IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

Pilot behavior in preview tracking task

To cite this article: A V Efremov *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **868** 012029

Pilot behavior in preview tracking task

A V Efremov, M S Tiaglik and I Kh Irgaleev*

Flight Dynamics and Control Department, *Moscow Aviation Institute* (National Research University), 4 Volokolamskoe shosse, Moscow 125993, Russia

*E-mail: pvl@mai.ru

Abstract. The influence of the input signal bandwidth and controlled element dynamics on the potential of the preview display for improving accuracy is considered. The pilot in the loop experiments in which the human operator tracked a program trajectory characterized by bandwidths of 0.2, 0.5, 1 rad/s were carried out with a number of simplified controlled element dynamics and with the predictive display/aircraft system dynamics. For the latter dynamics the experiments were performed for different preview times (from 0 up to 6 s) which allowed to define its optimal value.

1. Introduction

The majority of pilot-aircraft system investigations were carried out for the compensatory display. In that case only the error signal $e(t)$ is the stimulus that the pilot transforms in his actions (figure 1).

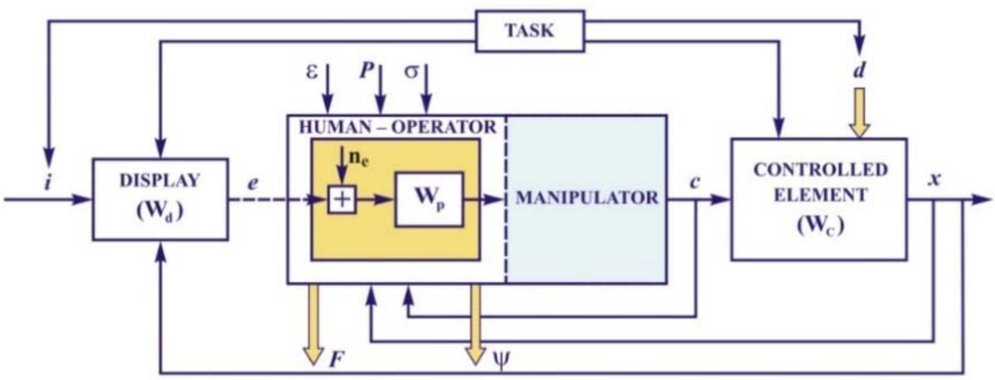

Figure 1. Pilot-aircraft system.

The fundamental regularities of human operator behavior were defined for such kind of system. They were used widely for solving different engineering problems (flight control system design, flying qualities criteria development, etc.). The compensatory tracking corresponds to a number of piloting tasks but not all of them. For example, in case of tracking a target flying against the background of clouds or the terrain and in the process of refueling, aside from the error signal, the pilot also perceives the input signal $i(t)$. In that case, the pilot-aircraft system corresponds to the so-called pursuit system. In case of flying through a mountain gorge or while driving a car, the pilot sees the planned trajectory $i(t+T_{prev})$ where T_{prev} is the preview time.

Initial studies [1, 2] of pursuit and preview tracking tasks carried out in the second half of the last century with simplified controlled element dynamics demonstrated that the perception of the planned trajectory leads to a considerable decrease in the variance of error for a preview time close to 0.5÷1 s. Increasing this time does not cause a decrease in the tracking error.

Broad investigations in this area were carried out at Delft University [3-10] for the gain coefficient and simple/double integrator controlled element dynamics, for a rectangular power spectrum input with different bandwidths ($\omega_i \geq 1.5$ rad/s). The maximum preview time T_{prev} was equal to 1 s in virtually all of these studies (except [10] where the preview time was equal to 2 s). The main accent in these studies was made on the definition of two pilot frequency response characteristics whose outputs (so-called "near/far view responses") were calculated after the experiments. The parameters of these characteristics were obtained from the preliminary measurements of two pilot describing functions, one describing the pilot response to the input signal $i(t+T_{prev})$ and the other describing the pilot response to the error signal $e(t)$. The methodology of these measurements and calculations is given in [6, 7]. All these studies exposed the effect of preview on pilot behavior characteristics and its potential for improving task performance, and the influence of the input signal bandwidth and controlled element dynamics on all these regularities. In spite of the importance of these results, all of them were performed for a high bandwidth of input signal which is not typical for the aircraft flight path motion. The planned aircraft trajectory is characterized by the spectrum density with lower bandwidths ($\omega_i = 0.2 \div 0.5$ rad/s) [11]. The interval of preview time accepted in these studies ($T_{prev} = 0 \div 2$ s) did not allow to obtain the optimum value of preview time. In addition, the dynamics of modern aircraft equipped with the display is defined by the dynamics of the aircraft-display system which is more complicated than the simple configurations investigated in [11]. As a matter of fact, the current state of technology has allowed to realize a display with a 3D presentation of the planned trajectory on the screen. This technology has caused a number of studies in defining the best way of presenting the information [2-6, 12]. Finally, the so-called "tunnel in the sky" display was proposed [12]. This display allows pilots to evaluate the current aircraft position in space and the future planned trajectory.

The following modification of this display is the so-called predictive display [13] where, aside from the tunnel, the surface moving inside of it and the aircraft velocity are also displayed (figure 2). The aircraft velocity vector is projected on this surface.

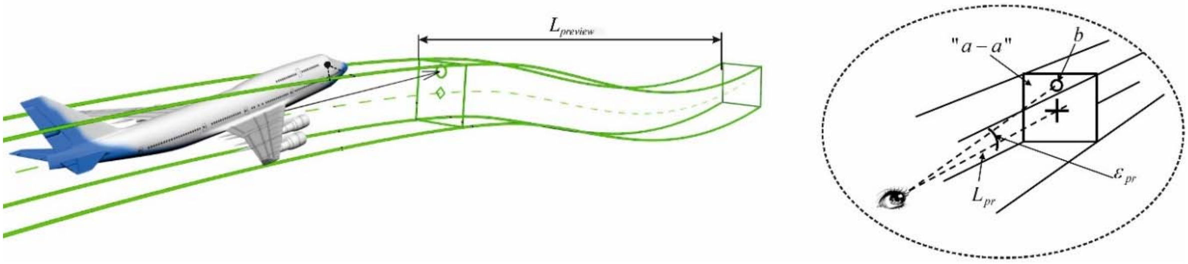

Figure 2. Predictive display with preview.

The selection of the distance between the pilot's eyes and the surface L_{pr} (or predictive time $T_{pr} = \frac{L_{pr}}{V}$) was carried out in [11] with the use of the traditional feedback control theory, aiming to provide the expected controlled element dynamics whose output signal is the predictive angle $\varepsilon_{pr} = \frac{h}{L_{pr}} + \gamma + \dot{\gamma}\frac{T_{pr}}{2}$, where γ is the path angle and h is the aircraft height displacement. It is shown in [11] that the controlled element dynamics of aircraft- display system in that case has the following describing function:

$$W_c(s)=\frac{\varepsilon_{pr}(s)}{X_e(s)}=\frac{K\left(T_{pr}s^2+2s+\frac{2}{T_{pr}}\right)}{s^2\left(s^2+2\zeta\omega s+\omega^2\right)}.$$

According to the technique proposed in [11], the selection of the predictive time is carried out by minimization of the variance of the current height error σ_Δ^2 where $\Delta=h-i(t)$. The results of this investigation demonstrated that the use of the predictive display allows to considerably improve tracking accuracy. In the current paper the integration of the predicted aircraft path with the preview of the planned trajectory on the same display and definition of the preview time providing the minimum task performance is considered. In addition, the influence of the planned trajectory bandwidth $\omega_i = 0.2 \div 1$ rad/s, which is more typical for path control tasks, on preview manual control behavior is studied too.

2. Experiment design

Two groups of experiments were performed with the goal of:

- exposing the effects of the planned trajectory with the bandwidth $\omega_i \le 1$ rad/s on characteristics of the pilot-aircraft system in pursuit and preview tracking;
- defining the optimum preview time providing the best task performance in case of using the predictive display in preview tracking and the influence of the input signal bandwidth on its value.

The first group of experiments was performed with the controlled element dynamics $W_c=\frac{K_c}{s}, W_c=\frac{K_c}{s^2}$ with different bandwidths of the input signal. The second group of experiments was performed with the dynamics $W_c(s)=\frac{\varepsilon_{pr}(s)}{X_e(s)}$ with the same input signal bandwidths. All experiments were performed on one of the fixed-based simulators in the Pilot-Vehicle Lab of Moscow Aviation Institute (figure 3).

Figure 3. Fixed-based simulator.

The human operators were seated in front of the display and applied the control input with a side stick. The images corresponding to compensatory, pursuit, or preview tracking task (figure 4) were generated on the screen of this display.

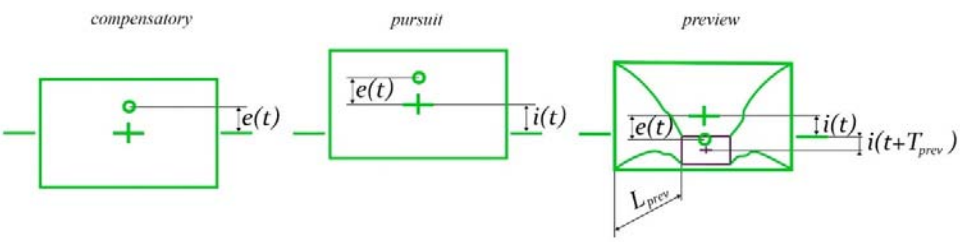

Figure 4. Different displays used in experiments.

The specific peculiarity of the preview display used in the current study is the image of the planned trajectory as a 3D tunnel with the dimensions of height and width of 3 and 4 meters respectively. Its centerline and the whole tunnel change vertical position according to the input signal $i(t+t')$. The error $e(t)$ and input $i(t)$ signals were displayed on a green surface presented on the screen. The distance between the green and grey surfaces $L_{prev} = T_{prev} * V$ is defined by the preview time. Along this distance the pilot perceives the future input signal $i(t+T_{prev})$. The input signal was presented by the polyharmonic signal $i(t) = \sum_{k=1}^{l} A_k \cos(\omega_k t)$ consisting of an orthogonal set of harmonics $\omega_k = k\omega_0$ where $\omega_0 = \frac{2\pi}{T}$ (T is the duration of the run equal to 144 sec).The selection of amplitudes and frequencies was carried out to provide the agreement of the power spectrum distribution with the spectral density of a random signal characterized by the spectral density $S_{ii} = \frac{K^2}{(\omega^2 + \omega_i^2)^2}$ according to the technique given in [14]. The experiments were performed for bandwidths $\omega_i = \{0.2, 0.5, 1\}$ rad/s for each controlled element dynamics. The variance of the input signal was equal to 4 cm^2 in all experiments.

For each combination of ω_i and W_c at least three runs were performed and the results were averaged. Three human operators participated in the experiments. The piloting task was to minimize the error signal.

The following set of pilot-aircraft system characteristics was calculated after the experiments: the frequency response characteristics of the pilot ($W_P = \frac{c(j\omega)}{e(j\omega)}$), closed-loop system ($\Phi = \frac{y(j\omega)}{i(j\omega)}$), variances of tracking error σ_e^2, control output σ_c^2 and their components correlated with the input signal ($\sigma_{e_i}^2$ and $\sigma_{c_i}^2$) and caused by the pilot remnant $n_e(j\omega)$ ($\sigma_{e_n}^2$ and $\sigma_{c_n}^2$). The calculation of Fourier transforms of all signals and components of the variances was carried out using the Fourier coefficients technique [14, 15] (figure 5).

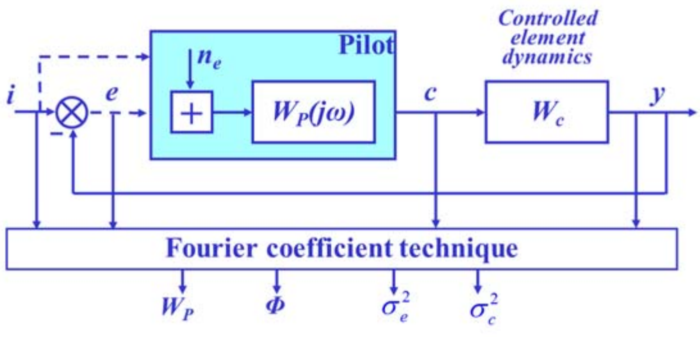

Figure 5. Characteristics measured in the experiments.

3. Results and discussions

3.1. The influence of the planned trajectory bandwidth on pursuit and preview manual control

The preview time in experiments with the preview display was equal to $T_{preview}$=1.5 s. The results of the experiments performed in cases of the controlled element dynamics $W_c = \frac{K_c}{s}$, $W_c = \frac{K_c}{s^2}$ for the

IOP Conf. Series: Materials Science and Engineering **868** (2020) 012029 doi:10.1088/1757-899X/868/1/012029

compensatory, pursuit, and preview tracking tasks are shown in figures 6-7. All these experiments were performed with the bandwidth of the input signal spectrum $\omega_i = 0.5$ rad/s.

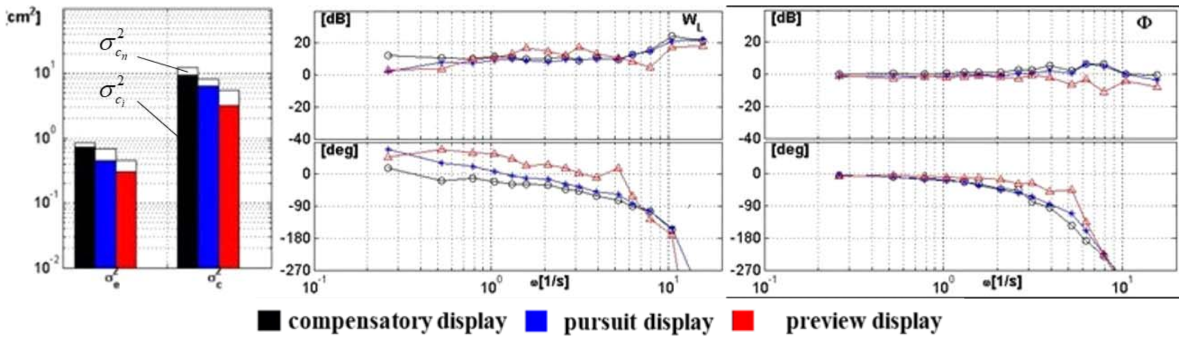

Figure 6. Influence of the piloting task, $W_c = \dfrac{K_c}{s}$.

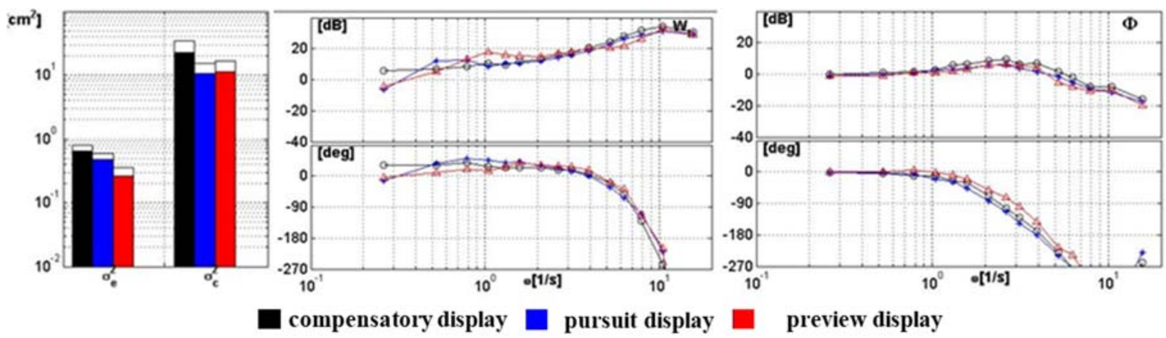

Figure 7. Influence of the piloting task, $W_c = \dfrac{K_c}{s^2}$.

The results demonstrated that in experiments with the controlled element dynamics $W_c = \dfrac{K_c}{s}$, the variance of error σ_e^2 stays approximately the same for all these displays. However, for the double integrator $W_c = \dfrac{K_c}{s^2}$ in the case of a pursuit task the variance of error is considerably lower in comparison to the experiments with the compensatory display, and in the case of the preview display it is more than twice as low.

It is also remarkable that for both dynamics the variance of the inceptor displacement σ_c^2 decreases, approximately by half in the case of the preview display in comparison with the compensatory display. The preview display allows the pilot to generate lead compensation in the crossover and low frequency ranges (see $W_L(j\omega)$ in figures 6, 7) to decrease the resonant peak by 3.2 dB and to increase the bandwidth ω_{BW} of the closed-loop system by 0.6 rad/s (see $\Phi(j\omega)$ in figures 6, 7).

For the small bandwidth of the input signal spectrum $\omega_i = 0.2$ rad/s, there is practically no difference in the frequency response and integral characteristics in compensatory, pursuit, and preview tracking tasks. In the case of the high bandwidth of the input signal spectrum $\omega_i = 1.0$ rad/s the difference between the characteristics is significant. For example, in that case for the controlled element dynamics $W_c = \dfrac{K_c}{s}$ (figure 8) the pursuit and especially the preview displays provide a decrease in the variance of error σ_e^2 and the variance of the inceptor deflection σ_c^2 by 2 and by 2.4 respectively in comparison to the experiments with the compensatory display.

The variance of the inceptor deflection σ_c^2 decreases from 13 cm^2 for the compensatory display up to 5.5 cm^2 for the preview display for this input signal, and the pilot lead compensation in the crossover and low frequency range and the closed-loop system bandwidth increase as well.

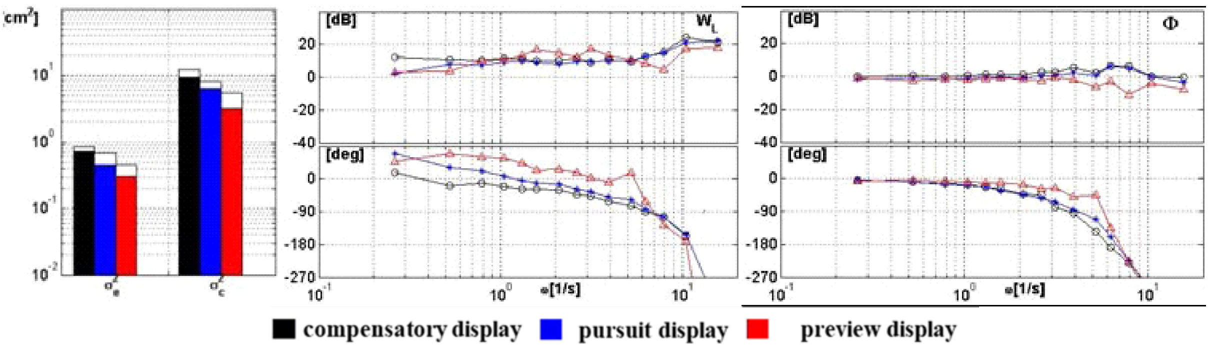

Figure 8. Influence of the piloting task, $\omega_i = 1.0$ 1/s.

3.2. Definition of the optimal $T_{preview}$

A set of experiments examining the influence of the preview time for a different bandwidth of the input signal was also carried out. As an example, the results for $\omega_i = 0.5$ rad/s are given in figure 9.

The analysis of these results demonstrates that an increase in the preview time from 0.5 s up to 2 s leads to a considerable improvement in tracking accuracy. In that case the pilot generates additional lead compensation in the crossover and low frequency ranges. It also causes an increase in the closed-loop system bandwidth by 1.2 rad/s and a decrease in the resonant peak by 3.5 dB. In the case of the following increase in the preview time up to 3 s, the variance of error became higher in comparison to the results of the experiments with $T_{preview}$=2 s.

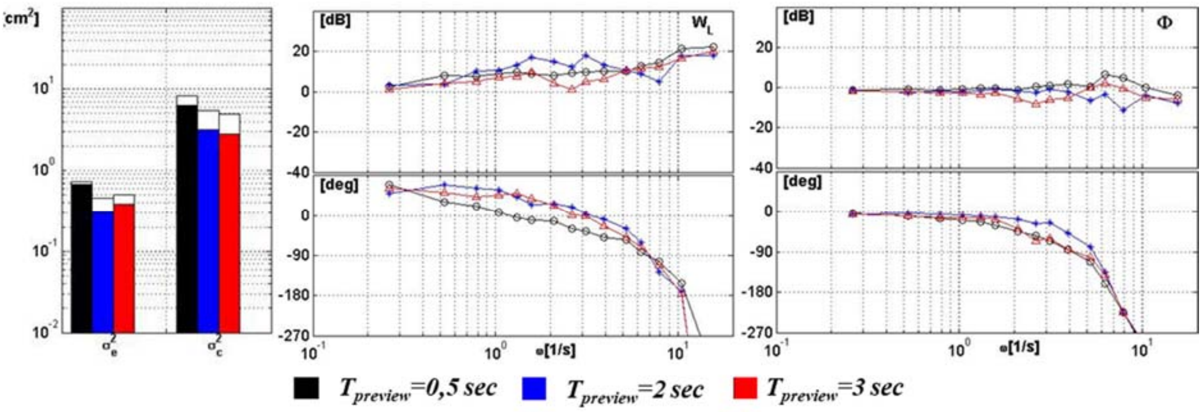

Figure 9. Influence of the preview time.

A separate series of experiments with the preview display were performed for different $T_{preview}$ from 0 up to 6 s. The experiments demonstrate the existence of an optimal value of $T_{preview}$ providing minimal variance of error whose value depends on the input bandwidth. This value is close to 2.4 s for $\omega_i = 0.5$ rad/s (figure 10). It was shown that for $\omega_i = 0.2$ rad/s – $T_{preview}$ = 3 s and for $\omega_i = 1.0$ rad/s – $T_{preview}$ = 2 s.

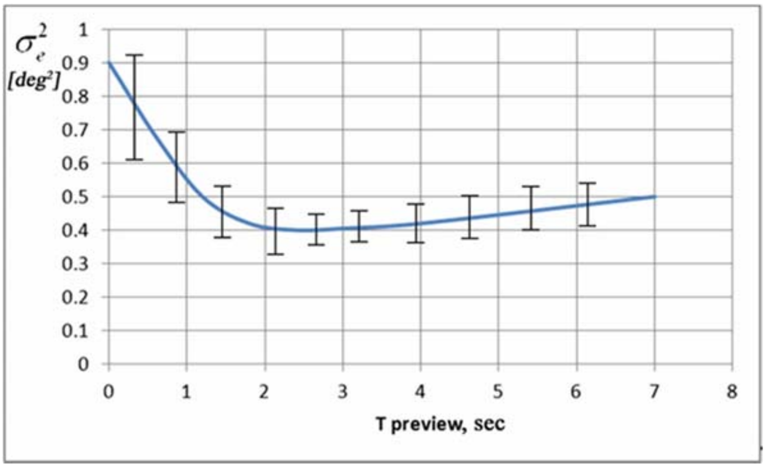

Figure 10. Definition of the preview time.

4. Conclusion

The results of the experiments performed for the planned trajectory bandwidth $\omega_i \leq 1$ rad/s demonstrated that the differences in all major characteristics in pursuit and preview tracking tasks in comparison with a compensatory task depend on the value of bandwidth and controlled element dynamics. It is practically unnoticeable in case of $\omega_i = 0.2$ rad/s and increases for $\omega_i = 0.5$ rad/s and $\omega_i = 1$ rad/s especially in a preview tracking task and in double integrator control. In these cases, the variances of error and inceptor deflection decrease by 2.3 times and 3 times respectively and the pilot generates considerable lead compensation. In a preview tracking task the close-loop system characteristics also improve (a decrease in the resonant peak by 3.2 dB and an increase in the bandwidth ω_{BW} of the closed-loop system by 1.2 rad/s). The preview time is characterized by the optimal value. It is equal to 2.4 s for $\omega_i = 0.5$ rad/s and it decreases from $T_{preview}$=3s to $T_{preview}$=2s when the bandwidth ω_i increases from 0.2 rad/s to 1 rad/s.

Acknowledgments

The results included in the paper are the results of the investigation that was sponsored by the Ministry of Science and Higher Education (contract ID: RFMEFI61619X0117).

References

[1] Reid L D, Drewell N H 1972 A pilot model for tracking with preview in process. *Proceedings of the 8th Annual Conference on Manual Control* (Michigan: University of Michigan Ann Arbor) pp 191-204

[2] Wilckens V, Schattenmann W 1968 Test Results with New Analog Displays for All Weather Landing. *AGARD Conference Proceedings "Problems of the Cockpit Environment"* (Amsterdam, Netherlands) pp 10.1–10.33

[3] Mulder M 1999 *Cybernetics of tunnel-in-the-sky displays*, PhD thesis, Delft University of Technology

[4] Mulder M and Mulder J A 2005 Cybernetic analysis of perspective flight-path display dimensions. *Journal of Guidance, Control, and Dynamics* **28(3)** 398 doi: 10.2514/1.6646

[5] Borst C, Mulder M, Van Paassen M M, Mulder J A 2006 Path-oriented control/display augmentation for perspective flight-path displays. *Journal of Guidance, Control, and Dynamics* **29(4)** 780 doi: 10.2514/1.16469

[6] Van der El K, Pool D M, Van Paassen M M, Mulder M 2018 Efects of Linear Perspective on Human Use of Preview in Manual Control. *IEEE Transactions on Human-Machine Systems* **48(5)** 496 doi: 10.1109/THMS.2017.2736882

[7] Van der El K, Pool D M, Damveld H J, Van Paassen M M, Mulder M 2016 An Empirical Human Controller Model for Preview Tracking Tasks. *IEEE Transactions on Cybernetics* **46(11)** 2609 doi: 10.1109/TCYB.2015.2482984
[8] Van der El K, Pool D M, Van Paassen M M, Mulder M 2018 Effects of Preview on Human Control Behavior in Tracking Tasks with Various Controlled Elements. *IEEE Transactions on Cybernetics* **48(4)** 1242 doi: 10.1109/TCYB.2017.2686335
[9] Van der El K, Padmos S, Pool D M, Van Paassen M M, Mulder M 2018 Effects of Preview Time in Manual Tracking Tasks. *IEEE Transactions on Human-Machine Systems* **48(5)** 486 doi: 10.1109/THMS.2018.2834871.
[10] Van der El K, Pool D M, Van Paassen M M, Mulder M 2020 Effects of Target Trajectory Bandwidth on Manual Control Behavior in Pursuit and Preview Tracking. *IEEE Transactions on Human-Machine Systems* **50(1)** 68 doi: 10.1109/THMS.2019.2947577
[11] Efremov A V, Tyaglik M S 2011 The development of perspective displays for highly precise tracking tasks. *Advances in Aerospace Guidance, Navigation and Control* (Germany: Springer) pp 163-174
[12] Grunwald A J 1985 Predictor Laws for Pictorial Flight Displays. *Journal of Guidance Control and Dynamics* **8(5)** 545 doi: 10.2514/3.20021
[13] Sachs G 2000 Perspective predictor flight – path display and minimum pilot compensation. *Journal of Guidance Control and Dynamics* **23(3)** 420 doi: 10.2514/2.4576
[14] Efremov A V, Rodchenko V V, Boris S 1996 Investigation of pilot induced oscillation tendency and prediction criteria development. *Final report WL-TR-96-3109,* Air Force Institute of Technology Wright-Patterson AFB (Dayton, Ohio) pp 1-138
[15] Efremov A V, Ogloblin A V, Predtechensky A N, Rodchenko V V 1992 *Pilot as a dynamic system* (Moscow: Mashinostroenie) p 332 (in Russian)