UDC 629.7.014 – 519: 656.7.052 (045)
DOI: 10.18372/2306-1472.71.11742

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FACTORS BEHIND EFFICIENCY OF INTERACTION BETWEEN REMOTE PILOT AND UNMANNED AERIAL VEHICLE

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Abstract

Objective. *Based on probable reasons of aviation accidents in civil unmanned aviation and relative risks, various factors that influence safe and effective interaction of remote pilot and unmanned aerial vehicle are considered.* ***Methods.*** *To solve the problem some assumptions, which lie in the fact that one "human-machine" system was considered, were made. This system consists of one human and one machine. Unmanned aviation complex that consists of unmanned aerial vehicle, ground control station and data links was taken as the machine. Problem is observed on the stage of operation life cycle of aviation engineering.* ***Results.*** *The following significant reasons (factors) are considered, defined and formalized: control mode of unmanned aerial vehicle, technical level of unmanned aviation system components, organization of operator's workplace of remote pilot, ambient environment (meteorological conditions) and quality of decision making of human – remote pilot. Based on summarized desirability function of E. Harington three experiments were performed and results were obtained.* ***Discussion.*** *The question of safe and effective unmanned aerial vehicle operation of commercial application is considered to be very problematic and therefore urgent.*

Keywords: desirability function; human-machine system; remote pilot; unmanned aerial vehicle.

1. Introduction

Nowadays the question of safe and effective unmanned aerial vehicle (UAV) operation of commercial application is considered to be very problematic and therefore urgent. Despite the advantages of UAV over manned aviation in the segment of «aviation works execution», in particular regarding significant cost reduction of flight hour and other benefits, inhibition process of aircraft fleet «rearmament» from manned to UAV is obvious, taking into account the amount of engineering projects across countries and real market of their application [1,2]. It is known that "inhibition" tendencies are related to various aspects of life cycle of unmanned aviation engineering (AE), and these tendencies appear clearer in initial phase of AE when the product only starts to transform from the engineering project, in the broad sense, into a product.

For unmanned AE, with the need to provide, first, aviation works (AW) execution, cargo transportation afterwards and shortly aviation works carrying out in joint airspace, the condition of maintaining the appropriate level of flight safety not lower than the level achieved in manned aviation is absolute. In fact, this is the main component of the problem stated in which we can highlight individual important components.

2. Applicability

Applicability of the article lies in identifying and ranging of factors.

Factors, which play the key role in "human-machine" system in the context of "communication" of remote pilot (RP) with UAV board via respective technical means for safe and effective performance of UAV flight mission [3].

3. Problem statement

First of all, problem solution is mapped through those reasons which contribute aviation accidents (AA). In manned aviation, these are known already and partially analyzed and presented in Table 1 [4].

A priori we can assert that indices from Table 1 cover almost full life cycle of AE, so in problem stated we must select only those indices which reflect AE operation stage and directly affect effective "communication" of RP with UAV board.

Data analysis of Table 1 suggests that this research does not need to take into account the reason 3, design drawbacks of unmanned aviation system (UAS) in general, because AE should enter the departments already certified, and so the UAV is appropriate for flight operation. Accordingly, the problem should be considered in the context of reasons 1, 2, 4 and 5.

4. Solution

To solve the problem some assumptions were made. They are formulated as follows:

1. One human-machine system (HMS) is considered. The system that consists of one human and one machine. The machine here is the complex comprised of UAV, ground control station (GCS) and data links.
2. The problem is considered at the AE operation stage of life cycle.
3. Assume, that "Ardupilot" software is used as the primary software, which is composed of ground and board parts: software of ground part is "Mission Planner", and onboard software is "Ardu Plane" respectively [5].

Table 1

Probable reasons (factors) of aviation accident in civil unmanned aviation

№	Probable factors (reasons/ preconditions) for AA of unmanned aircraft as a part of UAS	Distribution and problems inside the factor
1	UAV remote crew (human factor)	Problems with board transfer from one operator to another may occur; problems with "communication" operator and board, etc.
2	Air traffic control organization	The problem lie in the connection between board and GCS, between GCS and dispatch, and also between UAV and other boards
3	Disadvantages of UAS design altogether	UAV board
		GCS
		Data link disadvantages
4	Meteorological supply	Disadvantages in meteorological supply are practically the same as in piloted aviation
5	UAS maintenance	UAV board
		GCS
		Data link

5. Identification of significant factors, which influence the efficiency of human-machine system (HMS) interaction

Based upon Table 1 data and on experience of practical application of UAV, "UAV control mode" is assumed as first factor (*Factor A*). Its importance consists in the fact that operator's psychophysical load dramatically changes, for example, at transition from «AUTO» mode to any «MANUAL» mode when the discomfort level for operator increases strongly. That eventually leads to human factor role increase and decrease in the level of piloting fficiency: mistakes are made during all stages of flight, from take-off to safe landing. Procedures repeatability/reproducibility is low, which is not suitable for commercial use. Certainly we can artificially decrease the level of mistakes by quality of vocational selection of candidates. However, HMS dependence on human will be significant [6].

Assessment was carried out using points scale – conditional workload on RP in percent depending on the mode applied.

Main modes of UAV control, their subclasses, technical means of realization and assessments scale are given in Table 2.

Table 2

UAV main control modes, their subclasses and intervals of effective values of RP workload

Main control modes (MCM)	MCM subclass	Technical means (TM) of MCM implementation	Index, *RP workload eval. – points* (y_i)
Manual control	MAN. 1-in vision	Portable transmitter	100
	MAN. 2 first person view (FPV)– piloting out-of-vision	Portable transmitter + video image on monitor and telemetry	
Semi-automatic mode (flight stabilization mode)	STAB. 1– in vision	Portable transmitter + stabilizers of board steadiness are enabled	90
	STAB.2 FPV– piloting out-of-vision	Portable transmitter + video image on monitor and telemetry + stabilizers of board steadiness are enabled	85
Automatic control mode	According to instruction of technical operation (ITO) for board software and GCS	Without transmitter. Control via GCS telemetry through transmitting some packet data over telemetry	20
Autonomous mode	One human-machine interaction: uploading flight mission on board and pushing “start” button	Inboard technical means providing flight mission execution	10

\Excluding the factor «UAV control mode», the following factors were taken as decisive.

Factor B. Technical level of UAV components and data links (per 50 UAV launches).

It is known that technical level (TL) index is used to assess the product’s compliance with state-of-the-art on the market. Assume, that technical level of UAV types ranges from the aircraft which at sale (in the form of kits for self assembly) to certified UAVs with the quality and technical level beyond any doubt. We assessed the technical level on probability of failure occurrence depending on TL (Table 3).

Table 3

Technical level of UAS components and probability of failure occurrence (within 50 flights)

№	Short description of UAS components	Probability of failure occurrence (y_i)
1	UAVs that assembled on their own without involving kits; Analog data link, unsecure	0,2
2	Ready UAV, taking into account modern models of multirotors commercially available without the aircraft type certificate; Digital data link	0,1
3	Outdated UAV with type certificate, but, for example, with analog link, simple autopilot which operates rudder only or outdated autopilot types without “flight controller” status, etc;	0,12
4	Outdated UAV with type certificate, redesigned with modern software and avionics;	0,08
5	Modern UAV types, hardware, ground and board software which includes secure digital data link, full control of board systems, most UAV control modes (according to Table 2), auto tuning of control of proportional-integral differential (PID) laws, automatic antenna rotation at the aircraft, etc.	≤0,02

Factor C. Organization of operators workplace (OW) RP.

Organization of RP operators workplace play a major role in quality of board control and monitoring, quality of flight plan preparation, preflight checks execution, etc. Organization of OW assessed by quality units of operators position and divided into following sublevels (Table 4).

Table 4

Organization of UAV operators position and intervals of partial index effective values

№	Short description of operators position	Index, *OP quality evaluation – points* (y_i)
1	Simple open OW in form of laptop with additional portable transmitter; UAV remote pilot is standing	30
2	Operators position where personal computer (PC) is in closed case (or PC of industrial/military design), possible change of UAV remote pilot standing position to sitting with additional portable transmitter	50
3	Operators position where personal computer (PC) is in closed case (or PC of industrial/military design), possible change of UAV remote pilot standing position to sitting, controls concentrated in single, particular place	75
4	Closed OW located in mobile station, equipped with PC of industrial/military design, comfortable conditions of operation of UAV remote pilot	90
5	Closed OW located in mobile station and is guarded, equipped with several displays, comfortable conditions of operation of UAV remote pilot, several stationary powerful computers, check procedures are automated, etc	100

Factor D is Environment (meteorological conditions (MC). It is known, that in meteorological conditions evaluation taken into account wind, temperature changes, precipitation presence, wind shear and low altitude turbulence, etc. Notwithstanding the individual indices of MC, to perform their evaluation we used percentage of MC of flight restrictions (FR) of UAV, specified in UAV flight crew operation manual (FCOM). Thus, the following ranging levels were adopted (Table 5).

Factor E. Quality of the human decision-maker, the RP.

Table 5

UAV limitations after MC and intervals of partial index effective values

№	Percent of maximal flight restrictions after MC for UAV	Index, *percent of max. FR* (y_i)
1	110% and more from board flight restrictions or prohibition to start	110
2	100% and less from board flight restrictions; start is allowed	100
3	70% from board flight restrictions; start is allowed	70
4	40% from board flight restrictions; start is allowed	40
5	20% from board flight restrictions; start is allowed	20

Level of professional knowledge, skills and experience of professional operation, level of psychophysical qualities, especially stress resistance, actions of RP in emergency situations due to radio electronic warfare (REW), malfunction of data link, board malfunction affect the quality of decision making of RP.

In our opinion, index that demonstrates quality of decision making is quantity of RP mistakes RP due to large responsibility and workload in connection with planning and flight mission execution of UAV and UAS in general. Scale of mistakes of RP was developed and it shows that points decrease with increasing number of mistakes. The scale is shown at Table 6.

Table 6

RP mistakes scale and intervals of partial index effective values

№	Limits of mistakes quantity, *Km*	Character, quantity and mistakes result of RP	Assigned points,(y_i)
1	Km > 6 sig. m.	Planning of flight plan with more than 6 significant mistakes, that completely disables flight plan execution	0
2	4 sig. m ≤ Km ≤ 6 sig. m	Planning of flight plan with 4-6 significant mistakes that are corrected with external help; flight plan execution is often delayed	40
3	2 sig. m ≤ Km ≤ 3 sig. m	Planning of flight plan with 2-3 significant mistakes that are corrected independently; flight plan execution is slightly delayed	60
4	2 insig. m. ≤ Km ≤ 3 insig. m.	Planning of flight plan with 2-3 insignificant mistakes; timely execution of flight plan	80
5	0 insig. m. ≤ Km ≤ 2 insig. m.	Planning and execution of flight plan with 1-2 insignificant mistakes	100

For further problem solution we considered the generalized E. Harington desirability function. The basis of this function construction is conversion of natural values of formalized significant factors into relative [7]. The significant factors summarized to natural expressions are given in Table 7.

Table 7

Formalized significant factors for Harington function

Factor designation	Name of significant factor
A	UAV control modes
B	Technical level of UAS components
C	Organization of operator's workplace of RP
D	Environment (meteorological conditions)
E	Quality of decision made by human – RP

Feasibility of desirability function application is justified by the fact that each significant factor of "human-machine" system has its own content and dimension. So comparison of defined efficiency requirements with calculated indices must be made against a dimensionless scale.

Desirability scale is designed to establish consistency between non-physical (abstract) and numerical (specific) parameters [8]. As physical parameters, we suggest to understand the possible responses which characterize object operating, in our case that is in flight effective control of UAV with minimum risks. To obtain the desirability scale we used standard marks, summarized to consistencies between priorities in empirical and numerical measurements (Table 8) [9].

Table 8

Standard marks on desirability scale and respective code values of factors

Desirability	Partial desirability function, d_i	Partial response, y'	Significant factors and their code values (y_i)				
			A	B	C	D	E
Very good	1,00	3,00	10	≤0,02	100	20	100
Good	0,80	1,50	20	0,08	90	40	80
Satisfactory	0,63	0,85	85	0,12	75	70	60
Bad	0,37	0,00	90	0,1	50	100	40
Very bad	0,20	-0,50	100	0,2	30	110	0

Desirability scale has interval from 0 to 1. Value ***di*** = 0 corresponds to unacceptable level of parameter that characterizes the extreme inefficiency of UAV control up to task failure (maximum level of AA preconditions up to AA occurrence), and value ***di***=1 – the best parameter value, i.e. excellent flight plan performance and the practical absence of AA preconditions.

Choosing assessment on desirability scale 0,63 and 0,37 is explained by calculation convenience: 0,63=1-1/e, and 0,37=1/e. Value 0,37 usually corresponds to limits of permissible values. Desirability function is used to transform all dimensioned indices ***di*** into individual dimensionless indices y that characterizes efficiency level. Dimensioned indices are formed on the basis of Harington function using the formula [10]:

$$d_i = d\,(z_i) = \exp\,(-\exp(z_i)) \qquad (1)$$

Actually classical Harington desirability function (for unilateral limitation) has the following form:

a) maximum allowable value for such limitation is $d = e^{-e^{-z_i'}}$, if indices quality increases in case of sign growth to level of 100% (growth of index characterizes efficiency increase in the context of achieving the strategic objectives), and $d = e^{-e^{z_i'}}$, if indices quality increases in case of sing decrease, but to level of 100% (decrease of index characterizes efficiency increase in the context of achieving the strategic objectives);

Value **z'** was determined using the following formulas:

– for indices, which are unilateral increasing dependences, when their quality increases in case of sign increase but to level of 100%:

$$z_i = \frac{y_{i0} - y_i}{y_{i1} - y_{i0}}, \qquad (2)$$

– for indices, which are unilateral increasing dependences, when their quality increase in case of sign decrease but to level of 100%:

$$z_i = \frac{y_i - y_{i0}}{y_{i1} - y_{i0}}, \qquad (3)$$

where $\mathbf{y_i}$ – is value of *i*-th index; $\mathbf{y_{i0}}$ and $\mathbf{y_{i1}}$ – are the boundaries of the “satisfactory” area in output scale.

Value $\mathbf{d_{i0}}$ equals:

$$d_{i0} = d\,(z_i\,(y_{i0})) = 0{,}37;$$
$$d_{i1} = d\,(z_i\,(y_{i1})) = 0{,}69. \qquad (4)$$

At coded value of informative index z = 0 desirability function possessed the value 0,37 that corresponds to lower limit of “satisfactory” area, and at value z =1 possessed value 0,69 that corresponds to lower limit of “satisfactory” area.

In the case when the value of index is assigned with as clear restrictive limits or as the clear number, we have d = 1 inside limits, and d = 0 outside limits.

If the lower limit is assigned, then:

$$d = \begin{cases} 1, if\, z_i \geq z_{\min}; \\ 1, if\, z_i < z_{\min}. \end{cases} \qquad (5)$$

If the upper limit is assigned, then:

$$d = \begin{cases} 1, if\, z_i \leq z_{\max}; \\ 0, if\, z_i > z_{\max}. \end{cases} \qquad (6)$$

If clear number is assigned, then:

$$d = \begin{cases} 1, if\, z_i = z; \\ 0, in\ all\ other\ cases. \end{cases} \qquad (7)$$

In Fig.1 graphical interpretation of Table 8 data is shown, where: A – UAV control mode (RP workload level – points); B – technical level of UAS components (probability of failure occurrence ($\bar{x}_i$); C – organization of RP operator’s workplace (OW quality assessment – points); D – environment – meteorological conditions; percent of maximum flight restrictions (FR); E – quality of decisions made by human – RP (Km – number of mistakes).

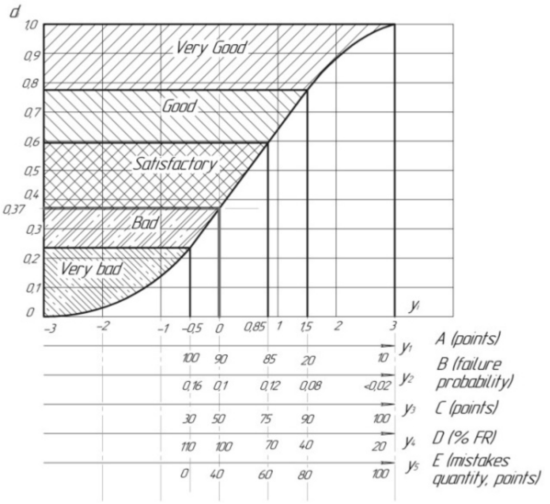

Fig. 1. Desirability function and factor value, recommended by UAV operators

To determine the general compliance level of efficiency indices we calculated respective integral index (D) by the formula:

$$D_1 = \sqrt[5]{d_1 \times d_2 \times d_3 \times d_4 \times d_5} \qquad (8)$$

where d_i – partial assessments of compliance level of efficiency indices; *n* – number of investigated indices.

Results of general compliance level of efficiency indices in three experiments are shown in Table 9.

Table 9

Natural and summarized responses by desirable function

№ of exp.	Response natural values					Partial desirability					D1	Assessment by desirability scale
	y1	y2	y3	y4	y5	d1	d2	d3	d4	d5		
1	20	0,12	50	70	40	0,77	0,59	0,37	0,59	0,77	0,578	**Satisfactory**
2	85	0,1	50	40	60	0,58	0,37	0.37	0,77	0,59	0,514	**Satisfactory**
3	90	0,2	30	100	80	0,37	0,23	0,27	0,37	0,77	0,365	**Bad**

6. Conclusions:

1. In the given research the following probable reasons that may lead to the AA of unmanned aircraft as a part of UAS were taken into account: UAV remote crew (human factor), air traffic control organization, meteorological supply and UAS maintenance. Design drawbacks of UAS in general, were not taken into account because AE should enter the department as certified, so is appropriate for flight operation.

2. As *factor A* we accepted «UAV control modes». Its importance consists in the fact that

operators psychophysical load dramatically changes, for example, at transition from «AUTO» mode to any «MANUAL» mode, in which discomfort level for operator strongly increases, that eventually leads to human factor role increase and decrease the level of piloting efficiency: mistakes are made during all stages of flight, from take-off to safe landing. Procedures repeatability/reproducibility is low, which is not suitable for commercial use. Assessment was performed using points scale – conditional workload on RP in percent depending on the mode applied.

3. *Factor B* refers to the technical level. It was applied to assess product's compliance with state-of-the-art on the market. It was determined that the technical level of UAV types ranges from the aircraft which at sale (in the form of kits for self assembly) to certified UAVs with the quality and technical level beyond any doubt. The technical level was assessed against the probability of failure depending on TL.

4. Operator's workplace of RP was chosen as *factor C* and it plays a significant role in quality of board control/monitoring, quality of flight mission preparation, execution of preflight checks, etc. Organization of OW was assessed by points of OW quality.

5. Environment was chosen as *factor D*, i.e. the meteorological conditions. Not taking into account separate indices of MC. For their assessment, we used percent of MC of flight restrictions of UAV board denoted in its FCOM.

6. *Factor E* is quality of decisions made by RP. Quality is influenced by level of professional knowledge, skills and experience of professional operation, level of psychophysical qualities, especially stress resistance, actions of RP in emergency situations due to REW, malfunction of data link, board malfunction, etc. To assess the quality, quantity of mistakes made by EP due to high responsibility and workload in connection with planning and flight mission execution of UAV and UAS in general were applied. The scale of RP mistakes was developed.

7. The problem was solved with the help of summarized desirability function of E. Harington. Feasibility of desirability function application is justified by the fact that each significant factor of "human-machine" system has its own content and dimension. Therefore, comparison of specified requirements of efficiency with calculated indices must be performed against a dimensionless scale.

8. Desirability scale has interval from 0 to 1. Value di=0 corresponds to unacceptable level of parameter, that characterizes extreme inefficiency of UAV control up to mission failure. Value di=1 corresponds to best parameter value, that is excellent flight mission execution and practical absence of AA preconditions.

9. Assessments selection on the desirability scale 0,63 and 0,37 is explained by convenience of calculation: 0,63=1-1/e and 0,37=1/e. Value 0,37 corresponds to limits of permissible values.

10. In the course o investigation, experiments were carried out on the basis of the developed desirability scale. Integral index *D* which is applied to determine general compliance level of efficiency indexes showed that factor ranges and their boundaries were chosen adequately. Especially, in three experiments performed the level of index *D* ranges within limit from 0,365 to 0,578, which corresponds to «bad» and «satisfactory» levels of assessment.

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Received 22 February 2017

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Фактори впливу на ефективність взаємодії оператора/зовнішнього пілота та безпілотного повітряного судна

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Мета: На основі ймовірних причини авіаційних подій у цивільний безпілотній авіації та відповідних ризиків, розглянуті різноманітні фактори, що впливають безпечну та ефективну взаємодію зовнішнього пілота та безпілотного повітряного судна. **Методи:** Задля вирішення проблеми були прийняті певні допущення, які полягають у тому, що розглядається одинична система «людина-машина» – система у складі однієї людини та однієї машини. Застосована крива Е. Харінгтона для перетворення натуральних значень формалізованих значимих факторів у відносні. В якості машини взятий безпілотний авіаційний комплекс у складі безпілотного повітряного судна, наземної станції керування та ліній зв’язку. Крім того проблема розглядається з позицій такого етапу життєвого циклу авіаційної техніки, як етап її експлуатації. **Результати:** Визначеними та формалізованими вважаються наступні впливові чинники – фактори: режим керування безпілотним повітряним судном, технічний рівень складових частини безпілотної авіаційної системи, організація робочого місця зовнішнього пілота, зовнішнє середовище (метеоумови) та якість прийнятих рішень людини – оператора/ зовнішнього пілота. **Обговорення:** Питання безпечного та ефективно використання безпілотних повітряних суден для комерційного використання являється дуже проблематичним а тому актуальним для вирішення питанням.

Ключові слова: безпілотне повітряне судно; зовнішній пілот; система людина-машина; функція бажаності.

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Факторы влияния на эффективность взаимодействия оператора / внешнего пилота и беспилотного воздушного судна

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Цель: На основе вероятных причины авиационных происшествий в гражданский беспилотной авиации и соответствующих рисков, рассмотрены различные факторы, влияющие на безопасное и эффективное взаимодействие внешнего пилота и беспилотного воздушного судна. **Методы:** Для решения проблемы были приняты определенные допущения, которые заключаются в том, что рассматривается единичная система «человек-машина» – система в составе одного человека и одной машины. Применена кривая Е. Харрингтона для преобразования натуральных значений формализованных значимых факторов в относительные. В качестве машины взят беспилотный авиационный комплекс в составе беспилотного воздушного судна, наземной станции управления и линий связи. Кроме того, проблема рассматривается с позиций такого этапа жизненного цикла авиационной техники, как этап ее эксплуатации. **Результаты:** Определенными и формализованными считаются следующие влиятельные факторы – факторы: режим управления беспилотным воздушным судном, технический уровень составляющих части беспилотной авиационной системы, организация рабочего места внешнего пилота, внешнюю среду (метеоусловия) и качество принимаемых решений человека – оператора / внешнего пилота. **Обсуждение:** Вопрос безопасного и эффективно использование беспилотных воздушных судов для коммерческого использования является очень проблематичным поэтому актуальным для решения вопросом.

Ключевые слова: беспилотное воздушное судно; внешний пилот; система человек-машина; функция желательности.

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