A NEW EMERGENCY LANDING CONCEPT FOR UNMANNED AERIAL VEHICLES

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Abstract: *Modern world is busy with newest UAV civil and military applications. Due to safety level provided by modern UAVs and UASs there are only few initiatives to apply UAV in habited areas to minimize damages and losses both in nature and environment, and in human beings, too. If the UAV must be landed in emergency situation fast and safe way, a human operator of the UAV having limited skills and abilities must be eliminated to ensure successful accomplishment of the emergency landing maneuver. The aim of the author is to establish a new concept of the emergency landing based upon multiple-criteria decision-making (MCDM) procedure.*

Keywords: *UAV, UAS, emergency landing, forced landing, multiple criteria decision making.*

1. INTRODUCTION

UAV applied in any mission can get in unsafe flight situation due to many reasons. If there is a human operator controlling the UAV he can make a decision about interrupting the flight mission. In the conventional fashion there are two common reasons that can lead to emergency landing of the UAV. First reason is loss of command signals. It is mainly handled with returning UAV to the place of take-off. This procedure is often known as RtH (Return-to-Home) mission.

Secondly, the loss of thrust provided by the propulsion system can lead to forced landing of the UAV. These two causes and their consequences have been exhaustively described in [6, 7, 10].

The main goal of the author is to identify and segment other reasons threatening flight safety of the UAV. Although there is a pre-flight inspection of the UAV to reach maximum of the flight safety, there are many reasons can lead to a critical flight situation.

It is needless to prove that UAV operator will plan the UAV flight mission with considerations of the all available initial data. The problem can arise here when external conditions (e.g. wind, deposit, temperature etc) are very changeable. Moreover, during simplest UAV applications at the operator's ground control station there is no information about flight conditions and processes turned into that of worse or extreme ones.

Regarding references of [4,6,7,10,11,12] dealing with UAV emergency landing many threats to flight safety of the UAV are still uninvestigated, and, only first steps are made in solution of problems related to UAV safe operations in emergency landing maneuver.

2. RELATED WORKS

The investigation of the emergency landing of the UAV in extreme flight situations is traced back almost a decade. It was, and still evident that onboard automatic flight control system must ensure flight safety minimums at any flight phase including emergency landing of the UAV.

The task of the safe execution of the emergency landing is very challengeable. Many early researches dealt with flight path planning ensuring landing on safe landing zones providing minimum losses and, minimized threat both to environment and to human being [4,6,7,10]. That problem often was combined with that of design of vision based automated landing of the UAV [6,11,12].

The emergency landing in many research works is originated back to engine failure leading to loss of the thrust and emergency landing is called for forced one [10].

3. CONDITIONS AFFECTING FLIGHT SAFETY OF THE UAV

Among those of possible hazardous conditions and events affecting UAV flight safety the followings are segmented by the author:

1. loss of the control signal;
2. engine(s) failure – partial or total loss of the thrust power;
3. weather conditions (atmospheric turbulences, wind gusts, deposits, icing, external temperature);
4. onboard hardware malfunction;
5. loss of orientation in general.

3.1 Loss of the Control Signal. The wireless control data link can interrupt data transmission between ground control station (GCS) and the UAV itself for a short, or, for a long period of time.

If control data transmission is interrupted due to any reason for a while, or, for a longer period of time the UAV must activate the 'Hold' regime of the automatic flight control system, if there is any applied. A 'Hold' function activates stabilization of the UAV at horizontal straight flight at constant speed and constant altitude with simultaneous stabilization of the Euler-angles.

If the duration of the signal loss of ΔT increases a predefined critical one of t_{crit}, i.e.

$$\Delta T \geq t_{crit}, \tag{1}$$

and the UAV has properly working thrust (power) system flight mission must be interrupted and, UAV flight control system must activate the RtH mission autonomously. The critical value of t_{crit} must be determined for the given class, and for the given type of the UAV.

3.2 Engine(s) Failure – Partial or Total Loss of the Thrust Power. The emergency situation when the autonomous landing of the UAV is highly needed is loss of thrust. Engine failure means that UAV losses the power needed to execute the given flight mission, or, the power of the UAV is drastically decreased and flight mission must be aborted. The 'Engine failure' can be identified evaluating following parameters:

– speed of rotation of the engine;
– current of the BLDC-motor(s).

If speed of the rotation (RPM) n is less than the predefined minimum of $n_{\min}$, i.e.

$$n \leq n_{\min}, \tag{2}$$

the procedure of the emergency landing must be activated finding best landing site ensuring minimization of the losses caused by the UAV.

When UAV rotor blade is driven by BLDC-motor, the status of the BLDC-motors can be monitored via its current required. If current required by BLDC motors is less or larger than its nominal value, i.e.

$$I_{\min} \le I \le I_{\max}, \tag{3}$$

and, if the UAV is a single-engined one, it must be abort flight mission and must enter a new maneuver of the unpowered forced landing.

If the UAV is the twin-engined, or multi-engined one, and there is a loss of a single BLDC-motor, the UAV must abort flight mission and, must enter the RtH maneuver.

The measurement of the current required by BLDC-motors is very important to predict flight time available and covered by electrical energy stored into batteries. The UAV on-board electronics can serve for measurement of the current required by the BLDC-motors. If there is any current values are far out of the current tolerance field, the BLDC-motor technical status can be evaluated, whether it is in normal mode or far out of that, and, it can be disconnected, for instance.

3.3. Weather Conditions. During UAV flights weather conditions can change very rapidly, and, bad weather conditions can threaten success of the flight mission, and can threaten the UAV itself. Although there is a thorough weather report available before flight planning, during UAV flight those weather conditions identified before may lead to a new set of weather minimums when flight mission must be interrupted.

Weather clearances are defined mostly in regulations and standards. For conventional aircraft there are famous standards of [2,3,5]. Besides those regulations many textbooks provide information about weather clearances, mainly the turbulent air modeling is in the focus of attention to derive mathematical models acceptable for preliminary computer simulations [1,9,13]. There are two ways to model atmospheric turbulences. First is the so-called deterministic model given in [1,2,3,5,9,13], which are represented in Figure 1, Figure 2 and Figure 3, respectively.

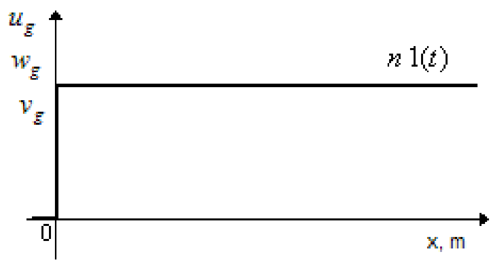

FIG. 1 Constant Air Speed.

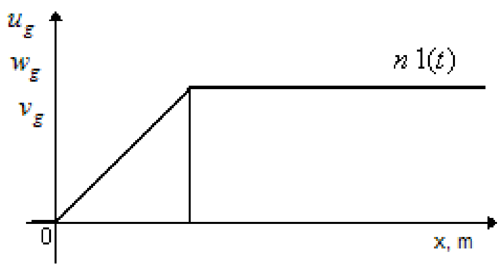

FIG. 2 Linear Gust Speed.

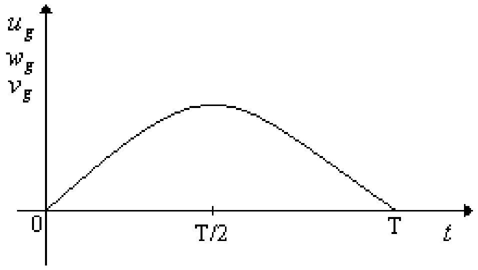

FIG. 3 (*1-COS*) GUST SPEED.

The second type of the atmospheric turbulence model is the random (stochastic) model of the turbulent air. Stochastic models of the turbulent air well-known and widely applied in aeronautical sciences, are the power spectral density (PSD) functions. Table 1 tabulates the most popular PSDs as defined in [1,2,3,5,8,9,13].

Table 1. PSD of the Air Turbulence Models

Model Name	PSD of the Air Turbulence Speed Components
Lumley–Panovsky Model	$\Phi_{vv}(\Omega) = \dfrac{1180\sigma_k^2}{c[(1+2950\Omega)^{2/3}]}$
Lappe–Model	$\Phi_{ii}(\Omega) = \delta_i^2 \dfrac{2\pi L}{(1+2\pi L\Omega)^2}$
The Model of the Royal Aeronautical Institute	$\Phi(\Omega) \approx K^{5/3} W_c,\, ha\; K > 0{,}5L$ $\Phi(\Omega) \approx K^{-1} W_c,\, ha\; K < 0{,}5L$
Lipman–Model	$\Phi_{vv}(\omega) = \dfrac{\sigma_\omega^2 L}{\pi U_o} \dfrac{2}{1+(\omega L/U_o)^2}$ $\Phi_{vv}(\omega) = \dfrac{\sigma_\omega^2 L}{\pi U_o} \dfrac{1+3(\omega L/U_o)^2}{1+\left[(\omega L/U_o)^2\right]^2}$
von Kármán–Model	$\Phi_{vv}(\Omega) = \dfrac{\sigma_\omega^2 L}{\pi} \dfrac{2}{\left\{1+(1{,}339L\Omega)^2\right\}^{3/5}}$ $\Phi(\Omega) = \dfrac{\sigma_w^2 L}{\pi} \dfrac{\left\{1+8/3(1{,}339L\Omega)^2\right\}}{\left\{1+(1{,}339L\Omega)^2\right\}^{11/6}}$
Dryden–Model	$\Phi_{uu}(\Omega) = \dfrac{2\sigma_u^2 L}{\pi} \dfrac{1}{1+(L\Omega)^2}$ $\Phi_{vv}(\Omega) = \dfrac{\sigma_v^2 L}{\pi} \dfrac{1+3(L\Omega)^2}{\left[1+(L\Omega)^2\right]^2}$ $\Phi_{ww}(\Omega) = \dfrac{\sigma_w^2 L}{\pi} \dfrac{1+3(L\Omega)^2}{\left[1+(L\Omega)^2\right]^2}$

The author published a paper dealing with atmospheric turbulences and generating time series of the wind speed components projected in the UAV body axis system using MATLAB [8].

If there are atmospheric turbulences and wind gusts having statistical parameters far out of that region of the weather clearances derived for the given class and given type of the UAV, an immediate emergency landing must be started and successfully executed ensuring safe UAV operations. The wind clearances are mostly defined for speed components of the atmospheric turbulences measured in the body-axis coordinate system of the UAV, and given by [1,2,3,5,9,13] as follows below:

$$u_g(t) \le u_g(t)_{crit};\; v_g(t) \le v_g(t)_{crit};\; w_g(t) \le w_g(t)_{crit}, \tag{4}$$

If there is any of those three inequalities defined by equation (4) is met, i.e.:

$$u_g(t) \ge u_g(t)_{crit}, \text{ or} \tag{5}$$

$$v_g(t) \ge v_g(t)_{crit}, \text{ or} \tag{6}$$

$$w_g(t) \ge w_g(t)_{crit}, \tag{7}$$

a safe UAV must start emergency landing maneuver. It is easy to understand that the above given problem is handled with the multiple criteria decision making (MCDM) able to handle simultaneous conditions formulated with inequalities defined by equations of (5)–(7).

3.4 Environmental Temperature. Temperature is an important weather condition for the given type of the UAV. Being designed to be robust one a UAV has the temperature range for normal flight scenarios such as:

$$T_{\min} \le T_{act} \le T_{\max}, \tag{8}$$

i.e. external temperature must lie between minimum and maximum values. UAV flights at lowest temperatures can threaten although with icing, or, with malfunctioning of the onboard electronics. UAV flights at highest temperatures can lead to worsening of the lift capabilities of the UAV. If there are temperatures out of the range allowed the UAV flight cannot be started, or, if there are so large changes during flights leading to extreme temperatures, the UAV must activate its emergency landing maneuver.

3.5 Onboard Computer and Sensor Hardware Malfunction. Onboard hardware serves for many purposes, and its functionality is no matter of question. To have reliable hardware system there are many methods, however, there is a unique one of building redundant systems.

It is easy to see that due to its complexity, due to increased sizes and weights, redundancy principle cannot be applied as the full-scale one for UAV onboard hardware of the micro-, mini or, for the small UAVs. For MALE and HALE UAV categories redundancy principle can be applied. Moreover, if UAV flies in non-segregated airspace, some UAV type worthiness and airworthiness requirements prescribe the redundancy principle as necessary design principle applied during conceptual design of the UAV.

Regarding general scheme of the UAV automatic flight control system described in [13] following crucial hardware elements are identified by the author:

1. onboard microcontroller (OMC);
2. INS unit;
3. GPS unit;
4. BLDC-controllers (BLDC-C);
5. sensorics (S).

The above listed hardware and their proper functioning is the crucial and key point of the safe UAV operations. The hardware must properly work simultaneously, in other words, if there is any of them is malfunctioning, the UAV is losing its airworthiness. The problem of the simultaneous functioning of the UAV hardware can be traced back to multiple criteria decision making problem (MCDM).

3.6 Losing Orientation (LO). The UAV flight executed in the environment with pure visibility, bad weather conditions, the busy airspace in which UAV flight happens can lead to the situation when UAV operator, in spite of being well-trained, well-prepared, disciplined and ready-to-flight can get in more complex flight situation leading to loose of coordinates and orientation of the UAV partially or totally. It is easy to understand that if it happens firstly the UAV must identify such conditions. If UAV identifies an LO, then the 'Hold' regime of the automatic flight control system of the UAV must be activated, if it is available onboard, i.e. the UAV must level itself at constant speed, and at constant altitude If the identified LO is a static one, in other words, the UAV remains in that uncontrolled flight operation for the time of $\Delta T \geq T_{crit}$, after the 'Hold' regime of the automatic flight control system of the UAV, the RtH mode must be activated after the no-return-point.

4. MULTIPLE CRITERIA DECISION MAKING APPLIED FOR UAV EMERGENCY LANDING SYSTEM

The scenarios described in the foregoing sections can be evaluated very effectively if to take into consideration that there are two types of the abnormal flight modes, namely, the Return-to-Home mode, and Emergency/forced landing modes are being examined after.

4.1 Activating 'RtH' Mode. Regarding segmented flight scenarios described above the activation of the RtH mode of the UAV is crucial via following logical rules for:

if $\Delta T \geq t_{crit}$, or (9)

$\Delta T \geq T_{crit}$, then activate 'RtH' mode. (10)

The RtH Mode means: finding direct heading angle to the landing zone with simultaneous stabilization of the altitude, and speed of the UAV.

4.2 Activating 'Forced Landing' (FL) Mode. Regarding segmented flight scenarios described above for the single-engined UAV the activation of the 'FL' mode must be activated if and only if: $n \leq n_{\min}$. The FL Mode means to land UAV in safe way with finding proper landing zone ensuring minimization of the losses caused by the UAV itself. The landing zone selection is mainly based upon onboard vision system.

4.3 Activating 'Emergency Landing' (EL) Mode. Regarding possible flight scenarios of the UAV activation of the 'EF' mode can be activated if and only if following set of logical conditions is met:

if $u_g(t) \geq u_g(t)_{crit}$, or, (11)

if $v_g(t) \geq v_g(t)_{crit}$, or, (12)

if $w_g(t) \geq w_g(t)_{crit}$, or, (13)

if $T_{\min} \leq T_{act} \leq T_{\max}$, or (14)

if OMC fails, or (15)

if INS fails, or (16)

if GPS fails, or (17)

if BLDC-C fails, or (18)

if S fails, (19)

then activate 'EL' Mode.

It is evident that if there is a single condition of the system of equation (11)–(19) met the automatic flight control system of the UAV, if there is any applied, must activate the 'EL' Mode to land UAV in the non-hazardous landing site selected via minimization of the possible losses caused by the UAV itself.

5. CONCLUSIONS AND FUTURE WORK

This paper addresses the UAV emergency landing concept. The existing solutions for UAV safe landing are very initial ones, dealing with the simplest flight scenarios, i.e. loss of thrust of the UAV, when forced landing of the UAV is activated. Besides of those failures of the engine(s) leading to the loss of thrust many threatening factors has been identified. There are three different modes of the automatic flight control system of the UAV are segmented. First one is the Return-to-Home Mode, and, logical conditions for activating RtH Mode were derived. A new principle is introduced here: the loss of orientation must be taken account when finding logical conditions for the RtH Mode.

Second mode fully and strongly connected to engine(s) failures leading loss of the thrust force. Failures can happen due to any reasons, i.e. due to failures in fuel system, in motor control system, or, due to icing of the rotor blades and leading edges of the wings.

The emergency landing is activated in case of any logical conditions met derived by equations (11)–(19).

The future work of the author in that field is devoted to application of the Fuzzy MCDM approach to take right decision in case of emergency situation, and ensure safe landing of the UAV with minimization of the losses caused by the UAV itself.

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