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DEVELOPMENT OF A METHOD FOR DETERMINING THE POSITION OF AN OBJECT USING A TYPICAL FORM OF ITS IMAGE

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Violating the observation conditions for the investigated objects leads to the formation of diverse typical forms of objects throughout the frame in the series. As a consequence, determining the exact position of the object on the frame becomes difficult. To this end, a method was devised to determine the position of an object using the typical form of its image on a series of frames.

This method is based on the formation of a typical form of a digital image of an object based on data from all frames of the series. This makes it possible to take into account the peculiarities of the very formation of the digital image of an object on each frame of the original series. Based on this, a more accurate assessment of the initial approximation of the parameters of all Gaussians of the object's image is performed. Adapting the method specifically for the typical form allows for a more accurate assessment of the positional parameters (coordinates) of the object in comparison with the analytically set profile. The estimation of the position of an object was obtained using the method of least squares. After that, minimization was performed using the Levenberg-Marquardt algorithm. Also, the use of the method makes it possible to improve identification with reference objects and reduce the number of false detections. The study showed a reduction in the standard deviation of frame identification errors by 7–10 times when using a typical digital image shape.

The method devised for determining the position of an object using the typical form of its image was tested in practice within the framework of the CoLiTec project. It was implemented in the intraframe processing unit of the Lemur software to automatically detect new objects and track known ones. Owing to the use of Lemur software and the proposed computational method implemented in it, more than 700,000 measurements of various objects under study were successfully processed and identified

Keywords: image processing, standard image shape, Levenberg-Marquardt algorithm, parameter evaluation

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1. Introduction

The issue of asteroid-comet hazard [1] has become the leading area for the use of astrometry [2] and photometry methods [3]. It includes automatic processing of the results of asteroid/cometary/satellite surveys. Huge astronomical catalogs [4] and archival big data [5] make it possible to accumulate, gain knowledge [6], and analyze the accumulated publicly available data and measurements [7] for the entire period of observation of specific celestial objects of the Solar System (SSO) [8].

However, the quality of shooting conditions significantly affects the quality of SSO images on frames that are formed by a charge-coupled device (CCD) [9]. This applies to both archival images and freshly formed frames. The quality of shooting conditions leads to the fact that the images of individual SSOs or the entire frame as a whole can be heterogeneous. This means that single SSO images can take a variety of standard shapes from frame to frame of the series. This fact significantly reduces the quality of SSO detection and the assessment of their position using already known computational methods.

Therefore, it is relevant to devise a method for determining the position of an object using the standard shape of its image on a series of frames. This method will make it possible to assess the positional coordinates of objects more accurately [10], which will allow them to be identified with those already known from the list of cataloged ones [4]. This method will also increase the conditional probability of correct detection (CPCD) of real objects and reduce the number of false detections [11].

2. Literature review and problem statement

Various significant synchronous displacements of all objects of a CCD frame over the entire time of exposure lead to the formation of a heterogeneous standard shape of the image of objects [12]. And this fact affects the accuracy of various imaging and machine vision tasks [13]. Namely, the accuracy of detecting and recognizing images of objects [14], performing parameter evaluation [15]. These methods are based on the analysis of only those pixels that potentially belong to the object under study. Their disadvantage is that with a variety of standard image shapes it is completely impossible to initially determine specific pixels and reject those whose intensity exceeds the specified limit value [2, 16].

Works [17, 18] consider the pixelation and segmentation of single images of objects only. The disadvantage of these methods is the impossibility of accurate processing of images of objects with an ambiguous number of brightness peaks due to the variety of the standard shape of the image. Such a variety also affects various methods for analyzing large data sets, namely wavelet transformation (analysis) [19] and time series analysis [20]. The disadvantage of these methods is that they are adapted to work only with "pure" measurements, so the heterogeneity of images will greatly spoil the overall indicator.

A matched filtering method [21] is known but it uses an analytical image model. The main disadvantage of this method is the fact that the method will not work correctly in the case when the typical image of the object on different frames of the series is different. An improved matched filtering method [22] using a standard image shape is also known. However, even it can only help filter the images of objects more accurately but not assess their position.

The disadvantage of the methods of frame addition [23] and machine vision [24] is the impossibility of application when the image of the object under study does not have clear boundaries on all CCD frames of the series. Therefore, it is necessary to devise a method for determining the position of an object using the standard shape of its image on a series of frames.

3. The aim and objectives of the study

The purpose of our study is to devise a method for determining the position of an object using the standard shape of its image. It is the preliminary formation of the standard shape of the image of an object on the basis of the frames of the original series that makes it possible to perform a more accurate assessment of the position of the object.

To accomplish the aim, the following tasks have been set:

– to form a standard shape of the image of an object and refine it on the basis of the frames of the series;

– to determine the number of Gaussians of the resulting typical image of an object and estimate the initial approximation of the parameters of their form;

– to determine the initial approximations for estimating the position of the image of an object;

– to propose an architecture of the method for determining the position of an object using the standard shape of its image;

– to verify the method of determining the position of an object using the standard shape of its image.

4. The study materials and methods

The object of the study is digital images of various objects on CCD frames. Within the framework of our study, the main hypothesis was put forward that the use of a standard image shape of an object will significantly increase its CPCD. Also, the method devised will increase the accuracy of estimating the parameters of objects when further performing the basic tasks of image processing by already known methods. The initial data are a CCD frame A_{in} the size of N_{CCDx}×N_{CCDy}. The image of the j-th single object is actually present on the frame and is also in the area of intra-frame processing (AIFP), which is a set *of* Ω_{Nobj} pixels. The research results, as well as the developed method for determining the position of an object, were converted into a program code using the C++ programming language. This code was implemented at the stage of intra-frame processing of the Lemur software package (Ukraine) [25] for automated detection of new and for monitoring known objects within the framework of the CoLiTec project [26].

As the initial data that were used during the study, information obtained from a variety of telescopes installed at observatories in Ukraine and the world was used. Namely, the ISON-Uzhgorod Observatory (Uzhgorod, Ukraine), the quantum optical system (QOS) "Sazhen-S" (Dunaivtsi, Ukraine), and the telescopes AZT8 (Dunaivtsi, Ukraine) and Takahashi BRC-250M (Uzhgorod, Ukraine); Mayaki Astronomical Observatory (Mayaki, Ukraine), the telescope OMT-800 [27]; Vihorlat Observatory (Humenné, Slovakia) [28]. The observational conditions were specially selected so that the initial test series of CCD frames contained a variety of standard shapes of images of the studied CCD [8].

The devised computational method, implemented in the Lemur software package (Ukraine), was used during the successful determination of the position of more than 700,000 various SSOs and their subsequent identification. With this fact, the method for determining the position of an object using the standard shape of its image confirmed its practical significance within the framework of the main hypothesis put forward.

5. Results of investigating the method for determining the position of an object using the standard shape of its image

5. 1. Forming a standard shape of the image of an object and its refinement on the basis of the frames of the series

Any CCD frame contains single images of objects, which can take a variety of object shapes from frame to frame in the series. The standard shape of the image of an object is considered to be the average of all images of the same object on all CCD frames of the series [12].

The standard shape of the image of an object on the frame is evaluated by N_{sel} pre-selected single images. To this end, a list of single images with the aperture (total) brightness of the pixels of the images of objects $A^*_{\Sigma m}$, is formed; 10÷20 % of those are rejected that exceed the estimate of the root mean square deviation (RMS) of the brightness of the frame background σ_{noise}.

For each single image, the eccentricity ε_m of an object image is calculated [29]:

$$\varepsilon_m = \frac{m_{20}+m_{02}-\sqrt{m_{20}-m_{02}+4m_{11}^2}}{m_{20}+m_{02}+\sqrt{m_{20}-m_{02}+4m_{11}^2}}, \quad (1)$$

where

$$m_{20} = \sum_{l=1}^{Nsm}\left(A^*_{l(i,k)m}-C_{fm}\right)\left(x_{l(i,k)m}-X_0\right)^2, \quad (2)$$

$$m_{02} = \sum_{l=1}^{Nsm}\left(A^*_{l(i,k)m}-C_{fm}\right)\left(y_{l(i,k)m}-Y_0\right)^2, \quad (3)$$

$$m_{11} = \sum_{l=1}^{Nsm}\left(A^*_{l(i,k)m}-C_{fm}\right)\left(y_{l(i,k)m}-Y_0\right)\left(x_{l(i,k)m}-X_0\right), \quad (4)$$

$$X_0 = \frac{\sum_{l=1}^{Nsm}\left(A^*_{l(i,k)m}-C_{fm}\right)x_{l(i,k)m}}{A^*_{\Sigma m}}, \quad (5)$$

$$Y_0 = \frac{\sum_{l=1}^{Nsm}\left(A^*_{l(i,k)m}-C_{fm}\right)y_{l(i,k)m}}{A^*_{\Sigma m}}, \quad (6)$$

where m_{20}, m_{02}, m_{11} – second-order moments;

$A^*_{\Sigma m} = \sum_{l=1}^{Nsm}\left(A^*_{l(i,k)m}-C_{fm}\right)$ – aperture brightness of the pixels of the m-th single image of an object;

$A^*_{l(i,k)m}$ is the brightness l of the (i, k)-th pixel of the set Ω_{Sm} of the m-th single image of an object;

$l\,(i, k)$ is the pixel l number in the set Ω_{Sm}, which is a function of the numbers of the ik-th pixel on the frame;

C_{fm} – pre-obtained average brightness of the background substrate of the frame;

X_0 and Y_0 are first-order moments;

$x_{l(I,k)m}, y_{l(I,k)m}$ are the coordinates of the $l(i, k)$-th pixel of the m-th single image of an object.

Next, the length L_m of a single image of an object is calculated using the following expression [30]:

$$L_m = \sqrt{\left(x_{m\max}-x_{m\min}\right)^2+\left(y_{m\max}-y_{m\min}\right)^2}, \quad (7)$$

where $x_{m\max}$, $y_{m\max}$, $x_{m\min}$, $y_{m\min}$ are the minimum and maximum values of the abscissa and ordinates of the m-th AIFP.

Single images of objects in the list are then rejected based on the following criteria:

– the estimation of the eccentricity ε_m of a single image does not exceed the limit permissible value of the eccentricity γ_ε=0.6;

– the estimate of the length L_m of a single image does not exceed the allowable relative deviation of the length of the image of objects γ_L=0.1.

After that, the refined list of bright single images of objects is ordered in descending order of aperture brightness. The final step is to exclude 10÷20 % of images of objects with the highest brightness. Thus, the standard shape of an object is based on the eccentricity ε_m (1) and the length L_m (7) of a single image.

5. 2. Determining the number of Gaussians of the resulting typical image and estimating the initial approximation of parameters

The resulting single image of the j-th object can be represented by a certain number of Gaussians, which should be evaluated separately from the Löwenberg-Marquardt algorithm (ALM) [31]. The desired number of Gaussians N_{Gj} is selected from the range of values $\overline{N_{Gfirstj}, N_{Gendj}}$.

The initial approximation of the Gaussian form parameter σ_{Gj0} corresponding to a single image of the j-th object can be defined by the following expression:

$$\sigma_{Gj0} = \frac{1}{N_{segj}}\sum_{m=0}^{N_{segj}-1}\sigma_{Gjm}, \quad (8)$$

where σ_{Gjm} is the estimation of the initial approximation of the Gaussian form parameter in the m-th segment.

The number of segments N_{segm} is defined by the following expression:

$$N_{segm} = \frac{L_m}{\Delta x_{seg}}. \quad (9)$$

During the studies, the width of the segment Δx_{seg} was set to 2÷3 pixels. In general, the desired number of Gaussians N_{Gjmin} of a single image of the j-th object corresponds to that at which the sum of the squares of deviations $F_{\Delta A\tau}\left(\Theta^{over}_{\tau jn}\right)$ is minimal. Therefore, it is necessary to estimate the initial approximation of the Gaussian form parameters from the vector $\theta^{over}_{\tau jn}$ of estimated parameters of a single image of the j-th object. To this end, the sum of the squares of deviations between the experimental A^*_{ikj} and model $A_{Sikmj}(\Theta_{\sigma m})$ brightnesses of the pixels of the m-th segment of the single image of the j-th object is applied to the ALM procedure [31]:

$$F_{\Delta A\sigma}\left(\Theta_{\sigma m}\right) = \sum_{k=\Omega_{segjm}}\left(A^*_{ikj}-A_{Sikmj}\left(\Theta_{\sigma m}\right)\right)^2 \underset{\Theta_{\sigma m}}{\rightarrow} \min, \quad (10)$$

where $\Theta_{\sigma m}$=(σ_{Gjm}, A_{Gjm}, y_{0jm}) is the vector of estimated parameters of the m-th segment of a single image of the j-th object;

$A_{Sikmj}\left(\Theta_{\sigma m}\right) = A_{Gjm}\exp\left\{-\frac{1}{2\sigma^2_{Gjm}}\left[\left(y_{kj}-y_{0jm}\right)^2\right]\right\}$ is the model brightness of the pixels of the m-th segment of a single image of the j-th object.

After minimization on the ALM procedure, the resulting number of Gaussians N_{Gjmin} and the initial approximation of the Gaussian form parameter σ_{Gj0}, it becomes possible to refine the standard shape of the image of the j-th object.

5. 3. Determining initial approximations for estimating the position of an object image

To determine the initial approximations for estimating the position of the image of an object, it is necessary to initially determine a rectangular AIFP, which will limit the pixels of the image of the single image under study. The determination of the size of such a rectangular region N_x×N_y, taking into account the double value of the size of the border N_{borx}, N_{bory} along the abscissa and ordinate axis, is performed using the following expressions:

$$N_x = N_{imgx} + N_{IPSmaxx} + 2\,N_{borx}, \quad (11)$$

$$N_y = N_{imgy} + N_{IPSmaxy} + 2\,N_{bory}, \quad (12)$$

where $N_{imgx} \times N_{imgy}$ is the size of the typical image of an object;

$N_{IPSmaxx}$, $N_{IPSmaxy}$ – the maximum size of AIFP of the digital frame.

In general, the initial approximations for estimating the position of an object image are its positional coordinates, which exactly belong to AIFP but may not be real coordinates. Thus, the initial approximations $x^0_{j(\ell,m)}$, $y^0_{j(\ell,m)}$ for estimates of the position of the $j(l,m)$-th image of an object belonging to the m-th AIFP are calculated using the following expressions:

$$x^0_{j(\ell,m)} = \frac{\sum_{i=0}^{Npj(\ell,m)} \sum_{k=0}^{Npj(\ell,m)} A_{sj(\ell,m)ik}\, x_{sj(\ell,m)i}}{\sum_{i=0}^{Npj(\ell,m)} \sum_{k=0}^{Npj(\ell,m)} A_{sj(\ell,m)ik}}, \quad (13)$$

$$y^0_{j(\ell,m)} = \frac{\sum_{i=0}^{Npj(\ell,m)} \sum_{k=0}^{Npj(\ell,m)} A_{sj(\ell,m)ik}\, y_{sj(\ell,m)k}}{\sum_{i=0}^{Npj(\ell,m)} \sum_{k=0}^{Npj(\ell,m)} A_{sj(\ell,m)ik}}. \quad (14)$$

5. 4. Architecture of the method for determining the position of an object using the standard shape of its image

The architecture of the method consists of the following steps:

1. Form a list of N_{sel} single images with aperture (total) pixel brightness of objects images $A^*_{\Sigma m}$, with subsequent rejection of 10÷20 % of those exceeding the RMS estimate of the background brightness of the frame σ_{noise}.

2. Calculate the eccentricity ε_m (1) on the basis of calculations of the moments of the second (2) to (4) and the first (5), (6) orders, and length L_m (7) of each single image of an object.

3. Determine the number of Gaussians N_{Gj} from the range of values $\overline{N_{Gfirstj}, N_{Gendj}}$ and the initial approximation of the Gaussian form parameter σ_{Gj0} (8) for each single image using the ALM procedure (10).

4. Determine the size of the rectangular region $N_x \times N_y$ (11), (12), taking into account the double value of the size of the border N_{borx}, N_{bory} along the abscissa and ordinate axis.

5. Determine the initial approximations $x^0_{j(\ell,m)}$, $y^0_{j(\ell,m)}$ (13), (14) for estimates of the position of the $j(l,m)$-th image of an object belonging to the m-th AIFP.

6. Perform MNC assessment of the position $x_{j(l,m)}, y_{j(l,m)}$ of images of an object (fitting) using a standard shape of its image according to (10) using ALM.

5. 5. Verification of the method for determining the position of an object using the standard shape of its image

To verify the devised method for determining the position of an object using the standard shape of its image, testing was carried out on a series of 245 frames. This series contained reference measurements of the coordinates of the spacecraft (SC): the laser alignment satellite "Etalon 1" (NORAD 19751, perigee 19900 km, apogee 25000 km, inclination 64.2°). The pixel scale for these test frames was 1.15 arcsec/pix, the frame exposure was 2 seconds, the stroke length was ~60±2 pixels, and the tracking mode. This test series of frames contained rectilinear extended images of an object under study. Statistical indicators [32] (percentiles, mean and RMS deviations of the resulting rectangular and angular coordinates of the spacecraft from the reference ones) using the analytical and non-analytical standard shape are given in Table 1. The analytical standard shape is the one obtained on the basis of the formed analytical mathematical model of the image of an object under study on the current frame [21]. The non-analytical standard shape is more refined and takes into account the peculiarities of the formation of the image of an object under study on each frame of the series [12].

Table 1

Rectilinear extended images of an object

Standard shape		Percentiles						Mean	RMS
		1	25	50	75	90	99		
Pixels									
Analytical	ΔX	–1.73	–0.01	0.13	0.28	0.39	0.63	0.11	0.34
	ΔY	–1.88	–0.59	–0.21	0.13	0.40	1.07	–0.23	0.54
Non-analytic	ΔX	–1.32	–0.03	0.14	0.28	0.45	0.80	0.11	0.32
	ΔY	–1.24	–0.47	–0.06	0.27	0.58	1.28	–0.07	0.53
Arc seconds									
Analytical	ΔRA	–0.77	–0.15	0.02	0.28	0.44	2.29	0.07	0.46
	ΔDE	–2.16	–0.69	–0.36	–0.02	0.33	1.09	–0.35	0.58
Non-analytic	ΔRA	–1.20	–0.21	0.02	0.26	0.49	1.17	0.02	0.43
	ΔDE	–2.61	–0.69	–0.35	–0.01	0.23	0.68	–0.38	0.55

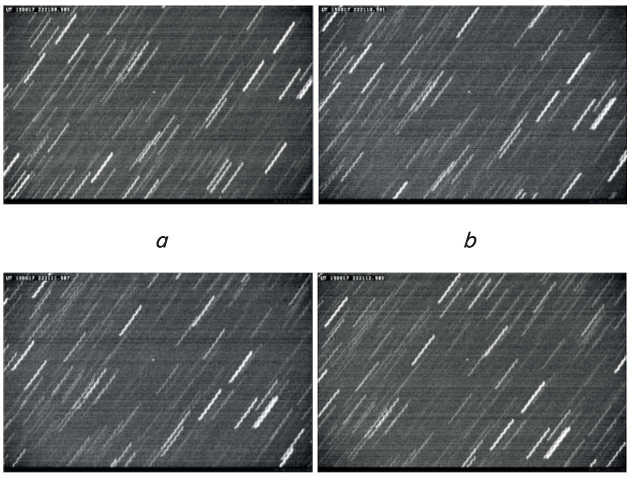
Errors in the identification of frames for indirect extended images of objects (Fig. 1) when assessing the position of an object (fitting) with the analytical and non-analytical standard shape are given in Table 2. Object of observation: spacecraft "PolyITAN-1" (NORAD 40042, perigee 599.8 km, apogee 618.3 km, inclination 97.9°). The pixel scale for these test frames was 8.05 arcsec/pix, the frame exposure was 1 second, the stroke length was ~114±2 pixels, and the tracking mode.

Table 2

Indirect extended images of an object

Coordinate	Analytical fitting			Non-analytical fitting		
	Number of stars	Mean	RMS	Number of stars	Mean	RMS
Frame 1						
ΔX, pix	39	–0.314	0.91	32	–0.023	0.124
ΔY, pix		0.575	1.794		0.095	0.22
ΔR, arcsec		1.235	4.976		0.134	0.971
ΔD, arcsec		–2.482	12.04		–0.773	1.764
Frame 2						
ΔX, pix	26	–0.897	1.067	31	0.01	0.293
ΔY, pix		0.503	2.05		0.029	0.241
ΔR, arcsec		0.025	2.965		–0.327	1.658
ΔD, arcsec		–1.192	6.95		0.489	2.386
Frame 3						
ΔX, pix	20	–1.00	1.279	25	–0.058	0.438
ΔY, pix		0.79	1.868		0.12	0.362
ΔR, arcsec		0.598	3.47		0.149	0.965
ΔD, arcsec		–1.464	11.648		0.478	2.081
Frame 4						
ΔX, pix	22	0.017	1.101	27	–0.035	0.303
ΔY, pix		0.611	1.712		0.025	0.423
ΔR, arcsec		0.57	4.606		0.531	0.966
ΔD, arcsec		1.292	8.788		–0.271	2.045

The indicators given in Tables 1, 2 indicate the successful application of the devised computational method. On frames with rectilinear extended images of objects, the use of non-analytical fitting with the procedure for calculating the center of reference of a superobject reduces the RMS of estimates of rectangular and angular coordinates of spacecraft by 7 % compared to the analytical fitting. It also reduces the offset of the estimate at one of the coordinates by 2 times.



a *b* *c* *d*

Fig. 1. Test series with indirect extended images of objects: *a* — Frame No. 1; *b* — Frame No. 2; *c* — Frame No. 3; *d* — Frame No. 4

When you identify frames with uneven and indirect extended images of objects, the non-analytical fitting gives better binding accuracy than an analytical fitting. The RMS of errors in the identification of frames in non-analytical fitting are 7–10 times less than that in analytical fitting. The average value of frame identification errors is also 3–5 times less than that in the analytical fitting.

6. Discussion of results of investigating the method for determining the position of an object using the standard shape of its image

The possibility of using a standard shape of a digital image of an object for the subsequent determination of its position was investigated. Existing methods of basic image processing and machine vision were also analyzed [13]. However, the accuracy of processing by existing methods directly depended on the quality of the original image of an object itself and the immutability of its typical image on a series of frames. Therefore, to devise a method for determining the position of an object, it was proposed to use an automated formation of a standard image shape instead of the classical use of an analytical form [12].

Within the framework of the CoLiTec project [33], studies were conducted on the application of the devised method for determining the position of an object using the standard shape of its image. Using the determination of the eccentricity (1) and length (7) of a single image, its standard shape was refined. Also, after obtaining estimates of the initial approximation (13) and (14) and MNC estimates, more accurate positional coordinates of an object were calculated. The study (Tables 1, 2) showed that the application of the method reduces by 7–10 times the errors of identification of images of cataloged (reference) objects [4]. This significantly affects the quality and accuracy of a number of tasks for obtaining data [34] and detecting the movement of objects on their basis. Also, the use of the devised method allows us to reduce the number of false detections by forming a clearer standard shape of the image of an object. This indicator clearly indicates that the tasks set have been successfully solved. The results given in Tables 1, 2 are due to the formation and refinement of the standard shape of the image of an object based on the frames of the entire series.

The limitation of this study is the variety of standard shapes of images of objects on a series of frames. Also, a limitation is the computing power of the equipment on which the processing will take place. The issue of security [35] of frames, namely encryption of input data, is also important. In this case, an additional decryption algorithm will be required before using the devised method.

The disadvantage of the study is the impossibility of applying the devised method immediately after receiving the first frame of the series. The formation of a standard image shape of an object requires the data of all its images on each frame of the series. And this leads to a delay in the processing pipeline and to the downtime of computing power.

Further research should focus on the application of the devised method for determining the position of an object before detecting its movement. To this end, it is necessary to use the method for sampling methods/services for the processing pipeline [36]. It is also necessary to assess the impact of the devised method on other methods of motion detection [10] that will be used later. For this, you can use machine learning [18], Wavelet analysis [37], analysis of time series [20], and forecasting method [38] for calculating qualitative indicators.

7. Conclusions

1. On a series of images, a selection of single images of objects with a variety of standard shapes was performed. For each image, the eccentricity ε_m, length L_m were calculated. Based on the selection criteria, single images of objects were rejected according to the obtained parameters and excluded from the list.

2. For a more accurate assessment of the initial approximation of the parameters of the form of Gaussians σ_{Gj0} for a single image of the j-th object, their quantity was determined. The subsequent assessment of the parameters of the form of each Gaussian was made using the vector $\Theta_{\tau jn}^{over}$ of the estimated parameters. Our calculations have made it possible, after minimizing on the ALM procedure, to refine the standard shape of a single image of the j-th object.

3. The determination of the size of a rectangular AIFP was based on a double value of the size of the border along the abscissa and ordinate axes. The specific dimensions of AIFP made it possible to more accurately calculate the initial approximations for estimating the position of the image of an object belonging to the m-th AIFP.

4. Owing to preliminary calculations, a method was devised for determining the position of an object using the standard shape of its image. With the help of ALM, an MNC assessment of the position $x_{j(l,m)}, y_{j(l,m)}$ of an object image was performed using its standard shape.

5. The devised method was tested on the basis of a series of 245 frames. The application of the method for a variety of standard image shapes reduces by 7–10 times the errors of identifying images of cataloged (reference) objects. This improves the accuracy of estimating the positional coordinates of an object by 20–25 % compared to using an analytical image model.

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.

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