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Distributed radar-based monitoring system for intelligent vehicles

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Abstract. The following article introduces a model of a distributed radar-based monitoring system for intelligent vehicles which is based on surround view monitoring and measuring the dimension of objects. Our model employs ultrawideband (UWB) transceiver modules with nearly omnidirectional antennas. We also suggest that the coordinates of the detected objects are to be measured using the information provided by several transceiver modules. The article shows that this system allows measuring the coordinates and dimensions of the objects detected around the vehicle with accuracy of 10 cm. The suggested model of the radar system will help provide an accurate and detailed estimation of the traffic conditions and increase the traffic safety.

1. Introduction

The end of the XX century witnessed emerging of the automotive radar systems market. Today car manufacturers use the radar systems as a part of the driver assistance systems which include mostly long range radars (up to 300 m) with the coverage of only up to 30 degrees [1]. Such radars alone cannot meet the safety requirements specified for the modern vehicles due to their coverage, as well as range and azimuth resolution limits. Therefore today we are witnessing the development of the systems based on the UWB short range radars. To insure the proper development, in 2004 European Telecommunications Standards Institute (ETSI) published standards for the automotive short range radars (up to 30m) operating in the 77-81 GHz band. Measuring the coordinates and the dimensions of the detected objects is essential both in city traffic and on cross-country roads. Any obstacles such as stones, fallen trees, sinkholes on cross-country roads, or road safety barriers, speed bumps, pedestrians or other vehicles in the city must be detected and accurately measured by the radar systems. For these purposes radar modules and antennas with 120 degree radiation pattern are usually employed as UWB transceiver modules [2].

Distributed radar-based monitoring system. This monitoring system can be used as a part of the driver assistance system, while the coordinates and dimensions measuring can serve the following purposes:

- to keep the vehicle within the driving lane;
- to ensure a safe vehicle maneuver, including safe passage of uncontrolled road intersections or pulling out of minor roads;
- to autonomously ensure collision avoidance;

- to detect objects (a pedestrian, a cyclist, or an animal);
- to assist parking.

Figure 1 shows the general structure of our model.

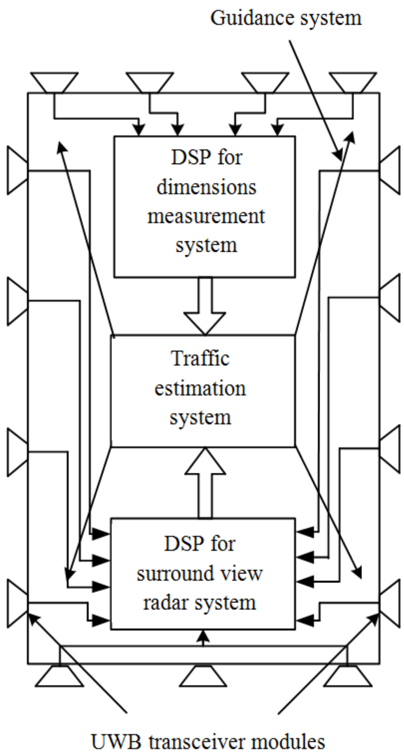


Figure 1. Block diagram of the radar-based monitoring system.

UWB antennas which provide the dimension measurements of the detected obstacles are found in the front part of the car. UWB short range surround view antennas are mounted all around the vehicle at regular intervals.

Data signal processing system includes DSP for dimensions measurement system as well as DSP for side view radar system. All the information on the detected objects, their coordinates and motion rates is processed in the traffic estimation system, which in an emergency will trigger the automatic braking system, lane keeping assist system, dynamic stability control, and anti-lock braking systems [3].

2. Surround view system

To ensure a 360° surround view the UWB transceiver modules must be mounted all around the car so that the blind spot, which is an area around the vehicle that cannot be directly observed by any of the modules, is eliminated as much as possible. Due to the specific design features of the car body, the number of the spots to locate UWB transceivers is very limited. Usually they are found under the front and rear bumpers, in the door handles, outside mirrors and fenders.

Coordinate measurements can be carried out using the well-known methods of calculating the intersection points of the position lines of the objects [4 – 8]. If there is only one object detected, its coordinates can be measured using the distance information provided by the two opposite-located transceivers. But when dealing with multiple targets, at least three transceivers are required to provide the distance measurements; otherwise the data is inconclusive. Figure 2 provides the transceiver location pattern. Numbers 1 and 2 represent the blind spot and the area which allows only the distance measurements. Accurate coordinate measurement of the objects detected in area, represented by number 2, cannot be carried out due to the object not being seen by at least three transceivers [7, 8].

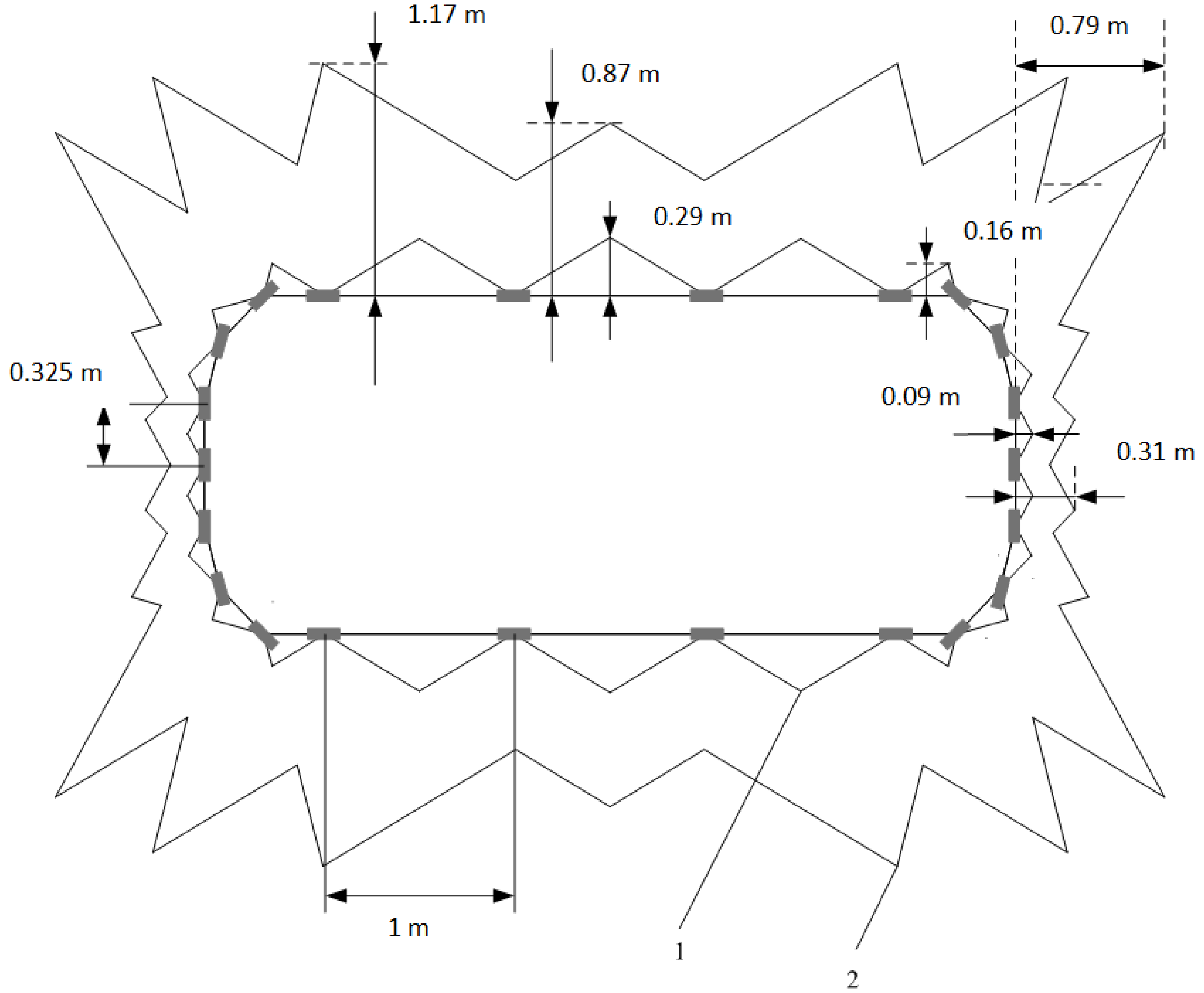


Figure 2. Blind spot and the area allowing distance measurements only.

On the front and rear bumper the UWB transceivers are mounted every 31.5 cm, while on either sides the interval is 1 m. The operating range of the system depends on the characteristics of the transceiver modules and normally stands at about 30 m [2].

Figure 3 provides the RMS errors in coordinate (x (a) и y (b)) measurement when using the distance measurement method with the x coordinate in case of a constant y = 20 m [8]. Numbers 1 and 2 represent the variations of the root standard deviation of the coordinate measurement error when using the long range method in case the interval between the modules is 2 m and 63 cm respectively.

Figure 3 shows that with the UWB transceiver modules mounted all around the car at regular intervals the RMS error in coordinate estimate is about 10 cm.

3. Dimensions measurement system in the front of the vehicle

Most of the detected objects are three-dimensional. Such objects can be presented as a number of independent point scatterers, generally referred to as highlights [9]. The range resolution of our model allows resolving the highlights of the particular objects such as road users, road infrastructure objects, or other obstacles.

Figure 4 (a) provides a geometric representation of a three-dimensional radar target. Generally the targets are not radar-transparent; therefore practically it's only possible to measure the height h and the lateral size a of an object. To make it easier to visualize we chose an objects with the highlights located along the two orthogonally related intersecting lines, which are represented by z and y axes in figure 4 (b).

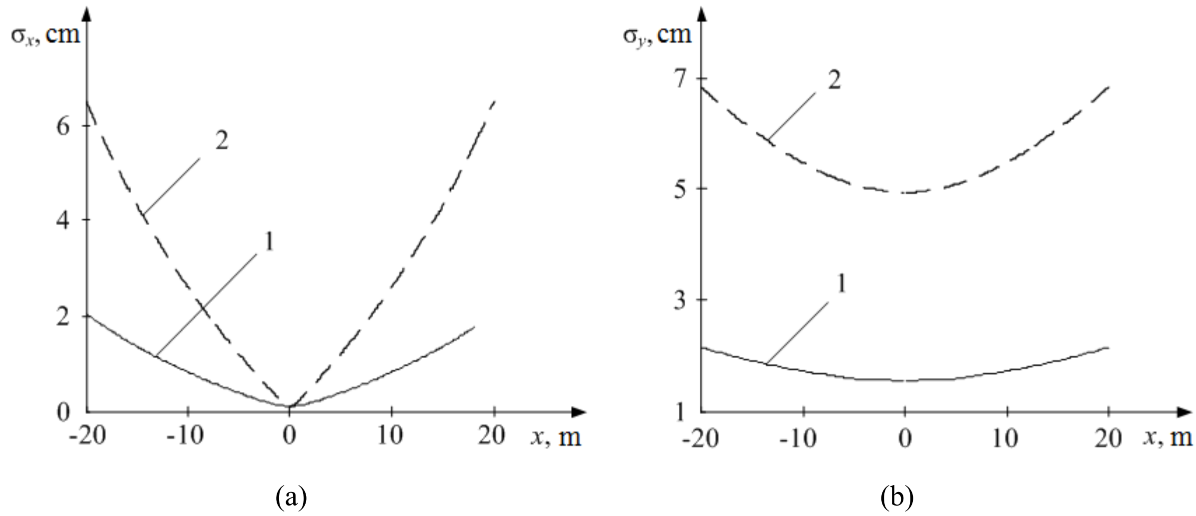


Figure 3. RMS errors in coordinate measurement when using the distance measurement method with the x coordinate in case of a constant y.

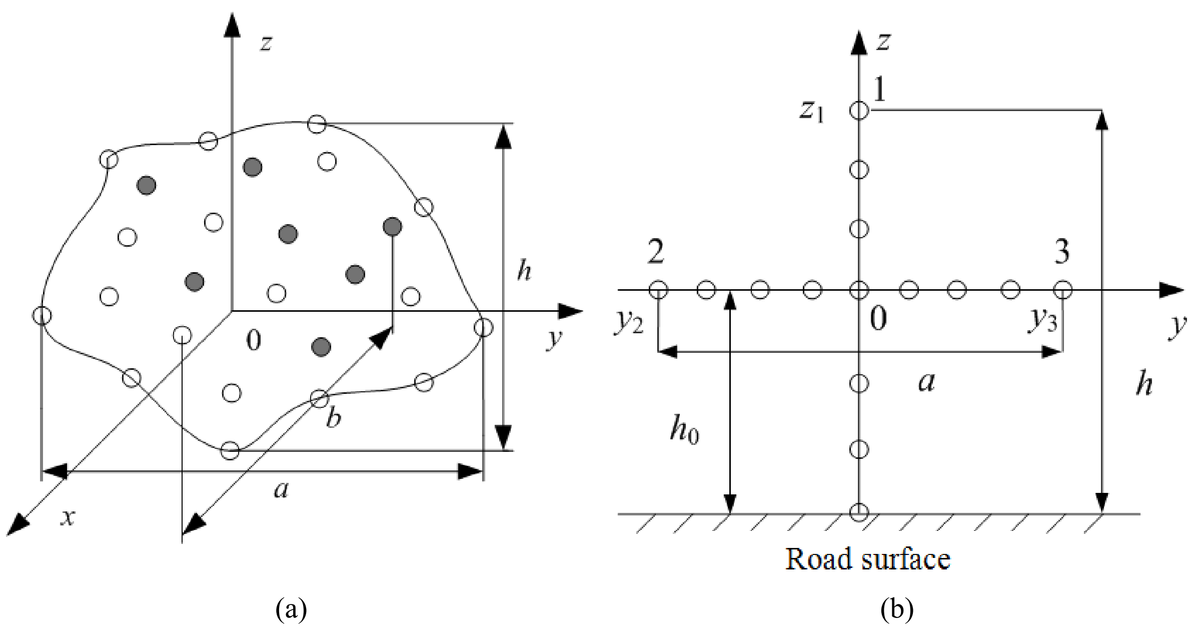


Figure 4. A model of a three-dimensional object.

h – height of the object;
h_0 – the distance between the road surface and the center of the coordinate system;
a – lateral size of the object;
b – longitudinal size;
z_1 – z coordinate of highlight No.1;
y_2 and y_3 – y coordinates of highlights No. 2 and 3 respectively.

Estimation of the highlights' coordinates allows us to estimate the dimensions of the detected objects. Normally the height of the target is measured with respect to some level, for example, the road surface for a vehicle radar system. Thus the height h of the target is equal to the z coordinate of the maximum value with respect to the road surface ($h = z_1 + h_0$). The lateral size of the object is equal to the difference between the y coordinates of the maximum and minimum values ($a = y_3 - y_2$) (figure 4 (b)).

Estimation of the coordinates of the highlights can be done by estimating the distance measurements by at least three transceiver modules. Figure 5 provides an image of a passenger car with UWB transceiver modules which are found in its front, particularly in its outside mirrors, the rearview mirror and the front bumper.

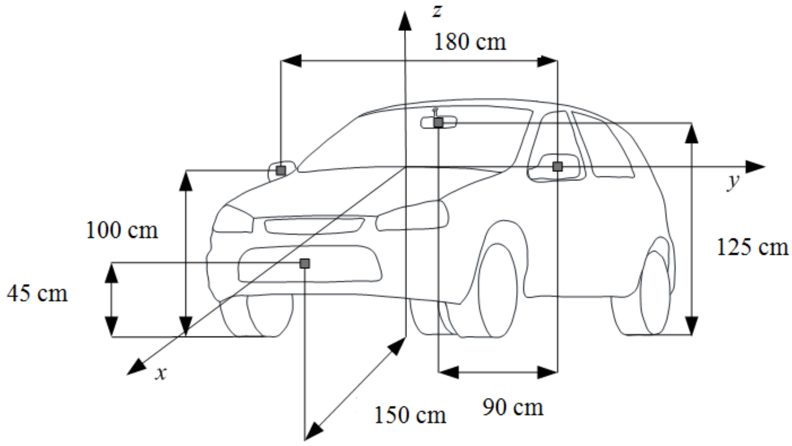


Figure 5. A passenger car with UWB transceiver modules.

The coordinates of the object can be estimated based on the distance measurements provided by three transceivers, position surfaces being spheres with radiuses R_1, R_2, and R_3 respectively. But the distance measuring method tends to give uncertain results in the situation with multiple targets. To avoid the uncertainty we use the information from four transceivers.

Figure 6 provides a system scheme, where 1, 2, 3 and 4 stand for receiving positions, T – for the target (or detected object), x_T, y_T, z_T – target coordinates, R_1, R_2, R_3 and R_4 – distance between the target and the receiving positions.

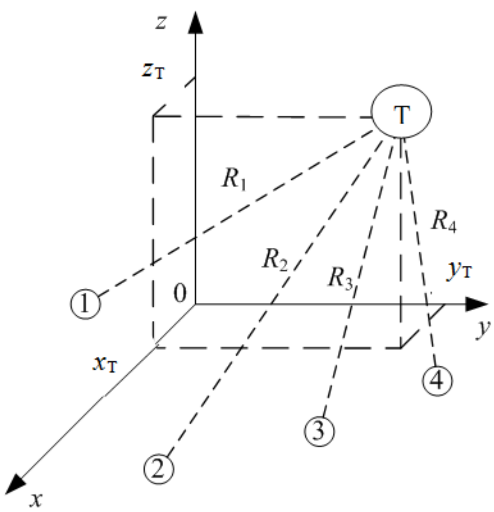


Figure 6. System scheme.

The coordinates of the target using the distance measuring method can be calculated by solving simultaneous equations:

$$\begin{cases} A_1 \cdot x^2 + A_2 \cdot x + A_3 \cdot y^2 + A_4 \cdot y + A_5 \cdot z^2 + A_6 \cdot z + A_7 = 0, \\ B_1 \cdot x^2 + B_2 \cdot x + B_3 \cdot y^2 + B_4 \cdot y + B_5 \cdot z^2 + B_6 \cdot z + B_7 = 0, \\ C_1 \cdot x^2 + C_2 \cdot x + C_3 \cdot y^2 + C_4 \cdot y + C_5 \cdot z^2 + C_6 \cdot z + C_7 = 0, \end{cases} \quad (1)$$

where coefficients A_1, A_2, A_3, A_4, A_5, A_6, A_7, B_1, B_2, B_3, B_4, B_5, B_6, B_7, C_1, C_2, C_3, C_4, C_5, C_6, C_7 are defined depending on the type of position surfaces which are actually second-order surfaces. The system of equations (1) can be solved in 8 different ways.

4. Accuracy of dimension measurements

Height h of the target is equal to the z coordinate of the maximum value with respect to the road surface (figure 4 (b)), while the lateral size of the object a accounts to the difference between the coordinates of the two highlights $y_3 - y_2$. Thus the accuracy of the height measurement depends upon the accuracy of the z coordinate estimation, while the accuracy in lateral size estimation depends upon the accuracy of the y coordinate estimation.

Assume that distance measurements for the highlights are not defined by any other conditions. This assumption is valid if in all the transceiver modules the highlights are resolved by distance estimates. Hence the estimates of y_2 and y_3 coordinates (figure 4 (b)) are independent either, and lateral size measurement error can be calculated as follows

$$\sigma_a = \sqrt{{\sigma_{y_2}}^2 + {\sigma_{y3}}^2}\,, \quad (2)$$

where σ_{y_2} and σ_{y_3} stand for the RMS errors in the y_2 and y_3 coordinate measurement.

Let us next resolve the RMS errors in the y and z coordinate measurement assuming that distance measurement errors are independent zero-mean Gaussian random variables.

Let us expand the coordinates estimation expressions, resolved from the simultaneous equations (1), into Taylor-series in the neighborhood of their true value. Using only those terms which have the first order derivatives, an expression for the RMS errors in coordinate measurement is as follows

$$\begin{aligned} \sigma_y &= \sqrt{\left(\frac{\partial y}{\partial \xi_1}\right)^2 \sigma_{\xi_1}^2 + \left(\frac{\partial y}{\partial \xi_2}\right)^2 \sigma_{\xi_2}^2 + \left(\frac{\partial y}{\partial \xi_3}\right)^2 \sigma_{\xi_3}^2}\,, \\ \sigma_z &= \sqrt{\left(\frac{\partial z}{\partial \xi_1}\right)^2 \sigma_{\xi_1}^2 + \left(\frac{\partial z}{\partial \xi_2}\right)^2 \sigma_{\xi_2}^2 + \left(\frac{\partial z}{\partial \xi_3}\right)^2 \sigma_{\xi_3}^2}\,, \end{aligned} \quad (3)$$

where $\partial y/\partial \xi_1$, $\partial y/\partial \xi_2$, $\partial y/\partial \xi_3$, $\partial z/\partial \xi_1$, $\partial z/\partial \xi_2$, $\partial z/\partial \xi_3$ represent partial derivatives of the y and z coordinates with primary measured parameters ξ_1, ξ_2 and ξ_3, while σ_{ξ_1}, σ_{ξ_2} and σ_{ξ_3} represent the RMS errors in in defining the primary parameters ξ_1, ξ_2 and ξ_3.

For the distance measuring method of coordinates estimate, the primary measured parameters are the distances to the object highlights: $\xi_1 = R_1$, $\xi_2 = R_2$, $\xi_3 = R_3$. Hence $\sigma_{\xi_1} = \sigma_{\xi_2} = \sigma_{\xi_3} = \sigma_R = c\sigma_\tau$, where c stands for the speed of light, $\sigma_\tau = 1/(q_{\text{out}} \cdot \Delta\omega_{\text{eff.}})$ – for the potential accuracy in signal delay measurement, $q_{\text{out}} = \sqrt{2E/N_0}$ is the maximum potential of signal to noise ratio at the outcome of the signal drive, where the signal is being stored coherently, E represents the received signal energy, N_0 – noise power spectral density, $\Delta\omega_{\text{eff.}}$ – the effective signal bandwidth.

To estimate the efficiency of the dimensions measuring we analyzed the UWB transceiver modules system with the modules mounted all around the vehicle (figure 6), assuming, the effective UWB signal bandwidth $\Delta f_{\text{eff.}} = 4$ GHz, proper detection expectation $D = 0.9$ and false alarm expectation $F = 10^{-6}$, signal to noise ratio at the outcome of the signal drive upon the given D and F values $q_{\text{out}} = 11.39$.

Figure 7 provides the RMS errors in estimating the height of the object using distance measuring method as a function of x coordinate and the height of the object h. For this we assumed that: 1) $x = 30$ m, $y = 0$ m (figure 7 (a)), 2) $y = 0$ m, $h = 1.8$ m (figure 7 (b)).

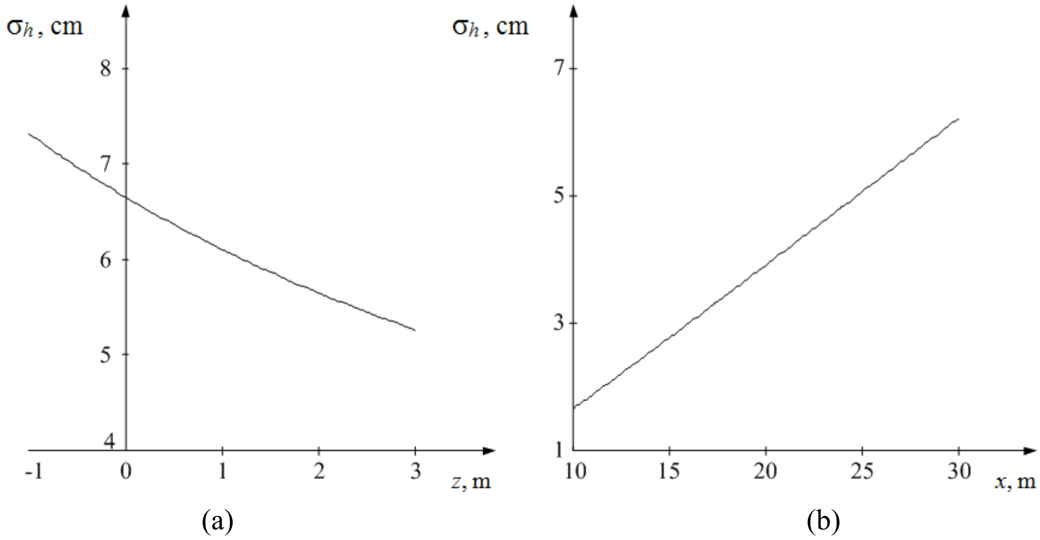


Figure 7. RMS errors in estimating the height of the object using distance measuring method as a function of x coordinate and the height of the object h.

Figure 7 shows that the less is the height of the object with x coordinate being constant, or the higher x coordinate value with the height being constant, RMS errors in estimating the height is always increasing, as the angle between the osculating planes to the position surfaces, drawn through their intersection point, is reduced (α and β angles in figure 8).

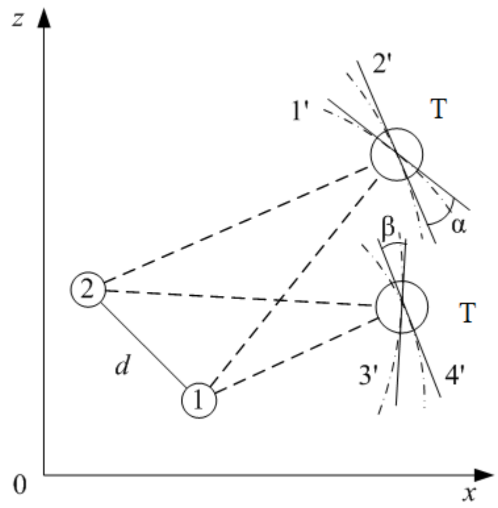
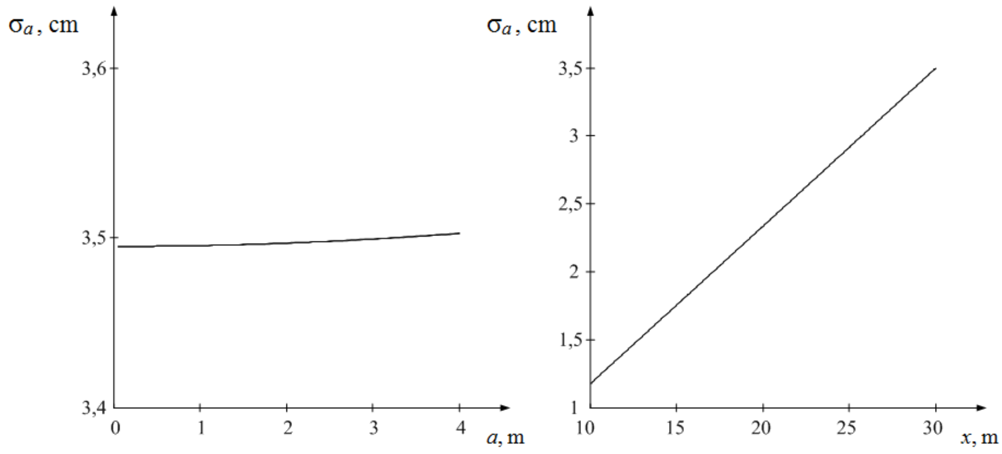


Figure 8. Ratio of the angle between the position surfaces to the height of the target.

1, 2 – transceiver modules;
T – target;
α and β – angles between 1` and 2`, 3` and 4` position surfaces respectively (α > β).

Figure 9 provides RMS errors in measuring lateral size of the object using the distance measuring method to define the highlights coordinates as a function to the lateral size *a* of an object and *x* coordinate value. For this we assumed that: 1) $x = 30$ m, $h = 1$ m (figure 9 (a)), 2) $a = 0.5$ m, $h = 1.6$ m (figure 9 (b)).



(a) (b)

Figure 9. RMS errors in measuring lateral size of the object using the distance measuring method as a function to the lateral size and *x* coordinate value.

Figure 9 (a) shows that the higher lateral size value with *x* coordinate being constant has few influence on the RMS errors in estimating the lateral size. This can be explained by the fact that the distance between the transceiver positions along the *y* axe is comparable to the lateral size of an object, and angles between the osculating planes to the position surfaces nearly do not vary with the changes of the lateral size of an object. Figure 9 (b) shows that the higher is the *x* coordinate value with the lateral size being constant, the higher is the value of RMS errors in measuring lateral size, as the angle between the osculating planes to the position surfaces, drawn through the intersection point, is reduced.

5. Conclusion

Our model based on dimension measuring and surround view monitoring allows real-time monitoring of the environment. This model of vehicle radar system ensures detailed information about the traffic conditions and increases the traffic safety.

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