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FLIGHT DATA ANALYSIS OF UNMANNED AERIAL VEHICLE ACCORDING TO TYPE OF CONTROL SYSTEM

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Abstract. The problem of unmanned aerial vehicle control systems is a complicated issue which requires consideration of the tasks and applications of unmanned aerial vehicles. The typology of control systems combination for civil unmanned aerial vehicle is suggested and justified. The methodology of the research was based on application of the varieties of the experts method for rationale of the variants of control system combinations for a specific type of unmanned aerial vehicle and the morphological analysis was used to generate the variants of control system combinations. The causes that lead to discrepancies in types of control systems for civil unmanned aerial vehicle are revealed. Compliance between remote radio control application and type of feedback signal are considered. Based on morphological analysis method, 25 variants of combined unmanned aerial vehicle control systems are suggested. Regulatory, substantive and technical components of basic unmanned aerial vehicle control systems are suggested. The practical experience of UAV design by Scientific Production Center of Unmanned Aviation “Virazh” is used to demonstrate the applicability of findings. Based on the flights performed by unmanned aerial vehicle under different control modes, comparative analysis of the selected types of control systems is conducted.

Keywords: civil unmanned aerial vehicle, automatic control system, remote radio control, morphological analysis, comparative analysis, modes of operation.

Introduction

Modern technical means of radio control, radio programming, automation, satellite air navigation support of flight revealed a whole layer of various Control Systems (CS) that allow the Unmanned Aerial Vehicle (UAV) perform very complicated tasks in the air.

In general, CS can be categorized into two basic groups of systems. The first group is called Remote Radio Control System (RRCS). The second large group includes Automatic Control Systems (ACS). There are formed the relationships between the group elements which eventually generate a particular type of UAV CS. For example “Ikarus” CS for small UAVs is a combination of RRCS with telemetry and video support (IKARUS OSD, 2016*)*.

Analysis of the latest research and publications

The Air Code of Ukraine identifies Civil Unmanned Aerial Vehicle (CUAV) as “the aircraft intended for the flight without a pilot on board, where the flight management and control is performed by a special control station located outside the aircraft” (The Air Code of Ukraine, 2011).

Circular № 328 ICAO expressly states that “in order to ensure the integration of the UAV application in the general airspace on common airfields, the pilot that is responsible for the flight of UAV is required. Pilot can use the appropriate equipment, such as autopilot, which helps to perform the pilot’s duties, but under no circumstances, in the foreseeable future the responsibility of the pilot will be transferred to the technology” (ICAO Circular 328, 2011).

Aim of the research

The main aim is analysis of flight data of Civil Unmanned Aerial Vehicle CS by suggested types. The specified task can be completed through the availability of UAV control system devices that can provide remote, automatic and combined UAV control. Comparative analysis of chosen CS types on different modes of flight was carried out.

It is known that modern Remote Radio Control (RRC) is industrially implemented in the form of the merged and dispersed systems. The merged RRC is the most common system which looks like a handheld transmitter (a remote control with two short handles – manipulators) produced by "Hi-Tec", "Futaba", etc. (Marks, 1980).

Research results

Analysis of modern UAV RRC revealed the significant difference in their functions. For example, in UAV "Tango" uses the "pure" radio control link "Futaba", whereas the control system of UAV "Orbiter" provides feedback in the form of telemetry link from on-board sensors (Deli 2010). Obviously, such a difference in the functions of RRC is motivated by the tasks/applications that are set for the RRC. Eventually, the only restriction for this issue is the question of flight within the optical sight or beyond it.

Flight beyond the optical sight via radio control system is possible only if there is a certain type of feedback.

Today among the technically implemented systems telemetry, terrain video image and virtual model of the area are able to provide feedback.

Given this, remote control of UAV could be typed as follows (Table 1).

Table 1. Compliance between RRC application and type of feedback signal

RRC type	Application	Type of feedback signal
D1	within the optical sight	None
D2	beyond the optical sight	telemetry
D3	beyond the optical sight	telemetry + real video image
D4	beyond the optical sight	telemetry + virtual video image
D5	beyond the optical sight	telemetry + real video image + virtual video image

The result of the analysis also revealed a great variety in the functions of automatic control (Nortrop – Grumman X47B). The simplest variant of automation is the automation of the flight at the level of such basic function as auto maintenance of speed, flight altitude and position in space between the RTP's, which are assigned "manually" ("simple" autopilot). However, today there are UAV control systems, which allow perform the flight task from the start to finish with the certain freedom of choice for the whole trajectory or its segment (Mil 1980). It is obvious that there are some intermediate types of AC in between of the first simplest and the last most difficult examples of automation.

If the first system of AC is taken as basic variant of ACS, then while adding some options to the basic variant in order to expand the range of its functions, the above mentioned types of UAV ACS can be represented in the following form of Table 2.

As shown in Tables 1 and 2, the generalized variants of remote radio control and automatic control systems of UAV can be formalized according to the identified types of CS. Each these variants can be considered as an independent type of CS. But usually when the existent UAV CS is analyzed, it can be noted that in the "pure" form, CS are used only in UAVs limited by the specific requirements. Thus, the systems of D1 type are used for sports and for scientific purposes. Systems of D2–D5 type are limited by time of continuous piloting by an external pilot. The more widely spread variants in military application are A2 and A3 types of AC, only in the class of short range UAV (5–15 km range) and small UAV (5–20 kg takeoff weight) (UAV systems 2005).

Table 2. Compliance of type and functions of different ACSs

Type of AC	Functions of ACS
A1	Automatic control of speed, altitude and position in space between RTPs defined "manually" ("simple" autopilot)
A2	Route automatic control ("simple" autopilot + flight program)
A3	Route automatic control, automatic take-off and landing ("complex" autopilot + flight program)
A4	Route automatic control ("complex" autopilot + flight program + subprograms archive of "behavior" on the route)
A5	Route automatic control with independent choice of movement "scenarios" on its segments ("complex" autopilot + flight program + subprograms archive of "behavior" on the route + elements of artificial "intelligence")

To obtain variants of CS combinations, presented in Tables 1 and 2, morphological analysis method was used (Lyamets, Tevyashev 2004).

The morphological matrix (Table 3), in this case, is a symbolic entry of remote and automatic control systems variants represented as:

Table 3. Morphological matrix of ACS variants

D1	D2	D3	D4	D5
A1	A2	A3	A4	A5

In order to generate a certain number of variants of combined CS it is necessary to multiply the amount of RC systems variants by the amount of AC systems variants, i.e.:

$$\sum n_v = n_D \times n_A. \tag{1}$$

Having arithmetically calculated by the formula (1) (5 × 5 = 25), we respectively obtain 25 variants of combined UAV CSs. Every combination should contain the element "D" and the element "A", for example, D2A3, D5A4, etc. Through detailed analysis of every variant, which is carried out using one of the experts method, for example, the method of synectics or "brainstorming", the accuracy of selecting a CS combination for a particular UAV type can be confirmed or denied. Let us consider the variant D2A3, used in "Bird Eye 400", while "Predator RQ-1" uses a D5A4 combination of systems.

It should be added that the basic variants of CS taken from Tables 1 and 2 are self-sufficient and appropriate to control UAVs in the specified part, so these variants can be used independently.

Table 3 shows the complete list of variants for the combination of systems “D” and “A”.

Based on the obtained variants for the combination of systems “D” and “A” some variants for individual UAVs and Unmanned Aviation Systems (UASs) can be defined. These variants were developed and are in operation at Scientific Production Center of Unmanned Aviation (SPCUA) “Virazh”.

Table 3. Variants for the combination of systems “D” and “A” and their designation

No var	Designation	No var	Designation
1	D 1A1	13	D3A3
2	D1 A2	14	D3A4
3	D1 A3	15	D3A5
4	D1 A4	16	D4A1
5	D1 A5	17	D4A2
6	D2 A1	18	D4A3
7	D2 A2	19	D4A4
8	D2A3	20	D4A5
9	D2A4	21	D5A1
10	D2A5	22	D5A2
11	D3A1	23	D5A3
12	D3A2	24	D5A4
		25	D5A5

UAV M-6-3 “Zhayvir” (UAV *M-6-3 “Zhayvir”* of SPCUA “Virazh”) and UAV M-10 “Oko-2” (UAV *M-6-3 “Zhayvir”* of SPCUA “Virazh”) uses D3A3 system combination, since the flights are not limited by optical sight.

Flight controller based on ArduPilot APM 2.6 is used on UAV M-6-3 “Zhayvir” and UAV M-10 “Oko-2”. It supports telemetry connection and is equipped with data recorder (Source: ArduPilot APM 2.6). Real time video images transmission from onboard cameras is utilized. ACS is used on preplanned routes, automatic take-off and landing.

In the course of UAV flight, qualitative assessment of deviation by several parameters of UAV flight was conducted. These parameters include roll and pitch attitude, altitude and Electronic Speed Controller (ESC) power output. Data were obtained from the onboard recorder UAV. Equal segments of UAV flight were reviewed and comparative analysis was conducted. Evaluation of each parameter was performed and the results were plotted on the graphs for manual and automatic control mode. RRC CS type reflects sharp commands of external pilot in manual control mode.

In Fig. 1, the results of onboard data recorder are shown for UAV roll attitude deviation under the manual and automatic modes of control.

It is known that manual mode of operation does not provide board-on stabilizers. Respectively, curve 1 represents for manual mode (Fig.1) and obviously shows the external pilot actions at a specified time interval between 15:02:30 and 15:02:54.

Absolute 50° deviation leftwards is observed at the 48 second of flight. Summarized rotation of aircraft on X axis constituted about 100°. Roll attitude limit was 35° and the external pilot exceeded the permissible value of roll attitude significantly: 50 – 35 = 15 degrees. This might have caused an aviation accident. Perhaps it did not happen only because of the high qualification of the specific pilot.

Based on analysis of roll deviation in automatic mode (all stabilizers are enabled) we can claim that absolute deviation was up to 18° on first seconds of flight, but after that roll attitude with value above 10° was not observed. We can confirm that UAV did not reach the flight limit of roll attitude set at 15°.

In Fig. 2, the results of onboard data recorder are shown for UAV pitch attitude deviation under the manual and automatic modes of control.

Negative deviation of pitch attitude (nose-down) by 3° was revealed at the 46 second of flight. Summarized rotation of aircraft on Z axis comprised 43°. Pitch attitude limit was 15°; external pilot significantly exceeded the permissible value of pitch attitude, namely 40 – 15 = 25 degrees.

Analysis of pitch attitude deviation in automatic mode (when all stabilizers are enabled) was performed. T can be highlighted that absolute deviation was equal to 5° at the 32 and 52 second of flight, but further roll attitude did not surpass 5°. We can claim that UAV did not reach flight limit of 15° of the roll attitude.

Having contrasted the absolute deviation of aircraft (Fig. 2), it can be claimed that the external pilot operating in manual mode abused pitch attitude 8 times (40°/5°) higher than the value of pitch attitude used by ACS.

In Fig. 3, the results of onboard data recorder are shown for UAV flight altitude deviation under the manual and automatic modes of control.

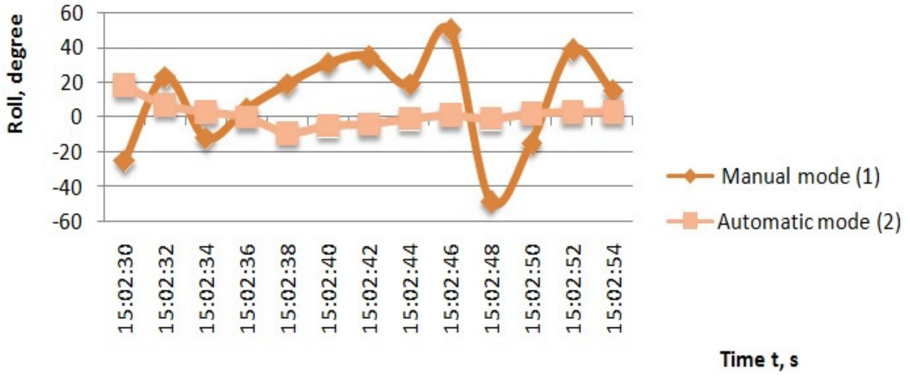

Fig. 1. Deviation of roll attitude in different modes of flight

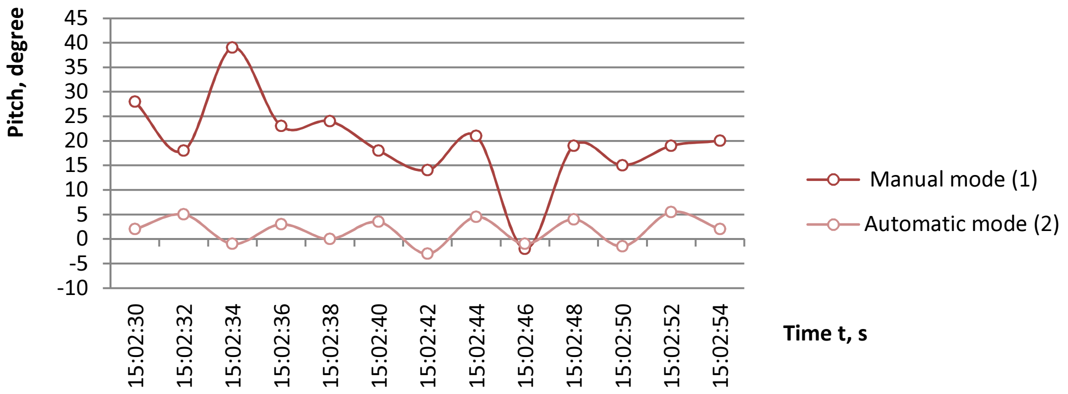

Fig. 2. Deviation of pitch attitude in different modes of flight

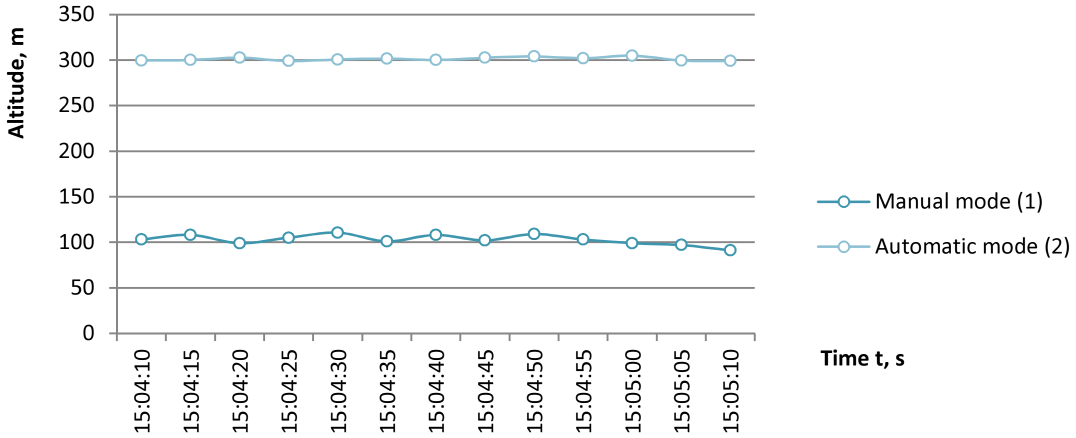

Fig. 3. UAV altitude deviation under different modes of flight

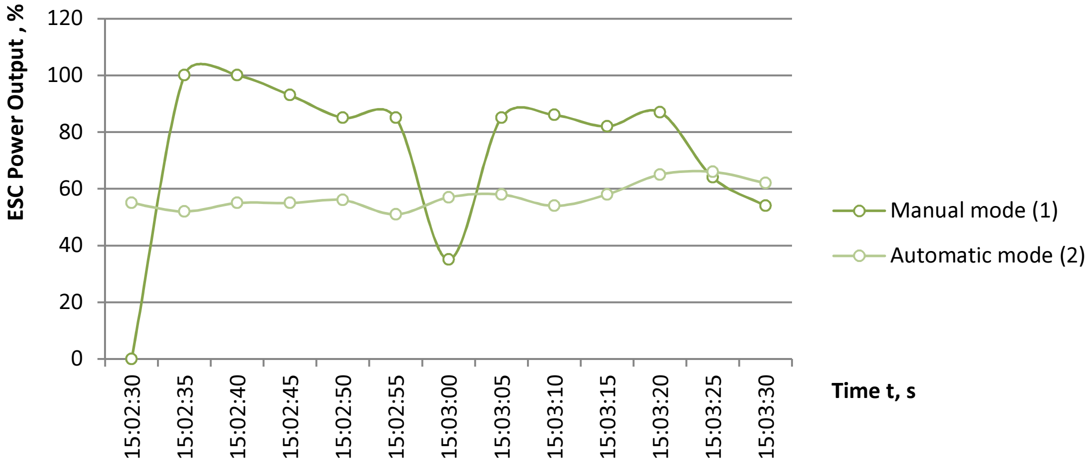

Fig. 4. Deviation of ESC Power Output under studied modes of flight

Deviation of UAV indicates that in the automatic mode deviation of aircraft altitude is by one order less than the deviation during flight piloted externally in manual mode of flight (all stabilizers disabled).

The absolute deviation (Fig. 3) in manual mode was equal to 4 m, and the corresponding value in automatic mode was 0.5 m. This revealed the advantage of automatic control to manual in the part of flight safety and efficiency of onboard battery energy consumption, due to minor load on the airplane servo.

ESC Power Output deviation which is the throttle control lever, also showed that in automatic mode throttle deviation is less significant. This indicates the advantage of automatic control to manual mode in terms of fuel efficiency or onboard battery capacity.

The autopilot deviated throttle to maximum 60%, while the external pilot exceeded this parameter more than 40%, i.e. manual mode deviation reached 105% (Fig. 4).

The graphical representation of deviation dependence on time under the studied flight modes (1) and (2) for ESC power output (throttle) was analyzed. From the obtained curves it is obvious that in automatic control mode deviation on ECS power output is lower.

Thus, the advantage of automatic control to manual mode in terms of fuel efficiency and onboard battery capacity was proven. It was obvious that the external pilot deviated ECS power output more than the automatic flight controller.

The finding were analyzed and enabled arriving at the following conclusions about UAV CS performance for the contrasted types of control systems.

Conclusions

1. The main reason that leads to ambiguity in typology of CUAV CSs is the contradiction between the need to ensure operation of CUAVs of different weight classes in common airspace and the absence of structures and composition of CSs, respective to these weight classes.

2. Due to significant overload of the external pilot of CUAV when “manually” piloting the UAV for a long period of time (5–10 hours) there is a need to automate the process.

3. ICAO regulations and the Air Code of Ukraine states that CUAV is, in the first place, a “remotely piloted aircraft”, so the automatic control is rather a desirable option, but not the main one.

4. Basic UAV CSs are entitled to two groups; the first group is remote radio control systems and the second group is the automatic control systems. Some relationships are formed between the elements of the groups that eventually produce a particular type of UAV CS.

5. To obtain specific combinations of the basic UAV CS variants the method of morphological analysis was used. In the future, for a detailed analysis of the specific variant of UAV CS the experts methods, for example, synectics or “brainstorming” can be employed.

6. Given the specified dependencies, the actions of the flight controller in comparison with the external pilot do not lead to:

- exceeding of the limits of UAV on pitch and roll attitude and altitude;
- occurrence of aviation accidents risks.

7. In addition, use of flight controller sharply reduced energy consumption of onboard battery because of small deflection angles of control surfaces and lower ESC Power Output (throttle).

8. The data obtained allow to conclude that the presence of autopilot on board and he automatic control mode “on” enable stable, smooth transitions in all segments of the studied time, regardless of the external environment, fatigue, sun and everything that can negatively influence the external pilot of UAV during piloting.

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