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DESIGNING AND TESTING A PROTOTYPE OF OPTICAL-ELECTRONIC STATION FOR DETECTING AND TRACKING MOVING OBJECTS IN THE AIR

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The object of this study is the process of detection and tracking of air targets.

The task being solved is to choose priorities between hardware and software solutions to eliminate structural contradictions in the design of a supporting and rotating device, which at the same time should ensure high speed and accuracy of tracking aerial objects for the optical-electronic station.

A prototype of an optical-electronic station was designed and built. The study of the effect of eliminating structural contradictions by hardware and software methods on the accuracy characteristics of the supporting and rotating device was carried out. We have developed original specialized software for testing the accuracy of command execution. A procedure for testing the optical-electronic station has been devised. All conducted tests were performed in compliance with accepted norms and standards.

The mechanism of influence of the method of controlling the servo drives of the supporting and rotating device on the characteristics of the optical-electronic station has been established. In this case, the program method has priority. In contrast to existing solutions, the developed software method of controlling the support-turning device makes it possible to exclude stops at the limits of the servo control period and to realize a smooth transition to a new value of the tracking speed. Owing to the improvement of forecasting and synchronization of servo parameters with the period of its control, it was possible to solve the investigated problem by the software method.

The mechanism of influence of the inertia of the supporting and rotating device on the characteristics of the optical-electronic station has been established. In this case, the hardware method has priority.

The results could be used to improve the characteristics of optical-electronic stations in the detection and high-precision tracking of moving objects in the air environment

Keywords: optical-electronic station, supporting and rotating device, control of servo drives, software method

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1. Introduction

The development of high-tech models of equipment capable of moving in the air space at high speeds puts ever greater demands on the systems of their detection, support, and processing of trajectory information. An important role in such systems belongs to high-precision stationary and mobile optical-electronic stations (OES). The high accuracy of OES measurements is ensured by the use of modern technologies and an elemental base, which is combined with high dynamic characteristics of electromechanical tracking systems with processing of measurement results on a computer.

The OES can perform various functions:

a) airspace monitoring in the visible and infrared ranges:

1) a circular survey of the airspace;

2) monitoring of the selected space sector;

3) detection, recognition, and classification of moving objects;

4) high-precision tracking of the selected object;

5) calculation and analysis of the parameters of the objects' movement trajectory;

b) external trajectory measurements during polygon tests of aerial objects:

1) measurement of the trajectory of movement and analysis of the parameters of the trajectory of the aerial object;

2) record the trajectory in spherical, local, and global coordinate systems;

4) metrological certification of trajectory measurements;

c) guidance of means of destruction of moving objects in the air space:

1) detection of targets in space;

2) automatic capture of a group of targets with temporal separation of measurement channels;

3) high-precision tracking of the selected object;

4) calculation and forecasting of the parameters of the trajectory of the selected object;

5) transmission of targets for means of destruction;

6) construction of the projection of the trajectory of objects on the topo base.

The given number of examples of OES functionality gives an idea of the level of demand for research in these areas. In many cases, the functionality of OES is, first of all, limited by the technical characteristics of the supporting and rotating platform (SRP). Therefore, designing OES SRP that meets modern requirements is an urgent task.

2. Literature review and problem statement

Work [1] describes the development and testing of a stabilized rotating platform for astronomical observations. The results are obtained from a mathematical model and experimental studies, which are then compared. It is important that the results of the simulation coincide with the results of the experiments. However, the research was conducted without the use of a payload, which makes it impossible to take into account the inertia of the rotary platform. Inertia is a critical parameter that must be taken into account at the stage of SRP design.

The use of piezo motors in study [2] made it possible to obtain significant results in the accuracy of rotation of SRP. But in comparison with the results of another study [3] on the development of SRP, which was also conducted with ultrasonic engines, the results are worse. This can be explained by the simplification of the construction and elements of SRP, as indicated by the authors, and the lack of high-quality design of SRP.

Paper [4] considers the development and production of a system for countering unmanned aerial vehicles (UAVs), the main component of which is OES. The work reports the results of the software component of the system, which successfully performs the search and tracking of UAVs. But due to insufficient coverage of SRP, which is a component of this system, it is impossible to make a clear conclusion whether the obtained results are the merit of the software or the hardware part of the system. It is possible to increase the effectiveness of this development if a clear division of tasks is made, which must be performed at the stage of SRP design, and which at the stage of software development.

The research carried out in [5] focused on the improvement of OES. The main problem identified in the work is nonlinear factors caused by the interaction of optical, mechanical, and electronic nodes. As a solution to the problem, various methods of controlling the engines of OES SRP were used. Despite the success in solving the planned tasks, the study did not pay attention to how the obtained results affect the accuracy of measuring the coordinates of aerial objects.

Article [6] considers the OES located on an artificial satellite of the earth. The influence of the torque of the 2-axis SRP during its rotation on the position of the satellite is studied. Mathematical modeling and experiments on specially designed and built prototypes were used. After testing the 1st prototype, the 2nd prototype was developed and built, taking into account the results of the 1st prototype testing. Comparisons of the test results of the two prototypes show a significant improvement in accuracy characteristics. This was achieved by the fact that specific goals and objectives were set during the design of the prototypes – reducing the torque. It is possible to achieve even better results by further reducing the mass of SRP.

A separate case is photoelectric measurement systems used to distribute projectile motion. An example of such a system is given in [7]. These systems do not require the use of SRP. The results of the measurement of projectile motion distribution obtained during the study show that the measurement error of the system can reach ±2 mm. This is explained by the highly specialized and structural features of this system. It is able to measure the position of the projectile only under laboratory conditions if the projectile passes directly through the light screen of the model. Despite the best achieved results in the accuracy of measuring the position of the target, this method is not suitable for the OES of tracking air targets.

The need for high-quality and clear design can be seen in work [8] that reports the analysis of weapon systems using lasers. The complexity of laser systems and their high requirements are shown, requiring a high-quality solution of all technical problems at the system design stage. But the paper does not show how SRP parameters will affect the characteristics of the system as a whole.

From the reviewed materials, it becomes clear that there is a problem of choosing priorities between hardware solutions at the design stage and software solutions to eliminate structural contradictions in the development of SRP. These solutions should provide OES with high speed and accuracy of tracking objects.

In order to eliminate structural contradictions, which are caused by the interaction of optical, mechanical, electronic nodes and software [1–8], it is necessary to determine which actions should be performed at the stage of designing the hardware part of OES SRP, and which should be solved by software methods.

3. The aim and objectives of the study

The goal is to design and test a prototype optical-electronic station using hardware and software solutions to eliminate structural contradictions of SRP that affect the accuracy of tracking air objects.

To achieve the goal, the following tasks were set:

– to design and manufacture station details;

– to evaluate the characteristics of the accuracy of working out of SRP commands;

– to estimate the speed of reversal of SRP;

– to assess the accuracy of the tracking of air objects using the designed OES.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of the study is the process of detection and tracking of air targets.

The research hypothesis assumes that design features directly affect the accuracy characteristics of OES. Clear requirements in the design of optical-electronic systems have a positive effect on all the characteristics of these systems.

Assumptions and simplifications adopted in the study:

– a limited number of factors affecting the operation of SRP and the characteristics of OES are accepted;

– inertia is proposed to be eliminated by a hardware method at the design stage of SRP of OES;

– to exclude stops at the limits of the servo control period and to implement a smooth transition to a new value of the tracking speed is proposed by software methods.

4. 2. Software for the design of an optical-electronic station

To conduct research, an operating prototype of OES was designed and manufactured. The development of design documentation for OES was carried out using the SolidWorks licensed software package – an automated design system (CAD) for the automation of work at the stages of design and technological preparation of production in the Microsoft Windows environment.

The principle of three-dimensional solid and surface parametric design was used when developing the design documentation for SRP in SolidWorks. The built and assembled three-dimensional parts of SRP are represented in the form of three-dimensional electronic models, according to which two-dimensional drawings and specifications were constructed in accordance with the requirements of the unified system of design documentation (ESKD).

Three-dimensional modeling of SRP helped eliminate product assembly errors at the design stage. Models of parts for processing on a numerically controlled (CNC) machine were built. Three-dimensional parts of SRP were obtained as a result of a combination of three-dimensional primitives. The successive expansion of 3D objects eventually allowed us to obtain SRP that meets all technical and technological requirements. The SOLIDWORKS Simulation package was used to conduct strength studies of the designed structure of SRP, which allowed us to accelerate the design process of SRP with guaranteed properties.

4. 3. Test conditions

The tests were carried out under normal climatic conditions according to GOST 22261-94. The conditions of the tests are given below:

– ambient air temperature, °C: 10±10;
– relative humidity, %: from 50 to 100;
– pressure, mm Hg: from 740 to 780;
– frequency of the power grid, Hz: 50±0.5;
– AC power supply voltage, V: 220±4.4.

5. Results of investigating the characteristics of the designed optical-electronic station

5. 1. Design and manufacture of station parts

Based on the design documentation prepared at the experimental plant of the Kharkiv National University of Radio Electronics (NURE), Ukraine, an SRP for an optical-electronic station for the detection and tracking of moving objects in the air environment was manufactured. During the design of SRP elements, 3D models were built on the basis of which molds were made using 3D plastic printing technology. These models were used to construct molds for parts to be manufactured by casting.

The process of manufacturing the supporting frame for SRP is shown in Fig. 1.

The production of a case for the optical-electronic station is shown in Fig. 2.

Using SolidWorks software, the center frame and placement of OEM components on it was designed so that the center of mass is at the point of intersection of SRP axes. The optimal position was searched for each optical device in OEM. This approach made it possible to achieve a static position of the center of mass during frame rotation. The result is the elimination of the inertia of SRP by the hardware method at the stage of designing OES.

The layout of the elements of the optical-electronic station is shown in Fig. 3.

Subsequently, the experimental model of OES for the detection and tracking of aerial objects was improved through the installation of a current collector, which allowed SRP to rotate 360 degrees, and an adjustment mechanism for the video camera and thermal imager was also made: Fig. 4. The manufacture of the housing for the power supply unit of OES is shown in Fig. 5.

a *b* *c* *d*

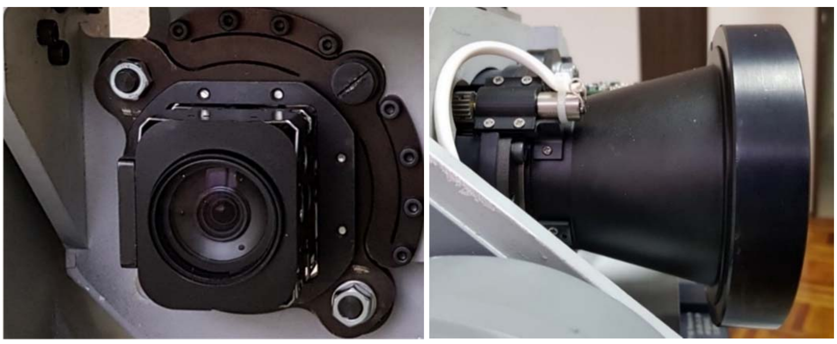
Fig. 1. Production of a supporting frame for the supporting and rotating device: *a*–*c* – the process of building a mold for casting the frame; *d* – cast frame before processing

a *b* *c* *d*

Fig. 2. Making a body for the optical-electronic station: *a* – work on painting the body of the supporting and rotating device; *b*–*d* – work on assembling the body

a *b* *c* *d*

Fig. 3. Layout of the elements for the optical-electronic station: *a*, *b* — installation of optical devices in the supporting and rotating device; *c* — cable switching; *d* — installation of the GPS antenna



a *b*

Fig. 4. General view of optical devices: *a* — FCB-EV7520 camera with an adjustment device; *b* — device for adjustment and drive for adjusting the focus of the thermal imager

a *b*

Fig. 5. Power supply equipment of the supporting and rotating device: *a* — general view of the power supply unit; *b* — placement of modules in the power supply unit

The optical-electronic component and the description of the algorithms for detection, capture, and tracking of targets are given in works [9, 10].

5. 2. Checking the accuracy of command execution by the servo drive

The test of the supporting and rotating device using the software method, which makes it possible to exclude stops at the limits of the servo control period and to implement a smooth transition to a new value of the tracking speed, was performed on the bench shown in Fig. 6.

Software has been developed to check the accuracy of the servo command execution. It was developed in the C and C++ programming languages in the Linux operating system.

Servo movement control is performed via the USB-CAN bus, which is an intermediary between the servo drive and a personal computer. This introduces some delays when processing commands, which must be taken into account when using the program.

Fig. 6. Bench for evaluating the accuracy of command execution by a servo drive

API (Application Programming Interface) is used to use servo drives – a programming interface for developing programs from the manufacturer. The API contains functions and commands for the convenience of interaction with servo drives.

Fig. 7 shows the main (basic) menu of the software.

The interface is controlled by entering numbers from the keyboard.

```
Main menu
1-Set move point
2-Set Zero point here
3-Go to zero
4-Exit
```

Fig. 7. Main menu of the software

The first menu item is setting the destination point for servo movement.

The second item in the main menu is to set zero to the current servo position. After turning, the program returns to the main menu.

The third item in the main menu is movement to the zero position. When this item is selected, the servo returns to the zero position. After turning, the program returns to the main menu.

During testing, the turning speed was limited to 1 degree per second and the maximum acceleration was limited to 1 degree per second squared. These parameters can be changed directly in the program code.

The test on the accuracy of the command execution by the servo drive was carried out by an experimental method. For measurement, a semiconductor laser (λ=0.63 μm) is used, which is fixed on a platform that rotates around the angle of the seat (Fig. 6). The direction of laser radiation coincides with the direction of the normal to the plane of the platform. The laser forms a mark on a scale-coordinate paper placed at a distance of 30 m. Before each measurement, the location of the center of the mark on the scale-coordinate paper is recorded and recorded in the measurement protocol. After executing the servo command «turn the platform to the specified angle», the location of the mark is fixed, and a new reference value is entered in the protocol. The distance between two marks is measured: before and after the start of movement. Having such data and using the formulas and properties of triangles, we are able to calculate the actual angle of rotation of the installation platform. The difference between the specified angle for executing the servo command and the experimentally determined angle of rotation of the platform is the error.

The servo's ability to execute commands is limited by its 19-bit encoder. The minimum step is 2.5 arcseconds (Table 1).

Table 1

Minimum rotation angle value

19-bit encoder, number of divisions	Minimum rotation angle, angle degree	Minimum rotation angle, arc second
524288	0.000686646	2.471923828

Gear backlash is 18 arc seconds. But due to the use of two encoders, the servo drive is partially able to remove this backlash.

The measurement error of the laser beam deviation is 1 mm in the center of the target and 2 mm at the edge of the target, which is 7÷14, respectively, arc sec (Table 2).

Table 2

Laser beam deflection measurement error

Measurement error, mm	Measured rotation angle, rad	Measured rotation angle, deg	Measured angle of rotation, arc sec
0.00	0	0	0.00
1.00	$3.37701 \cdot 10^{-5}$	0.001934884	6.97
2.00	$6.75402 \cdot 10^{-5}$	0.003869768	13.93

The maximum value of the error of the command execution by the servo drive does not exceed 28÷35 arc sec.

Experiment No. 1. Evaluation of the accuracy of command execution by a servo drive at a step of 0.1 degrees (360 arc sec).

An example of the obtained measurement results (a fragment of 3 values out of 100) is given in Table 3.

Table 3

Estimation of the accuracy of the execution of the command by the servo at a step of 0.1 degrees

Value	SRP rotation angle, degree	SRP rotation angle, arc sec	Measured rotation angle, degree	Measured angle of rotation, arc sec
1	0.1	360	0.1025487	369.18
2	0.1	360	0.1006139	362.21
100	0.1	360	0.0967441	348.28

The average value of experiment No. 1 is 357.57 arc sec.

Experiment No. 2. Evaluation of the accuracy of command execution by a servo drive at a step of 0.01 degrees (36 arc sec).

An example of the obtained measurement results (a fragment of 3 values) is given in Table 4.

Table 4

Estimation of the accuracy of command execution by a servo at a step of 0.01 degrees

Value	SRP rotation angle, degree	SRP rotation angle, arc sec	Measured rotation angle, degree	Measured angle of rotation, arc sec
1	0.01	36	0.007739535	27.86
2	0.01	36	0.007739535	27.86
100	0.01	36	0.009674419	34.83

The average value of experiment No. 2 is 43.11 arc sec.

5. 3. Checking the speed of command execution by the servo drive

The speed tests were carried out using a method that makes it possible to exclude stops at the limits of the servo control period and to implement a smooth transition to a new value of the tracking speed. A special program was also developed that makes it possible to obtain data for maximum speed calculations. Owing to flexible settings, it is possible to set the acceleration and speed limitation of the servo drive. The interface of the program has a similar appearance to the software for measuring the accuracy of movement.

The maximum speed is measured as follows – the servo is given a command to move, and the current position and time are read during the movement. After the end of the movement, the raw data is analyzed. During the movement, the indicators were read 20 times, the obtained data were recorded in a log file, from where the data were exported to Microsoft Excel for speed calculation. The program displays the following indicators on the console during servo movement: current position, delta (difference between previous and current position), time delta (time difference between previous and current measurement).

Experiment No. 3. Estimation of the maximum turning speed of the platform by azimuth. An example of the measurement results (a fragment of 3 values out of 100) is given in Table 5.

Table 5

Checking the maximum speed of turning the platform by azimuth

Value	Position, degree	Delta	Time delta	Speed, degree/s
1	–39.7925	–7.8443	51	153.8
2	–47.6340	–7.8415	52	150.8
100	–71.0239	–7.7571	51	152.1

The average value of experiment No. 3 is 150 degree/s.

Experiment No. 4. Estimation of the maximum turning speed of the platform by the angle of the site. An example of the measurement results (a fragment of 3 values) is given in Table 6.

Table 6

Checking the maximum turning speed of the platform by the angle of the site

Value	Position, degree	Delta	Time delta	Speed, degree/s
1	–1.3430	7.2352	51	141.9
2	5.9361	7.2791	51	142.7
100	12.7922	6.8562	51	134.4

The average value of experiment No. 4 is 140 degree/s.

5. 4. Evaluation of the quality of the algorithm for tracking aerial objects

Testing the accuracy of the tracking using a method that makes it possible to exclude stops at the limits of the servo control period and implement a smooth transition to a new value of the tracking speed was evaluated from the video recording of the aircraft tracking.

For each test record, an annotation (coordinates and dimensions of the object on each frame) was created manually in «XML» format. The result of the operation of the tracking algorithm is fixed, then a comparison of the annotations and the results of the operation of the tracking algorithm is performed. After the comparison, a report is generated in «XML» format with detailed statistics.

The «tracking error» measure is used to evaluate the performance of the tracking algorithm throughout the entire video sequence.

An example of the measurement results (a fragment of 3 values) is given in Table 7.

Table 7

Results of a manual comparison of the position of an object on the monitor screen in pixels

Value	Second	*X*, pixels	*Y*, pixels	Manual, *x* pixels	Manual, *y* pixels	Error, pixels
1	26	455	219	460	216	5.830952
2	27	375	207	378	203	5
100	28	270	191	272	189	2.828427

The resulting mean tracking error is 4.943176 pixels.

6. Discussion of research results regarding the designed optical-electronic station

Initially, before conducting tests, the principle of controlling the speed of movement to a given position was used in OES, in which, upon reaching the specified position, the system stops and fixes the drive in the given position. The advantages of this approach are that the current position of the video sensor is determined at the boundaries of the period, and it is possible to make a speed forecast for the next period. But during the tests, it was found that this control algorithm has a significant drawback – it is necessary to stop the movement of the platform with the video sensor at the end of each period. This significantly impairs the smoothness of tracking and leads to uneven tracking speed at the borders of the update period. The presence of stops complicates the prediction of the tracking speed because the positioning speed of the video sensor has a non-linear nature during control. At high speeds, sudden stops and accelerations significantly impair object support and lead to increased wear of drive elements and can lead to the destruction of optical-electronic station equipment. In contrast to the method of controlling the speed of moving the servo drive to a given position, a software control method was used, which makes it possible to remove stops at the limits of the control period and implement a smooth transition to a new value of the tracking speed due to the improvement of forecasting and synchronization of its parameters with the drive control period. Unlike research [4], the proposed method does not require the construction of a specialized controller.

The result is a reduction in the time of transient processes and the duration of inconsistency with the control signal. This ensures the obtained accuracy (Tables 3, 4) and speed (Tables 5, 6) of executing commands by servo drives.

Also, the original design of the servo drive has a positive effect on the accuracy characteristics. The servo used combines the servo itself, the encoder, and the digital controller. The high quality of the design ensures the accuracy and constancy of the parameters, and the presence of a built-in encoder in combination with the controller makes it possible to calibrate SRP. It should also be noted that SRP body is made of a solid cast frame, which ensures the rigidity of the structure. This also has a positive effect on accuracy characteristics.

From our results, it can be concluded that structural and technical contradictions were minimized in the designed OES.

The results of this study refer to OES for target detection and tracking and cannot be used for specialized means of trajectory measurements [7].

All tests were carried out under laboratory conditions. Because of this, the factors affecting OES and its components (the main one in this case is SRP) were not taken into account when testing in an open environment. It is not known how OES will behave under the influence of different meteorological conditions and whether the accuracy characteristics of SRP will change.

Our further research will involve carrying out field tests.

7. Conclusions

1. The design of the outer and inner frames and the placement of optical devices in the middle of SRP ensure the

invariance of the position of the center of mass of the SRP. This has a positive effect on the characteristics of accuracy and smoothness of target tracking. Hollows and stiffeners were included in the frame design in order to reduce the weight while maintaining the maximum rigidity of the structure. The production of the supporting frame of SRP was carried out using aluminum die-casting technologies. This made it possible to achieve high rigidity with minimal frame weight.

2. When executing the servo drive command «turn the platform to an angle α=36 arc sec» the average value of the platform turn, determined by 100 measurements, is equal to $\bar{m}$=43.11 arc sec, and the root mean square deviation δ=20.31 arc sec. The smooth movement of the camera in the process of tracking the target was noted owing to the improvement of the prediction and synchronization of the servo parameters with the period of its control, which subsequently ensured the accurate construction of the trajectory.

3. The turning speed of the platform by azimuth exceeds 150 degree/s, and in elevation it exceeds 140 degree/s. The absence of jerks in the movement of the camera during the tracking of the target was noted. This is achieved by eliminating the stops at the boundaries of the servo control period.

4. When tracking aerial objects, the average error is 5 pixels. This value is within the limits of determining the position of the object in the video by a person and does not exceed 10 % of the visible size of the object. The absence of frame jitter on the target was noted.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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