

The Task of Weapon Guidance onto the Aerial Target Using Optoelectronic Station of Trajectory Measurements

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Abstract—The work is devoted to the development of a simulation model of tracking and measuring the coordinates of the flight of a missile over rough terrain to a moving target. To guide the missile, target designation from the optical-electronic station of trajectory measurements is used.

Keywords—aerial object, optoelectronic station of trajectory measurements, simulation model.

I. INTRODUCTION

At the present time, the problem of detecting, tracking of mobile objects in the air and their recognition is extremely relevant for short-range missile artillery systems. In conditions of complete suppression of radar systems, optoelectronic stations on board the vehicle become the main equipment for target detection. This is confirmed by the growth in the number of such developments presented at exhibitions and reviews. For example, the fighting vehicle 2S38 of a self-moving anti-aircraft artillery complex (Russia) is equipped with an optoelectronic detection and aiming system, which was developed by the Minsk company «Peleng» [1, 2]. It allows for 360-degree panoramic observation of the terrain, as well as for a sector view.

The detection range through one of the video channels of a small unmanned aerial vehicle of the Bird Eye 400 type in the panoramic mode is declared of 700 m, and of 4900 m in the narrow field of view mode. The A-10 attack aircraft is detected in the first mode already at a distance of 6400 m, and in the second case at a distance of 12300 m. The thermal imaging channel allows detecting targets with a size of 2.3×2.3 m with a probability of 80 % at a distance of 10000 m and recognizing them at a distance of 4000 m. Fighting vehicles of similar characteristics have been developed in the USA, France, Great Britain, Israel, Canada, Russia, etc. However, the declared detection ranges can be provided only in open space. In reality, obstructing factor such as a terrain, trees and buildings always exists. In addition, the vehicle itself must be in cover so as not to become a target itself. To hit a target on a collision course, it

is necessary to obtain target designation in advance for guiding the missile. Given the restrictions on the use of own intelligence assets this is possible in the case of usage of a network of brought forward optical-electronic stations of trajectory measurement (OESTM) [3–9], which will provide fighting vehicles with target designation, and will also be able to correct the missile flight until it captures the target itself. To test the efficiency of such a scenario, depending on the number of OESTM, their location, and data transmission delays, it became necessary to develop a simulation model.

II. THE PROBLEM STATEMENT

1. Create a simulation model of a missile flight over the rough terrain to a moving target.
2. Carry out a simulation of tracking and measuring the coordinates of the flight of a missile and an aerial target using OESTM.
3. Adjust the flight parameters of the missile to reach the optimal guidance trajectory.

Within the framework of this report, a model of a missile flight over rough terrain to a moving target is considered and a method for calculating the pixel coordinates of these objects in the image taken by the OESTM camera is determined.

III. DEVELOPMENT OF A SIMULATION MODEL OF OBJECTS FLIGHT

To solve the first task, one needs to create the following models:

- land terrain;
- trajectories of the missile and target over the terrain surface;
- scene that ensures the relative position of objects during their movement.

A possible implementation of simulation modeling is shown below.



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A. Terrain modeling.

The terrain is modeled based on a height map. The RAW file format is used for storing height maps. This format, unlike a BMP file, is easy to read as it does not contain headers with any information about the image, such as size or type of image. The size of the map can be arbitrary, but it is more convenient to use a square one, with a side size multiple of 128: 128×128, 256×256, ..., 1024×1024. In 8-bit height maps, each byte within the RAW file represents the height of the peak. Height values range from 0 to 255, where 0 represents the lowest peak height and 255 (FF in HEX) is the maximum possible peak height. One can expand this range by using a scaling factor that is multiplied by the specified height value. To build a terrain from a height map, one first need to build a mesh of vertices with the same dimensions as that of a height map, and then use the point (pixel) height value from the height map as the height for the peak in the mesh of the peaks. Points are selected with certain step spacing. As known, any surface can be represented by triangles (surface triangulation). Therefore, any four adjacent points of the height map define a rectangle, which we can be divided into two triangles and drawn. In OpenGL, one can use a primitive of type GL_TRIANGLE_STRIP for this purpose.

Color interpolation can be applied to terrain painting. So, when drawing a triangle, a different color for each peak is needed to be set. In this case, OpenGL itself will interpolate the colors. In OpenGL, the color of one point in an image is described by three color components Red, Green and Blue. Defining all three components or only one of them as a function of height, allows getting a better representation of the terrain, specifically, high points will be lighter.

B. Modeling the trajectory of moving objects.

Two objects are moving over the terrain. There are a missile and a target. The trajectory of movement of each of them is determined by 4 points: R_{start} is the initial point; R_{finish} is the finish point; $R_{current}$ is the current point; R_{next} is the next point after the current one. The y coordinate of points is determined as a function of the flight altitude of objects at a point with coordinates x, z : $y = H(x, z)$.

The target starting position and the point where it moves are determined using random numbers. The x and z coordinates of the target points R_{start} and R_{finish} are determined by a random number generator: $x = \text{rand}()$; $z = \text{rand}()$. The R_{start} point of the missile is at the origin of the coordinate system (with $y = H(0,0)$), the finish point of the missile coincides with the R_{next} point of the target: $R_{rocket\ finish} = R_{next}^{target}$. The missile and the target move synchronously in a step-by-step mode, so that the positions of the points $R_{current}$ and R_{next} are defined as follows:

$$R_{current.X} = R_{start.X} + (R_{finish.X} - R_{start.X}) \cdot i/i_k,$$

$$R_{current.Z} = R_{start.Z} + (R_{finish.Z} - R_{start.Z}) \cdot i/i_k,$$

$$0 < i \leq i_k,$$

$$R_{current.Y} = H(R_{current.X}, R_{current.Z}).$$

Target defeat occurs when $i = i_k$.

C. Scene modeling.

The problem is solved on the basis of the mathematical apparatus of affine transformations. Two coordinate systems are used. In the local (polygon) Cartesian coordinate system (LCCS) $X_M Y_M Z_M$ the terrain is modeled, the points of the trajectory of objects and the position of the local coordinate system are determined. In the local coordinate system XYZ , a missile model is created. The missile model is represented by two mutually perpendicular triangles; the target model is a large point. The position of the local coordinate system relative to the LCCS is determined by the current point of the missile trajectory, as well as by the angles Ψ_R (yaw), Θ_R (pitch) and Y_R (roll).

The current parameters are determined by the points of the current missile position ($R_{current}$ and R_{next}):

$$dx = R_{next.X} - R_{current.X};$$

$$dy = R_{next.Y} - R_{current.Y};$$

$$dz = R_{next.Z} - R_{current.Z};$$

$$dl = \sqrt{dx^2 + dy^2 + dz^2};$$

$$\Psi_R = \text{atan}(dx/dz) \cdot 180/\pi;$$

$$\Theta_R = \text{asin}(dy/dl) \cdot 180/\pi;$$

$$Y_R = k \cdot d\Psi_R,$$

where $d\Psi_R = \Psi_R(i) - \Psi_R(i-1)$.

The coefficient k is set so that $Y_R < 45^\circ$.

The missile launch is initiated by pressing the P (launch) key. The parameters of the missile initial position are determined by the initial position of the target. Geometric transformations are implemented in OpenGL using the functions:

- `glTranslate (x,y,z)` performs a transfer, adding the values of its parameters to the coordinates;
- `glRotate (angle,x,y,z)` rotates the object by the angle value *angle* around the vector (x,y,z) ;
- `glLookAt (eyeX, eyeY, eyeZ, centerX, centerY, centerZ, upX, upY, upZ)` is the direction of view of the scene.



The explosion when the missile reaches the target is simulated by a sphere or a point of the large size `glPointSize(45)`.

IV. MEASURING THE FLIGHT COORDINATES OF A MISSILE AND AN AERIAL TARGET USING OPTICAL-ELECTRONIC STATION OF TRAJECTORY MEASUREMENT

Consider how the image of the observed object is formed from a geometric point of view. In particular, we look at the mathematics of how a point selected on the surface of a missile or aerial target in 3D space is projected onto the image plane. At a large distance from the camera, the entire object will be perceived as a point. Let us consider the case when one OESTM is installed on the terrain surface. OESTM is tracking a point object in space. Let us denote it by point P. The task is to find the pixel coordinates (u, v) of this three-dimensional point in the image taken by the OESTM camera. There are three coordinate systems involved in this model.

1. LCCS.

First, one need to determine the LCCS to find the location of an object in space:

- select a reference point: use the initial position of the missile in the polygon coordinate system as the reference point $(0,0,0)$;
- select the direction of the axes (X_M, Y_M, Z_M) of the local (polygon) coordinate system. Usually (X_M, OZ_M) is a plane, which is tangent to the surface of the reference ellipsoid at the origin point Y_M . The normal to this plane X_M is directed along the polygon main direction.

Using the above, the 3D coordinates of a point object at any given time can be found by measuring the distance to its position from the origin along the axes X_M, Y_M and Z_M . Further, an uppercase font (for example, X_M) is used to display the axes and a lowercase font is used to display the coordinates of the point (e. g. x_p). In LCCS the coordinates of the point P are x_p, y_p, z_p .

2. Camera coordinate system.

The image of the object will be captured using the OESTM camera, and therefore the three-dimensional coordinate system X_K, Y_K, Z_K , which is attached to this camera, is in consideration. Let us place OESTM on the terrain surface in some arbitrary place with coordinates x_s, y_s, z_s of the station in the polygon coordinate system X_M, Y_M, Z_M .

At the initial moment of time the camera view is in arbitrary direction. 3D rotation is described using three parameters that are yaw, pitch and roll. For a mathematical description, it is convenient to encode the rotation as a 3×3 matrix (three degrees of freedom). The coordinates of the LCCS and the coordinates of the camera are related by a rotation matrix R and a three-element displacement vector t . This means that the point P with x_p, y_p, z_p coordinates in the LCCS, has different x_k, y_k, z_k coordinates in the camera coordinate system. The two coordinate values are related by the following equation.

$$\begin{bmatrix} x_k \\ y_k \\ z_k \end{bmatrix} = R \begin{bmatrix} x_p \\ y_p \\ z_p \end{bmatrix} + t. \quad (1)$$

The 3×1 transfer vector is added as a column at the end of the 3×3 rotation matrix to produce a 3×4 matrix called the external matrix:

$$\begin{bmatrix} x_k \\ y_k \\ z_k \end{bmatrix} = [R/t] \begin{bmatrix} x_p \\ y_p \\ z_p \\ 1 \end{bmatrix}, \quad (2)$$

where the external matrix T has the form:

$$T = [R/t]. \quad (3)$$

A three-dimensional point (x, y, z) in Cartesian coordinates can be written as $(x, y, z, 1)$ in homogeneous coordinates. More generally, a point in homogeneous coordinates (x, y, z, w) coincides with a point $(x/w, y/w, z/w)$ in Cartesian coordinates. Homogeneous coordinates allow to representing infinite quantities using finite numbers. For example, a point at infinity can be represented as $(1, 1, 1, 0)$ in homogeneous coordinates.

3. Image coordinate system.

Once we get a point in the 3D camera coordinate system, applying rotation and transfer of the points in LCCS, we can project the point onto the image plane to get the location of the point in the image. In the image, we are looking at the point P with coordinates x_k, y_k, z_k in the camera coordinate system. Previously, we converted its coordinates to LCCS using an external matrix to get the coordinates in the camera coordinate system using equation (2).

The optical center (point aperture) is denoted by O_k . An inverted point image is formed on the image plane. For mathematical convenience, we simply perform all calculations as if the image plane is in front of the optical center, because the image readings from the sensor can trivially be rotated by 180 degrees to compensate the inversion. In practice, even this is not required because the sensor of a real camera simply reads data from the bottommost row in reverse order (from right to left), and then from bottom to top for each row. With this method, the image is automatically vertical and the left and right in the correct order. So in practice image rotation is not necessary. The image plane is located at a distance f (focal length) from the optical center. The following formulas give the image (x, y) of 3D point x_k, y_k, z_k :

$$x = f[x_k/z_k], \quad y = f[y_k/z_k]. \quad (4)$$

The above two equations can be rewritten in matrix form as follows:



$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_k \\ y_k \\ z_k \end{bmatrix}. \quad (5)$$

The K matrix shown below is called the internal matrix and contains the internal parameters of the camera.

$$K = \begin{bmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{bmatrix}. \quad (6)$$

The above simple matrix only shows the focal length. However, the pixels in the image sensor might not be square, so it should be two different focal lengths f_x and f_y . The optical center (c_x, c_y) of the camera may not coincide with the center of the image coordinate system. In addition, the nonzero angle γ between the x and y axes of the camera sensor gives slight skew. Taking all of the above into account, the camera matrix can be rewritten as:

$$K = \begin{bmatrix} f_x & \gamma & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix}. \quad (7)$$

However, in the above equation, pixel coordinates x and y are relative to the center of the image. The origin is at the upper left corner of the image when working with images. Let us represent the coordinates of the image as (u, v, w) :

$$\begin{bmatrix} u' \\ v' \\ w' \end{bmatrix} = \begin{bmatrix} f_x & \gamma & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_k \\ y_k \\ z_k \end{bmatrix}, \quad (8)$$

where

$$u = u/w', \quad v = v/w'. \quad (9)$$

Thus, the projection of a three-dimensional point in LCCS into the pixel coordinates of the camera is performed in three stages:

- a three-dimensional point is converted from LCCS to camera coordinates using an external matrix, which consists of rotation and movement between two coordinate systems;
- a new three-dimensional point in the camera coordinate system is projected onto the image plane using an internal matrix, which consists of the camera internal parameters, such as focal length, optical center, etc.

V. CONCLUSIONS

The development of a simulation model makes it possible to assess the efficiency of the OESTM in a network that unites

them with fighting vehicles, depending on the selected parameters and external conditions. As a result, due to the reasonable choice of parameters, operating algorithms and components, costs are reduced at the stage of manufacturing a prototype of the OESTM network.

Further research will consist of completion the solution of the assigned tasks and creation a convenient tool for practicing various scenarios for tracking and guiding a missile to a target. Also, recommendations will be developed on improving the accuracy of target designation, taking into account the influence of various factors:

- *network-related*: choice of topology, data transmission delays, data transmission errors, the number of OESTM involved and the distance of their placement from each other;
- *OESTM-related*: accuracy and resolution of missile and target coordinates measurement, maximum measurement range, measurement delays;
- *target-related*: trajectory, speed and flight altitude.

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