \{-3, 0, 3\}$, $z = \{15.7, 18.7, 21.7\}$,
- in plane E: $x = \{0, 5, 10, 15\}$, $y = \{18.7, ..., 18.7\}$, $z = \{0, 5, 10, 15\}$,
- in plane F: $x = \{0, 5, 10\}$, $y = \{13, ..., 13\}$, $z = \{0, 5, 10, 15\}$.

During tests, the air flow was directed toward the plane E. In this way, the plane B, C and D were perpendicular to the propeller. With this arrangement, it was possible to measure the distortion of alike the inlet air stream (plane F), a direct stream of air (plane E) and a cutting circular stream of propeller's plane (plane B, C and D).

It is very important to notice that planes B, C, D, E and F are only virtual. It means that they connect points of measurements but do not show the direction of the ultrasonic beam. In other words, planes were shown only for the purpose of the better understanding of the whole experiment. In each case, when measurement was taken, ultrasonic beam was perpendicular to the circular plane of the propeller. In a such way, influence of the air flow on distance measurement could be verified. As it was presented above, each plane has some number of places, for which, the measurements were done. These numbers of the unique places differ and depends on the plane:

- for plane B: 9 points,
- for plane C: 9 points,
- for plane D: 9 points,
- for plane E: 16 points,
- for plane F: 12 points.

Although number of places (points) differ, each point where measurement was taken, has had same number of the measurements for different speed of the propeller. After experiment was done, distortion of measurements was calculated as a standard deviation for each different measurement in particular point. In this case, reference distortion does not exist and cannot be measured. The results are grouped together and refers to certain plane. For the calculations, following algorithm was chosen:

1. Set the place of experiment (e.g. plane B, point B1),
2. Set duty cycle of the drive to 0%,
3. Collect measurments (about 700 samples),
4. Repeat steps 2 and 3 for the following duty cycles: 12, 15, 18,..., 72, 75, 78 [%],
5. Change place of the sensor (plane B, point B2) and repeat steps 1-4.

After the algorithm was executed, data was stored in memory. Based on it, standard deviation could be calculated from the formula:

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}, \quad (3)$$

where: n is a number of samples and $\bar{x}$ refers to mean value:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n}(x_i), \quad (4)$$

As it can be deduced, for each group of points (points on plane B, C, D, E or F) one unique chart with standard deviations can be obtained. Altogether, it gives 24 charts per one plane (or one point). Authors analyzed all chart and decided to show only chart where noise was extremely different i.e. for 0% and for 78% of duty cycle.

3.3. Studies of Impact of the Air Stream on Measurement Noise

The study was divided into several parts. The first concerned the planes B, C and D. These planes were parallel to each other and shifted by 3 cm to each other. In the results, the charts represent the standard deviation as a measure of the impact of the propeller on measurement disturbance. The first two graphs refer to the measurement noise in plane B. The graphs are shown in Fig. 8 and 9.

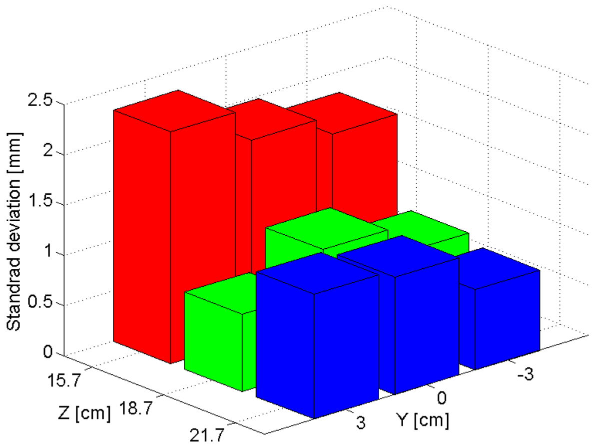

Fig. 8. *Noise in plane B for duty cycle of 78%*

As it can be seen the greatest disturbance occured when the sensor was near motor and then moved to the axis of propeller (duty cycle of 78%). It is obvious, because the air turbulence is the greater the nearer the ultrasonic sensor. In addition, it can be noted that the measurement error decrease when sensor is moved in the Y axis i.e. when the sensor moves away from the axis in which the motor is running - one can apply the same rules here as in the case of the Z axis. In the same plane, authors calculated the standard deviation when propeller was stopped (duty cycle 0%). Results can be seen in Fig. 9. Noise was totally random. What is interesting, the highest standard deviation was only 0.5 mm higher when the propeller was rotating then

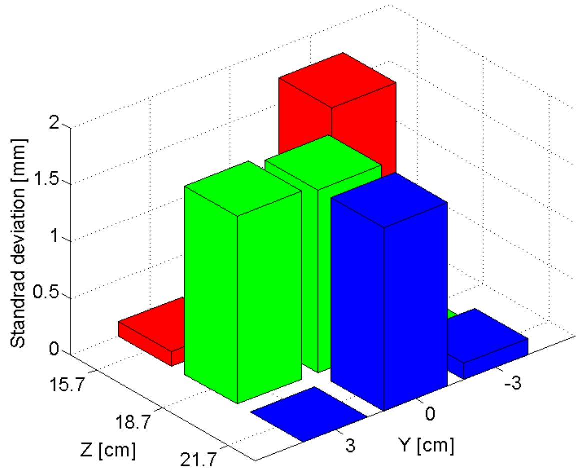

Fig. 9. *Noise in plane B for duty cycle of 0%*

when drive was turned off. Further results present the measurements noise in the planes C and D. As previously defined, these planes are shifted respectively by 3 and 6 cm from the plane B. The standard deviation for the plane C is shown in the graph 10 and 11. It is clear that the with the smaller distance of ultra-

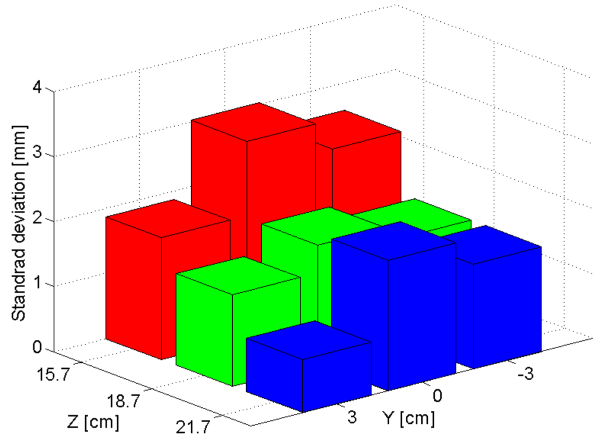

Fig. 10. *Measurement disturbances in plane C for duty cycle of 78%*

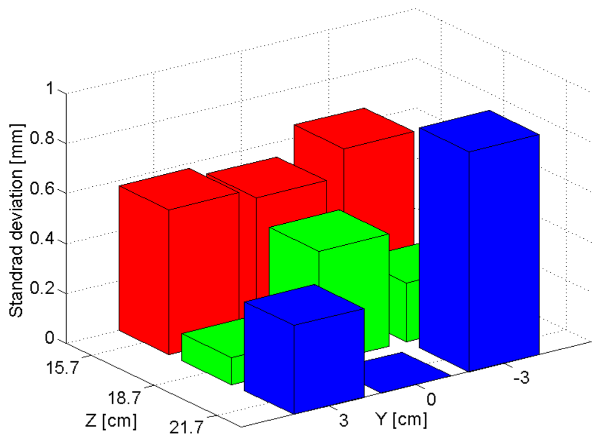

Fig. 11. *Measurement disturbances in plane C for duty cycle of 0%*

sonic sensor in Z axis the standard deviation increases. This main problem is caused by technical reasons. This distance can not be increased beyond the dimension of the robot. Additionally, it is preferably to move the sensor from the rotor axis in the plane where the Y axis lies. This effect can significantly reduce the measurement error. In Fig. 11 standard deviation for plane C was calculated but in different circumstances i.e. with zero velocity of the propeller. As it was discussed in a case of plane B, also here, standard deviation was random. Compared to plane B, noise in that case is much smaller and equals less then 1 mm.

Similar results as for the plane B and C were obtained for the plane D. In the experiment, planes B, C and D represent different position than parallel to each other planes E and F. For these planes, the air flow was perpendicular and intersecting (note that sensor beam was perpendicular to the plane E and F). The standard deviation for 16 points in the plane E is presented in Fig. 12 and 13. In order to improve the analysis a view

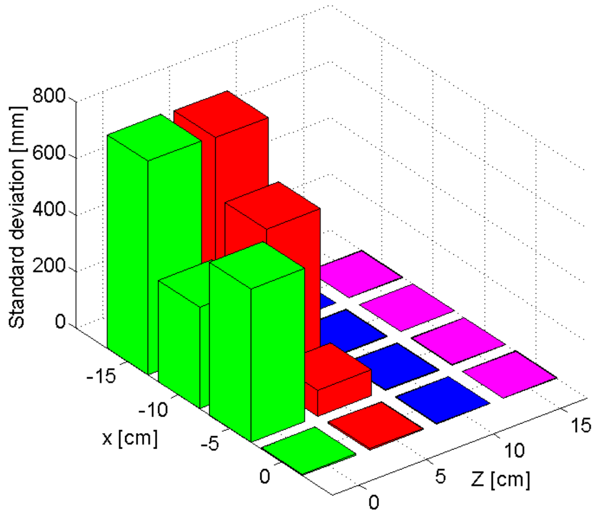

__Fig. 12.__ Measurement disturbances in plane E for duty cycle of 78%

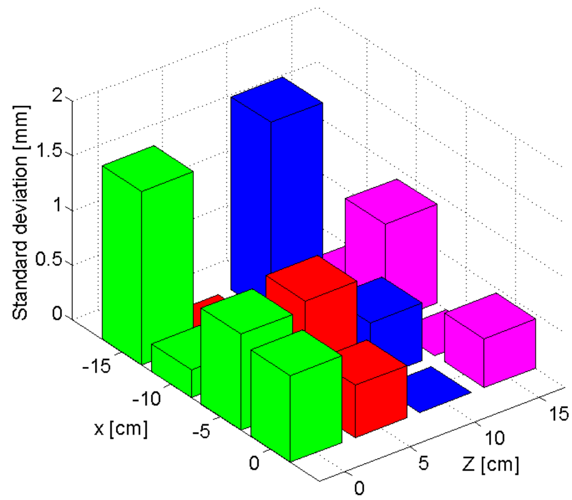

__Fig. 13.__ Measurement disturbances in plane E for duty cycle of 0%

of plane E in projection onto the motor's plane should be added. This projection is shown in Fig. 14.

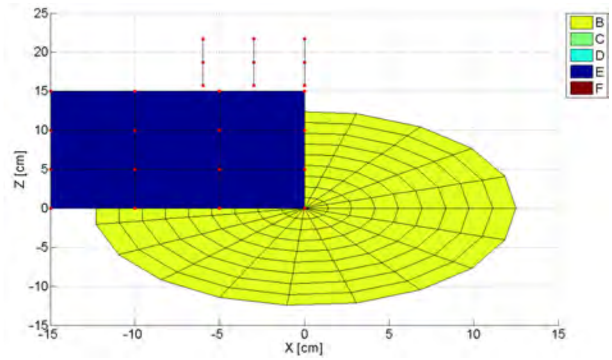

__Fig. 14.__ The projection of plane E onto the plane of the drive unit

In Fig. 12 increase of measurement error while approaching to the extreme point of $P = \{x : -15, z : 0\}$ is noticeable. This error decreases while increasing values (from 0 to 15) in the Z axis which is happening due to moving away from the air stream. Additionally, this error decreases when approaching the axis of the rotor in the X direction which is inconsistent with the theory of reducing the error when moving away from the stream. However, this effect can be explained in another way. Firstly, in the axis of the rotor air is not twisted. In other words it can be said that the central axis consists only of the air stream parallel to the axis. Since the sensor consist of transmitter and receiver, which are in distance of a few milimeters, this efect can be somehow beneficial for the sensor and only slightly distorts the distance measurement in extreme situations. Secondly, propeller can generate airstream originally inconsistent. It means, that in middle of the airstream, air does not flow with the speed of outer shells of the airstream. In Fig. 12 standard deviation was at the level of 800 mm, it gives straight statement: in that circumstances ultrasonic sensor does not provide any reliable data. In order to prove it, authors have calculated standard deviation for the same plane but when motor was stopped. Results were shown in Fig. 13. The highest noise occured in random point and its standard deviation was about 1.6 mm. The last measurement plane (F) was placed behind the drive unit. Thus, the sensor was in the intaken airstream. Feedback gathered during the tests allowed to draw conclusions. Measurement error depending on the position in the plane F was shown in Fig. 15 and 16.

In this case, the error slightly depends on the sensor position in the Z axis, however it strongly depends on the position in the X axis. It can be seen that this error increases when approaching the axis of the rotor. Thus, this situation is opposed to the case of the plane E. This is due to turbulence of the air sucked by the drive during normal operation. The accelerated air creates vacuum which generates turbulent areas concentrated around the motor spindle. Even though the measurement error is still observable, the influence of drive unit is small. It is proved in Fig. 13, where standard deviation was calculated for the duty cycle equals

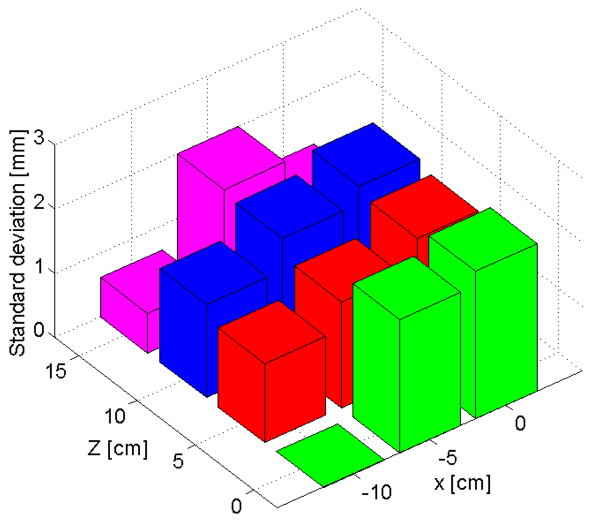

Fig. 15. *The standard deviation in the plane F for duty cycle of 78%*

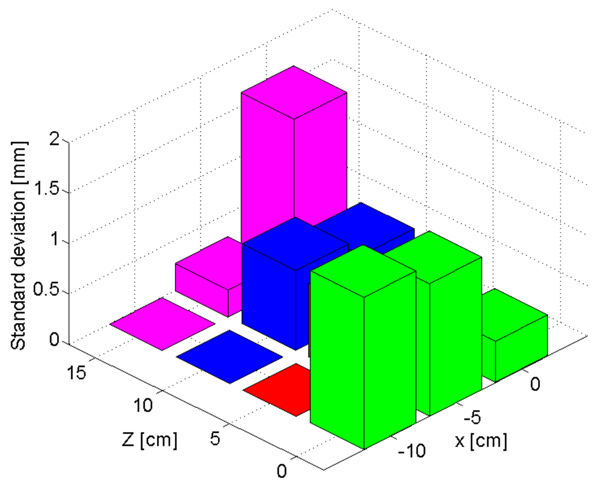

Fig. 16. *The standard deviation in the plane F for duty cycle of 0%*

0%. As it can be seen, the highest standard deviation is about 2 mm, where error for the 78% of duty cycle was about 3 mm. Therefore intaken airstream is not distorting measurement as much as it was in the case of plane E.

4. Results and Conclusions

On the basis of research, the conclusion was drawn: bad location of the ultrasonic sensors (which measures the distance to the walls/obstacles) can cause errors in measurements derived from them. Places where the influence of the drive unit on measurement is negligible were also determined. The best place for the ultrasonic sensor is between blades, so that the beam is directed according to the plane of the cutting blades. As it was shown in the case of plane B, C and D the error was relatively small (1-3 mm). Sesnor can be mounted around the propeller and the best place is to put the sensor in a plane of the propeller. On the other hand, the worst place is to measure the distance, when the sensor is under the propeller, so when it is within airstream. Sensor also should not be mounted above the propeller, especially in a center of the its axis. It was proved that the measurement error depends strongly on the sensor position. It was also shown that the influence of the airstream on the ultrasonic sensor is axled while using them in quadrocopters.

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