3D FLIGHT PATH PLANNING FOR MULTIROTOR UAV

Róbert SZABOLCSI
Óbuda University, Budapest, Hungary, szabolcsi.robert@bgk.uni-obuda.hu,
ORCID: 0000-0002-2494-3746

DOI: 10.19062/1842-9238.2020.18.1.1

Abstract: *In recent days, the multirotor UAV urban and semi urban applications predict a need for flight automation both in standard flight missions and in emergency flight tasks performed by UAV automatic flight control systems. The standard flight mission of the multirotor UAV might cover take-off, ascend, leveled flight, descend, and landing phases of the flight. If the flight is organized beyond visual line of sight (VLoS) the UAV onboard flight control system is a necessary condition. If any multirotor UAV flight is planned to be executed between the limits of the safe flight envelope of VLoS, in case of emergency, the multirotor UAV automatic flight control system can select the safe landing zone and it can conduct flight on safe landing paths. Military forward operation bases (FOB) are typically of very limited size and are very busy with military personnel, vehicles, weaponry, ammo, facilities and different equipment. They mostly serve for reconnaissance purposes, and any UAV platform used at FOB can improve their military value and importance. It is easy to see that in such a context the only UAV propulsion system proper to apply, is a rotorcraft propelled aircraft. Their special capabilities of vertical, or very short take-off and landing, and hovering put them into a privileged UAV class accessible to use. This paper deals with 3D flight path planning for multirotor UAVs giving solutions for problems handled in UAV take-off and in UAV landing flight phases.*

Keywords: *multirotor UAV, urban area applications, war theatre military applications, 3D flight path planning, UAV take-off and landing.*

1. INTRODUCTION AND LITERATURE REVIEW

The multirotor UAVs have a unique capability of vertical take-off or landing, which makes them very special in several flight missions. Additionally, UAVs might conduct take-off or landing as a STOL aircraft, and, this property, in many flight missions and applications, such as monitoring constructions, bridges, roads, pipelines etc., is used very effectively. Small UAVs require very small spaces to organize flights, however, ore attention must be paid for take-off and landing of the aircraft.

UAV applications are projected to increase tremendously in the closest period one cannot imagine. After several years of adjusting to the EU, the EASA accepted and published the drone regulation, awaited for so many years [1]. The basic idea of the procedures and rules of the UAV flights in urban area is related to the manual control of the UAV in the VLoS flight envelope. The flying of UAV near aerodromes might create difficulties in standard safety operation procedures of the aerodromes, and the UAV air space integration is still an ongoing one [10].

The wide variety of the UAV applications are discussed in [2, 3]. The UAV path planning for different flight phases and for different measurement technique used by the UAV is outlined in [4, 5, 6, 7, 8, 9].

Recently, there are many pilot projects of the UAV applications far beyond the VLoS, when an unmanned aircraft must be controlled autonomously, and the aircraft must be prepared for a given set of emergency situations, like collision avoidance, bird strike, loss of thrust, low level of energy available, forced emergency landing etc.

The wide range spread of UAVs used in different civilian and military missions and mostly flown by common non-expert users predicts a need of flight automation minimizing, or as the best, eliminating threat of the UAV crash. Thus, for the safe UAV's use the flight automation is necessary, however, cheap and easy-to-use solutions are highly preferred.

2. MULTIROTOR UAV FLIGHTS IN URBAN AND SEMI URBAN ENVIRONMENT

Many UAV applications are planned to be conducted in urban area. Delivering gifts, medical equipment, medicines, post, or, the traffic management, air pollution measurement might be based upon multirotor UAV platforms. As the first step in UAV regulations, only the manual control up to the limits of the VLoS is discussed in [1]. Figure 1 depicts the basic idea of the UAV flights: the flight must be conducted not to threaten any human or facility in the flight envelope.

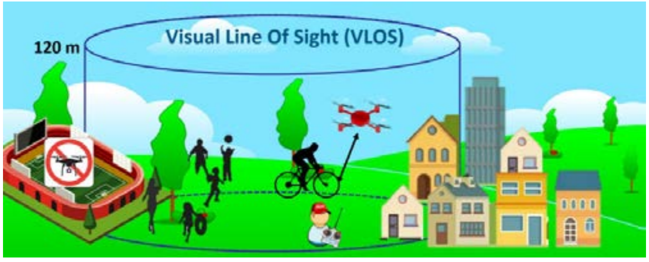


FIG. 1 The UAV urban flight in limited flight envelope [1].

If it cannot be omitted, the flight above humans is allowed for the minimum time durations at safe heights and at safe distances. The flight above crowds, like in sport facilities, is not allowed. The UAV regulations will delegate many new rights and, at the same time, responsibility, in all meanings to the UAV operator.

In modern cities, due to very limited spaces, the UAV flight must be designed very carefully, with the highest level of automations (Fig. 2). If the UAV flight is allowed to be conducted between buildings, in order to ensure successful flight missions with proper flight safety level, special flight paths planned for the given UAV mission are required. If UAV flight between buildings is not allowed the roofs might be used for take-off and landing zones.

FIG. 2 The UAV urban flight in limited flight envelope

The smart city concept integrates different sources of information to handle and support life in the modern cities. Figure 3 shows a sight of the public place in a capital.

FIG. 3 Modern capital 3D reconstruction plan animation

Figure 3 depicts the smart city concept integrating different sources of information to handle and support life (i.e. transport management) in the modern cities. Figure 3 shows a sight of the reconstructed public place in a capital. It is easy to see that due to numerous forms of transport like public or private one, and due to a square public place busy with old and modern buildings there is created a very good atmosphere for inhabitants and tourists, too. Taking a look at this 3D plan, there are tight however well enough spaces available to serve as UAV take-off, or landing zones, if it is necessary to conduct landing or take-off of the UAV. If a UAV arrives to the intersection from the right, with a slight right turn it might be landed on an emptied road having enough length for safe landing.

The multirotor UAV can be applied very effectively in semi urban area to monitor the environment, and any artificial object being erected for IT services, for harvesting wind energy etc. For this purpose, [1] gives the flight scenario depicted in Fig. 4.

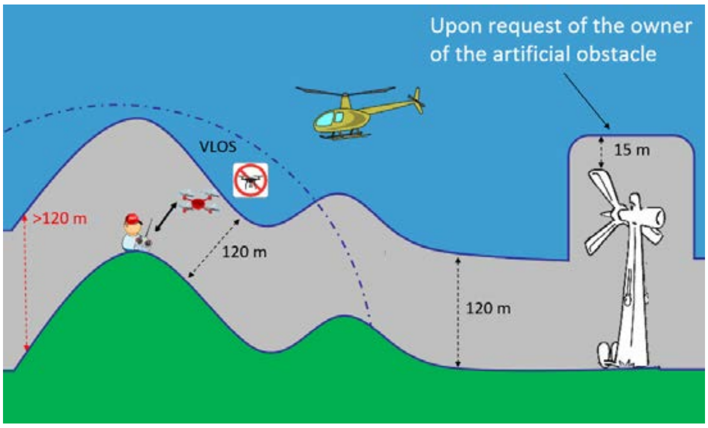


FIG. 4 The UAV semi urban flight in limited flight envelop [1].

In [1] a requirement of keeping 15 m distance to artificial obstacles required by owners of facilities is shown. In Figure 4 it is easy to see that the aircraft flight path ensuring flight above a given obstacle generates difficulties in path planning and design.

3. MULTIROTOR UAV FLIGHTS IN MILITARY OPERATIONS

The multirotor UAV is a promising tool to strengthen force protection (FP) skills of the military units, mostly serving as forward operation base (FOB). Figure 5 shows a 3D animation of the future military FOB camp.

FIG. 5 Military FOB facilities 3D animation

The FOB, as a rule, has very limited physical size. In desert war theatre with hilly places with fragmented relief it is a great strategic challenge to select an appropriate site for the construction of a FOB. After a decision making, a FOB is constructed (Fig.6)

FIG. 6 Construction of the war theatre military FOB between FP T-Walls

The FOB is designed with FP elements (Fig. 6). In Fig. 6 there can be seen some mechanical elements of the FP. It is easy to understand that to strengthen military unit FP capability located inside the walls with UAV recce capabilities, only the multirotor small UAV can be considered for application. If the military base is located at large open places (i.e. at airports etc.), the fixed wing UAVs also can be applied for improving FP capabilities.

4. MULTIROTOR UAV FLIGHT PATHS PLANNING FOR SAFE TAKE-OFF AND LANDING

In UAV flight automation there are several point of view how to design and plan flight paths. The first method is to use open source autopilots like Paparazzi and to give the UAV operator the opportunity to create the more feasible UAV mission flight paths. The advantage one can gain here is the freedom in path planning, and opportunity to develop flight paths toolbox for several UAV applications.

The drawback of the method is that it requires high level of knowledge and programming skills, which limits access and demand to those UAVs using this principle. The method competing this and eliminating difficulties with path planning is to have a reach toolbox of pre-programmed possible flight paths, and the UAV operator task is a simple selection of appropriate flight paths from a toolbox.

4.1. Flight path planning for multirotor UAV aggressive take-offs. The multirotor UAV take-off is supposed to be executed in very tight area like in military FOBs. It is supposed that UAV air space use is thoroughly regulated, and for UAV take-off the segmented and designated area is dedicated in the form of a rectangular cuboid with given sides.

For UAV flight path planning we considered a box with sizes of $10m * 10m * 20m$, and it is supposed that at height $H = 20\ m$ the UAV take-off flight phase will be finished. From among those infinite number of possible UAV flight paths, the unique one and chosen is fitted to the cylindrical surface with radius of $5\ m$ placed inside the cuboid.

The 3D path of multirotor UAV can be derived with the following set of equations:

$$x = X \cdot \sin\,(\omega x) \tag{1}$$

$$y = Y \cdot cos\,(\omega x) \tag{2}$$

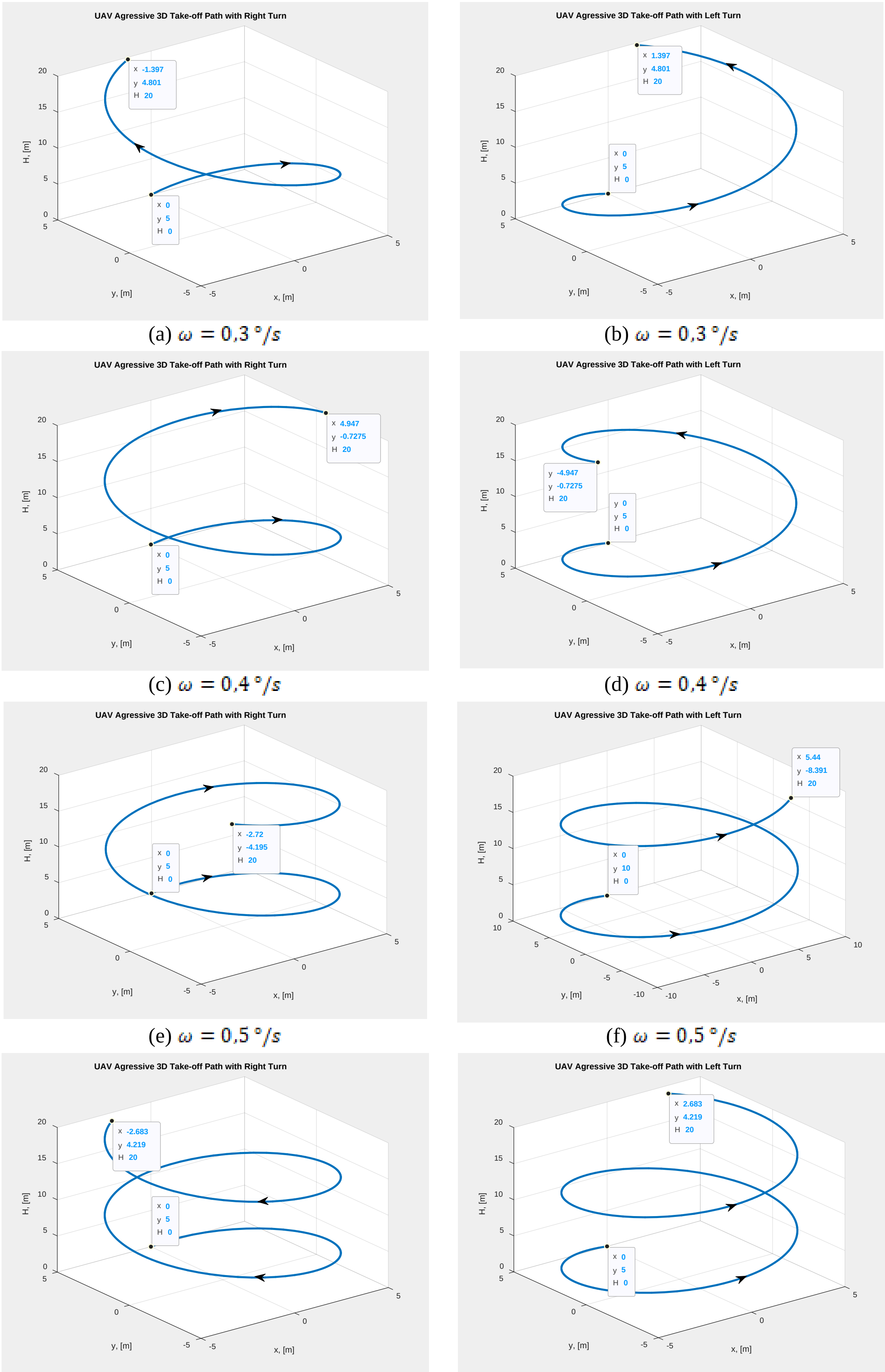
$$z = H_o + a * H \tag{3}$$

Using equations (1)-(3), the multirotor UAV 3D take-off paths can be designed using following parameters:

$$X = 5\ m; Y = 5\ m;\ H_o = 0\ m;\ a = 1 \tag{4}$$

Depending on the need or on the pre-requirements, the multirotor UAV take-off can be executed both with left and right turns. Such situations depicted in Fig. 7 [11, 12].

From Fig. 7 it is easy to see that varying angular frequency ω the UAV flight might have aggressive feature. To washout this, the angular frequency must be increased until it reaches the proper UAV behavior. The angular frequency is a design parameter able to serve in designing toolbox of flight paths segments. It is worth mentioning that this kind of flight paths designed might serve also in collision avoidance missions of the UAV, and , in changing flight altitude flight phases, too. The design parameter of a in equation (3) can be used for manipulation of the slope of the take-off path along the vertical axis. Varying initial data of the flight path wide variety of the possible geometry can be selected and used after for the UAV reference path to be followed.



(a) $\omega = 0{,}3\,°/s$ (b) $\omega = 0{,}3\,°/s$

(c) $\omega = 0{,}4\,°/s$ (d) $\omega = 0{,}4\,°/s$

(e) $\omega = 0{,}5\,°/s$ (f) $\omega = 0{,}5\,°/s$

(g) $\omega = 0{,}6\,°/s$ (h) $\omega = 0{,}6\,°/s$

FIG. 7 The UAV take-off paths planned with left and with right turns.

4.2. Flight path planning for multirotor UAV aggressive landing. The safe UAV landing is a basic criterion to eliminate damage, losses, and to be able to take part after in several flight missions. The landing must be pre-planned ending the UAV flight, and it can be a non-planned emergency one in case of necessity like in bad weather conditions, or in case of loss of thrust. The 3D landing path of multirotor UAV can be derived with the following set of equations:

$$x = X \cdot \sin(\omega x) \tag{5}$$

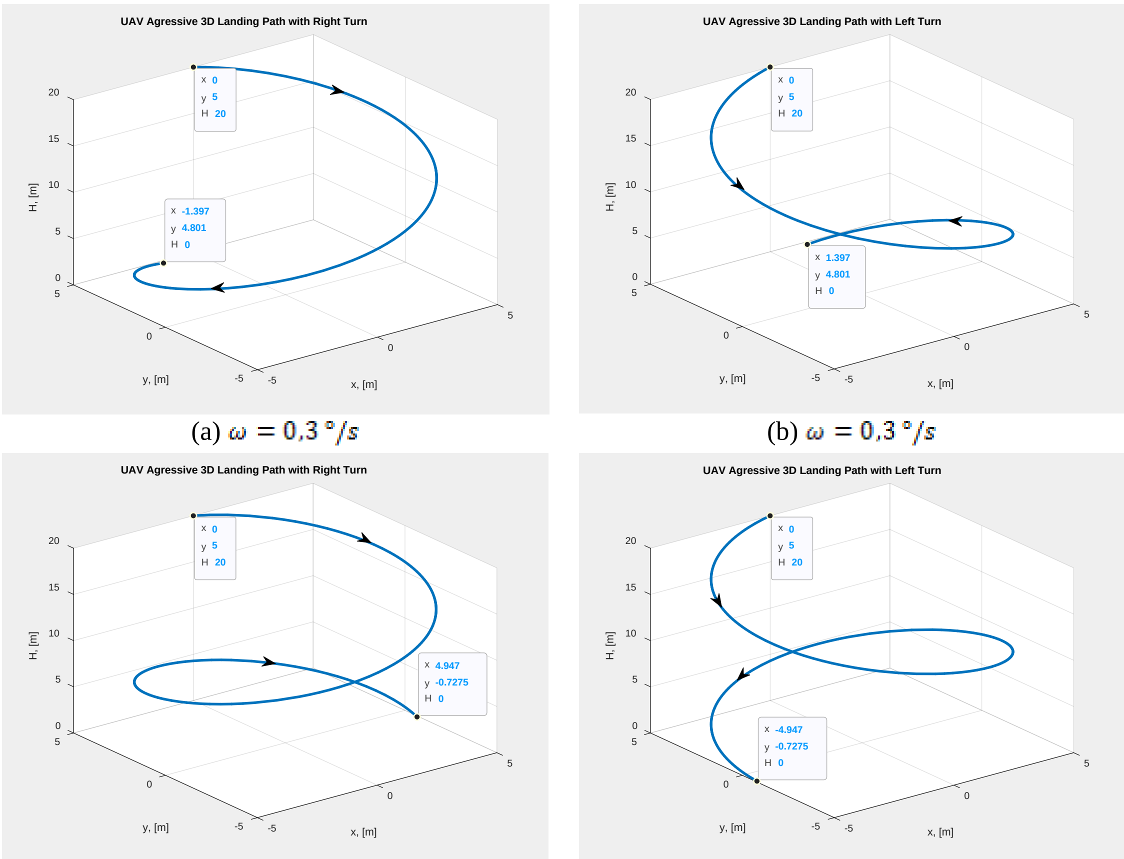
$$y = Y \cdot cos(\omega x) \tag{6}$$

$$z = H_o - a * H \tag{7}$$

Using equations (5)-(7), the multirotor UAV 3D landing paths can be designed using following initial parameters:

$$X = 5\ m; Y = 5\ m;\ H_o = 20\ m;\ a = 1 \tag{8}$$

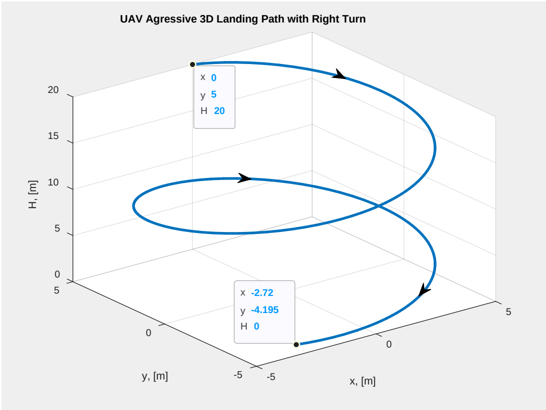
Depending on the need or on the pre-requirements, the multirotor UAV landing can be executed both with left and right turns, and such paths can be seen in Figure 8 [11, 12].



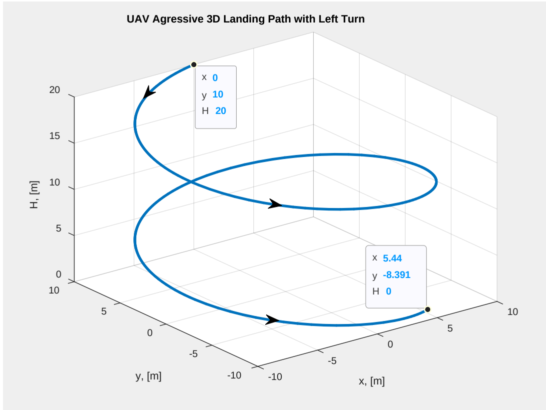
(a) $\omega = 0{,}3\ °/s$ (b) $\omega = 0{,}3\ °/s$

(c) $\omega = 0{,}4\ °/s$ (d) $\omega = 0{,}4\ °/s$

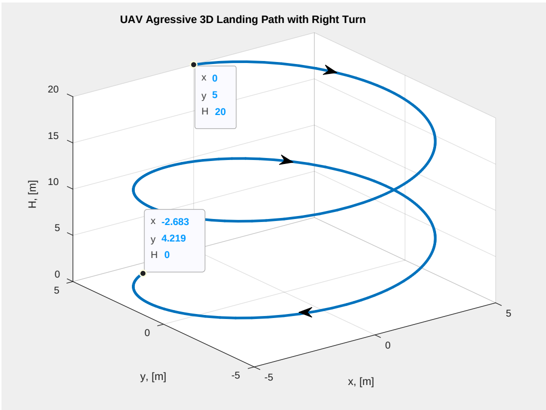
FIG. 8 The UAV landing paths planned with left and with right turns.



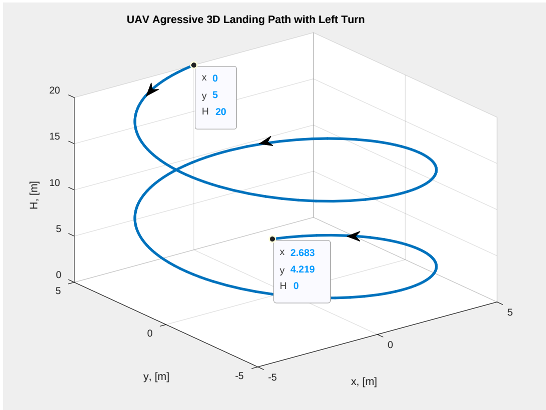
(e) $\omega = 0{,}5\ ^{\circ}/s$



(f) $\omega = 0{,}5\ ^{\circ}/s$



(g) $\omega = 0{,}6\ ^{\circ}/s$



(h) $\omega = 0{,}6\ ^{\circ}/s$

FIG. 8 The UAV landing paths planned with left and with right turns (Continued).

From Fig. 8 it is easy to see that varying angular frequency ω the UAV flight might have aggressive feature. To eliminate aggressive behavior of the UAV landing paths the angular frequency must be increased until it reaches the proper and expected pre-planned UAV behavior. The angular frequency is a design parameter able to serve in designing toolbox of flight paths segments. It must be emphasized that such kind of UAV landing flight paths designed might serve also in collision avoidance missions of the UAV, and, in changing flight altitude flight phases, too. The design parameter of a in equation (7) can be used for manipulation of the slope of the landing path along the vertical axis *oH*.

4.3. Exponential flight path planning for multirotor UAV landing. The basic idea of using exponential flight landing paths is well-known from manned aviation. However, the exponential reference flight path, which is standardized and fixed for traditional aviation can be used very effectively in flight automation of the UAVs. Having no pilots or passengers aboard, more intensive and although the aggressive maneuvers of the UAV can be planned. If the exponential flare flight path of the UAV is an option for its landing, the set of proper exponential function can be set up. In this case, the flight path equations are as follows below:

$$x = L_o + L \tag{9}$$

$$y = Z_o + b * L_{max} \tag{10}$$

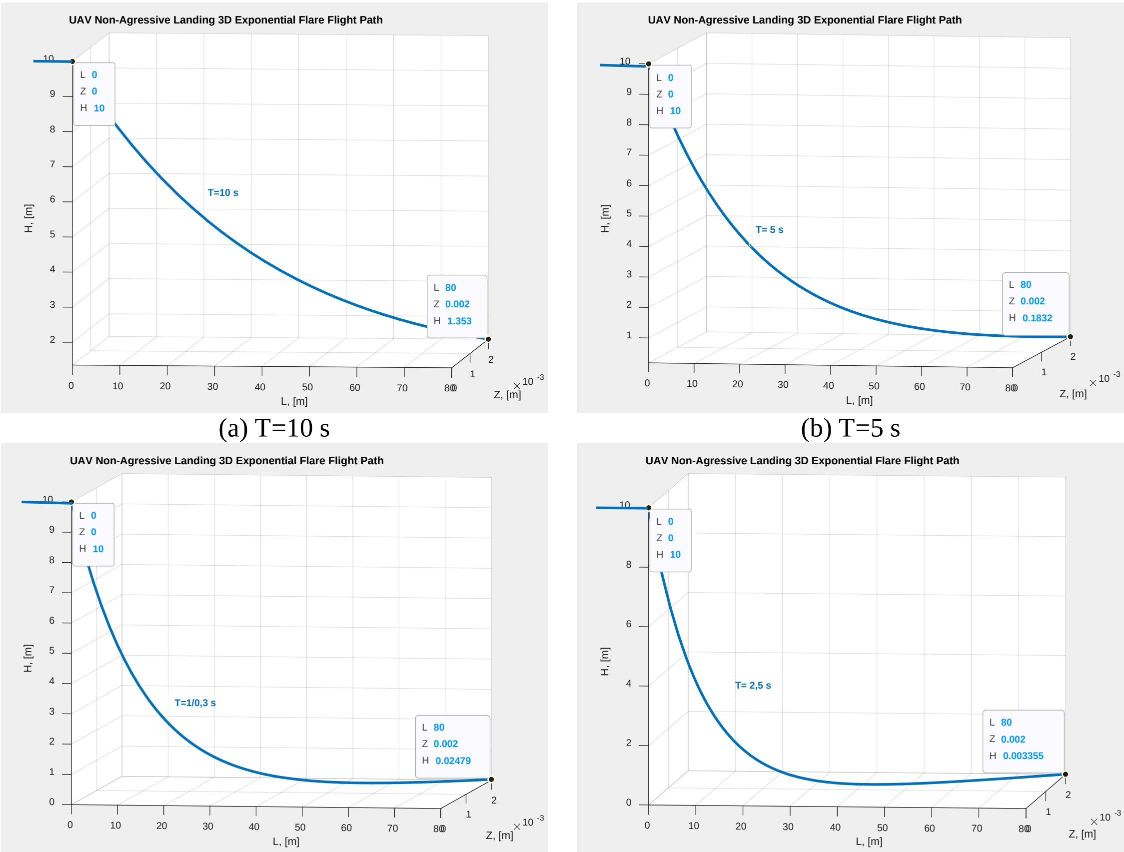
$$z = H_o * e^{-t/T}. \tag{11}$$

Using equations (9)-(11), the multirotor UAV 3D landing paths can be designed using the following initial parameters:

$$L_o = 0\ m;\ L_{max} = 80\ m;\ Z_o = 0\ m;\ \Delta Z \leq 0{,}2\ m;\ z_o = H_o = 10\ m;\ H|_{L=80\ m} \leq 0{,}5\ m;\ \ b = 0{,}0001 \quad (12)$$

.

Using initial data given by equation (12) for a given set of time constant of T traditional flare exponential functions were generated and tested for the UAV landing. Results of the computer simulation can be seen in Fig, 9 [11, 12].



(a) T=10 s (b) T=5 s

(a) T=1/0,3 s (b) T=2,5 s

FIG. 9 The UAV exponential landing paths.

From Fig. 9 it can be seen that the case of $T = 10\ s$ will give a very smooth landing path, however, at the end of the landing phase the height is $H = 1{,}35\ m$ (Figure 9., (a)), which is larger, than the pre-set criteria of $\Delta \leq 0{,}5\ m$. The case of $T = 5\ s$ (Figure 9., (b)) will ensure the prescribed performances whilst a landing path is still smooth enough to land safely the UAV, and the height deviation is $\Delta = 18\ cm$. The case of $T \cong 3{,}3\ s$ is a path famous for very intensive change of the slope of the exponential, which might be achieved with very intensive speed deceleration of the UAV, however, at the end of the exponential the height deviation is $\Delta \cong 2{,}5\ cm$. For all cases shown in Figure 9. the lateral displacement measured from the *oL* axis is $\Delta Z = 2\ cm$, which is in the range of the pre-defined tolerance field of ΔZ. It is easy to see that varying initial data a toolbox of possible standard exponential flare landing paths can be generated and can be used after as the landing path reference.

4.3. Exponential flight path planning for multirotor UAV aggressive landing. There are several reasons for planning unconventional landing paths for the UAV. Firstly, the urban area (Fig. 3) can generate the need of the existence of the pre-planned landing paths for the multirotor UAV selecting proper landing path from a pre-defined toolbox of the possible paths. For those cases requiring intensive maneuver of the UAV landing via exponential path but conducting left turns during landing, the following set of the equations is proposed to be used to generate flight paths:

$$x = L_o + L \tag{13}$$

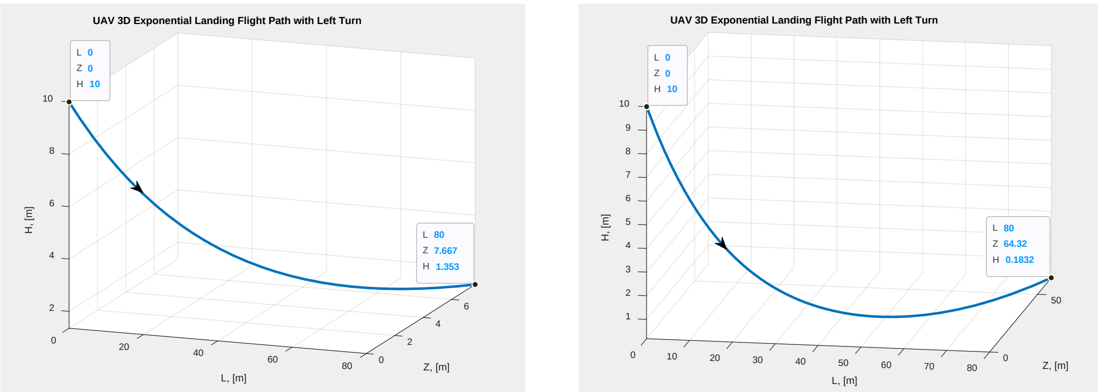
$$y = -1{,}2 + 1{,}2 * e^{t/T} \tag{14}$$

$$z = H_o * e^{-t/T}. \tag{15}$$

Using equations (13)-(15), the multirotor UAV 3D exponential landing paths with intensive left turns can be designed using the following initial parameters:

$$L_o = 0\ m;\ L_{max} = 80\ m;\ Z_o = 0\ m;\ z_o = H_o = 10\ m;\ H|_{L=80\ m} \le 0{,}5\ m \tag{16}$$

Using the initial data given by equation (16) for a given set of time constants the non-traditional flare exponential functions were generated and tested for UAV safe intensive landing. The results of the computer simulation can be seen in Fig. 10 [11, 12].



(a) T=10 s (b) T=5 s

FIG. 10 The UAV exponential landing paths with aggressive left turns.

From Fig. 10 it is evident that the lateral displacement Z depends on the exponential time constant of T. If it is larger, then the lateral displacement is larger, too. This kind of maneuver can be conducted not only for landing purposes, but for collision avoidance missions if there is a sudden emergence of any obstacle on the UAV path, and the collision with obstacle on the right is avoided with aggressive turn to left. The case shown in Figure 10. (a) will not meet pre-defined criteria for the height deviance, and case of $T = 5\ s$ will ensure the accurate height deviation of $H \cong 18\ cm$.

If the left turn is a non-achievable behavior, and the right turn of the UAV will serve effectively the collision, the following set of equations deriving 3D UAV can be applied:

$$x = L_o + L \tag{17}$$

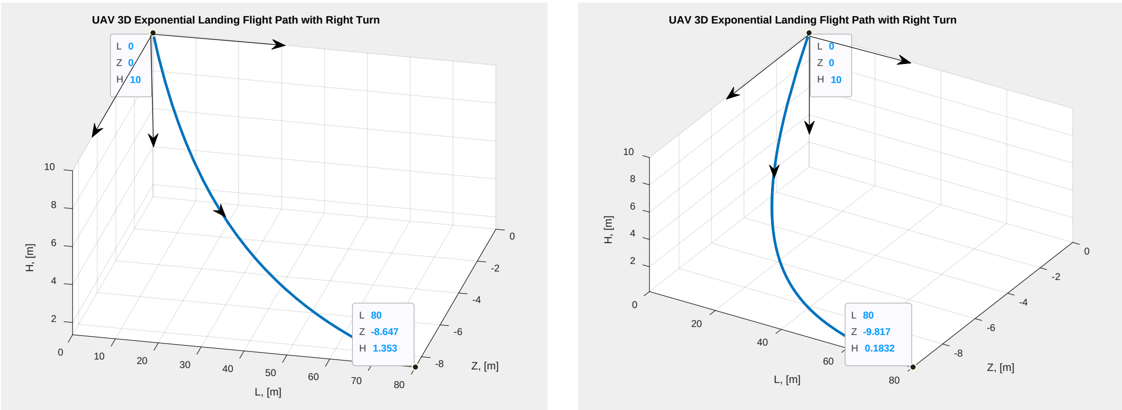
$$y = -10 + 10 * e^{-t/T} \tag{18}$$

$$z = y = 10 * e^{-t/T}. \tag{19}$$

Using equations (17)-(19), the multirotor UAV 3D exponential landing paths with intensive right turns can be designed using the following parameters:

$$L_o = 0\ m;\ L_{max} = 80\ m;\ Z_o = 0\ m;\ z_o = H_o = 10\ m;\ H|_{L=80\ m} \le 0{,}5\ m \tag{20}$$

Relying on the initial data given by equation (20) for a given set of time constants the non-traditional flare exponential functions were generated and tested for the UAV's safe intensive landing. The results of the computer simulation can be seen in Figure 11 [11, 12].



(a) T=10 s (b) T=5 s

FIG. 11 The UAV exponential landing paths with aggressive right turns.

From Fig. 11 it is easily seen that the change of the lateral displacement Z depends on the common time constant T of the exponential functions. As T is increasing the lateral coordinate will increase, too, and steady-state value of the height of the flight will be decreased.

It is evident that such flight path can be used in collision avoidance missions when the left turn is a non-achievable one, and to avoid collision with any kind of obstacle it is necessary to conduct aggressive right turns. Moreover, the flight paths shown in Fig. 10 and Fig. 11 can be used for collision avoidance missions in such cases when at UAV low altitudes further descend of the UAV due to ground proximity is not allowed. In these cases the ascend paths must be used. Having a robust set of pre-planned flight paths of the UAV basic flight missions can be automated, or, in case of emergency with proper landing zone selection the UAV might be landed automatically very safe way.

CONCLUSIONS

In contemporary days, the UAV flight automation is an up-to-date issue of modern control engineering. In this framework, the dynamical systems' reference test inputs are very important for closed loop automatic flight control system preliminary design, which is a computer assisted one.

The UAV flight automation is still an option, however is some countries this is a requirement for UAVs.

Both governmental and non-governmental UAV applications may meet a need of onboard autopilot supporting operators in standard and in non-standard situations they trained for. There is an opportunity to use open-source autopilots like Paparazzi to automate UAV's flight phases leaning on standard procedures based upon the toolbox of pre-programmed flight path geometry.

The author has shown a set of 3D paths planned to be followed in standard UAV flight management. These flight paths can serve as reference flight paths although in emergency flight situations. The mathematical models of the multirotor UAV 3D paths introduced and proposed to be used by the author are the first ones and varying initial parameters their number can be magnified creating a proper toolbox for the UAV operators.

REFERENCES

[1] European Aviation Safety Agency. *(EU) 2019/947, Commission Implementing Regulation on the Rules and Procedures for the operation of Unmanned Aircraft*, 24 May 2019. Available at https://www.easa.europa.eu/document-library/regulations/commission-implementing-regulation-eu-2019947, accessed on 21 May 2020;

[2] A. Claesson et al., Unmanned Aerial Vehicles (Drones) in Out-of-Hospital-Cardiac-Arrest, *Journal of Trauma, Resuscitation and Emergency Medicine (2016) 24:124*. DOI 10.1186/s13049-016-0313-5;

[3] G. Albeano et al., A systematic review of unmanned aerial vehicle application areas and technologies in the AEC domain, *Journal of Information Technology in Construction*. ITcon, Vol.24 (2019), pp(381-405);

[4] J. Kim and J. L. Crassidis, UAV Path Planning for Maximum Visibility of Ground targtes in an Urban Area, 21 May 2014. Available at https://www.researchgate.net/publication/224218547, accessed on 21 May 2020;

[5] J. Kwak and Y. Sung, Autonomous UAV flight control for GPS-based navigation, *IEEE Access*. Available at https://doi.org/10.1109/ACCESS.2018.2854712, accessed on 21 May 2020;

[6] J. Y. Lee et al., UAV Flight and LAnding Guidance System for Emergency Situations, *Sensor 2019, 19, DOI:* 10.3390/s19204468;

[7] N. Jenkins, *An Application of Aeriel Drones in Zoning and Urban Land Use Planning in Canada*, Master Thesis, Ryerson University, Toronto, Canada, 2015;

[8] S. Primatesta et al., Ground Risk map for Unmanned Aircratf in Urban Environments, Available at https://www.researchgate.net/publication/326225175, accessed on 21 May 2020;

[9] Z. Qui et al., Low Altitude UAV Air-to-Ground Channel Measurement and Modeling in Semiurban Environments, *Wiley Hindawi Wireless Communications and Mobile Computing*, Volume 2017, Article ID 1587412;

[10] T.Vas and M. Palik, *UAV Operations in Aerodrome Safety and ACS Procedures*, The 7th International Scientific Conference "Defense resources Management in the 21st Century", Brasov, 15 November 2012. Available at http://www.codrm.eu/conferences/2012/12_Vas.pdf, accessed on 18 May 2020;

[11] MATLAB R2020a, User's Guide, The MathWorks Inc., 2020;

[12] MATLAB R2020a Control System Designer/Control System Toolbox 10.8, User's Guide. The MathWorks, Inc., 2020.