AUTOMATIC VISION-BASED MONITORING OF THE SPACECRAFT DOCKING APPROACH WITH THE INTERNATIONAL SPACE STATION

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Abstract: The software package which allows to automate the visual monitoring of the spacecraft docking approach 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 spacecraft board. The offered algorithms of this video signal processing in real time allow to restore 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 video data about the docking approach of the spacecraft Progress 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 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.

The variant of a similar complex (determining parameters of the docking approach of the spacecraft (SC) with the International Space Station (ISS), on the TV image) is being described below.

The program complex for an automation of the visual control of the docking process of the SC with the ISS (further for brevity - complex) is intended to process in real time on the computers such as IBM PC the ISS TV-image, transmitted with the camera onboard SC, with the purpose of the SC and ISS

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relative location definition. The TV-signal is inputted into computer with the help of the framegrabber. Besides that, the opportunity of the processing already digitizing of sequences of the avi format images is stipulated. All complex is realized in OS Windows 98-XP.

An ultimate goal of the complex development is a complete automation of the visual monitoring of SC and ISS docking approach from the moment of ISS visibility in the TV-camera field of view (about 500 m) and up to the complete SC and ISS docking.

In the basic integrated steps - stages of the acquisition and processing of the visual data the complex works similarly to the operator - person.

The complex in addition (in relation to the person - operator) calculates and displays in the kind, accepted for the analysis, parameters describing the docking process.

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2 MEASURING SUBSYSTEM

The purpose of this software 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 of 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:

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

2) 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.

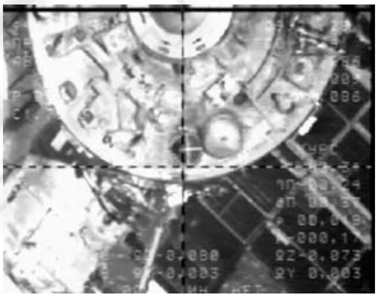
3) Self-checking of the image processing results on a basis of the a priori information about the observed scenes structure.

The ways of performing the calculation of the ROI position on the current image are:

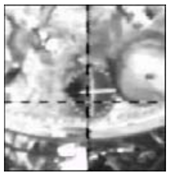
1) Calculation of the ROI coordinates (fig. 1) on the basis of the external information (for example, with taking into account a scene structure or by the operator selection).

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

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.



(a)



(b)

Figure 1: An example of the ROI positioning in the spacecraft TV-camera field of view. a) Full image of the field of view; b) The ROI image.

At the third processing stage the extraction of the objects of interest is performed. These objects are the station contour, the docking unit disk, the target cross and the target disk with small labels. The main features are the station 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 et al., 1999).

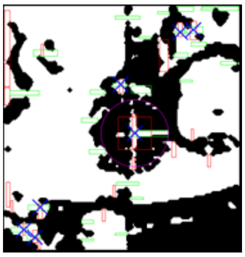
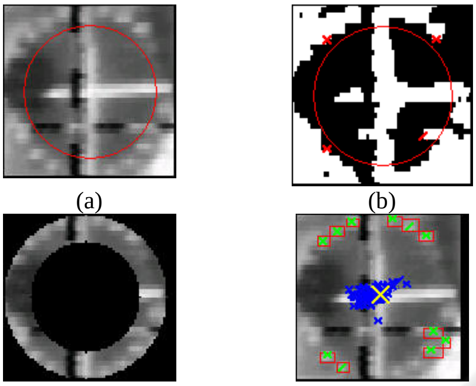
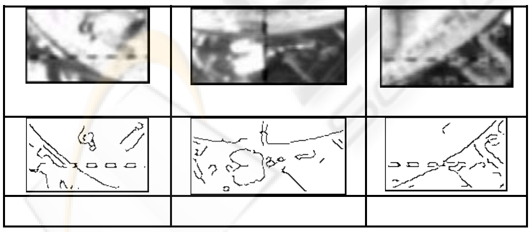


Figure 2: Selection of a cross among all target candidates on a basis of the a priori information (the sizes of the cross rods and their relative arrangement).



(a) (b) (c) (d)

Figure 3: Example of the target labels extraction on the basis of the target cross coordinates and a priori knowledge about the labels arrangement. (a) Estimation of the ROI placement for the labels recognition. (b) Coarse estimation of the target radius by the diagonal fragments processing. (c) Ring-shaped ROI with the target labels. (d) Results of the target labels recognition and the improved estimation of the target radius.



(a) (b) (c)

Figure 4: Example of the station contour recognition. (a) The fragment from the left part of the station image. (b) The fragment from the central part. (c) The fragment from the right part.

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 from a beginning of video data input);

X_C, Y_C – coordinates of the center of the cross on the target (real numbers);

N_1 – number of couples of points on the horizontal crossbar of the cross (integers);

X_i, Y_i $(i = 1, 2, \ldots, N_1)$ – coordinates of points on the top of the horizontal crossbar of the cross (integers);

X_i, Y_i' $(i = 1, 2, \ldots, N_1)$ – coordinates of points on the bottom of the horizontal crossbar of the cross (integers);

N_2 – number of couples of points on the vertical crossbar of the cross (integers);

U_i, V_i $(i = 1, 2, \ldots, N_2)$ – coordinates of points on the left side of vertical crossbar of the cross (integers);

U_i', V_i $(i = 1, 2, \ldots, N_2)$ – coordinates of points on the right side of vertical crossbar of the cross (integers);

X_O, Y_O, R – coordinates of the center of the circle on the target and its radius (real numbers);

N_3, A_i, B_i $(i = 1, 2, \ldots, N_3)$ – number of points on the circle and their coordinates (integers);

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. Some numbers of N_1, N_2, N_3 can be equal to zero. For example, the equality $N_1 = 0$ means the absence of the data X_i, Y_i. 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

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

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

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

As a rule, $|X_C - X_C^*|$ and $|Y_C - Y_C^*|$ do not exceed 1.5 pixels.

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 [1]. 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

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

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

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 $\| a_{ij} \| = \mathrm{diag}(1, -1, -1)$. 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 of the camera the coordinates

$$\xi_1 = \frac{fx_1}{x_3}, \quad \xi_2 = \frac{fx_2}{x_3}.$$

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

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

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

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

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

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

$$R = \frac{fr}{d_3} .$$

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. The portions have a fixed volume or they are formed by the data gathered on time intervals of fixed length. In the processing of the second and subsequent portions, the results of processing of the previous portions are taken into account.

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

$$d_1 = z_1 + z_2 t, \quad d_2 = z_3 + z_4 t, \quad d_3 = z_5 + z_6 t,$$
$$\varphi_1 = v_1 + v_2 t, \quad \varphi_2 = v_3 + v_4 t, \quad \varphi_3 = v_5 + v_6 t .$$

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

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

$$A_k = w_1 \left[X_C^{(k)} - X_O^{(k)} + \frac{f\,bd_1^{(k)}}{d_3^{(k)}[d_3^{(k)} - b]} \right]^2 + w_2 \left[Y_C^{(k)} - Y_O^{(k)} - \frac{f\,bd_2^{(k)}}{d_3^{(k)}[d_3^{(k)} - b]} \right]^2 + w_3 \left[R^{(k)} - \frac{fr}{d_3^{(k)}} \right]^2 .$$

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 [1]. 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 [2]. 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: $1 \to n-1$, $2 \to n$.

The described algorithm is rather similar to nonlinear Kalman filter. The matrix C_n in Kalman filter (compare the above C_2) is defined by the formula $C_n = (P_{n-1} + G_n)^{-1}$. Here G_n is the covariance matrix of the term in the difference $z^{(n)} - z^{(n-1)}$, which is caused by errors in the mathematical model at transition from the time interval $t_{K_{n-2}+1} \le t \le t_{K_{n-1}}$ to the interval $t_{K_{n-1}+1} \le t \le t_{K_n}$. 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

$$\rho = \sqrt{d_1^2 + d_2^2 + d_3^2}\ , \quad u = \frac{d\rho}{dt}\ ,$$

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

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 $|d_1| \ll d_3$, $|d_2| \ll d_3$ and

$$\alpha = \frac{d_2}{d_3}, \quad \beta = \frac{d_1}{d_3}\ .$$

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 $w(t) = (z_1 + z_2 t,\ z_2,\ z_3 + z_4 t,\ z_4, \ldots, v_5 + v_6 t,\ v_6)^T \in R^{12}$ is calculated by formulas

$$C_w = \frac{\partial w}{\partial z} P_n \left(\frac{\partial w}{\partial z}\right)^T$$

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

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

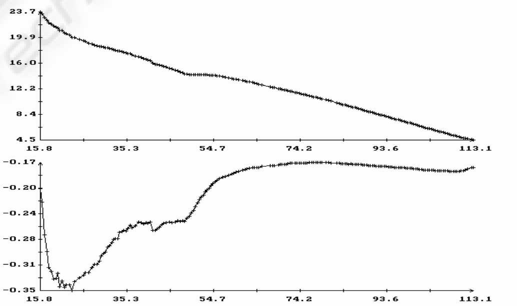
Fig. 5, 6 give examples of the operation of the described algorithm estimating the spacecraft motion. Fig. 5 contains the plots of the functions $\rho(t)$, $u(t)$, $\alpha(t)$ and $\beta(t)$ and $\varphi_i(t)$ $(i = 1, 2, 3)$, fig. 6 presents the plots of the standard deviations $\sigma_\rho(t)$, $\sigma_u(t)$, $\sigma_\alpha(t)$, $\sigma_\beta(t)$. 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 fig. 6, the spacecraft motion on the final stage of docking was defined rather accurately.

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

5 CONCLUSION

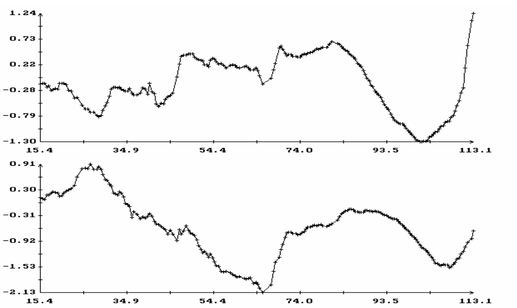
The described software package is used now as a means allowing the ground operators to receive the information on the motion parameters of the spacecraft docking to ISS in real time.

ρ (m), u (m/s)



t (s)

α, β (deg.)



t (s)

$\varphi_1, \varphi_2, \varphi_3$ (deg.)

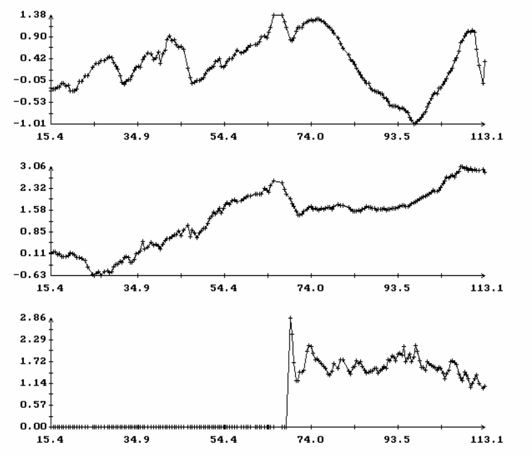


Figure 5: Results of determination of the spacecraft motion in docking approach.

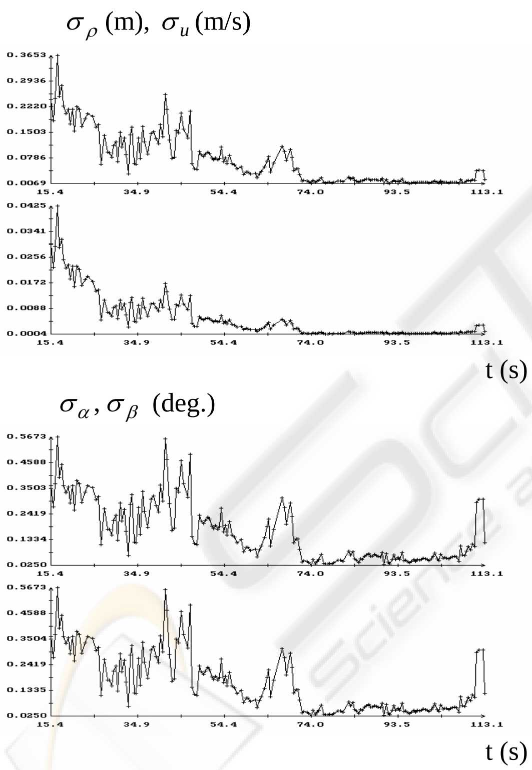


Figure 6. Accuracy estimations for the motion presented on Fig. 5.

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 from 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.

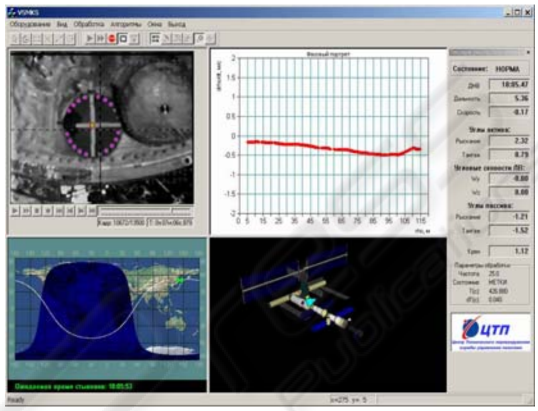


Figure 7: An example of the monitoring system main window. The distance is 5.3 meters. The main window is divided onto four parts. In the top left part the TV-camera field of view is displayed. In the bottom left part the ballistic trajectory of ISS and the day and night areas are shown. In the top right part the phase chart is displayed. In the bottom right part the 3D model of the ISS and spacecraft are rendered. In the grey panel (near the right edge of the main window) the current system parameters are displayed (the spacecraft speed, distance, orientation etc.).

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