AUTOMATIC VISION-BASED MONITORING OF THE SPACECRAFT ATV RENDEZVOUS / SEPARATIONS WITH THE INTERNATIONAL SPACE STATION

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Abstract: The system which allows automating the visual monitoring of the spacecraft ATV rendezvous / separations with the international space station is being considered. The initial data for this complex is the video signal received from the TV-camera, mounted on the station board. The offered algorithms of this video signal processing in real time allow restoring the basic characteristics of the spacecraft motion with respect to the international space station. The results of the experiments with the described software and real and virtual video data about the docking approach of the spacecraft with the International Space Station are being presented. The accuracy of the estimation of the motion characteristics and perspectives of the use of the package are being discussed.

1 INTRODUCTION

One of the most difficult and crucial stages in managing the flights of space vehicles is the process of their docking approach. The price of a failure at performing of this process is extremely high. The safety of crew, station and space vehicles also in many respects depends on a success of its performance.

The radio engineering means of the docking approach, which within many years have been used at docking of the Russian space vehicles, are very expensive and do not allow to supply docking to not cooperated station.

As reserve methods of docking approach monitoring the manual methods are applied, for which in quality viewfinders the optical and television means are used. For docking approach of the pilotless cargo transport vehicle “Progress” to the orbital station “Mir” a teleoperation mode of manual control (TORU) was repeatedly used, at which the realization the crew of the station, having received the TV image of the station target from a spacecraft, carried out the manual docking approach.

At the center of the flight management the control of objects relative motion parameters (range, speed, angular deviations) should also be carried out. The semi-automatic TV methods of the monitoring which are being used till now, do not satisfy the modern requirements anymore. Recently appeared means of both the methods of the visual data acquisition and processing provide an opportunity of the successful task decision of a complete automatic determination and control of space vehicles relative motion parameters.

Flights of the ATV have not begun yet. Therefore images of the ATV in ground-based conditions and simulated space images are available now. But already there are some papers discussing possible approaches to the decision of similar images analysis problems (Chi-Chang, H.J. and McClamroch, N.H., 1993; Casonato, G. and Palmerini, G.B., 2004). The described approach is based on experiments with similar system for the “Progress” spaceship (Boguslavsky et al., 2004).

The system for ATV has a number of differences from the system used for “Progress”. First of all, this various arrangement of the TV-camera and special target for the monitoring of rendezvous / separations processes. In the ATV case the TV-camera settles down on ISS, and by the transport vehicle the special targets (basic and reserve) are established. Besides that is very important for visual system, the images of objects for tracking in a field of view have changed.

In view of operation experience on system Progress - ISS, in system ATV - ISS essential changes to the interface of the control panel (see Part 4) were made.

The main stages of the visual data acquisition and processing in the complex are realized mostly in the same way as the actions performed by an operator.

In the presented field of vision:

1. An object of observation is marked out (depending on the range of observation, it can be the vehicle as a whole or a docking assembly or a special target);

2. Specific features of an object under observation defined the patterns of which are well recognizable in the picture (measuring subsystem).

3. Based on the data received:

The position of these elements relative to the image coordinate system is defined;

Parameters characterizing the vehicle and station relative position and motion are calculated (calculation subsystem).

In addition to operator actions, the complex calculates and displays the parameters characterizing the approach/departure process in a suitable for analysis form.

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2 MEASURING SUBSYSTEM

The purpose of this subsystem is the extraction of the objects of interest from the images and performance of measurements of the points’ coordinates and sizes of these objects. To achieve this purpose it is necessary to solve four tasks:

1) Extraction of the region of interest (ROI) position on the current image.

2) Preprocessing of the visual data inside the ROI.

3) Extraction (recognition) of the objects of interest.

4) Performing the measurements of the sizes and coordinates of the recognized objects.

All the listed above operations should be performed in real time. The real time scale is determined by the television signal frame rate. The other significant requirement is that in the considered software complex it is necessary to perform updating of the spacecraft motion parameters with a frequency of no less than 1 time per second.

For reliability growth of the objects of interest the extraction from the images of the following features are provided:

- Automatic adjustments of the brightness and contrast of the received images for the optimal objects of interest recognition.

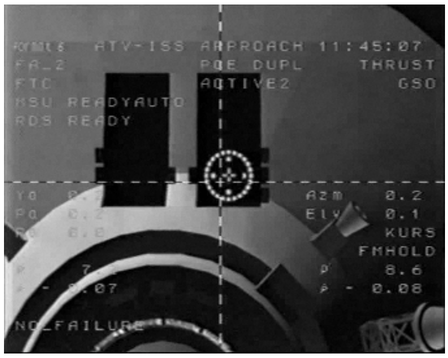
- Use of the objects of interest features of the several types. Such features duplication (or even triplication) raises reliability of the image processing when not all features are well visible (in the task 3).

- Self-checking of the image processing results on a basis of the a priori information about the observed scenes structure (in the tasks 1-4).

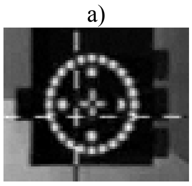
The ways of performing the calculation of the ROI position on the current image are (the task 1):

1a) Calculation of the ROI coordinates (figure 1) on the basis of the external information (for example, with taking into account a scene structure or by the operator selection).

1b) Calculation of the ROI coordinates and sizes on the basis of the information received from the previous images processing.



a)



b)

Figure 1: An example of identification of a region of interest in the TV camera field of view (1.a) way): a) – total field of view, b) – a region of interest.

The second (preprocessing) task is solved on the basis of the histogram analysis. This histogram describes a brightness distribution inside the ROI. The brightness histogram should allow the reliable transition to the binary image. In the considered task the brightness histogram is approximately bimodal. The desired histogram shape is provided by the automatic brightness and contrast control of the image source device.

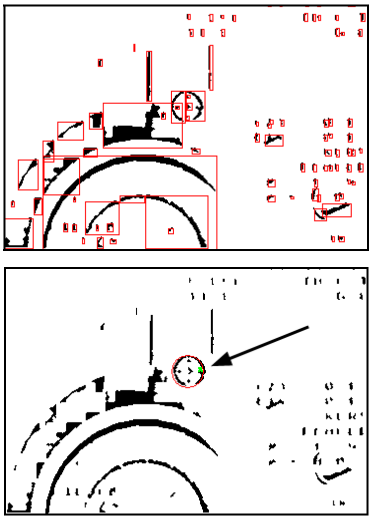
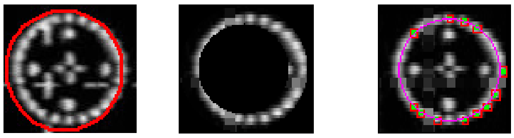


Figure 2: Coarse allocation of a target from all candidates on a basis of the a priory information: the relative sizes of labels and target plate and their relative location.

At the third processing stage (the task 3) the extraction of the objects of interest is performed. These objects are the spaceship contour, the docking unit disk, the target cross and the target disk with small labels. The main features are the spaceship contour, the cross and the target labels. These features are considered the main structured elements of the recognized scene and used for measurement. At features extraction both edge-based (Canny, 1986; Mikolajczyk et al., 2003) and region-based methods are used (Sonka and Hlavac, 1999).

With accordance to such elements set the processing of the current field image is being performed. For example, on distances less than 15 meters are made detection of a target plate, its labels and a cross. During such processing (figures 1, 2, 3) the results of the previous measurements can be used for estimation of the small area of interest position (figure 1, below). If the previous results are not present (for example, immediately after system start), as area of interest is processed the full field image. During processing among candidates for a target image of a target it selects the most probable candidate (figure 2). For its verification the detection of labels and of radius of a target (figure 3) is performed. After that the detection of a cross of a target is performed.



a) b) c)

Figure 3: An example of allocation of an image of a target on the basis of the coarse coordinates of a target plate and a priory of the information on an arrangement of labels of a target. a) - definition of area of interest on a basis a priory of the information and found coarse location of the plate; b) area of interest for search of labels of a target; c) - result of allocation of labels of a target.

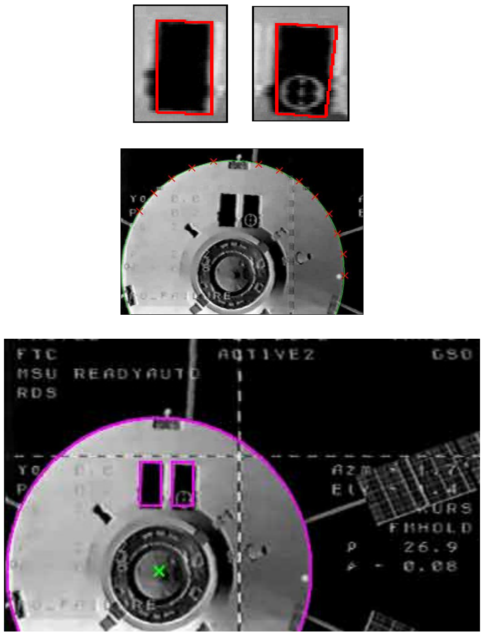


Figure 4: An example of allocation of edge of target boxes and external contour of spaceship (for distance >10 meters). Top-down: extracted edges of the left and the right boxes; contour of the spaceship; results of the frame processing (with the marked docking unit image centre).

On distances more than 15 m a label and a cross of a target reliably are not visible. Therefore the detection of an external contour of the ship and a target boxes (figure 4) is realized. Boxes of a target allow to confirm a hypothesis about the detection of the ship and to specify its roll position.

The fourth operation (performing of the measurement) is very straightforward. But for this operation it is necessary to recognize the reliable objects results from the previous processing stages.

3 CALCULATION PART

Preprocessing of a frame (more exactly, a half-frame) gives the following information:

T – reference time of a frame (in seconds); X_C, Y_C – real values coordinates of the center of the cross on the target; N_1 –number of couples of points on the horizontal crossbar of the cross; X_i, Y_i $(i = 1,2,\ldots,N_1)$ – integer coordinates of points on the top of the horizontal crossbar of the cross; X_i, Y_i' $(i = 1,2,\ldots,N_1)$ – coordinates of points on the bottom of the horizontal crossbar of the cross; N_2 – number of couples of points on the vertical crossbar of the cross; U_i, V_i $(i = 1,2,\ldots,N_2)$ – coordinates of points on the left side of vertical crossbar of the cross; U_i', V_i $(i = 1,2,\ldots,N_2)$ – coordinates of points on the right side of vertical crossbar of the cross; X_O, Y_O, R – coordinates of the center of the circle on the target and its radius; N_3, A_i, B_i $(i = 1,2,\ldots,N_3)$ – number of points on the circle and their coordinates; X_S, Y_S, R_S – coordinates of the center of the circle, which is the station outline, and its radius (real numbers).

Here all coordinates are expressed in pixels. Successful preprocessing a frame always gives the values of X_C, Y_C and X_O, Y_O, R, but if there is an opportunity, when appropriate $N_k > 0$, those quantities are determined once again by original information. Bellow we describe the calculation of those quantities in the case when $N_1 > 0, N_2 > 0, N_3 > 0$ and $R_S = 0$. If R_S differs from zero, the data are used in other way (see bellow).

Determining the coordinates of the cross center. We change the data

$$\frac{Y_i + Y_i'}{2} \to Y_i, \quad \frac{U_i + U_i'}{2} \to U_i \quad (i = 1,2,\ldots)$$

and get coordinates of two sequences of points, which lie in centerlines of horizontal and vertical crossbars of the cross. Those centerlines have equations $ax - y = c_1$ (horizontal) and $x + ay = c_2$ (vertical). Here a, c_1 and c_2 are coefficients. The form of the equations takes into account the orthogonality of these lines. The coefficients are determined by minimization of the quadratic form

$$\sum_{i=1}^{N_1}(aX_i - Y_i - c_1)^2 + \sum_{j=1}^{N_2}(U_j + aV_j + c_2)^2$$

on a, c_1, c_2, i.e. by solving the linear least squares problem. The coordinates of the cross center are

$$X_C^* = \frac{ac_1 + c_2}{1 + a^2}, \quad Y_C^* = \frac{c_1 - ac_2}{1 + a^2}.$$

Determining the radius and the center of the target circle is realized in two stages. In the first stage, we obtain preliminary estimations of these quantities based on elementary geometry. In the second stage, we solve the least squares problem minimizing the expression

$$\Phi_2 = \sum_{i=1}^{N_3}\left[\sqrt{(A_i - X_O)^2 + (B_i - Y_O)^2} - R\right]^2$$

on X_O, Y_O, R by Gauss-Newton method (Bard, 1974). Let its solution be X_O^*, Y_O^*, R^*. As a rule, $|X_O - X_O^*|$ and $|Y_O - Y_O^*|$ do not exceed 1.5 pixels. Below for simplicity of notations, we will not use an asterisk in designations of recomputed parameters.

3.1 Basic Geometrical Ratios

We use the right Cartesian coordinate system $Cy_1y_2y_3$, which is connected with the target. The point C is the center of the target circle, the axis Cy_3 is directed perpendicularly to the circle plane away from station, i.e. is parallel a longitudinal axis of the Service module, the axis Cy_2^+ intersects a longitudinal axis of the docking device on the Service Module. Also, we use right Cartesian coordinate system $Sx_1x_2x_3$ connected with the TV camera on the spacecraft. The plane Sx_1x_2 is an image plane of the camera, the axis Sx_3 is a camera optical axis and directed on movement of the spacecraft, the axis Sx_2^- intersects an axis of the docking device of the spacecraft. Let $\| a_{ij} \|_{i,j=1}^3$ be the transition matrix from the system $Sx_1x_2x_3$ to the system $Cy_1y_2y_3$. The transition formulas are

$$y_i = d_i + \sum_{j=1}^{3} a_{ij}x_j \ (i = 1,2,3),$$

$$x_j = \sum (y_i - d_i)a_{ij} \ (j = 1,2,3).$$

Here d_1, d_2, d_3 are coordinates of the point S in the system $Cy_1y_2y_3$.

The matrix characterizes ideal docking $\| a_{ij} \| = \text{diag}(1, -1, -1)$. In actual docking the transition matrix is

$$\| a_{ij} \| = \begin{Vmatrix} 1 & -\varphi_3 & \varphi_2 \\ -\varphi_3 & -1 & \varphi_1 \\ \varphi_2 & -\varphi_1 & -1 \end{Vmatrix}$$

where $\varphi, \varphi_2, \varphi_3$ are components of the vector of an infinitesimal rotation of the system $Sx_1x_2x_3$ with respect to its attitude in ideal docking. We suppose deviations from ideal docking are small.

If any point has in the system $Sx_1x_2x_3$ the coordinates (x_1, x_2, x_3), its image has in the image plane the coordinates $\xi_1 = \frac{fx_1}{x_3}$, $\xi_2 = \frac{fx_2}{x_3}$.

Here f is focal length of the camera. The coordinates ξ_1 and ξ_2, expressed in pixels, were meant in the above description of processing a single video frame. Let coordinates of the same point in the system $Cy_1y_2y_3$ be (y_1, y_2, y_3). Then

$$\xi_i = f \frac{(y_1 - d_1)a_{1i} + (y_2 - d_2)a_{2i} + (y_3 - d_3)a_{3i}}{(y_1 - d_1)a_{13} + (y_2 - d_2)a_{23} + (y_3 - d_3)a_{33}}.$$

The coordinates of the center of the target circle the C in the system $Cy_1y_2y_3$ are $(0,0,0)$, therefore

$$X_O = f \frac{d_1 - d_2\varphi_3 + d_3\varphi_2}{d_1\varphi_2 + d_2\varphi_1 - d_3}, \quad Y_O = -f \frac{d_1\varphi_3 + d_2 + d_3\varphi_1}{d_1\varphi_2 + d_2\varphi_1 - d_3}.$$

In docking $|d_1| << d_3$, $|d_2| << d_3$, so it is possible to use the simplified expressions

$$X_O = -\frac{fd_1}{d_3} - f\varphi_2, \quad Y_O = \frac{fd_2}{d_3} + f\varphi_1.$$

The center of the cross in the system $Cy_1y_2y_3$ has the coordinates $(0,0,b)$. In this case under the similar simplification, we have

$$X_C = -\frac{fd_1}{d_3 - b} - f\varphi_2, \quad Y_C = \frac{fd_2}{d_3 - b} + f\varphi_1.$$

So $X_C - X_O = -\frac{fbd_1}{d_3(d_3 - b)}, Y_C - Y_O = \frac{fbd_2}{d_3(d_3 - b)}$.

The radius r of the target circle and radius R of its image in the image plane are connected by the ratio $R = fr / d_3$.

The last three ratios allow to express d_3, d_1 and d_2 through R, $X_C - X_O$ and $Y_C - Y_O$. Then it is possible to find φ_1 and φ_2, having solved concerning these angles the expressions for X_O, Y_O or X_C, Y_C. As to the angle φ_3, the approximate ratio $\varphi_3 = a$ takes place within the framework of our consideration.

The processing a frame is considered to be successful, if the quantities d_i, φ_i $(i = 1, 2, 3)$ were estimated. As a result of successful processing a sequence of frames, it is possible to determine spacecraft motion with respect to the station. The successfully processed frames are used only for motion determination.

3.2 Algorithm for Determination of the Spacecraft Motion

The spacecraft motion is determined in real time as a result of step-by-step processing of a sequence of TV images of the target. The data are processed by separate portions.

In each portion is processed in two stages. The first stage consists in determining the motion of the spacecraft center of mass; the second stage consists in determining the spacecraft attitude motion. Mathematical model of motion is expressed by formulas

$$d_1 = z_1 + z_2t, \quad d_2 = z_3 + z_4t, \quad d_3 = z_5 + z_6t,$$
$$\varphi_1 = v_1 + v_2t, \quad \varphi_2 = v_3 + v_4t, \quad \varphi_3 = v_5 + v_6t.$$

Here t is time counted off the beginning of processing the frame sequence, z_i and v_j are constant coefficients. The ratios written out have the obvious kinematical sense. We denote the values of the model coefficients, obtained by processing the portion of the data with number n, by $z_i^{(n)}, v_j^{(n)}$ and the functions $d_i(t)$, $\varphi_i(t)$, corresponding to those coefficients, by $D_i^{(n)}(t)$, $\Phi_i^{(n)}(t)$.

Determining the motion consists in follows. Let there be a sequence of successfully processed frames, which correspond to the instants $t_1 < t_2 < t_3 < \ldots$. The frame with number k corresponds to the instant t_k. Values of the quantities X_C, Y_C, a, X_O, Y_O, R, which were found by processing this frame, are $X_C^{(k)}$, $Y_C^{(k)}$, etc. These values with indexes $k = 1, 2, \ldots, K_1$ form the first data portion, the value with indexes $k = K_1 + 1, K_1 + 2, \ldots, K_2$ – the second one, with indexes $k = K_{n-1} + 1, K_{n-1} + 2, \ldots, K_n$ – the n-th portion.

The first data portion is processed by a usual method of the least squares. The first stage consists in minimization of the functional

$$\Psi_1(z) = \sum_{k=1}^{K_1} A_k,$$

$$A_k = w_1\left[X_C^{(k)} - X_O^{(k)} + \frac{fbd_1^{(k)}}{d_3^{(k)}[d_3^{(k)} - b]}\right]^2 +$$
$$w_2\left[Y_C^{(k)} - Y_O^{(k)} - \frac{fbd_2^{(k)}}{d_3^{(k)}[d_3^{(k)} - b]}\right]^2 + w_3\left[R^{(k)} - \frac{fr}{d_3^{(k)}}\right]^2$$

Here $d_i^{(k)} = d_i(t_k)$, $z = (z_1, z_2, \ldots, z_6)^T$ is a vector of the coefficients, which specify the functions $d_i(t)$, w_i, is positive numbers (weights). The minimization is carried out by Gauss -Newton method (Bard, 1974). The estimation $z^{(1)}$ of z and the covariance matrix P_1 of this estimation are defined by the formulas

$$z^{(1)} = \left[z_1^{(1)}, z_2^{(1)}, \ldots, z_6^{(1)}\right]^T = \arg\min \Psi_1(z),$$
$$P_1 = \sigma^2 B_1^{-1}, \quad \sigma^2 = \frac{\Psi_1\left[z^{(1)}\right]}{3K_1 - 6}.$$

Here B_1 is the matrix of the system of the normal equations arising at minimization of Ψ_1. The matrix is calculated at the point $z^{(1)}$.

At the second stage, the quantities

$$\alpha_1^{(k)} = \frac{1}{f}\left[Y_O^{(k)} - \frac{fD_2^{(1)}(t_k)}{D_3^{(1)}(t_k)}\right], \alpha_2^{(k)} = -\frac{1}{f}\left[X_O^{(k)} + \frac{fD_1^{(1)}(t_k)}{D_3^{(1)}(t_k)}\right]$$

are calculated and three similar linear regression problems

$$\alpha_1^{(k)} \approx v_1 + v_2 t_k, \quad \alpha_2^{(k)} \approx v_3 + v_4 t_k,$$
$$a^{(k)} \approx v_5 + v_6 t_k \quad (k = 1, 2, \ldots, K_1)$$

are solved using the standard least squares method (Seber, 1977). We content ourselves with description of estimating the couple of parameters v_1, v_2. We unite them in the vector $v = (v_1, v_2)^T$. The estimations $v_1^{(1)}$ and $v_2^{(1)}$ provide the minimum to the quadratic form

$$F_1(v) = \sum_{k=1}^{K_1}\left[\alpha_1^{(k)} - v_1 - v_2 t_k\right]^2.$$

Let Q_1 be the matrix of this form. Then the covariance matrix of the vector $v^{(1)} = [v_1^{(1)}, v_2^{(1)}]^T$ is $Q_1^{-1} F_1[v^{(1)}]/(K_1 - 2)$.

The second data portion is carried out as follows. At the first stage, the functional

$$\Psi_2(z) = \left[z - z^{(1)}\right]^T C_2\left[z - z^{(1)}\right] + \sum_{k=K_1+1}^{K_2} A_k$$

is minimized. Here $C_2 = qB_1$, q is a parameter, $0 \le q \le 1$. The estimation of z and its covariance matrix have the form

$$z^{(2)} = \arg\min \Psi_2(z), \quad P_2 = \sigma^2 B_2^{-1},$$

$$\sigma^2 = \frac{\Psi_2\left[z^{(2)}\right]}{3(K_2 - K_1) - 6},$$

where B_2 is the matrix of the system of the normal equations, which arise at minimization of Ψ_2, calculated at the point $z^{(2)}$.

At the second stage, the quantities $\alpha_1^{(k)}$ and $\alpha_2^{(k)}$ (see above) are calculated and the estimation of the coefficients $v_j^{(2)}$ are found. The estimation $v^{(2)}$ provides the minimum to the quadratic form

$$F_2(v) = q'\left[v - v^{(1)}\right]^T Q_1\left[v - v^{(1)}\right] + \sum_{k=K_1+1}^{K_2}\left[\alpha_1^{(k)} - v_1 - v_2 t_k\right]^2.$$

Here q' is a parameter, $0 \le q' \le 1$. Let Q_2 be the matrix of this form. The covariance matrix of the estimation $v^{(2)}$ is $Q_2^{-1} F_2[v^{(2)}]/(K_2 - K_1 - 2)$.

The third and subsequent data portions are processed analogously to the second one. The formulas for processing the portion with number n are obtained from the formulas for processing the second portion by replacement of the indexes expressed the portion number: $1 \to n-1$, $2 \to n$.

Our choice of C_n and $\Psi_n(z)$ means that the covariance matrix of errors in $X_C - X_O$, $Y_C - Y_O$ and R is equal to $\mathrm{diag}(w_1^{-1}, w_2^{-1}, w_3^{-1})$.

It is easy to see that $C_n < B_{n-1}$, i.e. the matrix $B_{n-1} - C_n$ is positive definite. The introduction of the matrix G_n provides diminution of influence of the estimation $z^{(n-1)}$ on the estimation $z^{(n)}$. Unfortunately, the matrix G_n is unknown. In such situation, it is natural to take $C_n = qB_{n-1}$. One has $C_n < B_{n-1}$ if $q < 1$. The described choice of C_n means, that procession of the n-th data portion takes into account the data of the previous portions. The data of the n-th portion are taken in processing with the weight 1, the $(n-1)$-th portion is attributed the weight q, the $(n-2)$-th portion has the weight q^2, etc.

The results of processing the n-th data portion are represented by numbers $D_i^{(n)}(t_{K_n})$, $\Phi_i^{(n)}(t_{K_n})$ $(i = 1, 2, 3; n = 1, 2, \ldots)$. We calculate also the quantities $\rho = \sqrt{d_1^2 + d_2^2 + d_3^2}$, $u = \frac{d\rho}{dt}$,

$$\alpha = \arctan\frac{d_2}{\sqrt{d_1^2 + d_3^2}}, \quad \beta = \arctan\frac{d_1}{d_3}.$$

The angle α is called a passive pitch angle, the angle β is a passive yaw angle. If docking is close to ideal (considered case), then $|d_1| << d_3$, $|d_2| << d_3$ and $\alpha = d_2 / d_3$, $\beta = d_1 / d_3$.

The angle φ_1 is called an active pitch angle, φ_2 is an active yaw angle, φ_3 is an active roll angle. We remind these angles have small absolute values.

Characteristics of accuracy of the motion parameter estimations are calculated within the framework of the least squares method. For example, we defined above the covariance matrix P_n of the estimation $z^{(n)}$. In terms of this matrix the covariance matrix $C_w(t)$ of the vector $w(t) = \left(z_1 + z_2 t, z_2, z_3 + z_4 t, z_4, \ldots, v_5 + v_6 t, v_6\right)^T \in R^{12}$ is calculated by formulas

$$C_w = \frac{\partial w}{\partial z} P_n \left(\frac{\partial w}{\partial z}\right)^T, \quad \frac{\partial w}{\partial z} = \mathrm{diag}\,(\mathrm{U, U, U}), \quad U = \begin{Vmatrix} 1 & t \\ 0 & 0 \end{Vmatrix}.$$

These formulas concern to the motion which was found by processing the n-th of a portion of the data.

Knowing $C_w(t)$, it is possible to calculate the standard deviations $\sigma_\rho(t)$, $\sigma_u(t)$, $\sigma_\alpha(t)$ and $\sigma_\beta(t)$ of the quantities $\rho(t)$, $u(t)$, $\alpha(t)$ and $\beta(t)$. The standard deviation $\sigma_\rho(t)$ has the form

$$\sigma_\rho = \frac{\partial \rho}{\partial w} C_w \left(\frac{\partial \rho}{\partial w}\right)^T, \quad \frac{\partial \rho}{\partial w} = \left(\frac{d_1}{\rho}, 0, \frac{d_2}{\rho}, 0, \frac{d_3}{\rho}\right)^T.$$

The similar formulas define the others standard deviations. The values of ρ, σ_ρ, u, σ_u, etc., referring to the last instant of the processed data portion, are written on the computer display.

4 EXAMPLES

The experiments with the described complex were carried out on various samples of the initial data. The adjustment of system on the images of the transport ship ATV was carried out on photos of a breadboard model of the ship in a hangar and on rendered samples of the 3D ship model trajectories. Other initial data were real video received from a board of the ship "Progress". These data were used for an estimation of reliability and correctness of the detection of real objects, and also for the verification of algorithms of relative movement parameters calculation.

Figures 5, 6 give examples of the operation of the described algorithm estimating the spacecraft motion. Figure 5 contains the plots of the functions $\rho(t)$, $u(t)$, $\alpha(t)$ and $\beta(t)$ and $\varphi_i(t)$ $(i = 1, 2, 3)$. On $\rho(t)$ and $u(t)$ plots the scale on a vertical axis differs on 2 order.

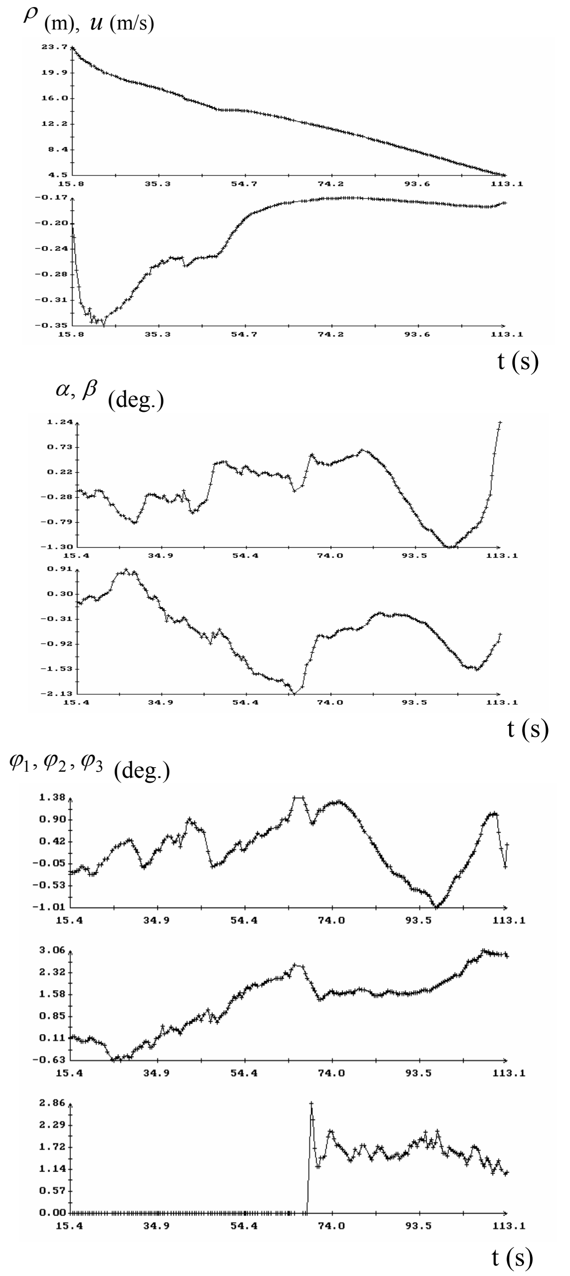


Figure 5: Results of the determination of the spacecraft motion in docking approach.

Figure 6 presents the plots of the standard deviations $\sigma_\rho(t)$, $\sigma_u(t)$, $\sigma_\alpha(t)$, $\sigma_\beta(t)$. The values of all these functions were calculated at the last instants of processed data portions. These values were shown by marks. Each portion contained 10 instants with measurements: $K_n - K_{n-1} = 10$. For clearness, the markers were connected by segments of straight lines, therefore presented plots are broken lines. Only the vertexes of these broken lines are significant. Their links are only interpolation, which is used for visualization and not always exact. As it is shown in figure 6, the spacecraft motion on the final stage of docking was defined rather accurately.

Figure 7 shows an example of the basic screen of the main program of a complex.

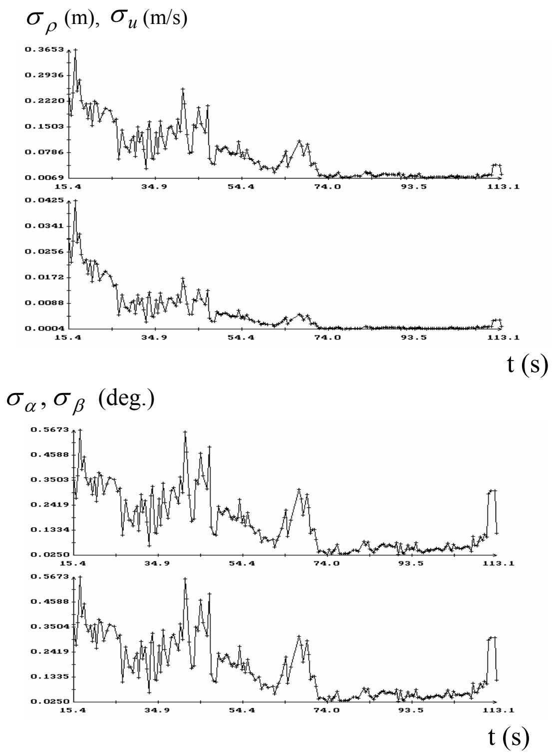


Figure 6: Accuracy estimations for the motion presented on Figure 5.

5 CONCLUSION

The described complex is being prepared for the use as a means allowing the ground operators to receive the information on the motion parameters of the spacecraft docking to ISS in real time.

The most essential part of this information is transferred to the Earth (and was always transferred) on the telemetering channel. It is also displayed on the monitor. However this so-called regular information concerns the current moment and without an additional processing can't give a complete picture of the process. Such an additional processing is much more complicated than the organizational point of view and more expensive than processing the video image. It is necessary to note, that the estimation of kinematical parameters of the moving objects on the video signal, becomes now the most accessible and universal instrument of solving such kind of problems in situations, when the price of a failure is rather insignificant.

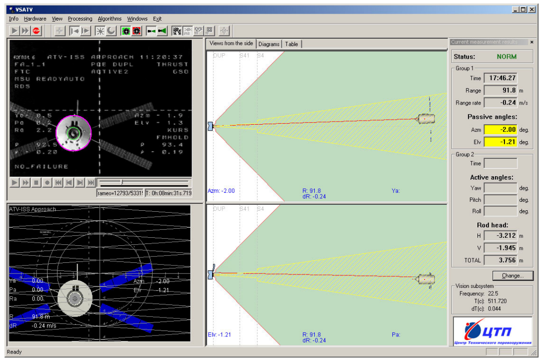


Figure 7: Main screen of the VSATV program.

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