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MODELLING UAV OPERATORS IN CLOSED LOOP FLIGHT CONTROL SYSTEMS

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Abstract: *The semi-automated control systems include human operators accomplishing different tasks. The UAVs' semi-automated control means a special 'man-machine' system. The UAV operators gaining real time information and leaning on experiences gained in the past will control the UAV. His knowledge and high level skills are required to conduct successfully any flight mission he was tasked for. Hence, to accomplish any regulation or tracking control problem, the UAV operator shall rely on his theoretical and practical skills to achieve goals of the UAV flights. Additionally, the UAV closed loop control system can be analysed leaning on mathematical models of the human operators. Different readiness of the UAV operators will ensure different efficiency of the UAV flight mission. This paper deals with UAV closed loop control system analysis when the pilot-in-the-loop (PiL) problem is addressed to show importance of use of different models of the UAV operators.*

Keywords: UAV operator, open loop control, closed loop control, computer-aided simulation, performance analysis

1. Introduction

The wide-broad applications of the UAVs, when different human operators play roles of the 'UAV pilot', have led to unavoidable evaluation of the role of the operators.

Not only their knowledge and skills but their physical and mental status gained extremely high importance.

The large-scale variety of the UAVs and their diverging applications require operators with different preliminaries. The hobby purpose nano- or micro UAV requires different knowledge, skills and training for the operators.

The governmental state aviation UAVs (e.g. military, police, border control etc.) represent another class of UAVs with more sophisticated applications requiring high level of skills and knowledge from the UAV operators.

The PiL problem is an old topic investigated by many scholars in the early advent both of the supersonic and space flights. In many remote control problems operators are key elements in control systems [2], [3], [4], [5].

In the rise of ground simulators and machine trainers the key problems of modelling of the human pilots were put at the first place. In the 1950's several mathematical models were set up to model pilots' behaviour both in open and in closed loop control systems [1], [6], [8].

Human operators, like an element of the automatic flight control systems were modelled using different mathematical models [7], [9].

For the assessment of the role, the physical and mental status, the level of training of the UAV operators gained in evaluation of closed loop control system dynamic performances is very important [9], [10].

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Thus, evaluation of their role, their physical and mental status, their level of training gained in stability analysis or in evaluation of closed loop dynamic performances is very important [6], [7], [8]. The path planning problems and their solution for UAVs are addressed and solved in [11], [12].

2. Identified Mathematical Models of the UAV Human Operators

The identified mathematical model of the UAV human operators can be derived as [1], [6], [8]:

$$Y(s) = \frac{x_{out}(s)}{x_{in}(s)} = K\frac{1+sT_L}{(1+sT_I)(1+sT_N)(s^2+2\xi\omega s+\omega^2)}e^{-s\tau}, \quad (1)$$

where:

- $x_{in}(s)$is a test input signal;
- $x_{out}(s)$is the output signal of the UAV operator;
- $K$is the UAV operator's gain;
- $\tau$is the reaction (dead) time;
- $\frac{1}{(1+sT_N)(s^2+2\xi\omega s+\omega^2)}$is the model of the humna's neuro-muscular system;
- $(1+sT_L)$is a real derivative lead term describing prediction ability of the operator based on experiences gained in the past;
- $\frac{1}{(1+sT_I)}$is a lag term describing data transmission properties of the human operator.

In the dynamic model given by eq (1) the second order term is often modelled with unit gain, and (1) is often simplified to the form of given below

$$Y_1(s) = \frac{x_{out}(s)}{x_{in}(s)} \cong K\frac{1+sT_L}{(1+sT_I)(1+sT_N)}e^{-s\tau}. \quad (2)$$

Using data from ground tests and from the test flights of pilots the mathematical model of (2) involves data lying in the ranges as they defined below [1], [6], [8]:

$$K = 5 \div 10; \quad T_L = (1 \div 1{,}5)s;\ T_I = (0{,}2 \div 1)s;\ T_N = (0{,}1 \div 0{,}3)s;\ \tau = (0{,}1 \div 0{,}3)s. \quad (3)$$

The nonlinear model of the UAV operator (2) can be linearized via expressing time delay in Padé approximation series, hence:

$$e^{-s\tau} \cong P_d(s) = \frac{N_d(s)}{D_d(s)} = \frac{\sum_{k=0}^{n}(-1)^k c_k\tau^k s^k}{\sum_{k=0}^{n} c_k\tau^k s^k}, \quad (4)$$

where coefficients in (4) are:

$$c_k = \frac{(2n-k)!\cdot n!}{2n!\cdot k!\cdot(n-k)!}; n = 1,2,3,\cdots; k = 0,1,2,3,\cdots,n. \quad (5)$$

The larger the order of the approximation the larger is the model complexity. Hence, to reach proper approximation error, $n = 5$ was selected. For this order,

$$e^{-\tau s} \cong \frac{1-\frac{\tau}{2}s+\frac{\tau^2}{12}s^2-\frac{\tau^3}{120}s^3+\frac{\tau^4}{1680}s^4-\frac{\tau^5}{30240}s^5}{1+\frac{\tau}{2}s+\frac{\tau^2}{12}s^2+\frac{\tau^3}{120}s^3+\frac{\tau^4}{1680}s^4+\frac{\tau^5}{30240}s^5}. \quad (6)$$

Regarding physical and mental status of the operators, and considering the level of their training, expertise, experiences, knowledge and skills, tasks to be conducted and accomplish in any control system, the UAV operator model (2) might have different forms like:

- $Y_2(s) = \frac{x_{out}(s)}{x_{in}(s)} \cong K\frac{1+sT_L}{(1+sT_N)}e^{-s\tau}$: T_I is negligible small, the operator is very fast in his actions;
- $Y_3(s) = \frac{x_{out}(s)}{x_{in}(s)} \cong K\frac{1}{(1+sT_N)}e^{-s\tau}$: both T_I and T_L are negligible small, i.e. due to lack of proper experiences and expertise the UAV operator has no prediction skills and ability;
- $Y_4(s) = \frac{x_{out}(s)}{x_{in}(s)} \cong K\frac{1+sT_L}{(1+sT_I)}e^{-s\tau}$: T_N is negligible small; i.e. the UAV operator is in perfect physical and mental status having proper prediction skills and ability;
- $Y_5(s) = \frac{x_{out}(s)}{x_{in}(s)} \cong K\frac{1}{(1+sT_I)}e^{-s\tau}$: T_N is negligible small, but the operator has no prediction ability (beginner, non-professional pilot)
- $Y_6(s) = \frac{x_{out}(s)}{x_{in}(s)} \cong K(1+sT_L)e^{-s\tau}$: $T_I$andT_N are negligible small, the UAV operator has fast reaction to the input subjected, and has good prediction ability and skills (professional pilot).The UAV pilot behaviour described by the

transfer function $Y_6(s)$ might mean his 'aggressive' feature, or as the best, might mean over actuated PiL dynamical system.

The step responses of the different UAV operator models for the test input of $x_{in}(t) = 1(t)$ are depicted in Figure 1.

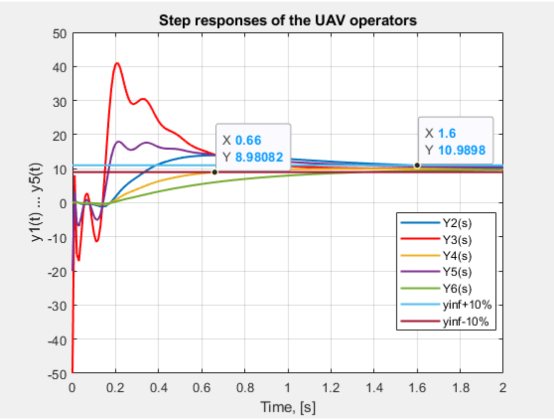

Figure 1: Transient behaviour of the operators.

From Figure 1 it is easily can be determined that the fastest response is provided by the UAV operator modelled by $Y_4(s)$ transfer function.

The slowest response is provided by the UAV operator modelled by $Y_2(s)$.

The largest peak in response function is provided by the UAV operator modelled by the transfer function of $Y_3(s)$.

Regarding UAV operators' data given by equation (3) and leaning on different forms of the transfer functions given above, three typical pilot behaviour data were segmented and tabulated in Table 1.

The UAV operators' models were tested in time domain. Results of the computer simulation are depicted in Figure 2.

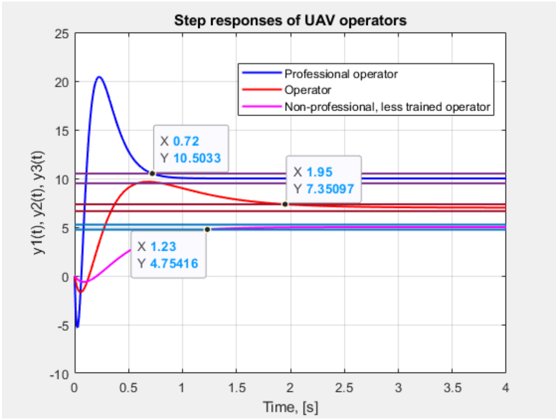

Figure 2: Transient behaviour of the operators.

Table 1 Human operators' data

UAV operator	K	T_L, [s]	T_I, [s]	T_N, [s]	τ, [s]
Professional operator (experienced, well-trained and well skilled)	10	0,5	0,1	0,1	0,1
Operator (with appropriate level of skills and knowledge)	7	1	0,5	0,2	0,2
Non-professional operator (non-experienced, less trained, less skilled)	5	1	1	0,3	0,3

From Figure 2 it is evident that the non-professional UAV operator reacts very carefully, i.e. he under actuates the UAV manoeuvres.

3. UAV Human Operators in the Closed Loop Flight Control Systems

It is well-known that control systems can be classified by its test input signals. If the reference input $x_{in}(t)$ is of a constant physical value, the closed control system regulates it. If the reference input is a deterministic function of time (i.e. flare during UAV landing manoeuvres), the closed loop control system tracks it.

Thus, in the error signal-driven closed loop control systems the role of the UAV operator is to nullify or to minimize the error signal with his active control over the error signal being eliminated.

It is evident that in tracking missions (i.e. in weapon delivery, precise navigation tasks, landing etc.) the error signal might vary very intensively. Thus, reference signal tracking activity might put hard load on the UAV operators.

For further discussions, let us evaluate the closed loop control system in PiL missions

of the small fixed-wing aircraft ‘Trainer-60’.
Let us consider the lateral rotational motion of the UAV given with its state space representation:

$$\dot{\boldsymbol{x}} = \boldsymbol{Ax} + \boldsymbol{Bu} = \begin{bmatrix} \dot{v} \\ \dot{p} \\ \dot{r} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} -0,7724 & 0 & -18,9671 & 9,0867 \\ 1,9247 & -19,9149 & 7,7565 & 0 \\ 69,1314 & -23,8689 & -2,5966 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} v \\ p \\ r \\ \phi \end{bmatrix} + \begin{bmatrix} 0 & 2,2582 \\ -23,8289 & 1,5015 \\ -11,7532 & -15,2855 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_a \\ \delta_r \end{bmatrix}, \quad (7)$$

where: v is the lateral translational speed; p is the roll rate; r is the yaw rate; ϕ is the roll angle; δ_a is the angular deflection of the ailerons; δ_r is the angular deflection of the rudder.
Supposing that the UAV operator is able to eliminate the phugoid long period motion of the UAV; hence, the model defined by equation (7) might be reduced to the SISO short period model of the form given below:

$$\dot{\boldsymbol{x}} = \boldsymbol{Ax} + \boldsymbol{Bu} = \begin{bmatrix} \dot{p} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} -19,9149 & 0 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} p \\ \phi \end{bmatrix} + \begin{bmatrix} -23,8289 \\ 0 \end{bmatrix} \delta_a. \quad (8)$$

Using matrices $\boldsymbol{A}, \boldsymbol{B}$ of (8), the controllability matrix can be calculated to be:

$$\boldsymbol{Co} = [\boldsymbol{B} \quad \boldsymbol{AB} \quad \boldsymbol{A}^2\boldsymbol{B} \quad \dots \quad \boldsymbol{A}^{n-1}\boldsymbol{B}] = \begin{bmatrix} -23.8289 & 474.5502 \\ 0 & -23.8289 \end{bmatrix}, \quad (9)$$

which rank is 2; thus, the UAV is controllable by the Kalman criteria. Using matrices $\boldsymbol{A}, \boldsymbol{C}$ of (8), the observability matrix can be calculated to be:

$$\boldsymbol{Ob} = [\boldsymbol{C} \quad \boldsymbol{CA} \quad \boldsymbol{CA}^2 \quad \dots \quad \boldsymbol{CA}^{n-1}]^T = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ -19.9149 & 0 \\ 1 & 0 \end{bmatrix}, \quad (10)$$

which has rank of 2; thus, the UAV model is observable.
The roll angle semi-automatic control has block diagram as it given below in Figure 3.

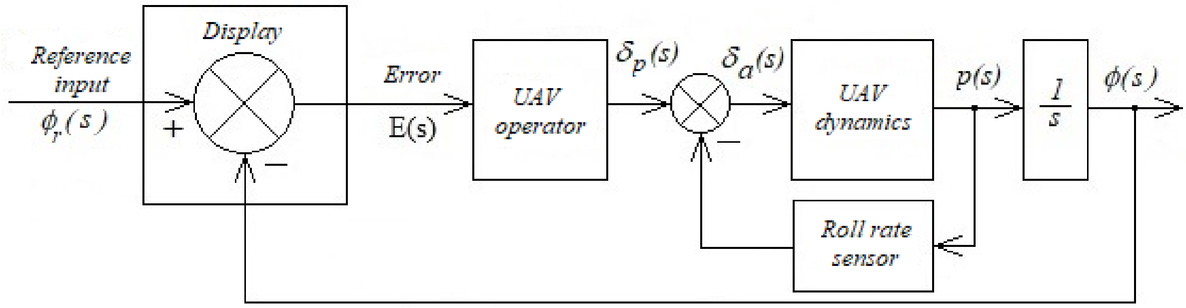

Figure 3: Semi-automatic roll angle control system of the UAV.

From Figure 3 it is evident that the UAV spatial motion is controlled by the operator, and the negative feedback by the roll rate is implemented. The UAV short period lateral rotational motion equation (8) can be represented in the following form:

$$\dot{p} + 19,9149p = -23,8289\delta_a, \quad (11)$$

or can be rewritten using its Laplace transform for zero initial conditions as:

$$sp(s) + 19,9149p(s) = -23,8289\delta_a(s). \quad (12)$$

Using equation (12) following transfer function can be obtained:

$$Y_{UAV}(s) = \frac{p(s)}{-\delta_a(s)} = \frac{23,8289}{s+19,9149}. \quad (13)$$

The roll rate sensor has transfer function as given below:

$$Y_S(s) = 0,5. \quad (14)$$

The display is to be considered to be an all pass and fast device with unit gain.

4. Time Domain Analysis of the PiL System of the Small UAV

The UAV closed loop impulse response functions are depicted in Figure 4.

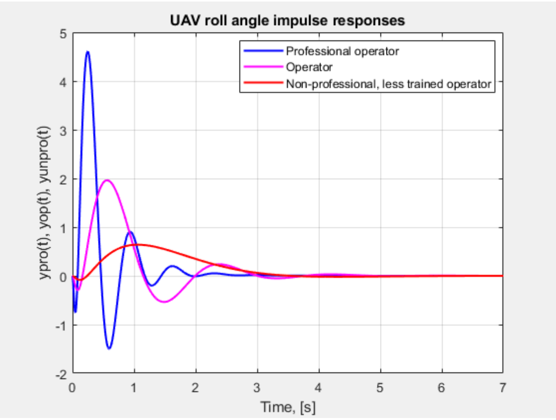

Figure 4: Transient behaviour of the PiL UAV system.

From Figure 4 it can be seen that all the 3 different UAV operators ensure stability of the closed loop control system. Nevertheless, there are different actions were made by the operators. The professional operator being too much self-confident creates oscillations of the closed loop control system over actuating it. The beginner, the less skilled and less trained operator gives his inputs very carefully keeping stability of the UAV at the first plane. The common operator gives medium inputs leading to moderate oscillations related to the professional pilot.

The closed loop of the UAV PiL system step response function can be seen in Figure 5.

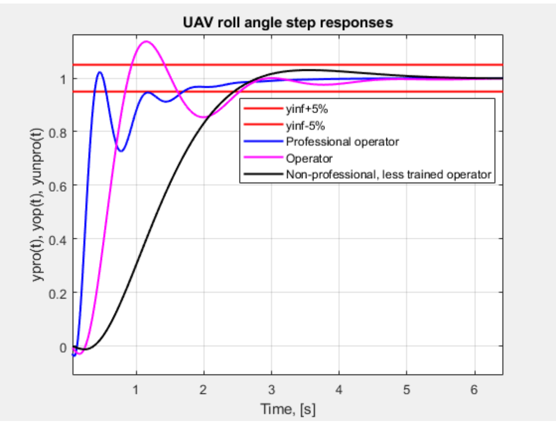

Figure 5: Transient behaviour of the PiL UAV system.

From Figure 5 it is clear that all the UAV operators are able to manage to follow the square input signal in the roll angle ϕ_r.

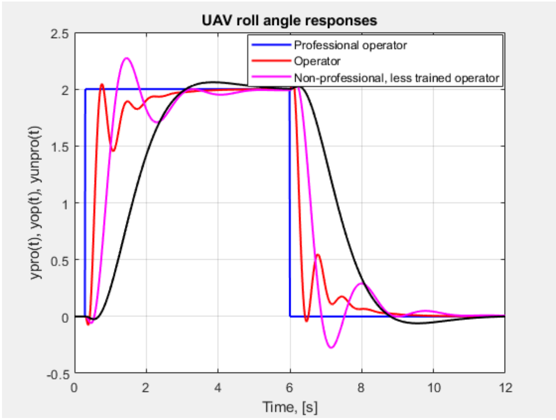

Figure 6: Transient behaviour of the PiL UAV system.

However, it should be stated that they behaves different way and accomplish their reference signal tracking task with different dynamic performances. The professional pilot behaviour is the more oscillatory, but he is the fastest to conduct his mission. The less skilled operator gives his δ_p inputs very carefully and moderately. The common operator is faster than the beginner pilot but his control activity also leads to large overshoots in the oscillation processes.

In UAV flight path control several reference input signals are used being smooth. Let us consider the following reference input of the roll angle subjected to the closed loop system input:

$$\gamma_r(t) = 1 - e^{-0{,}7t}. \tag{15}$$

Results of the computer simulation can be seen in Figure 7.

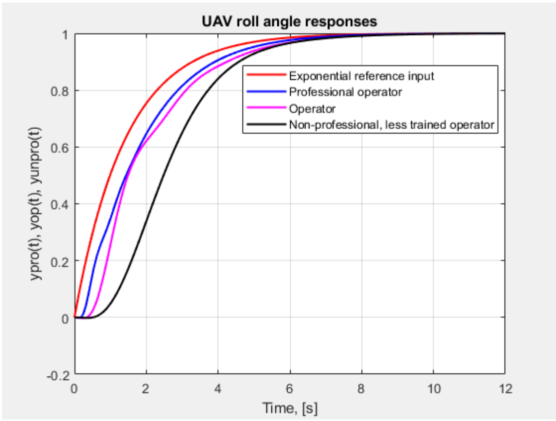

Figure 7: Transient behaviour of the PiL UAV system.

From Figure 7 it can be easily seen that there is no meaningful difference between behaviour of the UAV operators.
In other words, if the reference input in roll angle changes smooth the largest difference between the closed loop PiL system is the dead times of the UAV operators.
Let the next reference input of the roll angle subjected to the closed loop system input be the logistical sigmoid function of the form:

$$\gamma_r(t) = \frac{1}{1+e^{2(2{,}8-t)}} \tag{16}$$

Results of the computer simulation can be seen in Figure 8.

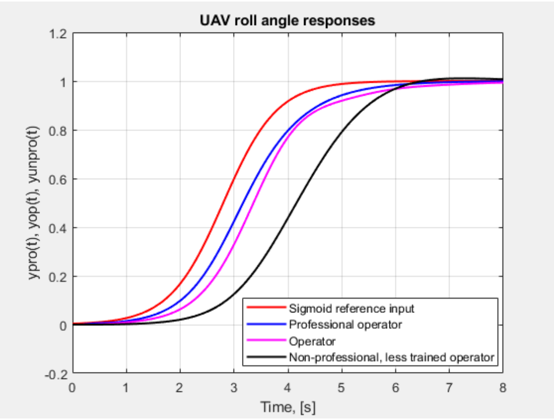

Figure 8: Transient behaviour of the PiL UAV system.

From Figure 8 it is evident that all the UAV operators are able to manage the reference input signal tracking activity, however, as they degrade by skills as the transient time increases.
Let us consider the following reference input of the roll angle subjected to the closed loop system input defined below:

$$\gamma_r(t) = 2 - 2 \cdot \cos(2 \cdot \pi \cdot 0{,}2 \cdot t). \tag{17}$$

This signal is a smooth with slow appearance and with the same slow disappearance. Results of the computer simulation can be seen in Figure 9.
It is worth to mention that in the monotone increase phase of the test input signal all the UAV operators are able to track the reference input signal $\gamma_r(t)$.
However, at the decay phase of the reference test input signal there are large differences between behaviour of the UAV operators.

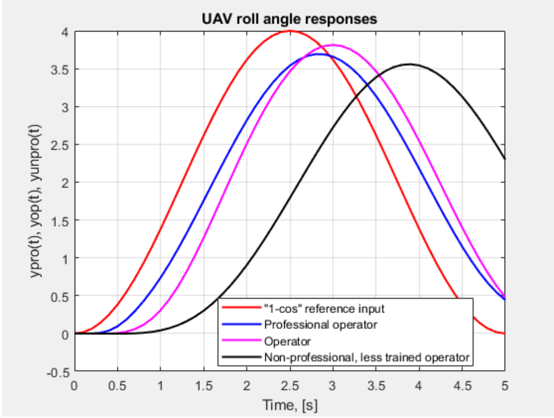

Figure 9: Transient behaviour of the PiL UAV system.

The worst case might happen when the less skilled and less trained operator tries to track and fails in the reference input signal setting.
It can be stated that the '1-cos' type signal subjected to the input of the UAV closed loop control system cannot be tracked by beginner operators.

5. Frequency Domain Analysis of the PiL System of the Small UAV

The open loop control system of the UAV was tested for harmonic input signals. The Bode diagram of the frequency response function is depicted in Figure 10.

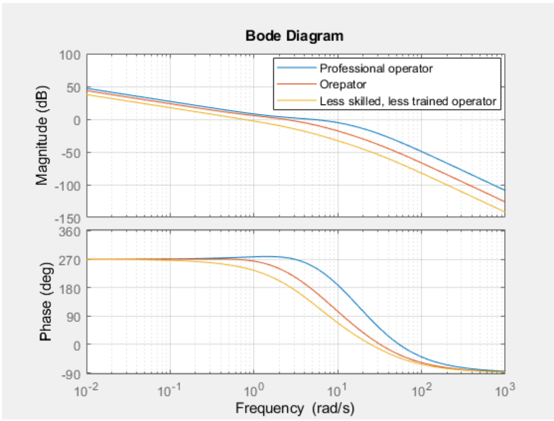

Figure 10: Bode diagram of the open loop UAV PiL system.

From Figure 10 it can be deduced that in low frequency domain all the operators behaves similar way: open lop system gains are decreased as the level of the professionalism of the operators lowers, whilst phase shifts are practically

unchanged.
In middle frequency ranges phase shifts vary very intensively and are reduced significantly. Dynamic performances were found and are tabulated in Table 2.

Table 2 Dynamic performances of the UAV open loop PiL system

UAV operator	$Gain\ margin\ ,[dB]$	$Phase\ margin,[deg]$
Professional operator (experienced, well-trained and well skilled)	6	72,9
Operator (with appropriate level of skills and knowledge)	7,16	54,7
Non-professional operator (non-experienced, less trained, less skilled)	13,7	63,8

From Table 2 it is easy to see that the open loop phase margin is reduced as the level of training reduces. It is important to emphasize that the gain margin increases as level of training reduces.
This sounds about perceptions of the operators about their own skillness. The professional operator creates the smallest gain margin in the open loop system ensuring high level of sensitivity to control inputs leading the closed loop time domain behaviour to several oscillations.
The less-skilled and less-trained operator creates the largest gain margin streaming to stability of the closed loop control system.

6. Conclusions and Outlook

The semi-automated closed loop control systems with operator inside still gain extreme importance.
The PiL problem, or the human operator in the (Ho-i-L) loop problem is an important matter also for the small UAV operators.
UAV operators might be highly skilled and highly trained mostly in governmental UAV applications; and also might be less skilled, less trained amateur beginners, too.
Easy to agree with that between these classes there are large differences expressed in different meanings.
To fly the UAV in hobby purpose flights require sufficiently lower level of training than professional UAV operators accomplishing important flight missions require.
Any case, operators must be familiar with their physical and mental skills and readiness to fly a UAV.
Moreover, UAV operators shall understand importance of their training, of their flying experiences helping them to develop prediction ability and skills improving effectiveness of flight missions conducted by them.

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