Ultrasonic Localization of Multiple Robots

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Abstract: In this work, we are focused on mathematic entity of localization by trilateration. Mathematical equations are usable for localization of source of ultrasonic waves. These can be measured in plane or 3D space by microphone array. We solve step-by-step localization by two, three and four sensors. Work also contains parts about localization without microphone array. For these measurements are used only distances between robots. We discuss about usability of ultrasonic, its advantages and necessity of temperature and humidity compensation.

Keywords: Ultrasound, swarm, microphone array, localization.

1. INTRODUCTION

At the time when robots are slowly deployed in almost every life activity, from industry, through household, medicine, education, sports, entertainment, to nanotechnology, it is needed to assess the future direction of these technologies. We require the use of swarm robotics and next reducing concerning to nanotechnology for a near future period. Swarm robotics in the current period of natural disasters and armed conflicts that which can save countless lives. In this I found the motivation why to develop this work.

In the previous activity we were talking about the movement of the group of robots in the external area with barriers. Suggested algorithms were simply applied also to the internal area, the only problem was the localization. GPS in this area is not applicable. In this work we are going to concern on the creating of the system that will measure ultrasound made by one or more robots with help of the microphone array. By the measured values we will be able to localize the ultrasound source in a space and then to locate the position of all robots.

The choice of ultrasound is conditioned with suitable environment, accurate measurement and the unheard to hear this for humans. The ultrasonic receivers and transmitters are simply available, cheap and life-threatening.

We will focus on the selection of a suitable source of ultrasonic and sensors. We will seek to ensure redundancy of our solution, able to identify the failures in the measurement and removal of faulty sensors. In the case of deployment of our system in the external area we will be able to correct the measured values of Global Positioning System with the use of local position data.

2. SWARM ROBOTICS

Swarm robotics is with its properties very similar to group of people or animals. Animals have always hunted in packs or carried out certain work together. These activities lead to a biologically inspired control methods and their results are robots that are cooperating on exact activities.

To the basic and the simplest task there can be included the maintaining of formation. The formations have to do some task, as it is in the case of living organisms, doing activity with the greatest efficiency at the lowest energy expenditures. An example of such a grouping could be flying geese in the flock.

Figure 1: Formation of flying birds.

3. ULTRASOUND

By the technological side, the ultrasound began to develop during the First World War. It took care of that evolution of submarine transmitters. The rapid development occurred after the sinking of the Titanic in 1912. It has been shown that the detection of icebergs

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E-ISSN: 2409-9694/15

is better at higher frequencies. This led to the development of sound waves out of the audible spectrum. The first was a pioneer Langevin, who is in general considered as the father of ultrasound. The term ultrasound we understand a sound which frequency is above the audible spectrum. For an audible sound spectrum we consider the frequencies from 20Hz to 20kHz. Borders of the spectrum are different for each person and with the aging of people the spectrum gets reduced [1].

3.1. The Effect of Temperature on the Speed of Sound

For the use of sound / ultrasound in the real environment is therefore needed correction of temperature and humidity. According to [2] is the speed of sound can be written in the form:

$$V = Vo(1+\gamma\vartheta)(1+AV\delta) \tag{1}$$

Where:

V_0–The speed for 0°C and 0% relative humidity,

V_0=331, 46 ms^{-1},

γ – Temperature coefficient of speed around 0°C,

γ= 1,83. 10^{-3}°C^{-1},

AV–constant of the area for 50÷200 kHz AV ≈ 2,2.10^{-4},

δ–Relative air humidity in %,

θ–Temperature of the air in °C,

This relationship is true if $\lambda > a$ (a is the mean free path of molecules), i.e., for frequencies up to 100MHz.

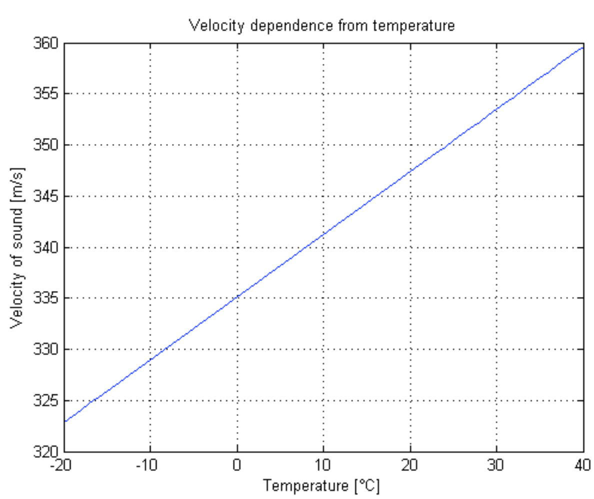

Figure 2: Effect of temperature on velocity of sound.

In practice realizations it is not necessary to do any compensation of the speed of sound according to the changes in pressure. In theory, the speed V is independent of the pressure during the changing $P0$ it grows also $\rho 0$. This leads to the independence of the speed of sound from the altitude. The average range of atmospheric pressure 90÷110kPa is the change of speed for about 3.10^{-6}% [2, 4].

3.2. Effect of Wind on the Ultrasound Propagation

In the case of ultrasound measurements outdoors there is needed the correction of flowing of the sound, practically of wind. Progressing wind takes the ultrasonic wave and thus causes the measurement uncertainty. If the wind is flowing in the direction of ultrasound, the measured distance value is less than the real distance and in the case of upstream flow, this value is longer.

The actual measurement of the wind speed and its direction can be measured using four microphones placed at the corners of a square, directed with active areas to each other.

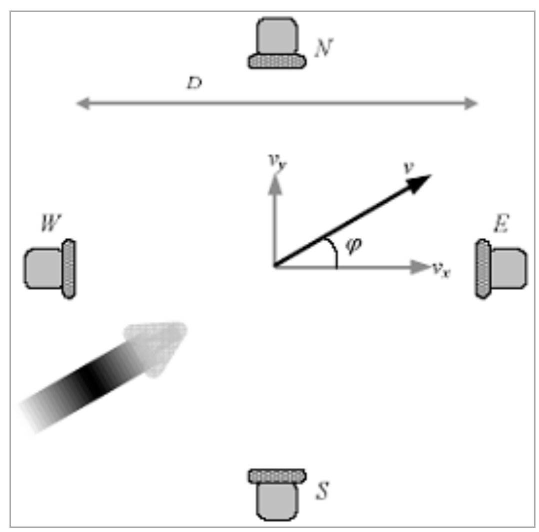

Figure 3: Measurement of air velocity.

This system is used to measure the speed with using of TOF method. It is measured the time of flight of ultrasound in the direction of x-axis and y-axis. According to the following relationships we are able to calculate the speed of wind in the directions of the individual axes [3].

$$v_x = \frac{D}{t_x} - V$$
$$v_y = \frac{D}{t_y} - V \tag{2}$$

t–TOF in the direction of certain axis,

v_x–Velocity of wind in the direction of x-axis,

v_y–Velocity of wind in the direction of y-axis,

D–Distance between adjacent sensors,

V–Velocity of ultrasound in certain area,

Total speed of wind and the direction of the wind are given by the equations:

$$|v| = \sqrt{v_x^2 + v_y^2} \qquad \varphi = arctg\frac{v_y}{v_x} \tag{3}$$

4. DISPOSITION OF SENSORS

Sensors disposition directly affects the capacity to detect the source of ultrasound.

4.1. Two Ultrasonic Sensors

In the case of using two ultrasound' sensors, we are able to directly determine the distance from the source of the robot in the plane.

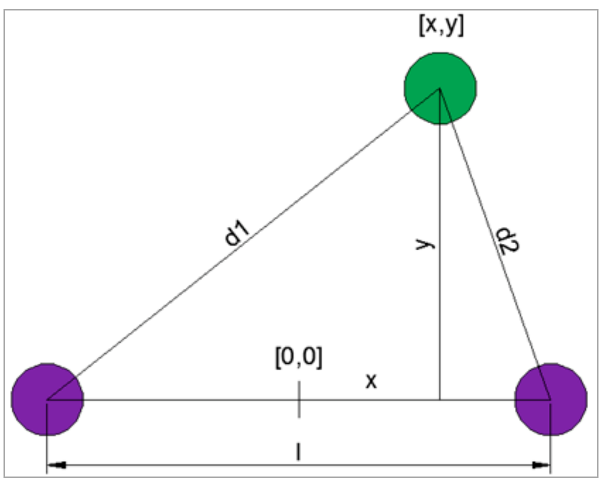

Figure 4: Two ultrasonic sensors.

Equations describing the distance of the source are divided from the Pythagorean Theorem.

$$x = \frac{d_1^2 - d_2^2}{2l} \qquad y = \sqrt{d_2^2 - \left(\frac{l}{2} - \frac{d_1^2 - d_2^2}{2l}\right)^2} \tag{4}$$

Where l is the distance between the sensors and x_1, x_2 are the distances measured from the ultrasound. System with two receivers is suitable only for the using in embosomed spaces where the robot moves along the flat floor. There is no wind and the transmitter is placed at the same height above the ground as the receivers are placed. The presence of the inequalities could cause the movement of the robot in the Z axis direction and this change cannot be compensated in use of two receivers. The presence of wind could cause a change of speed and direction of ultrasound.

Measuring with two microphones are described in [4], this system is analogous to the human ear.

4.2. Three Ultrasonic Sensors

If the measuring device comprises 3 sensors, this system is able to locate the source of the ultrasound in the area.

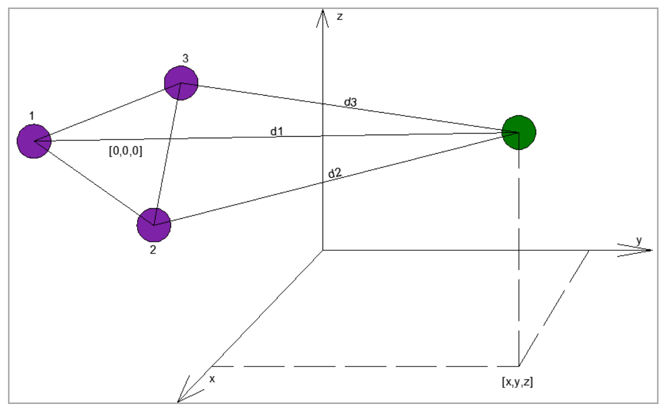

Figure 5: Three ultrasonic sensors.

For the system shown in the Figure **5** solution leads to three equations with three unknowns. The sensors are located at the vertices of an equilateral triangle with sides of length l, which is located in the plane XZ. If the coordinate system is placed in the center of gravity, then the coordinates of the sensors are:

1. $\left[\frac{l}{2}, 0, \frac{v}{3}\right]$

2. $\left[-\frac{l}{2}, 0, \frac{v}{3}\right]$

3. $\left[0, 0, -\frac{2}{3}v\right]$

Where the v is height of the triangle and its growth is:

$$v = \sqrt{l^2 \frac{l_2}{4}} \tag{5}$$

The final location of the ultrasonic source can be calculated from the following equations:

$$\begin{aligned} d_1^2 &= \left(x-\frac{l}{2}\right)^2 + y^2 + \left(z-\frac{v}{3}\right)^2 \\ d_2^2 &= x^2 + y^2 + \left(z+\frac{2}{3}v\right)^2 \\ d_3^2 &= \left(x+\frac{l}{2}\right)^2 + y^2 + \left(z-\frac{v}{3}\right)^2 \end{aligned} \tag{6}$$

Solution of these equations leads to source coordinates in a 3D space:

$$\begin{aligned} x &= -\frac{d_1^2-d_3^2}{2l} \\ y &= \pm\frac{\sqrt{\begin{array}{l} -\frac{d_1^4l^2}{4} - d_1^4v^2 + d_1^2d_2^2l^2 - \frac{d_1^2d_3^2l^2}{2} + 2d_1^2d_3^2v^2 \\ +\frac{d_1^2l^4}{4} + d_1^2l^2v^2 - d_2^4l^2 + d_2^2d_3^2l^2 - \frac{d_2^2l^4}{2} + 2d_2^2l^2v^2 \\ -\frac{d_3^4l^2}{4} - d_3^4v^2 + \frac{d_3^2l^4}{4} + d_3^2l^2v^2 - \frac{l^6}{16} - \frac{l^4v^2}{2} - l^2v^4 \end{array}}}{2lv} \\ z &= \frac{6d_1^2 - 12d_2^2 + 6d_3^2 - 3l^2 + 4v^2}{24v} \end{aligned} \tag{7}$$

As we can see from the equation for Y coordinate, a solution are two values, one is a source in front of distance sensors and one behind the sensors. One of these values is usable and the other one is not because of practical using. From the final disposal of sensors on the robot we will be able to ignore this value.

4.3. Four Sensors

For our needs we chose system with four sensors. This distribution causes a redundancy of sensors. With regard to the connections of the system, it is able to evaluate whether all the sensors are functional. In the case of failure of one sensor, the system is switching to the system with three microphones.

In our construction, the sensors are located at the vertices of a square with sides of length l which is located in the plane XZ. If we place the origin of the coordinate system to the point of intersection of the diagonals of the square, the coordinates of the sensors are:

1. $\left[\frac{l}{2},0,\frac{l}{2}\right]$
2. $\left[\frac{l}{2},0,\frac{l}{2}\right]$
3. $\left[-\frac{l}{2},0,-\frac{l}{2}\right]$
4. $\left[-\frac{l}{2},0,-\frac{l}{2}\right]$

From these positions we can write down the following equations describing the position of the ultrasound transmitter:

$$\begin{aligned} d_1^2 &= \left(x-\frac{l}{2}\right)^2 + y^2 + \left(z-\frac{l}{2}\right)^2 \\ d_2^2 &= \left(x-\frac{l}{2}\right)^2 + y^2 + \left(z+\frac{l}{2}\right)^2 \\ d_3^2 &= \left(x+\frac{l}{2}\right)^2 + y^2 + \left(z+\frac{l}{2}\right)^2 \\ d_4^2 &= \left(x+\frac{l}{2}\right)^2 + y^2 + \left(z-\frac{l}{2}\right)^2 \end{aligned} \tag{8}$$

Square construction provides four times system of three sensors. This solution gives us four position of ultrasonic generator [x, y, z]. Without first sensor:

$$\begin{aligned} x_1 &= -\frac{d_2^2-d_3^2}{2l} \\ y_1 &= \pm\frac{\sqrt{\dfrac{-d_4^2 + 2d_2^2d_3^2 + 2d_2^2l^2}{-2d_3^4 + 2d_3^2d_4^2 - d_4^4 + 2d_4^2l^2 - 2l^4}}}{2l} \\ z_1 &= \frac{d_3^2-d_4^2}{2l} \end{aligned} \tag{9}$$

Without second sensor:

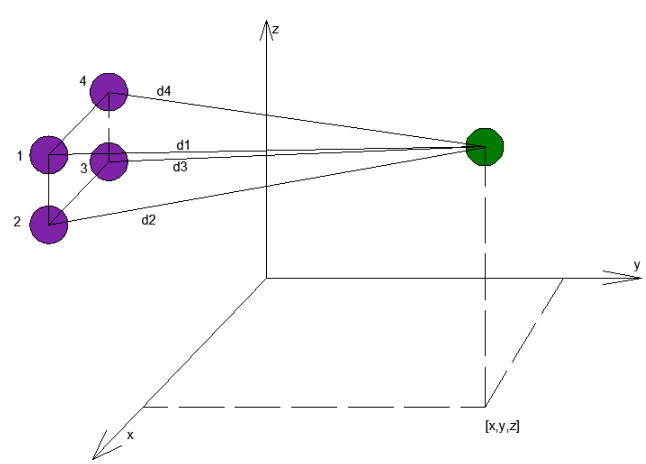

Figure 6: Four ultrasonic sensors.

$$x_2 = -\frac{d_1^2 - d_4^2}{2l}$$
$$y_2 = \pm\frac{\sqrt{\begin{array}{c}-d_1^4 + 2d_1^2 d_4^2 + 2d_1^2 l^2 \\ -d_3^4 + 2d_3^2 d_4^2 - 2d_3^2 l^2 + 2d_4^4 - 2l^4\end{array}}}{2l} \quad (10)$$
$$z_2 = \frac{d_3^2 - d_4^2}{2l}$$

Without third sensor:

$$x_3 = -\frac{d_1^2 - d_4^2}{2l}$$
$$y_3 = \pm\frac{\sqrt{\begin{array}{c}-2d_1^4 + 2d_1^2 d_2^2 + 2d_1^2 d_4^2 \\ -d_2^4 + 2d_2^2 l^2 - d_4^4 - 2d_4^2 l^4 - 2l^4\end{array}}}{2l} \quad (11)$$
$$z_3 = \frac{d_1^2 - d_2^2}{2l}$$

Without fourth sensor:

$$x_4 = -\frac{d_2^2 - d_3^2}{2l}$$
$$y_4 = \pm\frac{\sqrt{\begin{array}{c}-d_1^4 + 2d_1^2 d_2^2 + 2d_1^2 l^2 - 2d_2^4 \\ +2d_2^2 d_3^2 - d_3^4 - 2d_3^2 l^2 - 2l^4\end{array}}}{2l} \quad (12)$$
$$z_4 = \frac{d_1^2 - d_2^2}{2l}$$

4.2. Wrong Sensor Selection

For final localization and wrong sensor separation, we can use average of all measurements. Wrong sensor can be given by following equations:

$$\begin{array}{l}
\frac{([x_1,y_1,z_1]+\varepsilon_1)+([x_2,y_2,z_2]+\varepsilon_2)+([x_3,y_3,z_3]+\varepsilon_3)}{3} \neq [x_4,y_4,z_4]+\varepsilon_4 \\
\frac{([x_1,y_1,z_1]+\varepsilon_1)+([x_2,y_2,z_2]+\varepsilon_2)+([x_4,y_4,z_4]+\varepsilon_4)}{3} \neq [x_3,y_3,z_3]+\varepsilon_3 \\
\frac{([x_1,y_1,z_1]+\varepsilon_1)+([x_3,y_3,z_3]+\varepsilon_3)+([x_4,y_4,z_4]+\varepsilon_4)}{3} \neq [x_2,y_2,z_2]+\varepsilon_2 \\
\frac{([x_2,y_2,z_2]+\varepsilon_2)+([x_3,y_3,z_3]+\varepsilon_3)+([x_4,y_4,z_4]+\varepsilon_4)}{3} \neq [x_1,y_1,z_1]+\varepsilon_1
\end{array} \quad (13)$$

The ε is error of measurement. If measured values from sensor are out of average range, then values are corrupted. Final measured value will be arithmetic average of remaining three positions. In the case when all sensors measured values in acceptable range, final position will be average of all four measurements.

4.3. Reciprocal Activity

Three and four sensors systems can be extended by reciprocal functionality of sensors. This can be used for better accuracy. Ultrasonic sensors can receive waves as well as transmit them. This principle is used in Walkie-Talkie. In this case operator has to switch button on radio to talk or listen. If we used sensor also for transmitting, the system would begin to show same errors like radios. In given time is only one way communication possible. If receiver is transmitting, it can't receive another signal, which can be delayed or reflexed. This information disappears in communication. Similar problem occur among switching, when transmitter didn't start transmitting and receiver already stopped listening.

4.4. Base Rotation

Given equations give us information about location of tracked object, but no about its rotation. We need to solve this parameter by another way for future localization and control.

One solution is let tracked object to make arbitrary movement. If we measured two different positions, we are able to solve relative rotation by:

$$\alpha = \tan^{-1}\left(\frac{x_0 - x_1}{z_0 - z_1}\right) \quad (14)$$

If we don't design flying or swimming robots, we can remove z coordinate from equation of rotation. Robot will be able to track another even on uneven ground or with different altitude, because both are placed on the ground.

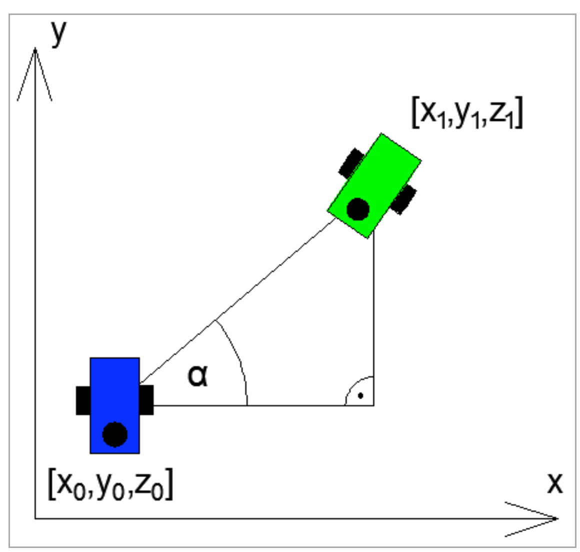

Figure 7: Relative rotation of robots.

When we know rotation of one robot in global position system, by using (4), (6), (7) and equation (14) we are able to solve positions of all following subjects in global position system.

Another way to solve rotation of group is using additional sensors for leading robot. These will provide missing rotation information. In this case solution doesn't need equation (14).

5. LOCALISATION WITHOUT MICROPHONE ARRAY

Robot localization by ultrasonic can be used without microphone array. To determine position of robots we only need to know distances between them and position with rotation of leading robot. Using one microphone and transmitter on each robot we are able to measure relative distances between robots.

In a case of three robots, we can obtain 6 distances, which describe relative position of formation. Just using 3 distances, solution provides us clearly specified triangle defined by three sides.

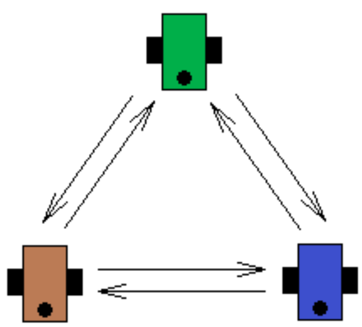

Figure 8: Distances between robots.

If every measurement is made from both sides, final position can be solve from bigger data base and more precisely. Every robot extension in formation provides more possible mutual measurements. Four robots formation provide twelve distances, which can be used for localization measurement.

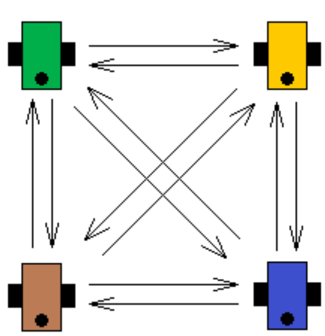

Figure 9: Measurement of distances in formation.

At least one known rotation of robot in this localization is very important. Single measurement provides us information about robots distances but no about rotation of whole formation in global position system. Solution for this problem can be leading robot equipped by other sensors, which can measure this rotation.

For position calculation from individual measurement we can use equations (4), this case is same like measurement with two sensors.

Formation of four robots can in some cases compensate obstacle in formation. We are able to solve final position of formation even without any distances. Problem can occurred if obstacle is placed directly in middle of formation. Missing distances in diagonals may leads to confusion. Final formation can be square as well as rhombus. In a case of three robots, we are no able to solve final position of formation without one measurement.

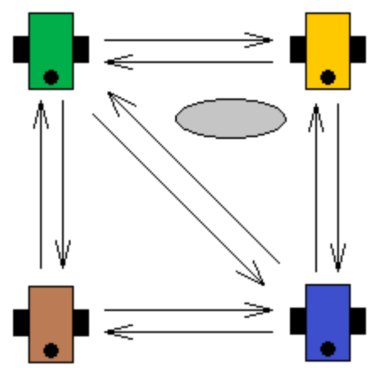

Figure 10: Obstacle information.

5.1. Impact of Robot Position on Measurement Precision

Every measurement is affected by some error. This is also true for localization of group of robots. In calculation of position with respect to measurement error, we are able to locate area, which probably contains given robot. One factor, which affects expanse and shape of this is angle between robots.

If we want to localize green robot, we have to measure distances *a* and *c*. By using (4) with known distance *b* we are able to solve final position. Precision of this measurement is influenced by angle *α.* If value of this angle is close to zero (what is not possible because motors has some size) measurement is influenced by biggest error. If angle is closer to 90°, error will be smallest. In this case distance *b* is equal to infinity. Angle α can be solved by next formulas:

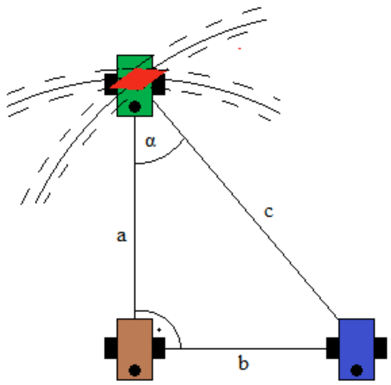

Figure 11: Localization error.

$$\cos\alpha = \frac{a}{c}$$
$$\tan\alpha = \frac{b}{a} \quad (15)$$

Rotation-error dependence is given by cosine and tangent of Alfa.

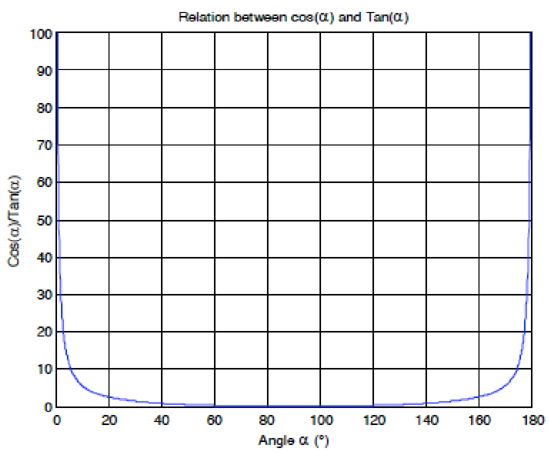

Figure 12: Relation between Cosine and Tangent.

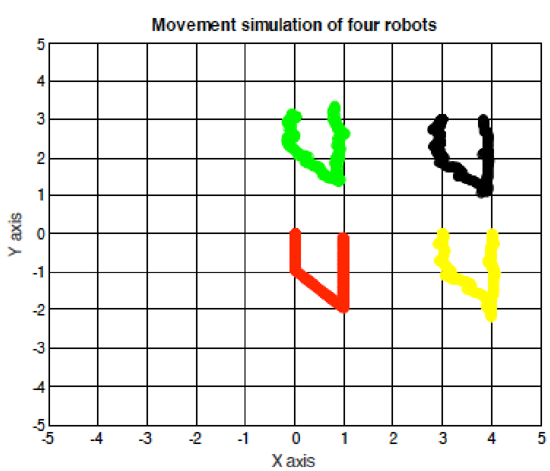

Figure 13: Group simulation.

6. SIMULATION EXPERIMENT

We simulated movement of four robots without microphone arrays. These moved in formation and their main goal was stay in formation.

Formation stayed stable, even when errors occurred on each followings robot. In this formation, red robot is leader of formation. Green and Yellow robot directly follow leader and black robot follow yellow robot. This robot don't have direct information about leading robot.

FUTURE WORK

In present, we work on impulse generator of ultrasonic waves. Future work will be focused on construction of microphone array and evaluation units. These will be used for localization of ultrasonic generator from measured distances in X, Y, Z coordinates.

ACKNOWLEDGEMENT

This paper was processed in the frame of the Req-00347-0001and KEGA 003STU-4/2014 projects.

CONCLUSION

Our designed methods provide base algorithms for localization of group of robots in unknown environment without necessity of artificial land marks. Localization of robots is solved by mutual cooperation and reciprocal measurement. These algorithms can be simple implemented in explosive environment. Ultrasonic localization compered to laser localization is more easily and cheaper, however it is less accurate and affected by temperature, humidity and air flow.

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Received on 24-11-2015 Accepted on 14-12-2015 Published on 31-12-2015

DOI: http://dx.doi.org/10.15377/2409-9694.2015.02.02.2