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PILOT INDUCED OSCILLATIONS OF THE SMALL UNMANNED AERIAL VEHICLES

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Abstract: *The unintentional inputs of the UAV operators in certain conditions might lead to the unwanted, pilot induced oscillations (PiO) of the aircraft. The PiOs might cause severe damages of the UAV, or as the worth, might lead to the loss of the aircraft. The PiOs of the manned aircraft are in the focus of attention for many decades. However, the PiOs of the UAVs became an important issue worth to investigate only in the past few years. Thus, scientific results and proven statements gained in this field might enrich both the on-going UAV operator training programs and UAV autopilot design based mostly on traditional synthesis methods and procedures.*

Keywords: UAV, human operator, PiO, PiO categories, stability analysis

1. Introduction and Motivation

The PiO is a well-known and long-time investigated phenomenon of the history of the flight dynamics. In the manned aircraft aviation, since the early 1950's several accidents and catastrophes were happened due to high aircraft speed, due to unconventional airframe used, and due to weak pilot training.

It is well-known that behind any PiO occurred there might be different causes differing from each other in much.

The PiOs were documented from the first time they happened. These events were documented thoroughly, and statements of the investigations were published widely.

As UAVs spread widely in the past years in several UAV airframes there were applied different unconventional aerodynamical arrangements for the design and manufacturing.

Easy to agree with that some kinds of the PiOs can be created by the improper steering activity of the UAV operators traced back to their low level theoretical and practical trainings, to the missing minimum skills of the UAV operators and finally to the lack of physical and mental fitness during the flight conducted by the operator.

The purpose of the author is to show how physical and mental fitness, and the flight control activity of the UAV operator might affect both the open and closed loop performances the UAV operator belongs to.

2. Scientific Preliminaries

The activity of the human operators and its investigation and modelling has long tome history. As UAVs spread widely and very fast penetrating everywhere it could, due to different national regulations, it became very important to see how the less trained operators are able to handle different flight situations keeping flight safety at the proper minimum levels.

Leaning on results of both different laboratory and real flight tests several mathematical models of the human

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operators were identified and summarized in [1], [2], [3], [4].

The pilot-in-the-loop problem was thoroughly analyzed both for the open and closed loop flight control system. Results and findings of these works are outlined in [5], [6].

The UAV recce applications are shown in [7] and [8], explaining flight path planning and flight paths optimization, too.

The definition of the PiO is given by [9]. The backgrounds of the establishment of the PiOs were discussed by [10], [11], and [12]. The handling of the PiOs and their mitigation was achieved using methods and procedures of the modern control engineering [13], [14].

The PiOs of the UAV/UAS systems were investigated by [11] and [15] leaning on linear mathematical models of the human operators in closed loop flight control systems.

3. About the PiO

The PiO is a sustainable, or uncontrollable oscillation of the aircraft mostly caused by improper control activity of the human operator [9].

It is obvious, that any human operator can change his behavior in wide range when he acts in any control system, including gains and time constants or time delays.

In this regard, the operator can adapt himself to different aircraft types and to different flight situations he acts in.

Thus, this will lead to different open and closed loop control system models he is involved in. The UAV operator activity can be described as [10], [11], [12]:

- compensation of the error signals using null-indicators;
- compensation of the error signals with regards of both the input and output signals, like semi-automatic landing using ILS;
- compensation with prediction skills and abilities of the operator;
- pre-cognitive (predictive skills based upon experiences) behavior of the skilled and highly trained UAV operators;
- pre-cognitive, compensating behavior in multiple control channels.

Besides normal control activity of the UAV operators, several improper behavior pattern can be determined [10], [11], [12]:

- improper, not disciplined behavior;
- improper adaptation to flight situations requiring different behavior pattern;
- agile, or aggressive behavior in control of the aircraft with extremely large gains;
- improper transitions between forms of behavior described above;
- ‘freeze’ at the end of the transient processes.

Main causes of the PiOs are as they summarized in [10]:

- unfitness of the operator:
  - o improper, weak training;
  - o improper adaptation skills;
  - o transition of the improper control skills from one aircraft to another aircraft;
- nonrealistic expectations for adaptation skills of the UAV operators;
  - o the expected gains, time delays and prediction skills are far beyond the existing abilitiesof the operator;
  - o low adaptation speed of the operator excluding proper damping of the oscillations;
  - o improper skills to handle nonlinearities of the flight control systems by the operator;
- coupled ‘limb-body’ system of the operator;
  - o unintentional pilot inputs due to high loads acting on pilots.

PIOs can be categorized as follows below:

3.1. CAT I PIO: Oscillations of the Linear ‘Pilot-Aircraft’ System

PiOs of this category happen in linear flight control system when the operator model used is also a linear one. In these casePiOsare caused by high open loop

gains. These PiOs might appear frequently and can be eliminated by freeing aircraft controls or reducing pilot gains.
As a rule, the CAT I PiOs rarely destroy flight safety at all. However, fast and high energy control inputs implemented might lead to oscillations threating with lose of the UAV.
The CAT I PiOs might appear for aircraft having large dead times and time delays. PioS of this category might have both large or small amplitudes.

3.2. CAT II PIO: Oscillations of the Quasi-Linear 'Pilot-UAV' System with Saturated Servo Actuators

In this category the UAV has a nonlinear servo actuator connected series in the feedforward path of the UAV flight control system. The servo actuator has static nonlinearities like dead zone plus saturation.
Moreover, several other dynamic nonlinearities like aerodynamic nonlinear functions might be added to the static nonlinearities (e.g. dynamic pressure vs airspeed, air density vs height of the flight etc.) mentioned above.
The CAT I PiOs behavior is very close to CAT II PiOs but differing in time delays caused by nonlinearities. The CAT II PiOs' amplitude might diverge and lead to severe oscillations of the UAV.

3.3. CAT III PIO: Oscillations of the Highly Nonlinear 'Pilot-UAV' System

These PiOS are mainly caused by the nonlinear UAV dynamics, by the static nonlinearities of the flight control system of the UAV, by the nonlinear engine dynamics, and by the nonlinear aerodynamic functions as it was explained for CAT II PIOs.
The CAT III PiO can be also caused by different behavior pattern of the UAV operator, by the transitions between different kinds of behavior, by the sudden appearance of different flight tasks, by the inadequate pilot inputs selected for the given maneuver.

4. CAT I PIO of the Small UAVs

UAVs are widely used for detection of extreme meteorological events and phenomena, such as gusts and wind shears.
In Figure 1 the 'Phastball' small UAV is depicted used for different scientific research purposes.

Figure 1: Machining features and their tool access directions
Source:https://nari.arc.nasa.gov/sites/default/files/Yu_Gu.pdf

4.1. Open Loop Control of the 'Phastball' SUAV in CAT I PiO

Let us consider the following open loop flight control system of the UAV depicted in Figure 2.

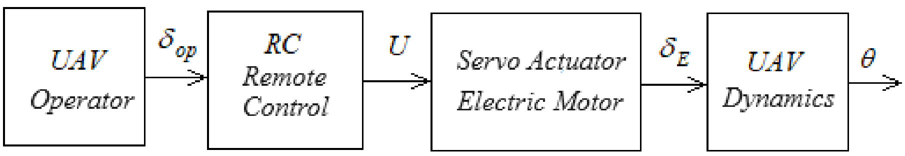

Figure 2: The open loop control system of the 'Phastball' UAV
Source: Author

From Figure 2 it is evident that the UAV operator creates the UAV input signal δ_{op}

to control the UAV as regarded. The RC unit dynamics involves the whole dead time of the data transmission and receive, the data processing time in digital devices, time required by signal processing and required to produce control input U. Thus, the transfer function of the RC unit can be derived as follows below [5]:

$$Y_1(s) = \frac{U(s)}{\delta_{op}(s)} = e^{-(\tau_{op}+\tau_{RC})s}, \quad (1)$$

where 's' is the Laplace-operator, $\tau_{op} = 0{,}17s$ is a dead time of calculations and data processing, $\tau_{RC} = 0{,}1s$ is a time delay defined by the radio signal transmissions and receive.

Further we will use the 5th order Padé approximants to express time delays in any process modelled. The servo actuator is an electrical motor with dynamical model [5]:

$$Y_2(s) = \frac{\delta_E(s)}{U(s)} = \frac{0{,}0217}{0{,}1222s+1}. \quad (2)$$

The small UAV longitudinal flight dynamics model used to model CAT I PiOs is as follows [5]:

$$Y_3(s) = \frac{\theta(s)}{-\delta_E(s)} = \frac{8{,}882\cdot10^{-16}s^3+29{,}11s^2+123{,}4s-56{,}09}{s^4+7{,}406s^3+24{,}05s^2-12{,}11s+0{,}3362}, \quad (3)$$

where $\theta(s)$ is the pitch angle, $\delta_E(s)$ is the change of the angular position of the elevators.

The step response function of the small UAV to the input of $\delta_E(t) = 20\cdot 1(t)$ can be seen in Figure 3 [16], [17]:

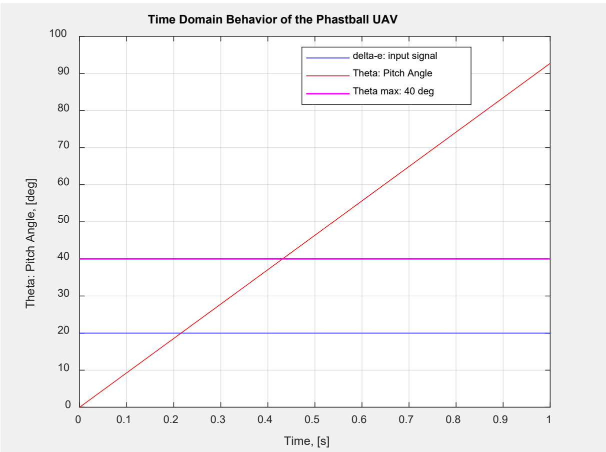

Figure 3: Step response of the small UAV MATLAB-script: author

From Figure 3 it is easy to see that the UAV reacts very fast to the control input and reaches the maximum available θ_{max} in very short time of 0,43s. The poles and zeros of the UAV dynamics defined by Eq (3) are tabulated in Table 1.

Table 1 Poles and zeros of the small UAV (made by the author)

Poles(p_i) and zeros(z_j)	Damping ratio, ξ, [-]	Frequency, ω, [rad/s]
$p_1 = 0{,}0295$	-1	0,0295
$p_2 = 0{,}414$	-1	0,414
$p_{3,4} = -3{,}92 \pm 3{,}48\cdot i$	0,748	5,25
$z_1 = -3{,}2774\cdot 10^{16}$		
$z_2 = -0\cdot 10^{16}$		
$z_3 = 0\cdot 10^{16}$		

Applying `minreal.m`built-in function of MATLAB with 10% of approximation the poles and zeros were cancelled, and the approximated transfer function is as follows [16], [17]:

$$Y_3(s) = \frac{\theta(s)}{-\delta_E(s)} = \frac{8{,}882\cdot 10^{-16}s^3+29{,}11s^2+123{,}4s-56{,}09}{s^4+7{,}406s^3+24{,}05s^2-12{,}11s+0{,}3362} \cong$$

$$\frac{8{,}882\cdot 10^{-16}s+29{,}11}{s^2+4{,}624s-0{,}1373} = Y_4(s). \qquad (4)$$

The step response function of the UAV to the input of $\delta_E(t) = 20 \cdot 1(t)$can be seen in Figure 4 derived for both the original and for the reduced dynamical models [16], [17]:

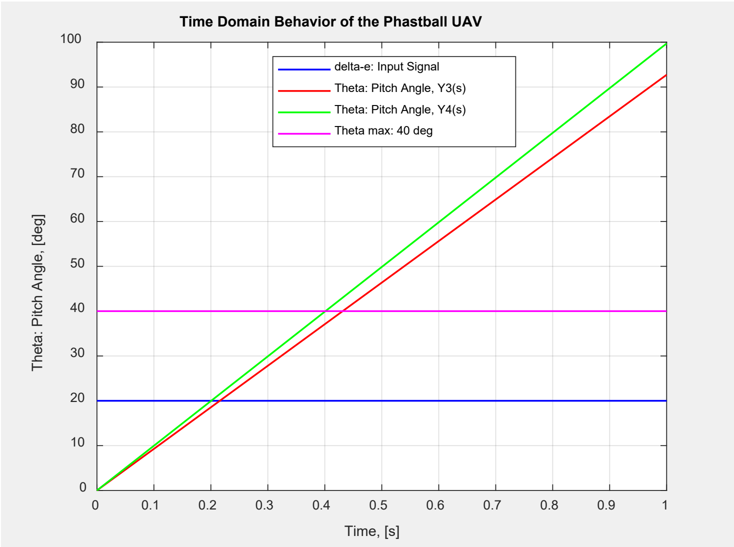

Figure 4: Step response of the small UAV MATLAB-script: author

From Figure 3 it is easy to see that the model reduction has led to decrease of the time needed to reach the maximum of the pitch angle.

Figure 5 shows the Bode diagram of the original and the reduced dynamics of the UAV.

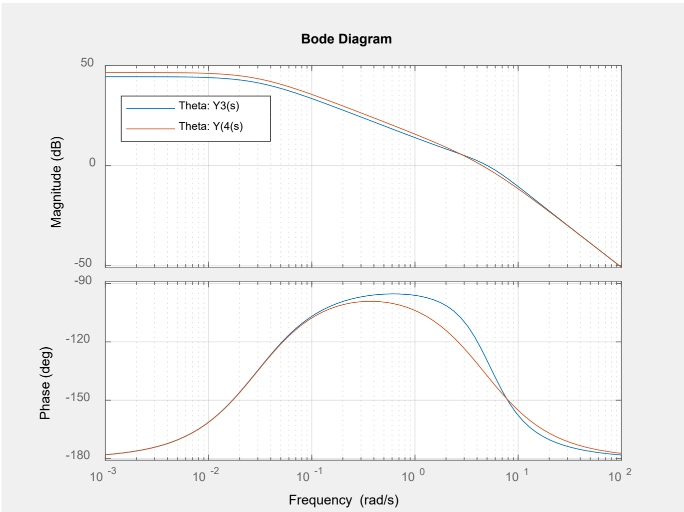

Figure 5: Frequency domain response of the UAV MATLAB-script: author

From Figure 4 it is evident that gains will change a few, whilst the phase shift angle will change much in mid frequency range.
Using Eg (4) it can be stated that the UAV has a CAT I PiO unstable dynamics, due to negative coefficient in its denominator. [5]

Using transfer function $Y_4(s)$ representing the reduced dynamical model, the system poles and zeros were calculated and are depicted in Table 2 [16], [17]:

Table 2 Poles and zeros of the small UAV (made by the author)

Poles(p_i) and zeros (z_j)	Damping ratio, ξ, [-]	Frequency, ω, [rad/s]
$p_1 = 0{,}0295$	-1	$0{,}0295$
$p_2 = -4{,}65$	1	$4{,}65$
$z_1 = 3{,}6882 \cdot 10^{-7}$		

Due to the positive $\boldsymbol{p_1}$ pole the 'Phastball' SUAV will respond to the sudden step input in $\boldsymbol{\delta_E(t)}$with aperiodically diverging, unstable pitch angle $\boldsymbol{\theta(t)}$.
The resulting transfer function of the open loop control system of the UAV depicted in Figure 2 representing the UAV pilot in the loop can be found as:

$$Y_{O.L.}(s) = \frac{\theta(s)}{\delta_{op}(s)} = Y_1(s)Y_2(s)Y_3(s) = e^{-(\tau_{op}+\tau_{RC})s} \cdot \frac{0{,}0217}{0{,}1222s+1} \cdot \frac{8{,}882 \cdot 10^{-16}s + 29{,}11}{s^2 + 4{,}624s - 0{,}1373} \quad (5)$$

Applying fifth order Padé approximant to the time delay expressed in Eq (5) will lead to an 8th order system dynamics.
It is easy to agree with that due to unstable UAV dynamics involved into the open loop control system the whole open loop control system is unstable.
The open loop control system and the open loop system with reduced dynamical model frequency domain behavior can be seen in Figure 6.

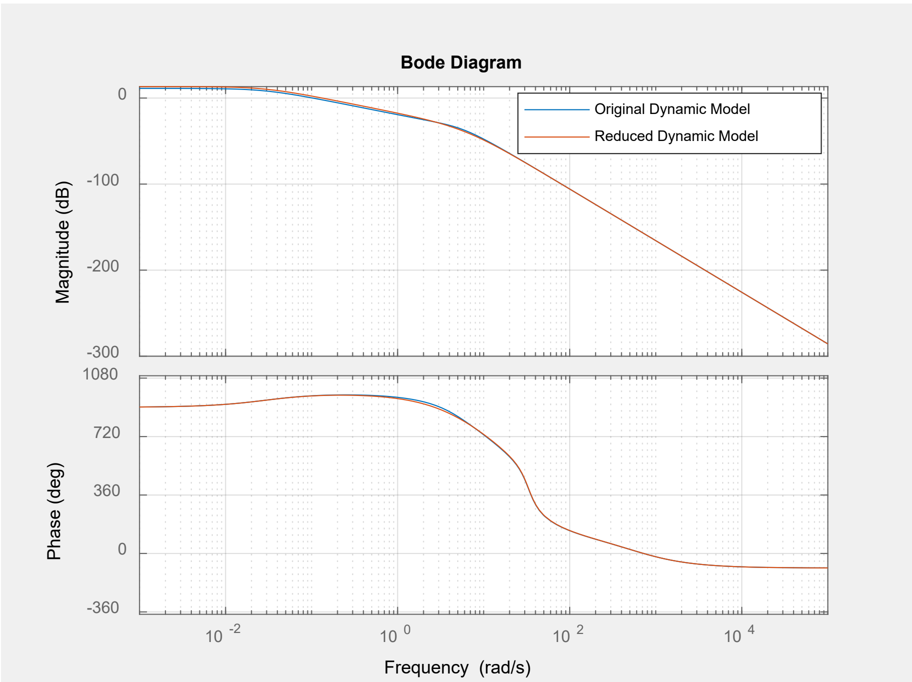

Figure 6: Frequency domain response of the UAV open loop control system MATLAB-script: author

From Figure 6 it is evident that the model reduction does not affect much the whole system behavior, thus, further we will use the reduced dynamical model of the UAV.

4.2 Closed Loop Control of the 'Phastball' UAV in CAT I PiO

The CAT I PiO of the small UAV will be evaluated using Neal-Smith criterion based upon evaluation of the closed loop control system when the UAV operator takes active part in the closed loop control. [5]

The block diagram of the SUAV closed loop control system is depicted in Figure 7.

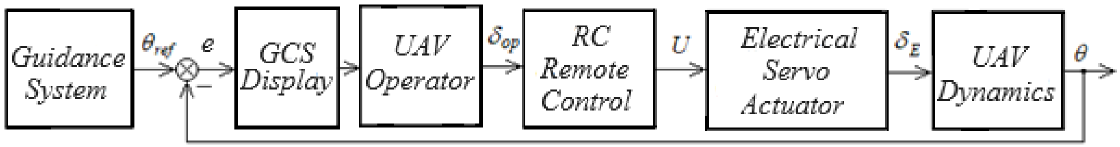

Figure 7: The closed loop control system of the 'Phastball' UAV
Source: Author

In this manner, the ground control station (GCS) display will show for the operator the error signal $e(t) = \theta_{ref}(t) - \theta(t)$ should be eliminated. Further, the GCS display will be modelled with unit static gain.

The Neal-Smith criterion suggests for the UAV operator modelling to use following transfer function:

$$Y_2(s) = \frac{\delta_{op}(s)}{e(s)} = K\frac{1+sT_L}{(1+sT_N)}e^{-s\tau}. \quad (6)$$

It is well-known that UAV operator model defined by Eq (6) has identified T_L, T_N, K, és τ parameters depicted in Table 3. [1], [2], [3], [4], [5], [6]

Table 3 Identified parameters of the UAV operators (made by the author)

UAV operators	K	T_L, [s]	T_N, [s]	τ, [s]
Well-trained, professional UAV operator	10	0,5	0,1	0,1
UAV operators with average skills and knowledges	7	1	0,2	0,2
Novice UAV operator	5	1	0,3	0,3

Using operators' data depicted in Table 3 the closed loop control system was designed to eliminate unstable CAT I PiO of the UAV behavior.

The closed loop control system given in Figure 7 was tested for the reference input given by $\boldsymbol{\theta_{ref}(t) = 10 \cdot 1(t)}$. Result of the computer simulation are shown in Figure 8 [16], [17].

From Figure 8 it is easy to see that the full state feedback by the pitch angle will ensure the closed loop control system stability.

To find settling time the tolerance field of $\Delta = \theta(\infty) \pm 5\%$was set on the steady-state value of the pitch rate.

From Figure 8 it is evident that UAV operators with different skills, knowledge and training levels will behave with differently when to act in the closed flight loop control system.

The largest percent overshoot is provided by the UAV operator with average skills. This property is registered likely due to high-level of self-confidence of those operators who have left behind the novice status and who start to behave as a professional showing more agility, or aggressiveness in controlling the UAV.

Moreover, the control activity of this operator will lead to the largest transient time of$t = 6{,}48s$ and to the very oscillatory behavior of the whole closed loop flight control system.

The well-trained UAV operator is the fastest in maintaining the reference input signal to have settling time of $t = 3{,}82s$ driving the UAV with large oscillations

close to those maintained by the UAV operators with average skills.
It is interesting to mention that the novice UAV operator has transient times $t = 3{,}85s$ close to that maintained by the professional operators, but he behaves more carefully with no agile or aggressive features.

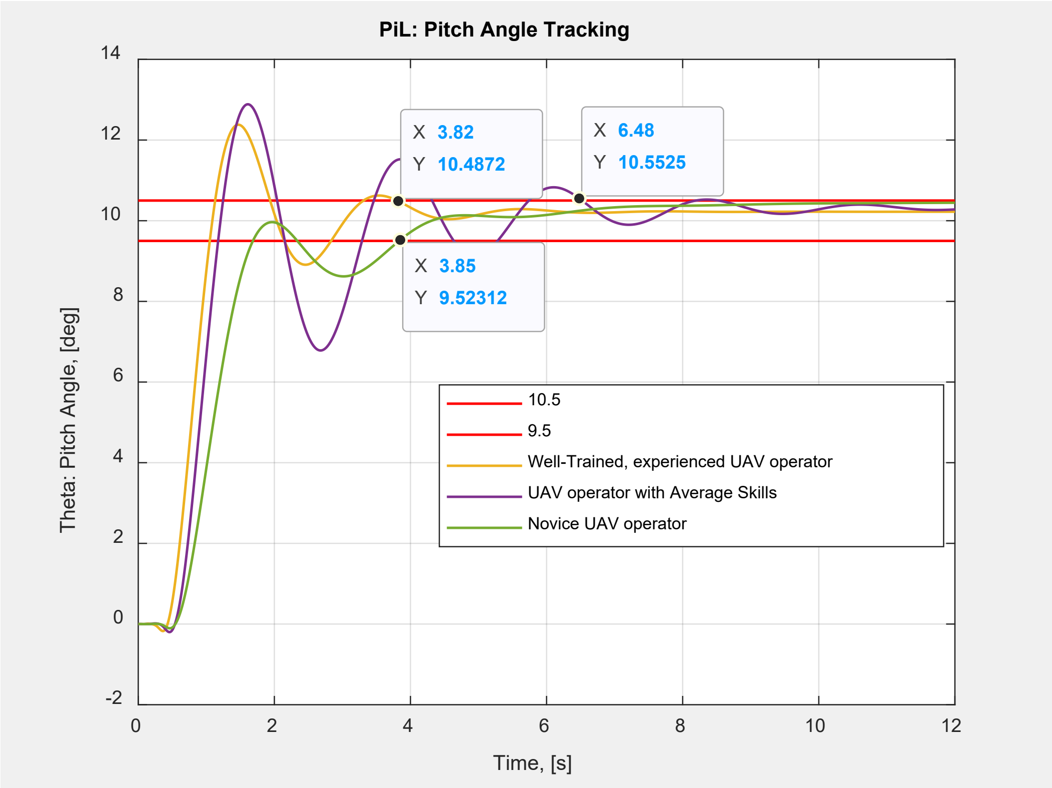

Figure 8: Step response of the closed loop control system with different models of the operator MATLAB-script: author

5. Conclusions and Outlook

The flight control of the UAV is often maintained with open loop flight control systems. In this manner, the UAV operator in his visual control subjects control inputs to the UAV leading to the proper spatial motion and to the adequate new equilibriums. Majority of the hobby-purpose and entertainment UAV flights has such feature. Due to low levels of skills or low levels of training the novice UAV operators might create over actuated inputs leading to appearance of the PiOs.
If any GCS is implemented, the UAV operator might control the UAV leaning on visual information provided on displays of the GCS.In this case, the UAV operator acts in the closed loop flight control system and will provide necessary inputs to keep UAV on the flight path planned.
In different flight missions it might happen to the operator that he has to act in multiple control channels. In these flight missions, operators are subjected to high level of stress leading him to worsened dynamic performances, i.e. the time delay will be increased meaningfully, or more agility or aggressiveness would be shown to conduct flight missions.
It is well-known that mathematical models of the UAV operators applied for different purposes might differ. Moreover, these models have different identified parameters. Despite the high sensitivity of the topic, for future work it is promising to find worst case parameters of the operators, in other words, the physical and mental status of the operators fitting the flight missions being executed with no trends to any PiO event.

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