Stereoscopy in Object's Motion Parameters Determination

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***Abstract*—**Computer vision is the science and technology of machines which are able to extract information from an image that is necessary to solve some task. As a scientific discipline, computer vision is concerned with the theory that extract information from images. It must be noticed that computer vision is still very strong and fast developing discipline because of technology expansion especially computers and cameras. The image data can take many forms, such as video sequences or views from multiple cameras which is in interesting of this paper.

Paper presents method of calculation of object's movement parameters in three-dimensional space using system which ensure stereoscopic vision. There was described the algorithm of movement discovering and moving object tracking, including methods of separate and actualization of background, method of distinguishing moving objects and its position's calculation on acquired pictures. Next the methods of object's coordinate calculation in three dimensional space basis on data retrieved from stereoscopic image computation was discussed in detail. More over the problem of images rectification and stereovision system calibration was in detail discussed. At last the method of movement's parameters calculation in 3D space was described. At the end of the paper some chosen results of research which were conducted in laboratory conditions were presented.

***Keywords*—**stereovision, movement detection, motion parameters, rectification.

I. Introduction

Viewing a scene from two different positions simultaneously allows make inferences about distance to objects, provided that it is possible to match up corresponding points in the images. The visual systems of humans and some other animals make use of this, and it is very important in attempts to develop practical computer vision systems.

As a first, The Victorians invented technology for presenting stereo pairs, and were enthusiastic about viewing them. Every so often, film-makers discover they can use stereoscopic presentation to dramatic effect, though the audience has to wear glasses with coloured or polarising filters to ensure that a different image goes to each eye. Map-makers use stereo presentation of aerial photographs to estimate ground topography [6], [13].

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The literature about stereovision is very voluminous. Starting from very basing information like stereo geometry [2], [13], through the problem of object position estimation and region comparison [2], [7], [9], [13], ending on robot perception [1], [6], [11], moving object's parameters determination [10], [14] and circular dynamics stereoscopy [5].

The stereo pair of images can be obtained using two cameras which positions are separated horizontally. Viewing the images normally, it is possible to see how the change in camera position has resulted in a change in the position of the object of interest relative to the images of other objects [6], [13].

Described in paper system consists of two digital cameras which together create stereovision system. Simultaneously acquired, from two cameras, images of the same scene allows on detection on every of image the movement, and then basis on calculated position of movable object on every of images and applying the technique stereovision it is possible to calculate the spatial position of movable object. In next step comparing the spatial position of object with positions in which object found in previous moments we can calculate object's parameters of movement in 3D space.

II. Moving Object Detection

The algorithm of detecting movable objects is executed on acquired from digital camera images, which can be treated as two-dimensional matrix of points. For simplifying the working of algorithm (without losing quality of detection) the algorithm use during calculations the image's luminance ignoring the information about colours. The detection of movable objects is making by comparison of current frame of image with kept image of background. The image of background is acquired automatically and actualized to slowly running changes in field of camera vision. Basis on comparison of every frame of image with image of background the actual image is divided on background and first plan. Pixels which belongs to the first plan are grouped giving the same possibility to determine position of movable object and, alternatively, to calculate dimensions of movable object.

Assuming that every image is a matrix of points which are described by color's components R, G and B, we can write [3]:

$$
\begin{aligned}
&O=\{p_{x,y}\}\Big|_{x\in[0,w],\ y\in[0,h]} \\
&p_{x,y}=\{R_{x,y},G_{x,y},B_{x,y}\} \quad R_{x,y},G_{x,y},B_{x,y}\in[0,1]
\end{aligned} \tag{1}
$$

where: O - matrix which includes actual image;
$p_{x,y}$ - value of pixel at position x, y;
w and h are respectively width and height of image;
$R_{x,y}, G_{x,y}, B_{x,y}$ - color's components of given point of image respectively red, green and blue.

It is possible to determine the luminance of every point of image using following equation:

$$
L=\{v_{x,y}\} \quad v_{x,y}=\frac{R_{x,y}+G_{x,y}+B_{x,y}}{3} \tag{2}
$$

where: L - is a matrix of luminance;
$v_{x,y}$ - value of luminance at position x, y.

It is preponderant for algorithm working to divide image on background and first plan. The background is stored separately and is bring up to date by recurrent equation [3]:

$$
\begin{aligned}
&T=\{b_{x,y}\}\Big|_{x\in[0,w],\ y\in[0,h]} \\
&T_{i-1}=T_{i-1}(1-\beta)+T_i\beta \quad 0\le\beta<<1
\end{aligned} \tag{3}
$$

where: T_i - background of *i*-th image of sequence;
$b_{x,y}$ - element of background at position x, y;
β - coefficient of background update.

Thanks to the recurrent updating of background using coefficient close to the zero the background reacts on slow changes of image (for example the change of lighting) and the quickly moving elements do not come in to the update. Such solution requires delivering initial background.

Using comparison of current images with background it is possible to identify on him the moving objects. Subtracting actually acquired image from background we have the map of differences which after tresholding will unambiguously separate background from first plan. It can be done as follow [3]:

$$
\begin{aligned}
&R=\{d_{x,y}\}\Big|_{x\in[0,w],\ y\in[0,h]} \quad d_{x,y}=\left|b_{x,y}-v_{x,y}\right| \\
&M=\{f_{x,y}\} \quad f_{x,y}=\begin{cases}1 & d_{x,y}\ge t\\ 0 & d_{x,y}<t\end{cases}
\end{aligned} \tag{4}
$$

where: R if a matrix of difference between background and image;
$d_{x,y}$ - value of difference at point x, y;
M - bit map which divides image on background and first plan; t - level of tresholding.

Using such prepared bitmap it is possible to, easily and fast, determine groups, its borders and center of gravity. The center of gravity for given group of points can be determined using following equations [3]:

$$
g_x=\frac{\sum_S x f_{x,y}}{\sum_S f_{x,y}}, \quad g_y=\frac{\sum_S y f_{x,y}}{\sum_S f_{x,y}} \tag{5}
$$

where: g_x, g_y - coordinate of center of gravity for given group;
S - surface occupied by given groups of points;
x, y - coordinate of point;
$f_{x,y}$ - defined by (4).

Realizing this algorithm for left and right camera of the stereoscopic system allows to calculate the coordinates of position of moving object on every image. This allows on determine the spatial position of moving object.

III. Calculation Position of Moving Object

Stereoscopy is a technique used for recording andrepresenting stereoscopic (3D) images. It can create an illusion of depth using two pictures taken at slightly different positions. Stereoscopic picture can be taken with a pair of cameras, similarly to our own eyes [7]. The most important restrictions in taking a pair of stereoscopic pictures are the following: cameras should be horizontally aligned (see Figure 1A), the pictures should be taken at the same instant, camera's working parameters should be the same [6], [13].

Stereoscopic pictures allow us to calculate the distance between the camera(s) and the chosen object within the picture. Let the left picture be taken in location S_L, and the right picture in location S_R. B represents the distance between the cameras and φ is camera's horizontal angle of view (see Figure 1B). Object's position (distance D) can be calculated by doing some geometrical derivations. Assuming that optical axes of the cameras are parallel, where φ_1 and φ_2 are angles between optical axis of camera lens and the chosen object, we can express distance B as a sum of distances B_1 and B_2 [7], [15]:

$$
B=B_1+B_2=D\tan\varphi_1+D\tan\varphi_2 \tag{6}
$$

Distance D is as follows: [7], [15]:

$$
D=\frac{B}{\tan\varphi_1+\tan\varphi_2} \tag{7}
$$

Using basic trigonometry, we can find: [7], [15]:

$$\frac{x_L}{\frac{x_0}{2}} = \frac{\tan\varphi_1}{\tan\left(\frac{\varphi_0}{2}\right)}, \quad \frac{-x_R}{\frac{x_0}{2}} = \frac{\tan\varphi_2}{\tan\left(\frac{\varphi_0}{2}\right)} \tag{8}$$

According to above the distance D can be calculated as follows [7], [15]:

$$D = \frac{Bx_0}{2\tan\left(\frac{\varphi_0}{2}\right)(x_L - x_R)} \tag{9}$$

where: x_0 is number of horizontal pixels;

x_L and x_R are the horizontal position of object on the images acquired respectively from left and right camera.

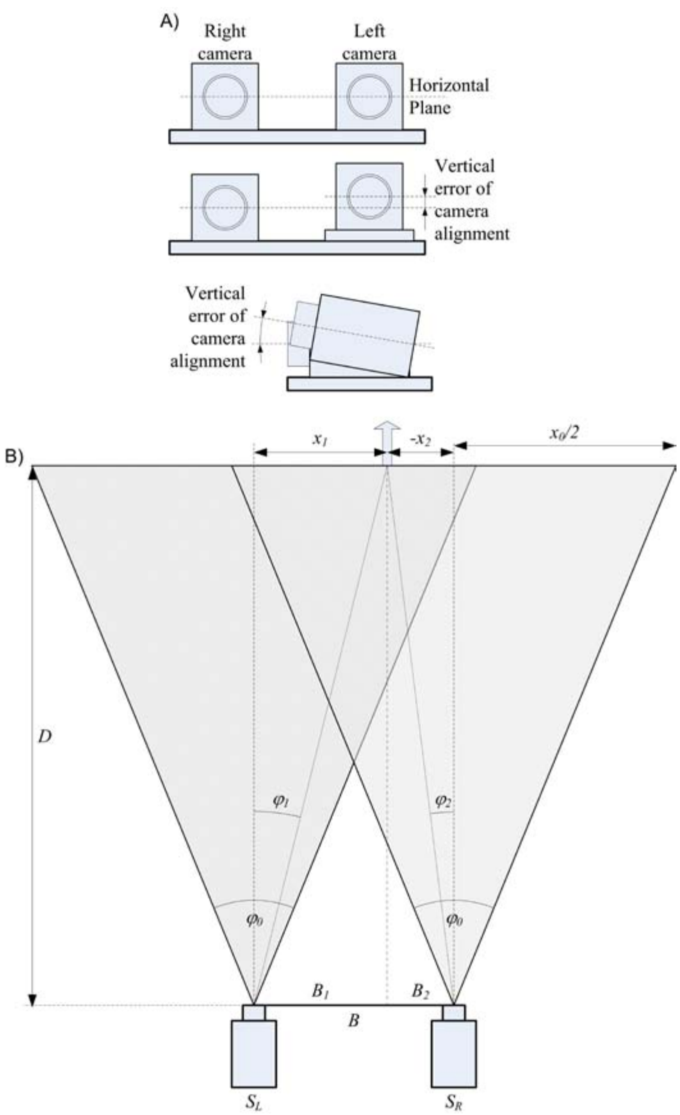

Fig. 1. Stereoscopic vision. A) correct alignment of the cameras, B) the image of the object taken from two cameras.

Parameters x_0, φ_0 and B in equation (9) are determined basis on geometrical sizes of stereoscopic system and technical parameters of using camera. Parameters x_L and x_R are determined during process of movement detection on images. Distance D can be treated as z coordinate of object in 3D space assuming that reference coordinate system is the rectangular system with origin positioned exactly in half way between optical axis of cameras and in line of optical system of cameras link.

The error in calculated position, it means distance D, depends on several variables. Location of the object in the right and left images can be found accuracy of few pixels. Each pixel corresponds to the following angle of view:

$$\Delta\varphi = \frac{\varphi_0}{x_0} \tag{10}$$

Figure below shows angle of view $\Delta\varphi$ changed by one pixel positioning error which cause distance error ΔD. In this figure we can found as follow [7]:

$$\frac{\tan\varphi}{\tan(\varphi - \Delta\varphi)} = \frac{\Delta D + D}{D} \tag{11}$$

Now, using basic trigonometry, the distance error can be expressed as follows:

$$\Delta D = \frac{D^2}{B}\tan(\Delta\varphi) \tag{12}$$

Notice that the actual error of distance calculation can be higher due to optical errors such as: distortion, aberration etc.

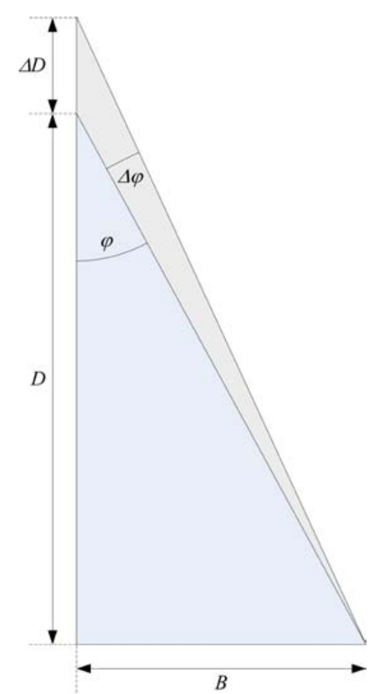

Fig. 2. Distance calculation error caused by one pixel positioning error

IV. IMAGES RECTIFICATION

In practical construction of stereovision systems it is hard to positioning in such way cameras that we get the canonical configuration. Applying appropriate projection it is possible to transform the coordinates of pair of images from noncanonical system to canonical coordinate system. Such transformation is called rectification of stereo images. Due to finding the pair of appropriate transformation matrices it is necessary to calibrate the stereovision system particularly to determine the intrinsic and extrinsic parameters of cameras [9].

Extrinsic parameters (figure 3) are describing the position against each other cameras or against the arbitrarily chosen external coordinate system. Extrinsic parameters for single camera are defined by three coefficient vector T which is fixing the offset between camera coordinate system (X_c, Y_c, Z_c) and arbitrarily chosen external coordinate system (X, Y, Z) as well as matrix of rotation R which is determining the rotation between axis of this two coordinate systems. If point P which is given in external coordinate system $P = [X, Y, Z]^T$ and also in camera coordinate systems $P_c = [X_c, Y_c, Z_c]^T$, then extrinsic parameters of camera are defining relation between coordinates of point P and P_c according to the following equation [2], [9]:

$$P_c = R \times P + T \tag{13}$$

where: R is a matrix of rotation of coordinate systems;
T is a vector of translation.

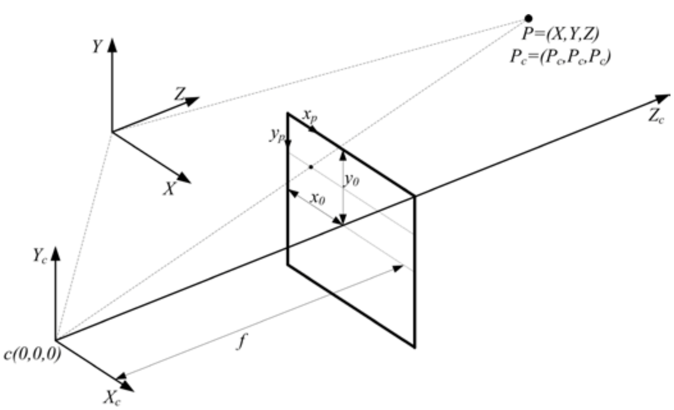

Fig. 3. Single camera with coordinate systems and intrinsic parameters [9]

It is assumed that single camera coordinate system has it origin at focus c of camera (figure 3).

Knowledge about the intrinsic parameters of each camera is necessary to determine the correction of cameras optical systems geometrical distortion. The intrinsic parameters can be divided into two groups. First is the metrics parameters, which are given in such called camera's matrix [2], [9]:

$$A = \begin{bmatrix} f_x & \gamma & x_0 \\ 0 & f_y & y_0 \\ 0 & 0 & 1 \end{bmatrix} \tag{14}$$

where: f_x, f_y the focus of camera expressed in number of pixels it means $f_x = k_x f$, $f_y = k_y f$, where k_x is the number of pixels per millimeter in horizontal direction, k_y is the number of pixels per millimeter in vertical direction,

x_0, y_0 the coordinate of the main point which is defined as a intersection of image's plane with normal to image's plane which is going through the focus c of camera

γ –coefficient which is determining the angle between X and Y axis for camera (if they are perpendicular than $\gamma = 0$)

To the second group of camera's intrinsic parameters includes the parameters which are determining the geometrical distortion introduce by camera optical system. The following coefficients are distinguish: coefficients related to radial distortion and coefficient related to tangencional distortion.

Matrix A is determining the relation between so called standard coordinates of point in space, given be equations: $x_n = X_c / Z_c$, $y_n = Y_c / Z_c$, and corresponding to its, coordinates of point and image (figure 3) [2], [9]:

$$\begin{bmatrix} x_p \\ y_p \\ 1 \end{bmatrix} = A \times \begin{bmatrix} x_n \\ y_n \\ 1 \end{bmatrix} \tag{15}$$

After granting the geometrical distortion, the standard coordinates are given by following equation [2], [9]:

$$\begin{bmatrix} x_d \\ y_d \end{bmatrix} = (1 + k_1 r^2 + k_2 r^4) \begin{bmatrix} x_n \\ y_n \end{bmatrix} + \Delta \tag{16}$$

where:

$$r^2 = x_n^2 + y_n^2, \quad \Delta = \begin{bmatrix} 2 p_1 x_n y_n + p_2 (r^2 + 2 x_n^2) \\ 2 p_2 x_n y_n + p_1 (r^2 + 2 y_n^2) \end{bmatrix}$$

k_1, k_2 are the coefficients of radial distortion;
p_1, p_2 are coefficients of tangencional distortion;
Δ is a vector of tengencional distortion.

For camera's model which is granting the geometrical distortion equation (15) which is determining the coordinates of camera's image can be written as follow [2], [9]:

$$\begin{bmatrix} x_p \\ y_p \\ 1 \end{bmatrix} = A \times \begin{bmatrix} x_d \\ y_d \\ 1 \end{bmatrix} \tag{17}$$

In stereovision system, on the ground of extrinsic left camera's parameters R_L and T_L and right camera's parameters R_R and T_R which are defining the position of respective coordinate systems against the same external system it is possible to determine the rotation matrix R and translation vector T which are determining the one to each other cameras position [2], [9]:

$$R = R_R R_L^T, \quad T = T_L - R^T T_R \tag{18}$$

Matrix R and vector T are so called the extrinsic parameters of stereovision cameras system. For given point P which is laying in space, the relation between its coordinates for left and right camera is as follow [2], [9]:

$$P_R = R(P_L - T) \tag{19}$$

On the ground of knowledge the extrinsic parameters of noncanonical stereovision systems R and T as well as intrinsic parameters of left and right camera it is possible to determine the pair of translation matrices M_R and M_L. This matrices can be used to rectifying the images from cameras which are in noncanonical system. The coordinates of "straight" images for left camera (x_{rectL}, y_{rectL}) and right camera (x_{rectR}, y_{rectR}) are defined as follow [2], [9]:

$$\begin{gathered} \begin{bmatrix} a_L \\ b_L \\ c_L \end{bmatrix} = M_L \times \begin{bmatrix} x_{pL} \\ y_{pL} \\ 1 \end{bmatrix}, \quad x_{rextL} = a_L / c_L, \quad y_{rextL} = b_L / c_L \\ \begin{bmatrix} a_R \\ b_R \\ c_R \end{bmatrix} = M_R \times \begin{bmatrix} x_{pR} \\ y_{pR} \\ 1 \end{bmatrix}, \quad x_{rextR} = a_R / c_R, \quad y_{rextR} = b_R / c_R \end{gathered} \tag{20}$$

V. CALIBRATION OF CAMERAS

The quality of the calibration of a stereovision system determines partially the accuracy of euclidian reconstruction. The robust and high-performance calibration methods usually require both the 3D coordinates of some points of the viewed scene and the measures of the 2D coordinates of their images. The calibration object refers to a specific object which contains points whose 3D coordinates are known [4].

Construction of a full 3D model of observed scene from the stereo pair requires calibration of the camera system using software. The stereovision system is accurately specified by intrinsic and extrinsic parameters which are determined for both cameras. The intrinsic camera parameters specify a pinhole camera model with radial distortion. The pinhole model is characterized by its focal length, image centre, pixel spacing in two dimensions and the radial distortion. The extrinsic parameters describe the relative position and orientation of the two cameras. Intrinsic parameters for a given camera are constant, assuming the physical parameters of the optics do not change over time, and thus may be pre-calculated. Extrinsic parameters depend on the relative camera poses and will be constant if the cameras are fixed relative to one another [9].

Both intrinsic and extrinsic calibration parameters are calculated using the Tsai's method [12]. As a calibration target was used the chessboard. The flowchart at figure 4 shows the step of camera calibration [4].

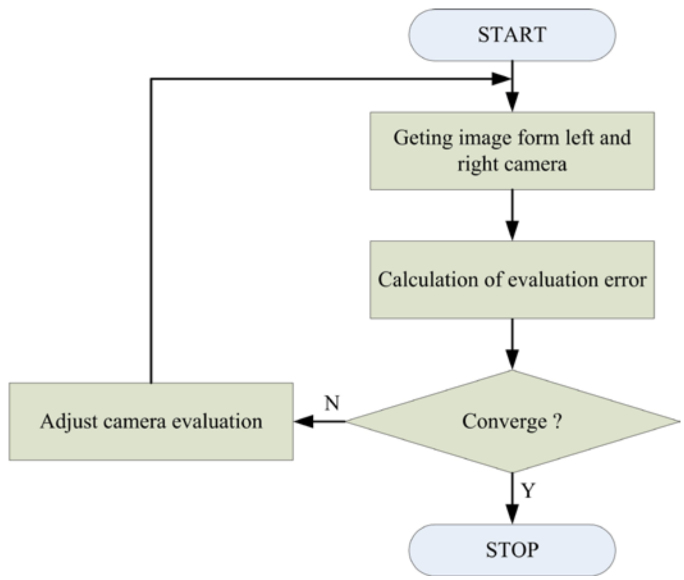

Fig. 4. Flowchart of Tsai's method of stereovision system calibration

The first step is to get a set of images in digital form and start to evaluate the error between the images of left and right. If the images are not converge each other then the system will adjust the value of the camera evaluation until they converge. The adjusted value or parameters will be used as a result for calibration process to be used in rectifying process. The result contains of intrinsic parameters and extrinsic parameters. These values are represented in pixel intensity values and can be called for rectification process to align the epipolar line on stereo images [4].

The rectification of stereo image pair can be carry out under the condition of camera's parameters in Tsai's method. To quickly and accurately search the corresponding points along the scan-lines, rectification of stereo pair are performed so that corresponding epipolar lines are parallel to the horizontal scan-lines and the difference in vertical direction is zero (se figure 5). Image rectification is the undistortion according to the calibration parameters calculated in the Tsai's calibration.

After all intrinsic and extrinsic camera parameters are calculated, they can be used to rectify images according to the epipolar constraint [4].

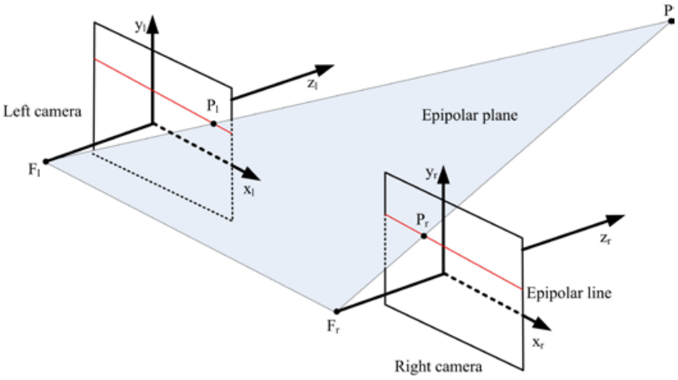

Fig. 5. Epipolar plane of stereo vision

VI. Determination of movement parameters

After detection of moving object on images and after processing stereoscopy images we have determined positions of moving object, which is described by coordinates . Having this information and measuring position of moving object again after time delay it is possible to calculate motion parameters of object which is moving in 3D space (see figure 6), what can be written as follow [14]:

$$v_x = \frac{x_2 - x_1}{\tau}, \quad v_y = \frac{y_2 - y_1}{\tau}, \quad v_z = \frac{z_2 - z_1}{\tau} \tag{21}$$

where: v_x, v_y, v_z - velocity components al long the main axis of reference coordinate system.

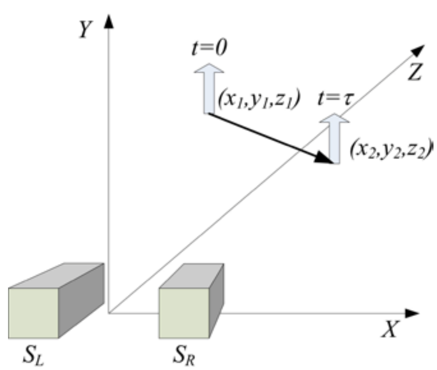

Fig. 6. Algorithm of determining movement parameters in 3D space

Resultant velocities of moving object is described by equation [14]:

$$v = \sqrt{v_x^{\,2} + v_y^{\,2} + v_z^{\,2}} \tag{22}$$

Using the same way it is possible to calculate the direction of movement. Assuming that object is moving in XZ plane, the following equation can be used [14]:

$$\alpha = \arctan\frac{d_x}{d_z} \tag{23}$$

where: $d_x = x_2 - x_1$, $d_z = z_2 - z_1$

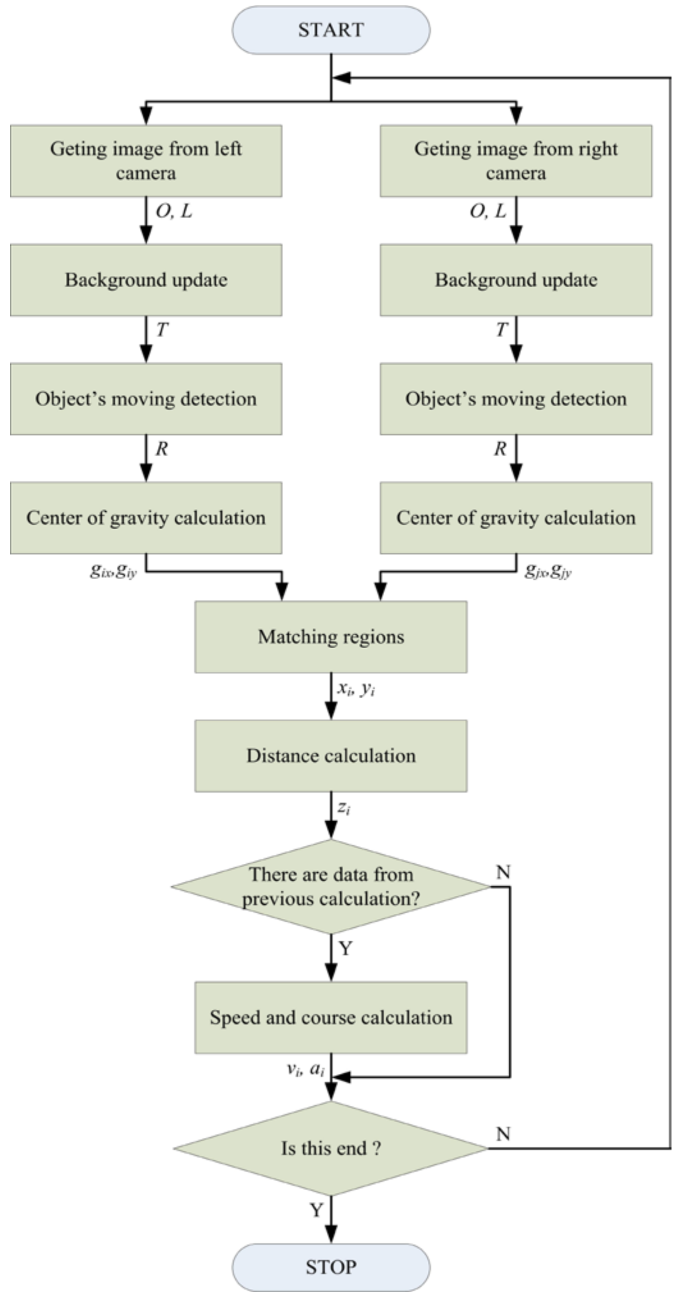

Fig. 7. Algorithm of determining movement parameters in 3D space using stereoscopy images

Described above method of detecting the movement, calculating position of object in 3D space as well as the determining the parameters of movement were implemented on PC computer. System was provided on device to stereoscopic vision produced by Minoru, which allows to check the correctness of algorithms as well as it made possible to execute investigations in laboratory conditions. Stereoscopic device consisted of two digital cameras which optical axis remote to each other by 60 mm are parallel and lie in one plane. The device is connected to the PC computer using the USB interface. Mobile circular robot was movable object. This robot can act autonomically, can be programmed via radio or eventually can be remotely controlled via radio. Robot in observation by stereoscopic system area was moving with constant, programmed speed. The test was conducted for several directions of movement of robot. Created application was working according to algorithm presented on figure 7.

During working of system, the position of moving object in 3D space was calculate up with the times. Moreover the resultant speed and components of moving object speed in adopted coordinate frame as well as direction of movement were determined. The results of calculation against fixed values of parameters of moving object were presented on table I. It must be noticed that calculated direction of movement as well as speed of moving differs from this fixed during researches a little.

TABLE I
RESULTS OF CALCULATIONS

Given values		Measured values	
Direction [deg]	Velocity [m/s]	Direction [deg]	Velocity [m/s]
0	0.9	5	0.7
30	0.7	27	0.6
60	0.7	58	0.6
90	0.4	91	0.4
180	0.9	176	0.8
210	0.7	208	0.6
240	0.7	242	0.7
270	0.4	271	0.4

The results of research (results of created application execution) conducted in laboratory conditions were presented on figures 8 to 10.

Fig. 8. Results of research - image of the background

Fig. 9. Calculation of movement parameters of object, detection of moving (object is moving in perpendicular line to the optical axis of cameras with speed of 0.4 m/s)

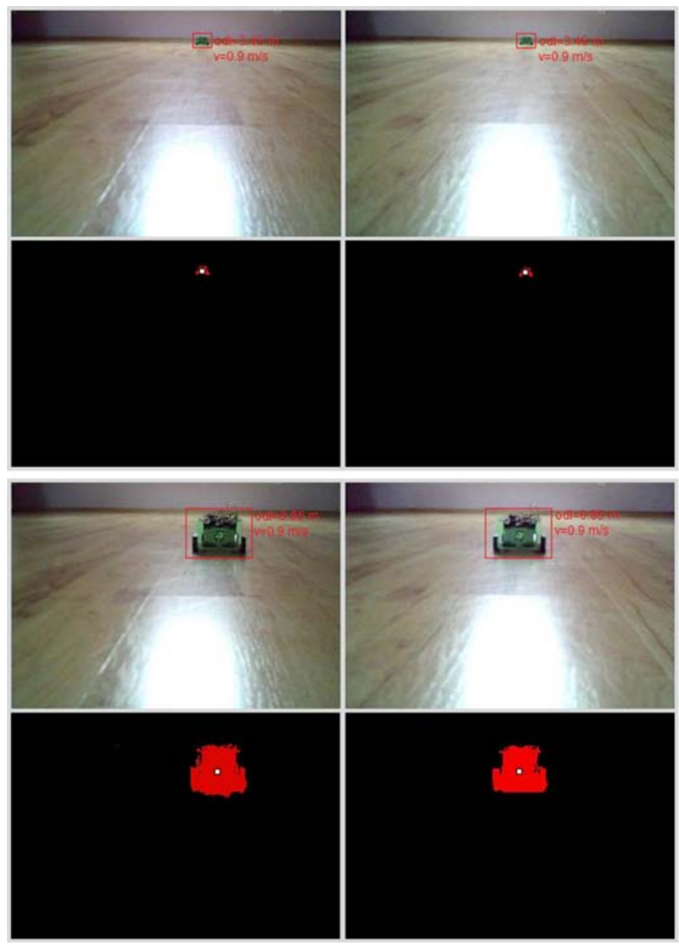

Fig. 10. calculation of movement parameters of object, detection of moving (object is moving in parallel line to the optical axis of cameras with speed of 0.9 m/s)

VII. CONCLUSIONS

The paper presents system which task was to motion parameters determination in 3D space basing on acquired stereoscopic images. Actually system is laboratory phase of investigations and is still improved. Receipt so far results of research confirm the correctness of used methods of solution the task of determine movement parameters in 3D space using stereoscopic vision. The position of object in space as well as his speed is determined with sufficient and satisfaction precision. From investigation we can conclude that the mistakes in calculation the movement parameters of object which moves in parallel to optical axis of camera directions are larger than in case when the object moves in directions of perpendiculars. This results are caused probably by inaccuracy in determination the distance to the moving object.

In the closest time, working of the system become checked for system equipped in professional cameras configured to the stereoscopic vision and situated on turn-table what enable to change the area of observation. The correctness of system's working should be also verify in real conditions.

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