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COMPUTER VISION SYSTEM FOR SPACECRAFT RELATIVE POSE DETERMINATION DURING RENDEZVOUS AND DOCKING

Introduction. *The leading countries of the space industry are intensively working to create service spacecraft for inspection and servicing of non-cooperative spacecraft without special docking devices. The use of optical systems, the so-called computer vision systems, for determination of the position allows automatic approaching and docking with a non-cooperative spacecraft.*

Problem Statement. *Development of efficient methods of vision-based relative pose estimation of spacecraft is currently an urgent precontrol system problem. In this paper, we consider the criteria for the effectiveness of the solution to be in accordance with the technical requirements for the system in terms of accuracy and performance.*

Purpose. *The purpose of this research is to design a general system architecture, to create a mathematical model of the mutual approach dynamics, to develop methods for solving the precontrol system problem of determining the relative position of a solid body, as well as software and algorithmic support.*

Materials and Methods. *Image processing methods, computer graphics, orbital dynamics, ellipsoidal estimation of nonlinear dynamical systems, methods of solving nonlinear systems, methods of graph theory and learning.*

Results. *General schemes and approaches that ensure the fulfillment of tasks are proposed. Mathematical methods and algorithms that implement the general scheme for solving the precontrol system problem are described.*

Conclusions. *Bench tests showed the possibility of applying the proposed methods and technical solutions to meet the technical requirements.*

Keywords: *computer vision systems, relative pose estimation, non-cooperative spacecrafts, ellipsoidal estimates, nonlinear dynamical systems, inverse precontrol system problems, and image recognition.*

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In recent decades, many countries have been working intensively to create service spacecraft (SS) for the inspection and maintenance of so-called non-cooperative spacecraft (NCS), ie spacecraft (SC) that are unable to do controlled maneuvers and are not equipped with special docking devices. An important component of these operations is rendezvous and docking, in the final stages of which optical systems are used for determining the position and orientation of the NCS relative to the service spacecraft [1]. The optical systems are used because of a high resolution of the optical signal and, accordingly, a potentially high accuracy of determining the relative position and orientation of the NCS. Such systems are called computer vision systems (CVS). In particular, CVS allow solving this precontrol system with the use of 3D graphic model and images of NCS control system maintained by a camera mounted on service spacecraft [1–4].

An important stage in the creation of CVS is testing developed algorithms, software applications, and other technical solutions, in particular, in series of ground-based field tests in simulated space conditions.

The research presents the theoretical foundations, software and hardware of CVS, as well as the results of its testing on a special stand. Aspects of CVS development, including basic requirements to CVS (Section 1); specifications for the CVS camera and the structure of the CVS device, technical means necessary for its implementation (Section 2); mathematical and algorithmic support of CVS (Section 3); ways to increase the accuracy and speed of CVS (Section 4); mathematical modeling of docking with NCS (section 5); stand for field tests of CVS (Section 6); the results of modeling the algorithms of CVS operation and the results of stand tests (Section 7) have been considered.

1. Assignment of CVS

CVS is installed on service spacecraft and is designed to determine the mutual position and orientation of the two spacecraft on video image at

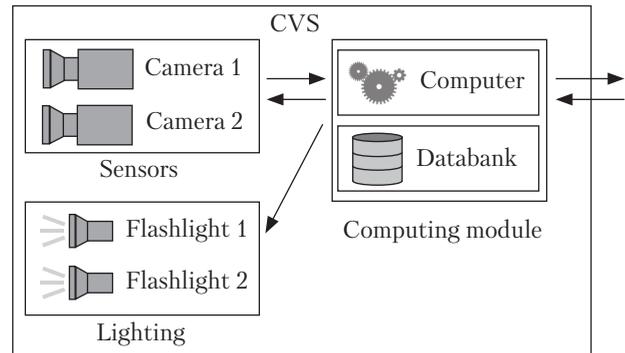


Fig. 1. CVS module of the rendezvous and docking system

the stage of rendezvous. The corresponding orthogonal coordinate systems (CS) are rigidly connected to the service spacecraft body and to the NCS body. To determine the mutual position and orientation of NCS relative to the service spacecraft means to determine the relative position of their coordinate axes.

The CVS module (Fig. 1) determines the parameters of the relative position and the NCS motion and transmits them to the service spacecraft control system to control a rendezvous. This module consists of a sensor system represented by two camcoders, a computing module (CM), and a target illumination system.

The camcoders are designed to receive images of NCS and to transfer them to the computing module. Camera lenses have no moving parts, their focal lengths are fixed. Only one of the CVS sensor system cameras (the active camera, AC) may be used at once. Its parameters provide the clearest image at a specific distance to the NCS.

The computing module is designed to compute, using a 3D graphical model of the target NCS, the parameters of the NCS relative position, which are stored in the CM memory. The parameters of NCS relative motion are computed according to the algorithms described in Sections 4 and 5. The parameters of the NCS relative position and motion computed by the computing module are transmitted to the service spacecraft. There they are used to control the spacecraft motion. The computing module also provides control over the operation of the CVS, receives control com-

mands, and output data about the NCS from the service spacecraft, emits service signals and requested data.

The target illumination system is designed for additional lighting of the NCS in order to create favorable shooting conditions. The illumination system consists of several directional light sources operating in continuous or pulsed modes, with power adjustment option.

The additional requirements for CVS in terms of the conditions for its operation in space flight are as follows:

- ◆ The CVS shall be suitable for solving the problem of determining the relative position and orientation for different target NCS;
- ◆ CVS camcorders shall be rigidly attached to the service spacecraft body. The fixture coordinates and the installation angles shall be precisely known;
- ◆ In order to increase the CVS reliability and accuracy, the lenses of video cameras shall have a fixed focal length;
- ◆ The camcorder shall be programmed to adjust the shutter speed depending on the brightness of the light reflected by NCS.

The camera optical characteristics that follow from the CVS specifications are given below.

2. Camcorder Specifications

The camcorder parameters, namely, focal length, angle of view, aperture, number of pixels and matrix size have been determined. This allows implementing the CVS specifications. The optical system characteristics shall be such that any shift in the NCS position and orientation by a value equal to a given accuracy leads to a change in the image that can be recorded by the optical system.

To assess the sensitivity of the image to changes in the NCS relative position and orientation, the necessary coordinate systems and the conversion of the design of 3D objects to the frame plane have been identified.

To obtain a mathematical model for the construction of optical system images, the relative position of the NCS and the currently used CVS ac-

tive camera is considered. The optical circuit is chosen given the following conditions:

- ◆ The focal length and the angle of view of the camera are fixed;
- ◆ The NCS image shall occupy as large area as possible in the image; at close range, the docking surface shall go as little as possible beyond the field of view of the used camera;
- ◆ The NCS shall be inside the clearly depicted camera space;
- ◆ At the selected angle of view, the camera matrix resolution shall allow detecting changes in the NCS image, as the NCS position and orientation shift by values specified by the accuracy requirements.

Simultaneous fulfillment of the specified requirements with use of one camera is impossible. One camera with a fixed angle of view cannot cover the entire specified range of distances. Therefore, the use of two cameras is considered. Each camera provides obtaining frames of the required quality at its range: the LRC camera (long-range camera) with a narrow field of view and the SRC camera (short-range camera) with a wider field of view.

Having done the necessary calculations, the parameters of the cameras have been determined; their specifications are shown in Table 1.

3. Mathematical and Algorithmic Support of the Technical Vision System

The purpose of CVS is to measure the relative position and orientation of a given NCS at the final stage of rendezvous. This period of active

Table 1. LRC and SRC Specifications

	LRC	SRC
Matrix size, mm	36 × 24	36 × 24
Number of pixels	3000 × 2000	3000 × 2000
Lens focal length, mm	16	30
Vertical angle of view, deg	74	44
Diaphragm diameter, mm	5	10
Range of working distances to NCS, m	Up to 5	> 5

operation is quite short; most of the time the CVS is off. Since CVS is switched on, it shall continuously perform its measurement function in real time. To do this, the CVS shall be initialized, i.e. to contain all the necessary source data (shooting frames, instantaneous estimates, static data defined in advance, and other data to be calculated).

The CVS operation is divided into the two stages: preparatory and active. The first one includes operations to initialize the static data. The second one covers operations performed directly in the process of rendezvous with the NCS in real time. The information about the NCS is based on its 3D graphical model (GM).

In order to ensure the CVS operation in real time at the active stage, it is necessary to minimize the amount of computations directly in the course of rendezvous. Since the NCS GM is set at the preparatory stage, it is possible to simultaneously perform the necessary calculations that depend only on the GM. The resulting informative data about the NCS in the form of a multidimensional array are stored in the CVS memory.

Operational initial data for computing the NCS position and orientation come only from the active camera that is chosen on the basis of current distance to the NCS and provides receiving an accurate image. Shooting is performed with a specified periodicity. The resulting digital color image is converted into a monochrome image I , a 2D array of brightness of pixels with the number of columns W and rows H . To compare data D and information from the image I , it is necessary to perform a transformation of design that is determined by vector c^1 (the parameters of the camera mathematical model). At the stage of active operation of CVS, vector c^1 is considered known; it shall be set or found at the preparatory stage. Unknown components of vector c^1 are identified while calibrating in the ground conditions, during the survey of a special test object having a given geometry. To reduce the amount of computations at the stage of active operation, the results obtained in the course of work with previous frames are used.

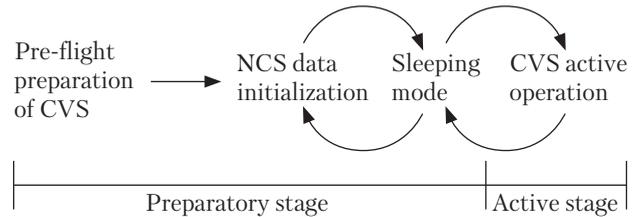


Fig.2. The sequence of CVS operations

The sequence of CVS operation consists of several phases. The first one is pre-flight preparation that includes determining the location of the cameras in the CVS body and their parameters. The second phase is the initialization of NCS data (downloading the GM and extracting from it the necessary information data that are structured and stored in the CVS permanent memory. Upon the completion of the second phase, the CVS is switched to sleep mode or shuts down. The third phase is the direct active operation of the CVS in the course of rendezvous with the NCS. It starts with switching on the CVS upon a signal from outside, which comes from the control system. The CVS is switched on and operate continuously while approaching the target NCS within the distance range of 1.5–30 m from the NCS surface. The NCS position and orientation are measured when the NCS is in the field of view of the cameras, with the readings transmitted to the service spacecraft control system. The second and third phases are repeated when working with new NCS. The process flowchart is shown in Fig. 2.

Extracting informative data from the captured frame is presented in the form of a sequence of steps. The stages are determined by the complexity of the analyzed data: from a complex complete image to simpler individual fragments. The general process scheme is shown in Fig. 3.

General scheme of the problem solution. Depending on the mutual location of CVS active camera and the NCS, we can distinguish three main situational dispositions that determine the initial conditions of the problem and, accordingly, the approach to be used for its solution.

The first position of the CVS active camera and the NCS is such that the NCS is completely

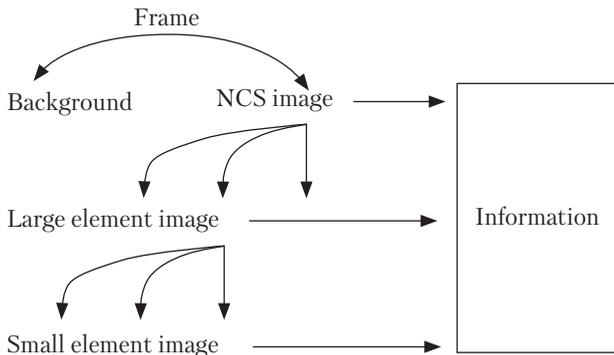


Fig. 3. Image processing scheme to determine the informative features: image segmentation chart (left); image analysis stages (right)

visible for the active camera. This means that in addition to the docking surface, other surfaces fall into the frame as well. The second possible option is the mutual location of the active camera and the NCS, when the frame displays only the docking surface. It is fully visible, with other planes of the NCS being out of sight. On the NCS, there are distinguished elements of the docking surface. It is possible to determine the outer contour of the docking surface. The third option is when the distance between the NCS and the CVS decreases so much that only a part of the docking surface gets into the frame, while the contour of the NCS docking surface is not visible.

According to the situations of mutual alignment, it is possible to distinguish different sets of informative features from the images. Each set determines the initial data for finding the NCS position and orientation relative to the active camera. According to the nature of the available information, there are three modes of CVS operation, which use different approaches to solving the problem and require different data on the NCS.

The first operation mode of the CVS, after the signal switches it on, corresponds to a significant distance to the NCS, at which small and medium-sized features and details of the NCS are unrecognizable. According to the general scheme for extracting informative signs shown in Fig. 3, the mode is characterized only by the first stage of processing: the NCS image is separated from the

background, in the frame received from the active camera. The general scheme for solving the problem is shown in Fig. 4. In this mode, the CVS operates from the first determination of the parameters of the NCS position and orientation at a distance of 30 m and until switching to the second mode is possible.

The second and third operation modes are characterized by the fact that because of increasing angular dimensions of the NCS, in the course of rendezvous, it becomes possible to find and to recognize in NCS image all the smaller details and to use them as separate reference points. According to the general scheme of extracting informative signs shown in Fig. 3, these modes are characterized by successful execution of the second and third stages of processing of the original frame, i.e. on the NCS image, groups of large and small elements are recognized. This makes it possible to find images of the NCS elements, the location of which relative to the NCS is known from the GM. There is no fundamental difference between modes 2 and 3. In the second mode, the reference points are distinguished on the basis of large elements (the docking surface contour). In the third mode, the docking surface contour is not observed, so the small elements of the visible part of the docking surface are used as reference. The general scheme of problem solution is shown in Fig. 5.

To track the position of the reference elements, the position and orientation estimated on the basis forecasted on the basis of the previous steps. At the same time, there may be situations when some of them disappear from the camera field of view and accordingly are absent in the following images. Further, it may happen that in the case of certain maneuvers in the course of rendezvous they fall into the image again, with re-recognition and follow-up required.

CVS software ensures the implementation of all phases of the CVS operation sequence. Out of the problems to be solved, the main one is to determine the NCS position and orientation with respect to CVS active camera in real time, at the stage of CVS active operation.

The solution of the problem of determining the NCS position and orientation with respect to the active camera is based on the use of information about the NCS position and orientation, which is contained in the digital image I and in data D combined with the help of a camera design model with known parameters c' . If there is no useful information from one source, the problem cannot be solved. Let us consider in what form the required information can be contained in a digital image.

The type of image I obtained by the active camera is completely determined by:

- ◆ objects that are in the field of view of the active camera (shape, colors, surface material);
- ◆ Their location relative to the active camera;
- ◆ Illumination conditions;
- ◆ Camera characteristics (design, distortion);
- ◆ Noise.

In the case where in the field of view of the active camera there is only the NCS for which the shape, color, and surface properties are specified in the GM, the image may be represented as a function

$$I = F(M, p, l, \vec{c}, \varepsilon),$$

where M is the GM of the NCS, p is the vector of the parameters of the NCS position and orientation relative to the active camera, l is the illumination conditions, \vec{c} are the parameters of the active camera model, ε is noise. Noise shall mean additive perturbations of the brightness of the pixels of the NCS image, as well as all non-zero background pixels. Parameter F is called a visualization function that is determined by the algorithm for calculating the image pixels and is known. The mathematical methods and the description of the visualization function are explained in detail by the authors in [2]. To construct realistic images, a beam tracing algorithm has been used: the brightness is calculated by summing the illumination along the set of light propagation paths. Images I at the same p can differ sharply. This means that in addition to information about the NCS position and orientation, which may be used to solve the CVS problem, digital images contain a lot of unnecessary infor-

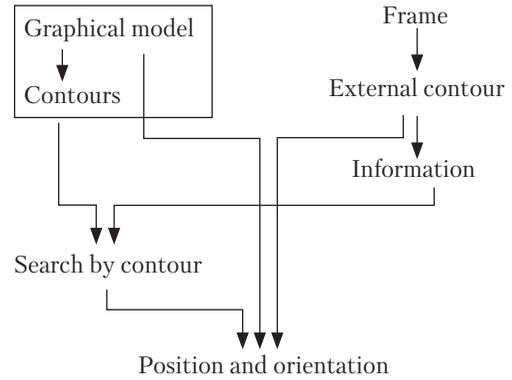


Fig. 4. The scheme for solving the problem in the first mode

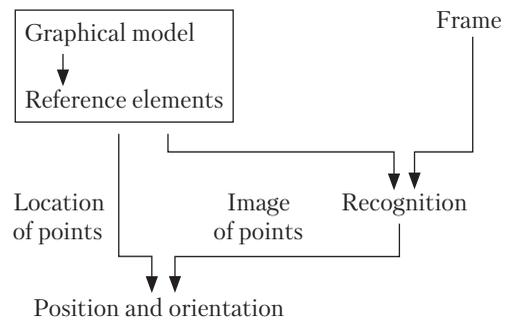


Fig. 5. The scheme for solving the problem in the second and third modes

mation. According to the existing classification of image informative features [5], there are three groups of features: color, texture, and shape. The informativeness of the image features depends on the complexity of the original image. The fewer objects are in the original image and the simpler is their shape, the more informative may be the features. For example, if the NCS is far away, small details of the structure are missing in the image, and the available informative features are determined with a low accuracy. The algorithm for solving the problem of determining the NCS position and orientation with respect to the active camera depends on what informative features may be obtained. Depending on the mutual location of the CVS active camera and the NCS, three main situational dispositions have been identified. They determine the initial conditions of the problem and, accordingly, the approach to be used for solving the problem.

The CVS operation is controlled by a special control module (SCU), one of the most important tasks of which is to control the operating conditions, i.e. to choose an operating mode based on the data obtained. Switching modes provides a continuous process of measuring the vector of NCS position and orientation parameters to ensure the maximum possible accuracy.

The second task is to tie the found boundaries into closed loops. The task is sensitive to noise, so the connection of points may go along false boundary. It should be borne in mind that the boundary pixels may differ significantly in the magnitude of the brightness gradient. Several methods have been developed to find the image contours, the main one being the Kenny operator [6].

Recognizing objects in an image is a challenge because of the ambiguity and variety of their sizes, shapes, and relative positions. The ultimate goal is to determine the position of reference points on the object surface and to find their position in the image. Having a 3DNCS graphic module, through modeling images based on it under different illumination conditions (simulating image capture by a video camera in space), one can determine the reference points. The list of these elements is formed in advance and is guaranteed to provide the possibility of simultaneous determination and maintenance of a sufficient number of special points for calculations of the mutual location of the active camera and the NCS by the proposed method.

The software architecture is presented in the form of several specialized modules that include interfaces and program applications for solving all CVS-related problems. Below, the CVS software modules are listed and described:

- ◆ control module (CM) monitors the general functional state of the CVS, controls its components, as well as serves as an interface for external control of the CVS;
- ◆ Data exchange module (DEM): information exchange between the CVS and the external environment;

- ◆ Preprocessing module (PPM): preliminary preparation of the necessary informative data about the NCS on the basis of downloaded NCS GM;
- ◆ Image acquisition module (IAM): capture and primary processing of images from the CVS cameras;
- ◆ Data storage module (DSM): long-term storage of all CVS data, including NCS GM and selected informative data;
- ◆ Parameter determination module (PDM) implements all calculation algorithms to solve the problem of measuring the position and orientation based on an individual frame;
- ◆ Condition assessment module (CAM): assessment of the current and projected parameters of the relative position, orientation, and movement of the NCS based on the use of all available measurements and the motion model.

4. Estimate of SC Rotational Mode Parameters

The use of the NCS dynamic model in filtering allows determining the rendezvous speed and angular velocity of rotation, which is necessary for rendezvousing and docking with the NCS. The dynamics of orbital motion and rotation around the center of mass may be considered separately. For the purpose of docking, the accuracy of the rotation parameters estimates is more important, so attention is focused on the use of a dynamic filter to estimate the rotation parameters.

The problem of estimating the parameters of the relative rotational motion of two spacecraft, when the sensor of angular coordinates is CVS that is mathematically and algorithmically formulated by the authors in [4]. The characteristics of the TOPEX / Poseidon satellite are taken as a model for NCS. The measured quaternion of the NCS coordinate system orientation relative to the service spacecraft coordinate system has been obtained by the methods described in [2, 4].

The results of numerical simulations [4] have shown the efficiency and effectiveness of using an ellipsoidal filter in solving the problem of esti-

mating the parameters of the relative rotational motion of two spacecraft, when the angular coordinate sensor is a computer vision system. Based on a NCS video image received with the help of the camera installed on the service spacecraft, the quaternion of the NCS orientation relative to the NCS and the angular velocity rotation vector of the NCS have been reproduced. These parameters are necessary for docking the service spacecraft with NCS. At the same time, due to the effective filtering obtained through ellipsoidal estimate, the accuracy of signals [4] significantly increases as compared with direct measurements.

The problem of filtration has been solved with some simplifications that should not significantly affect the results of research. In particular, one of such simplifications is the assumption that the camera is mounted in the center of mass of the service spacecraft, which is not actually true. The real situation complicates the conversion formulas in the part of the equations related to measurements, but is not an obstacle to the implementation of the proposed algorithms. The small disturbing moments of the forces constantly acting on the NCS are also neglected. All these and other insignificant details need careful attention in the course of implementing the proposed algorithms in the conditions of real devices and breadboard models. This is the direction to be developed further in authors' research.

It should be noted that the application of the proposed algorithms is extremely important. According to the authors, these algorithms are indispensable in the implementation of automatic docking of rotating service spacecraft and NCS. Computing and doing maneuvers in the course of rendezvous and docking with the rotating NCS are impossible unless high-precision values of orientation and angular velocity parameters are known.

5. Mathematical Modeling of the Process of Joining Service and Non-Operated Space Vehicles

Let us consider the motion of a service spacecraft and an NCS in the process of their rendezvous,

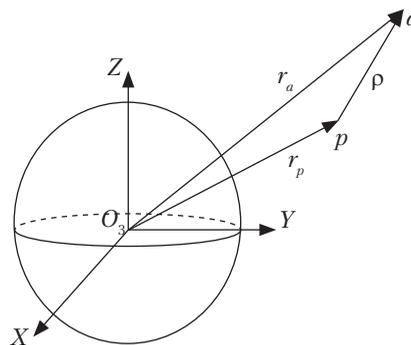


Fig. 6. Configuration of satellites in inertial space

ignoring the perturbations from the non-sphericity of the Earth's gravitational field (EGF), as well as the factors of higher order of smallness. The motion parameters of the active and passive spacecraft are denoted by symbols with indices a and p , respectively. The differential equations of the spacecraft motion relative to the basic inertial system (BIS) in the vector form are written as follows [7–10]:

$$\frac{d^2 r_p}{dt^2} + \mu \frac{r_p}{\|r_p\|^3} = 0, \quad (1)$$

$$\frac{d^2 r_a}{dt^2} + \mu \frac{r_a}{\|r_a\|^3} = a_a, \quad (2)$$

where r_p and r_a are current radius vectors of passive and active spacecraft in ICS, $\|r_p\|$ and $\|r_a\|$ are length (Euclidean norms) of the corresponding vectors (distance from the spacecraft to the center of the Earth), a_a is driving acceleration of the active spacecraft, $\mu = 398\,600,4 \text{ km}^3/\text{s}^2$ is gravitational constant of the Earth (Fig. 6).

Let us introduce relative position vector $\rho = r_a - r_p$, as shown in Fig. 6 (ρ is line of sight), point O_3 is Earth gravitational center.

In this case, the two spacecraft relative motion equations are written as follows:

$$\frac{d^2 \rho}{dt^2} + \mu \left(\frac{r_a}{\|r_a\|^3} - \frac{r_p}{\|r_p\|^3} \right) = u, \quad \rho = r_a - r_p, \quad u = a_a. \quad (3)$$

Having substituted expression $r_a = r_p + \rho$ into (3), we obtain

$$\frac{d^2 \rho}{dt^2} + \mu \frac{r_p + \rho}{\|r_p + \rho\|^3} - \mu \frac{r_p}{\|r_p\|^3} = u. \quad (4)$$

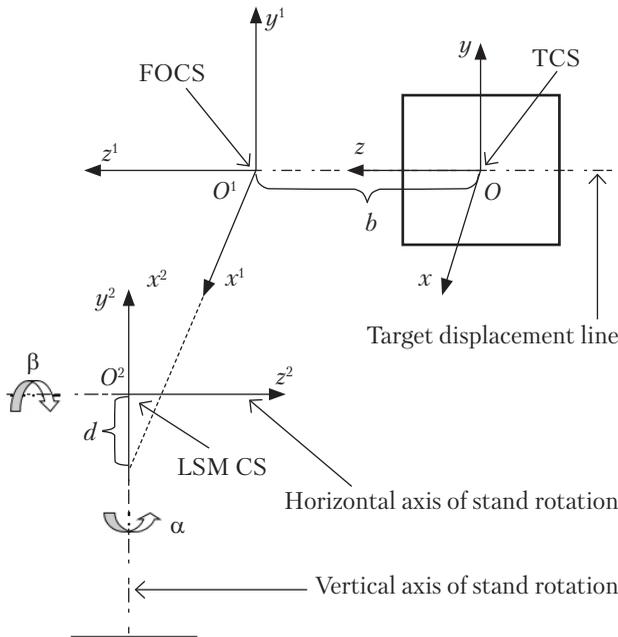


Fig. 7. Stand coordinate systems

Equation (4) describes the motion of the service spacecraft relative to the NCS in the ICS.

The rotational motion of the active spacecraft is described by the dynamic Euler equation:

$$J\dot{\omega} + \tilde{\omega}J\omega = M, \quad (5)$$

where $J = J^T > 0$ is positive definite symmetric matrix of the service spacecraft inertia tensor representation in the associated CS; $\omega = (\omega_1, \omega_2, \omega_3)^T$ is vector of absolute angular velocity of the spacecraft, which is set by projections to spacecraft

coordinate axes $O_a x_a y_a z_a$; $\tilde{\omega} = \begin{pmatrix} 0 & -\omega_3 & \omega_2 \\ \omega_3 & 0 & -\omega_1 \\ -\omega_2 & \omega_1 & 0 \end{pmatrix}$; $M = (M_1, M_2, M_3)^T$ is vector of driving moments.

The service spacecraft orientation relative to the NCS is described by the kinematical equations [11]:

$$2\dot{\Lambda} = B(\Lambda) (\omega - S(\Lambda) \omega_*), \\ S(\Lambda) = I_3 - 2\lambda_0 \tilde{\lambda} + 2\tilde{\lambda} \tilde{\lambda}, \quad \tilde{\lambda}$$

where $\Lambda^T = (\lambda_0, \lambda^T)$ is quaternion of the orientation, $\lambda^T = (\lambda_1, \lambda_2, \lambda_3)$, $S(\Lambda)$ is directional cosine matrix,

$B(\Lambda) = \begin{pmatrix} -\lambda^T \\ \lambda_0 I_3 + \tilde{\lambda} \end{pmatrix}$, I_3 is 3×3 unity matrix, ω_* is NCS

absolute angular velocity vector set by projections on coordinate axes of the associate coordinate system $O_p x_p y_p z_p$.

Similarly to [12], we formulate the statement of the docking problem at the approach section as a general problem of the synthesis of accelerations $u = u_c$ and driving moments $M = M_c$ in dynamic Euler equation (5) of the service spacecraft motion, provided at a given time $t = t_E$ the following relationships are met:

$$d(t_E) = \|\rho(t_E)\| = 0, \quad \|\dot{\rho}(t_E)\| = 0, \\ S(t_E) = I_3, \quad \|\omega(t_E)\| = 0. \quad (6)$$

Given the substantiated argumentation given in [12], we also neglect the heterogeneity of the EGF, because of the relative smallness of the spacecraft spatial coordinate fluctuations in the time interval of the final stage of docking (the approach stage).

Conditions (6) are general for approach control systems with an arbitrary composition of the complex of measuring equipment. They provide that as a result of solving the problems of optimal synthesis based on typical known criteria, optimal controls can be obtained as a function of complete status vector system Z and time t : $u_c^* = u_c(Z, t)$, $M_c^* = M_c(Z, t)$, $Z^T(\rho, \dot{\rho}, \Lambda, \omega)$. However, in this research, it is provided that video camera is the only measuring device of the control system. Therefore, to study the observability of the obtained systems of equations related to the dynamics of spatial and rotational motion of service spacecraft based on the measuring information of the video camera is a relevant problem.

6. Description of Test Stand and Coordinate System

The CVS test stand is used for ground adaptation of algorithms for determining the NCS position and orientation and also for check of CVS accuracy. The stand is created in the research chamber of PJSC *Elmiz*. The equipment available there allows turning the camera, with a high precision, for azimuth and roll angles and also changing horizontal position of the docking surface model.

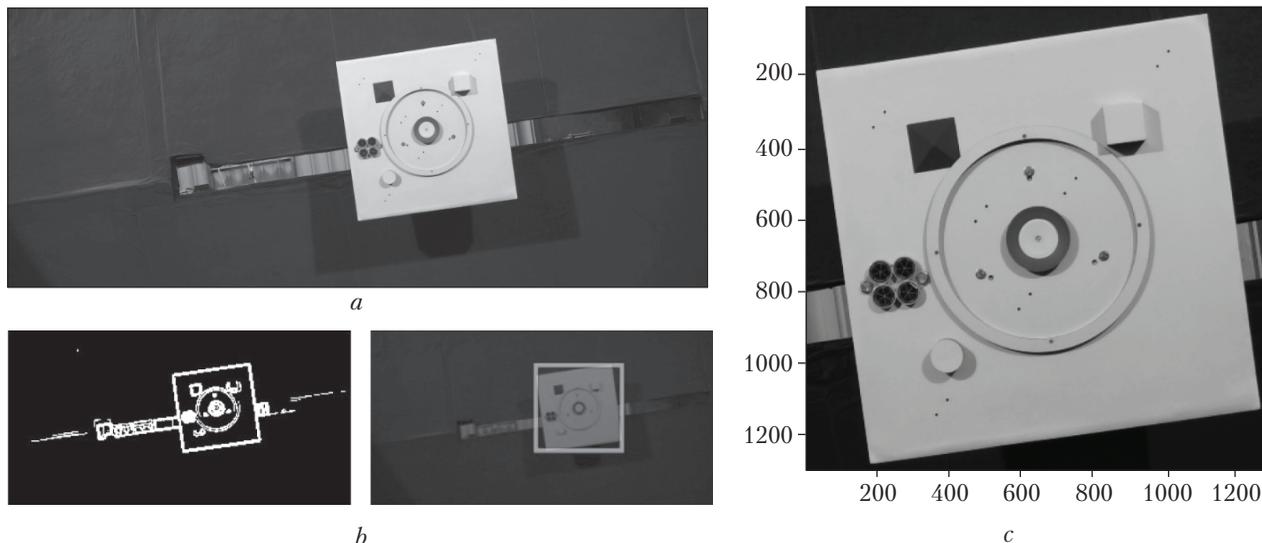


Fig. 8. Selection of areas of interest in the frame: *a* – source frame; *b* – gradient and the found area on the image compressed 16 times; *c* – a fragment of the image, which is transmitted for further analysis

The CVS camera selected in accordance with section 2 is rigidly fixed on a high-precision rotary stand that has remote equipment for turning and measuring the magnitudes of these turns. The stand provides high-precision angular rotation of the camcorder around two mutually perpendicular axes to simulate changes in the relative angular position of the camcorder and the target at different azimuth and roll angles. It is also possible to move the prototype along the horizontal axis to simulate the deviation of the target from the docking axis. This turntable also has two flashlights to illuminate the target. The test stand has two pairs of flashlights to simulate front and back (behind the docking surface target) lighting, respectively.

The camera is mounted on a horizontal rotating rack that can rotate around two intersecting orthogonal axes: vertical and horizontal. The optical axis of the camera is in the horizontal plane and is parallel to the horizontal axis of the rack rotation. To set the camera position relative to the turntable, let us refer it to the CS. The reference point of this coordinate system is placed at the intersection of the rotation axes, the x-axis is directed along the horizontal axis, the y-axis is oriented along the vertical axis, and the z-axis is perpen-

dicular to these axes. This coordinate system is right-hand one.

In this CS, the position of the center of the light-sensitive matrix can be set by its coordinates in the related CS $(x, y, z) = (d_1, d_2, d_3)$.

The target is a flat square located in the plane parallel to the vertical axis of the turntable. It can move in the horizontal direction only. The position of the target and the rotary stand is set in a fixed orthogonal coordinate system (FOCS). Let us assume that axis x^1 is perpendicular to the plane of target displacement, axis y^1 is directed vertically upward, parallel to axis y^2 of the turntable, axis z^1 is perpendicular to the above axes so that this coordinate system is right-hand one (Fig. 7).

The reference point of this coordinate system is located at the intersection of the projection of stand's vertical axis on the plane of target motion and the horizontal axis of the target motion. In this coordinate system the target position is set by coordinates of its reference point $(x^1, y^1, z^1) = (0, 0, z^1)$, i.e. by horizontal coordinate z^1 .

The position of the coordinate system that is associated with the turntable (CST) and is movable relative to the selected FOCS is characterized by setting the coordinates of its reference

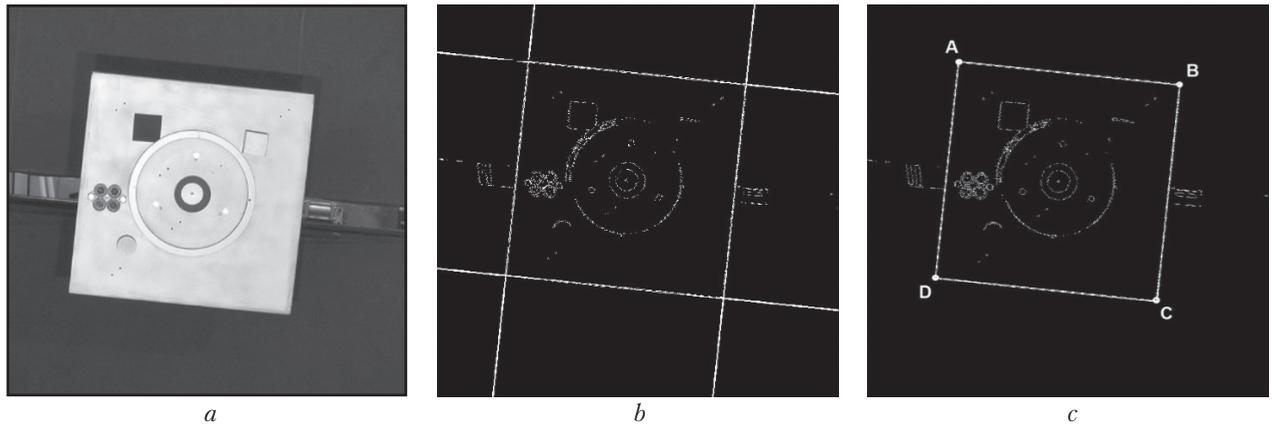


Fig. 9. Determining the position of the angular points of the docking surface: *a* – source frame; *b* – recognition of straight lines on a binary image; *c* – determination of angular points of the docking surface

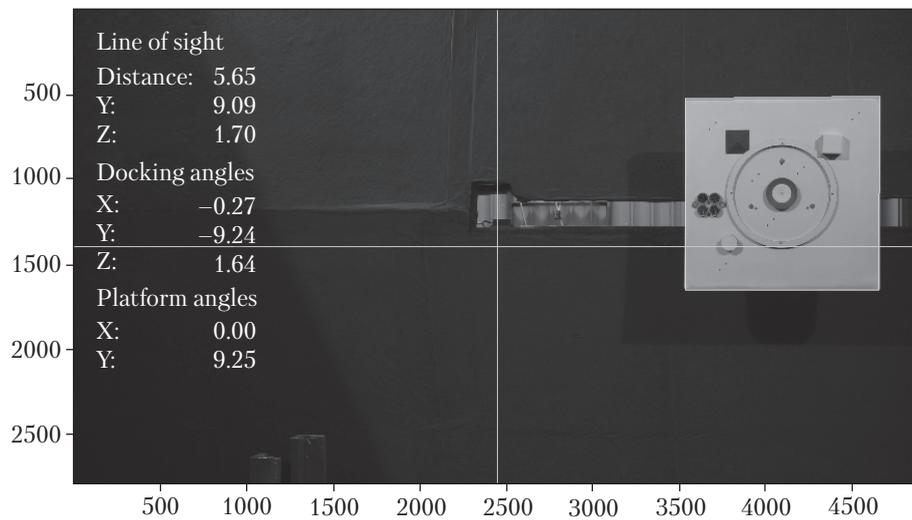


Fig. 10. Determination of the position and orientation based on the reference points (angular points of the docking surface of the NCS prototype)

point $(x^1, y^1, z^1) = (0, y^1, 0)$, i.e. by vertical coordinate y^1 only.

It is necessary to determine the location of the center of mass of the target in the coordinate system associated with light-sensitive matrix of the camera (LSM CS) and the mutual orientation of the coordinate system related to the target (TCS) and the LSM CS, based on the given data on the stand position (rotational angles α and β (Fig. 7) relative to the vertical and horizontal axes, respectively, and coordinate $y^1 = d$ of the axes intersection in FOCS) and on the target

location (coordinate $z^1 = b$ (Fig. 7) of the target center location in FOCS).

7. CVT Tests on the Stand

Experiments have been carried out at the stand to test the practical suitability of the proposed methods for solving individual problems.

The first task is to find the NCS image in the frame and to determine the area to be further analyzed. To fulfill the task, a special search function has been developed to find a compact closed area with clear boundaries in the image. The sour-

ce data is a full frame in shades of gray. The results are shown in Fig. 8.

The second task is to solve the problem of determining the NCS prototype position and orientation relative to the camera by the method described in Section 3.

Fig. 9 shows the result of distinguishing NCS visible boundaries. The resulting binary image is used to determine straight lines by the method described above. As a result, we obtain lines, the intersection of which makes it possible to determine the position of the angular points of the docking surface in each image with a high accuracy.

To verify the accuracy of the method on the stand, the NCS prototype orientation and position relative to the CVS camera at the angles of rotation of the stand structure have been re-computed. The results are shown in Fig. 10.

Fig. 10, on the left, features the calculated parameters. Parameters 1–3 (line of sight) determine the relative position: the direction to the reference point of the NCS CS and the distance to it. The first parameter (distance) corresponds to the Euclidean norm of position vector $\|t_{21}^1\|$ and is expressed in meters. The second and third parameters determine the angles of the line of sight: the shift to the right by azimuth and the upward above the horizon. Their values are given in degrees. Parameters 4–6 (docking angles) are Euler angles that determine the NCS prototype orientation relative to the camera. The last two parameters are calculated based on parameters 1–6, known position of the camera on the platform, and estimates of the angles of its rotation. The first value is the roll angle of the platform; the second one is the azimuth angle of platform rotation. These values are calculated from the CS

associated with the NCS prototype, so the platform roll angle is almost equal to the roll angle of the NCS prototype relative to the camera, with a negative sign. The same applies to the azimuth angle of platform rotation.

Since the NCS orientation is determined at a too great distance, the estimates of platform rotation angles contain errors. The true angles of rotation of the stand platform are zero. The camera pitch tilt of approximately $1.5\text{--}1.6^\circ$ is caused by uneven fixing of the camera on the turntable. Having made a series of experiments under different lighting conditions, we obtain estimates of the orientation parameters (see Table 2) that belong to the following intervals:

- ◆ in terms of distance from the camera to NCS: [5.63; 5.67] m;
- ◆ in terms of the angles of line of sight: $[-0.24; -0.02]$, [1.52; 1.62] deg;
- ◆ in terms of the orientation angles: $[-0.01; 0.03]$, $[-0.92; -0.71]$, [1.47; 1.57] deg.

Analysis of the Results and Conclusions

Based on the requirements for the developed CVS, the potential possibilities for meeting them have been analyzed, and the general schemes of CVS structure and operation have been proposed.

A scheme for solving the problem of determining the NCS position and orientation relative to the CVS, based on the use of information extracted from the digital image has been designed. According to it, the method for calculating the parameters is chosen depending on the possibility of obtaining the corresponding source data from the frame. The proposed specific solution methods cover the entire operating range of distances to the NCS.

Table 2. Variation of Parameter Estimates

Series	Distance, m	Direction, deg	Roll angle, deg	Azimuth and pitch attitude angle, deg
0,0,0 д.	5.66 – 5.67	–0.24 – –0.09; 1.52–1.57	0.01 – 0.03	–0.85 – –0.71; 1.47 – 1.52
10,-10 д.	5.71 – 5.72	–11.08 – –11.07; –0.42 – –0.38	–9.99 – –9.76	9.25 – 9.26; –0.26 – –0.30
0,0,0 б.	5.63	–0.06 – –0.02; 1.58 – 1.62	–0.01 – 0.02	–0.92 – –0.88; 1.53 – 1.57
8,10 б	5.64 – 5.65	8.95 – 8.97; 2.86	–8.12 – –8.06	–9.13 – –9.11; 2.70

The general architecture of program modules has been developed; subtasks that require the implementation of solutions in the form of separate program procedures have been identified. The proposed schemes and methods form the mathematical and software-algorithmic framework for CVS support.

The ellipsoidal filtering algorithm that enables obtaining high-accuracy estimates of the NCS orientation quaternion with respect to the inertial coordinate system and the angular velocity vector of the NCS has been proposed.

In addition, several problems of rendezvous and docking with non-cooperative objects have been solved. In particular, the equations for relative spatial and rotational motions of two spacecraft have been obtained. These equations are used in the problem of synthesis of active spa-

cecraft control at the stages of close rendezvous and direct docking. This implies that the only source for measuring the parameters of relative motion of the spacecraft is a video camera of service spacecraft CVS that allows the developed algorithms to directly determine the current positional motion parameters: the NCS relative orientation and the distance to it.

The tests have showed the operability of software of the main modules and practicability of the proposed methods for solution in general.

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СИСТЕМА ТЕХНІЧНОГО ЗОРУ ДЛЯ ВИЗНАЧЕННЯ ВЗАЄМНОГО ПОЛОЖЕННЯ КОСМІЧНИХ АПАРАТІВ ПРИ ЗБЛИЖЕННІ ТА СТИКУВАННІ

Вступ. У країнах-лідерах космічної галузі інтенсивно ведуться роботи зі створення сервісних космічних апаратів для інспекції та обслуговування некооперованих космічних апаратів, які не оснащені спеціальними засобами для стикування. Застосування оптичних систем, так званих систем технічного зору, визначення положення дозволяють здійснити автоматичне зближення і стикування з некооперованим космічним апаратом.

Проблематика. На сьогодні проблема розпізнавання за відеозображенням взаємного положення космічних апаратів при зближенні і стикуванні, ще не має ефективного розв'язання. Під ефективністю розуміється виконання технічних вимог до бортової системи технічного зору за точністю та швидкістю при допустимих обсягах обчислень і збереження інформації. Тому актуальним є побудова системи технічного зору, створення відповідного математичного, алгоритмічного та програмного забезпечення з перевіркою запропонованих рішень у стендових випробуваннях. Систему призначено для автоматичного зближення і стикування з некооперованим космічним апаратом.

Мета. Розробка науково-технічних основ побудови системи технічного зору та методів розв'язання задачі визначення положення космічного апарата відносно некооперованого космічного апарата, створення математичного опису процесу зближення та стикування, а також програмно-алгоритмічного забезпечення системи технічного зору, що задовольняє задані вимоги.

Матеріали й методи. Використано методи фільтрації та обробки цифрових зображень, комп'ютерної графіки, динаміки космічних апаратів, методи еліпсоїдального оцінювання стану нелінійних динамічних систем, методи розв'язування систем нелінійних рівнянь, методи теорії графів та навчання.

Результати. Створено математичне, алгоритмічне та програмно-технічне забезпечення системи технічного зору для визначення положення та орієнтації космічного апарата відносно некооперованого космічного апарата, придатне для практичного застосування.

Висновки. Проведені випробування системи технічного зору на стенді показали працездатність запропонованих науково-технічних рішень та можливість використання їх на практиці.

Ключові слова: системи технічного зору, положення та орієнтація космічних апаратів, некооперовані космічні апарати, еліпсоїдальне оцінки, нелінійні динамічні системи, обернені задачі, методи розпізнавання з навчанням.