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THE FLYING QUALITIES IMPROVEMENT FOR THE VEHICLES WITH TIME DELAY IN THEIR DYNAMICS

Efremov A.V., Tyaglik M.S., Tyaglik A.S., Aleksandrov V.V.
Moscow aviation institute

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Abstract

It is proposed to compensate the time delay in the vehicle response by the display demonstrating the vector of predictive velocity projected on the surface located on the preliminary defined distance from the operator's eyes. The effectiveness of the approach is demonstrated for the docking and lunar rover control tasks.

1 Introduction

The phase delay in control channel characterizes the control process of highly augmented aircraft and the execution of some mission of space vehicle. The phase delay in control channel of highly augmented aircraft is defined by the different filters and prefilters installed for suppression of the rate limit of control surface deflections effects, dynamics of actuator and some other reasons. Such phase delay can be evaluated with help of the element $e^{-p\tau}$, where τ reaches 0,1÷0,15 s, and for aerospace vehicle Buran – 0.2÷0.25 s.

The control of such dynamics is accompanied by generation of considerable pilot lead compensation , what decreases the amplitude margin of pilot-aircraft open-loop system and, as a consequence, causes the considerable resonant peak of the closed-loop system reaching up to 10÷12 dB. In condition of variability of pilot gain coefficient it can lead to temporary loss of stability in the closed-loop system and appearance of so-called pilot induced oscillation (PIO) event. The means for suppression of PIO event – the adaptive prefilter and active manipulator with dynamically variable spring stiffness considered in [1, 2] are proposed for suppression of PIO effects. These means allow to decrease resonant peak in closed-loop system and to improve slightly the accuracy of control. However in case of considerable delay these means do not provide the stable and accurate control.

The delay accuracy in space vehicle teleoperator control ("TORU") at docking is caused by the other reason. It is defined by the time necessary for coding, decoding of signals transmitted from the International Space Station (ISS), where the operator locates and carries out the docking with spacecraft, and signals transmitted back on the ISS board. Such time delay can reach 1÷1.5 s, what deteriorates considerably the docking process.

The last 15÷20 years are characterized by the intensive development of unmanned air vehicles. The researches in the area of their control are dedicated to the considerable number of paper [3, 4, 5] including the articles where time delay 0.2÷1 s, caused due to transmitting of signals from ground control station through commutation satellite is considered [6, 7]. The considerable higher time delay reaching 4 s, accompanies the lunar rover control process from the ground control station. It leads to "step and go" process of its control what deteriorates its research potentialities. The possibility of compensation of time delay occurring in teleoperator control by use of perspective display is considered in this paper. As an example it is considered the potentiality of such way for control of space vehicles: lunar rover and spacecraft (during the docking at TORU regime).

2 Compensation of time delay by use of predictive display

The potentiality of predictive display for the execution of a number of piloting task – refueling, landing and some others is considered in [8].

The proposed here display (predictive display) consists of the 3D corridor, window, symbols of current position and predictive information. In the piloting process pilot has to control aiming angle $\varepsilon = \theta_{pr} + \frac{\Delta H}{L_{pr}}$ where L_{pr} the distance between the human operator eyes and window displayed on the display screen. Here θ_{pr} is the predictive path angle $\theta_{pr} = \dot{\theta}\frac{T_{pr}}{2} + \theta$, T_{pr} is the predictive time $T_{pr} = \frac{L_{pr}}{V}$, ΔH - change of height, V - flight velocity, θ - path angle.

It was proposed to expand this idea for the vehicle path control characterizing by considerable time delay.

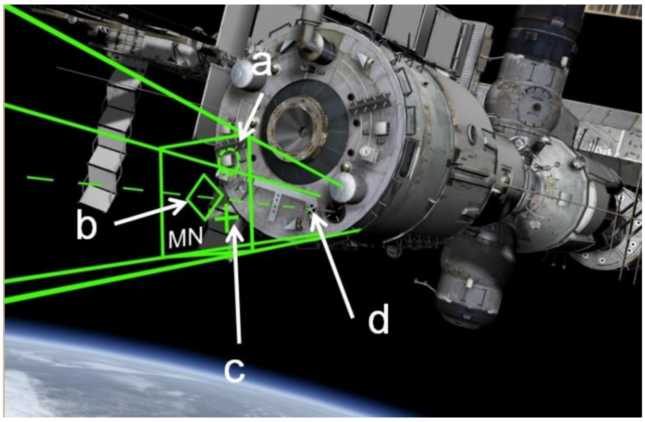

Fig. 1 Predictive display

In the docking task it was proposed to generate such predictive information in the form of symbol which position is proportional to the projection of spacecraft velocity measured relatively ISS (symbol a, fig. 1) calculated on the board of ISS with assuming the absence of time delay arousing at transmitting and transformation of data. Such symbol is displayed on the surface MN (fig. 1) located at the distance L_{pr} and moving in front of the spacecraft inside the corridor limited by sizes of the surface MN with velocity equal to the velocity of its motion relatively ISS. The center of such corridor is presented by rhombus "b". The crossing of its axes lies on the line passing through the target "*d*" located at the ISS.

Except these symbols the center of the screen "c" is reflected on the screen too. Thus the operator task is the combining the predictive symbol "a" with the center of the predictive window "b" and with symbol "c" by use of jets. During the motion along the program trajectory these symbols have to be coincided and directed to the target of ISS and the projection of velocity vector will demonstrate the direction of the further motion of the vehicle relatively the program trajectory. This principle of the time delay compensation is shown on fig. 2.

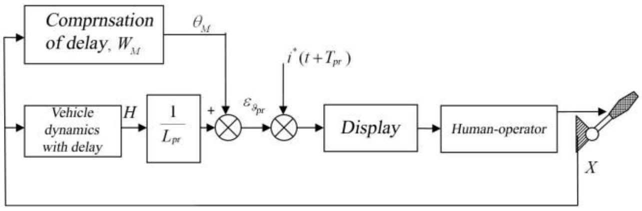

Fig. 2 Principle of time delay compensation

Here $i^*(t+T_{pr})$ - the prediction of program trajectory, projected on the display. At the preliminary stage of selection of optimal predictive time T_{pr} the linearized vehicle dynamic model describing the vehicle height motion was used:

$$W_c = \frac{K_c \frac{V}{s}}{s(T_{en}s+1)} e^{-s\tau} \qquad (1)$$

In the time delay compensation loop the following linearized model describing the path angle displacement was used:.

$$W_M = \frac{K_c}{s(T_{en}s+1)} \qquad (2)$$

Here T_{en} - constant time of aperiodic motion, taking into account the dynamic of jet, V - relative velocity of approach spacecraft to the ISS.

Thus the dynamic of controlled element dynamics describing the dynamics of the predictive information $\varepsilon_{\theta_{pr}}$ is the following:

$$W_c^* = \frac{K_c(e^{-s\tau} + sT_{pr})}{T_{pr}s^2(T_{en}s+1)}, \text{ where } T_{pr} = \frac{L_{pr}}{V}.$$

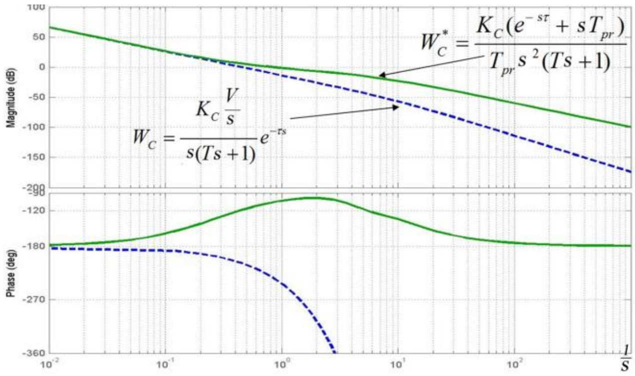

Fig. 3 Controlled element frequency response

Fig. 3 demonstrates that usage of predictive information decreases the slope of amplitude frequency response up to -20 dB/dec and improves the phase in the frequency range ω=0.6÷6 1/s considerably, what has to simplify the piloting process evidently.

The same equations and analysis take place and for the lateral motion.

The optimization of predictive time T_{pr} was carried out from consideration of human-operator-vehicle system shown on fig. 4. The parameters of the pilot structural model $W_p(j\omega)$ were selected by minimization of variance of error $\Delta\varepsilon(t)$ fig. 4 for each parameter T_{pr} defining the controlled element dynamics $W_c = \frac{\varepsilon_{\theta_{pr}}}{X} = \frac{K_c(e^{-s\tau} + sT_{pr})}{T_{pr}s^2(T_{en}s+1)}$. Here $\Delta\varepsilon(t)$ is the signal error perceived by pilot at the distance L_{pr}. The procedure for selection of pilot model parameter is given in [2, 7]. The dependence of normalized error $\bar{\sigma}^2_{\Delta\varepsilon} = \frac{\sigma^2_{\Delta\varepsilon}}{\sigma^2_{\Delta\varepsilon\max}}$ is given on fig. 5. After the procedure for selection of pilot structural model parameters, it was calculated the variance σ_e^2 where error $e(t) = y(t) - i(t)$ defines the accuracy of mission task execution. Here $i(t)$ - the program trajectory synthesized in the process of approach to the target of ISS, y(t) - is the spacecraft height displacement (height). By carrying out such investigations for each value T_{pr}. The calculation of variances $\sigma^2_{\Delta\varepsilon}$, σ_e^2 - was carried out by use MATLAB/Simulink according to the scheme shown on fig. 4.

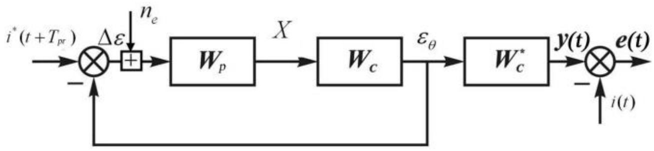

Fig. 4 Scheme of human-operator-vehicle system

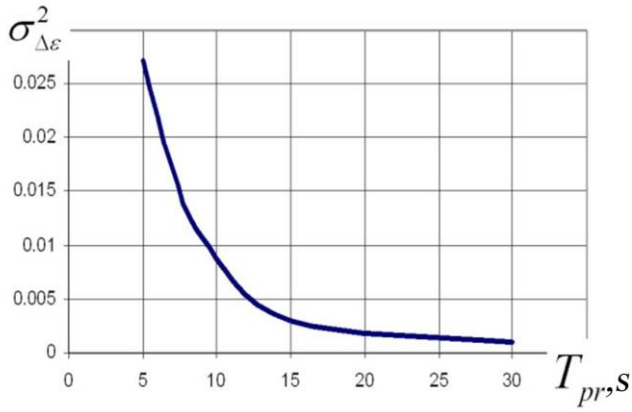

Fig. 5 Variance of signal $\Delta\varepsilon$

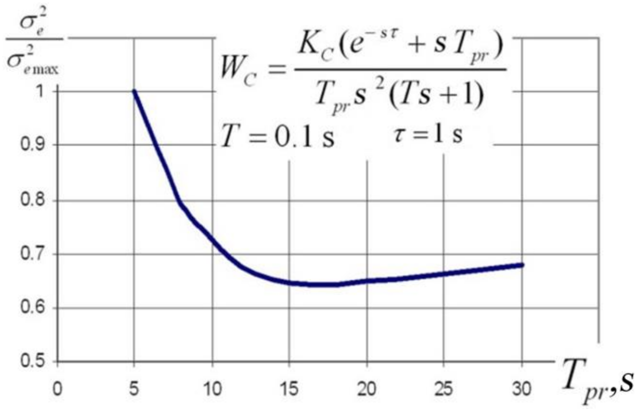

Fig. 6 Normalized variance of current error $e(t)$

It is seen that increase of T_{pr} up to 30 s leads to decrease of variance of error $\sigma^2_{\Delta\varepsilon}$. At the same time the variance of current (not predictive) error of spacecraft height has the other character of its dependence on T_{pr}. From the dependence given of fig. 6 it follows, that the optimal value of T_{pr}, providing the minimum of variance of error in tracking of height in current moment is about 17 s. In the mathematical modeling in was determined that optimal value T_{pr} changes insignificantly for the different parameters of input signal. Because of it the predictive time can be accepted constant and lies in interval T_{pr} =16÷18 s. It is necessary to notice that increase of variance of input signal only increases the variance of error proportionally. In the task of teleoperator control of lunar rover it was used the same principle for the compensation of time delay. In this case the human-operator has to keep the vector of rover velocity at the program trajectory. In the compensation loop it was used the model of the rover yaw control $W_M = \frac{K_c}{s(Ts+1)}$. The optimal predictive time was selected according to the considered above technique and equal to T_{pr} =7÷8 s.

3 Results of experimental investigations

In ground-based simulation it was taken into account the second order pole in the origin in the spacecraft linear and angular motion. Except it, the additional dead-zone was installed in control loop, providing the improvement of accuracy and the eccentricity arising at the inclusion of the jets using for the linear motion control and causing the spacecraft rotation were taking into account.

For improvement of flying qualities the angular velocities feedbacks were used in angular control channels. Such automation allows to reduce the order of pole in the origin and the effect of eccentricity of jets using for the spacecraft linear motion control. The same principles were used in height and side motion control channel. For experimental investigation of the docking MAI ground-based simulator with wide angle stereoscopic visual system (SVS) was used. The software of this system generates the scenario corresponding to the docking task with frequency 120 Hz and displaying ISS, rotating Earth, sky and different lighting effects. Except it the image of display was put on the image of virtual reality. The generated integrated scenario is shown on fig. 7. In the lunar rover control the SVS generates the lunar surface, where the program trajectory and projection of velocity vector were demonstrated (fig. 8). The algorithms and software for the visual system generating the lunar surface are described in [10].

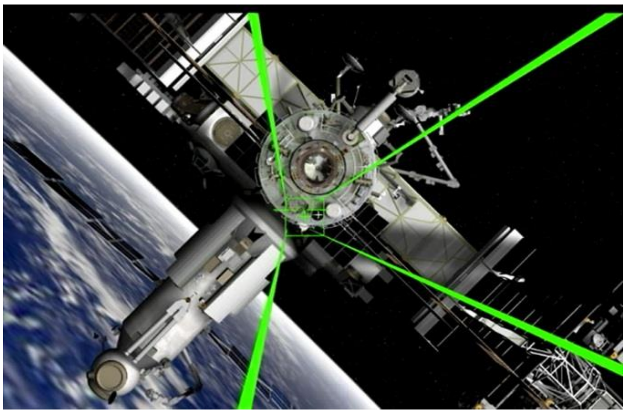

Fig. 7 Scenario for the docking task

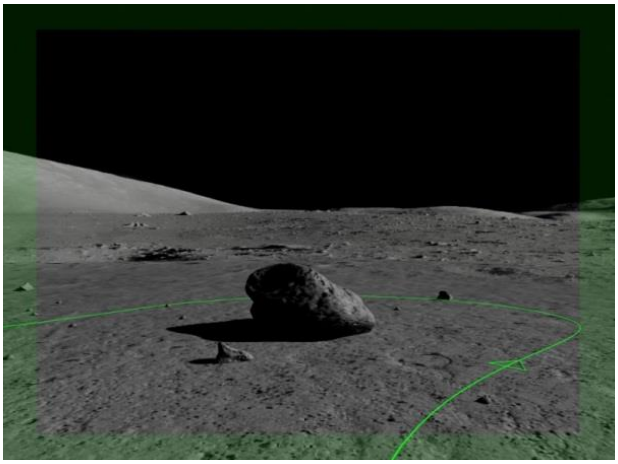

Fig. 8 Scenario for lunar rover control

On fig. 9-14 there are given the following mean square:

- Vertical V_y and lateral V_z components of spacecraft drogue in moment of docking $V_{y,z} = V^*_{y,z} + q(r)l$, where $V^*_{y,z}$ - linear components of velocity vector, q, r - pitch or yaw rates, l - the distance between the center of gravity and end of drogue.
- The linear coordinate Z and Y in the moment of contact.
- Yaw and pitch angles,

measured in experimental investigations.

Analysis of these results demonstrates that regime TORU, for which it was taken $\tau = 2$ s, was accompanied by considerable deterioration of accuracy of all state variables in comparison with case of manual docking ($\tau = 0$). The usage of feedback (FB) leading to suppression of spacecraft rotation when the jet used for control the linear motion is switched on, and to reduction of pole order in the origin causes to the high decrease of variability of all variables. Wherein the mean square error of the angles, reaching 1÷1.4 deg in experiments without feedbacks, do not exceed 0.1÷0.2 deg, the mean square error of linear velocities decreases in 4÷10 times, and mean square errors decreases the linear coordinates (Z, Y) in 2÷4 times. Such improvement of accuracy is typical for manual control ($\tau = 0$) and for docking executing in TORU regime. The further improvement of accuracy reaches in the introduction of predictive indication (version: “FB+display”). The compensation of time delay provides the variability of the contact points not exceeding 1 sm, what corresponds to the variability taking place in case of the absent of delay. The accuracy of angles and components of velocity corresponds to the values achieved at the manual docking control. Thus the usage of feedbacks and compensation of time delay in TORU regime lead to considerable decrease of variability of all phases at the tracking of program trajectory.

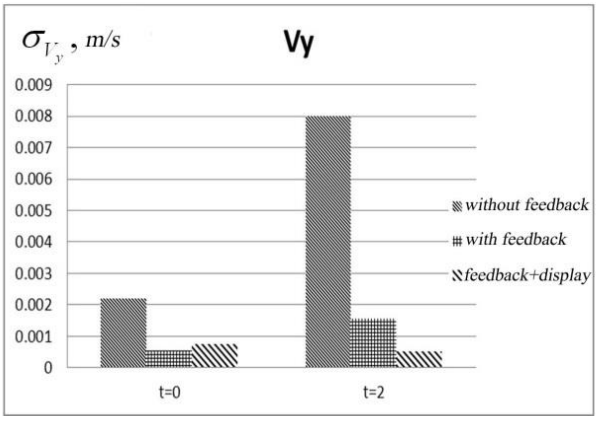

Fig. 9 Influence of automatization on mean squar error V_y

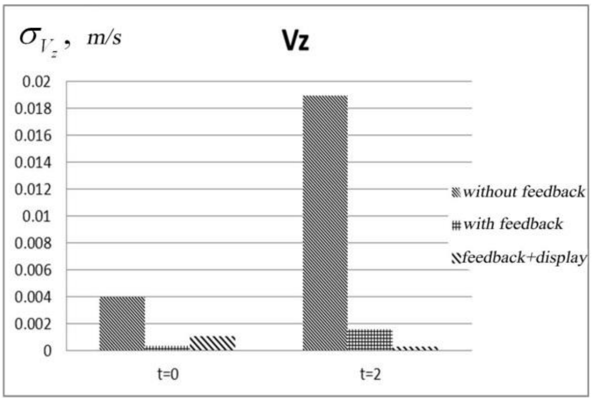

Fig. 10 Influence of automatization on mean squar error V_z

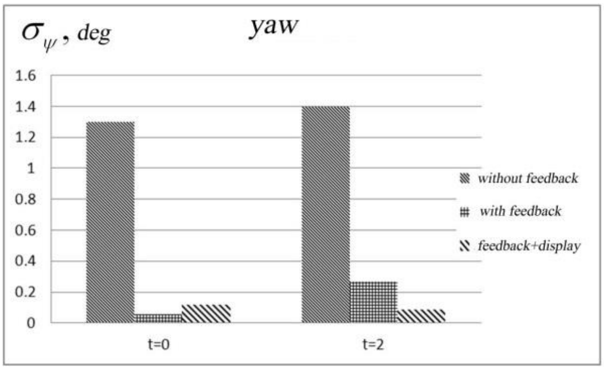

Fig. 11 Influence of automatization on mean squar error yaw angle, ψ

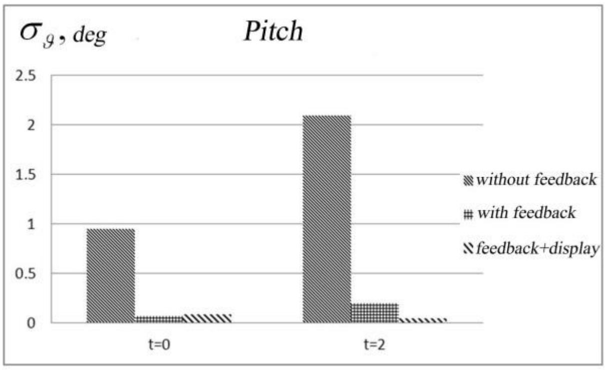

Fig. 12 Influence of automatization on mean squar error pitch angle, ϑ

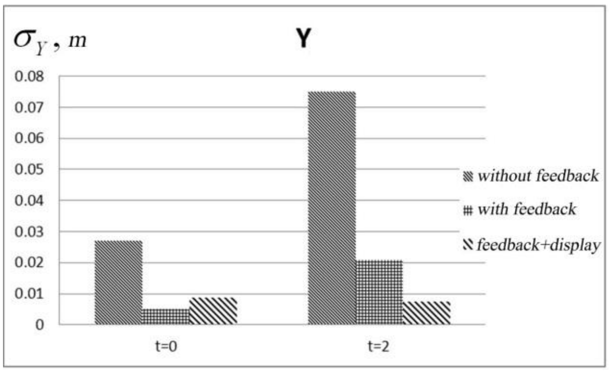

Fig. 13 Influence of automatization on mean squar error vertical position, Y

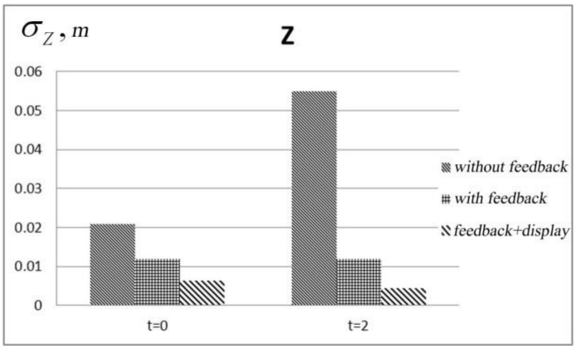

Fig. 14 Influence of automatization on mean squar error side position, *Z*

Experimental investigations of the lunar rover control task demonstrated that the discrete process of control typical for the usage of standard means of indication (fig. 15) transforms in continuous when the predictive display was used (fig. 16). Except it the speed of the rover motion on the Lunar surface increases in 2÷2.5 times in the last case.

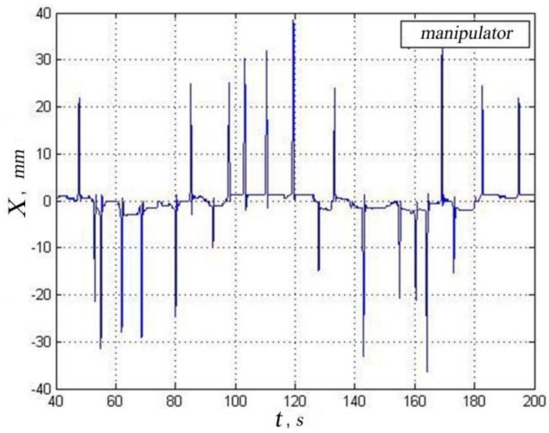

Fig. 15 Deflection of manipulator for the rovel control without predictive display

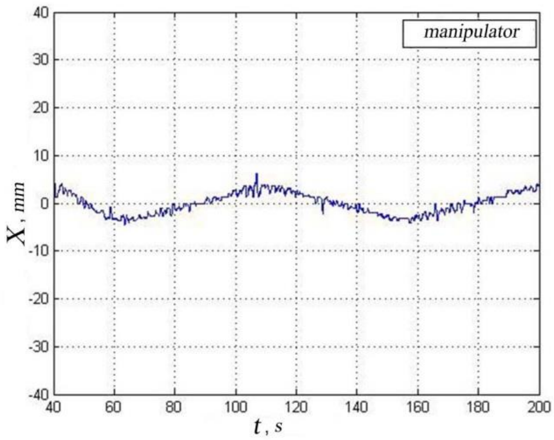

Fig. 16 Deflection of manipulator for the rovel control with predictive display

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