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Flight Control of a Trirotor Mini-UAV for Enhanced Situational Awareness

Igor Astrov and Andrus Pedai

***Abstract*—**This paper focuses on a critical component of the situational awareness (SA), the control of autonomous vertical flight for an unmanned aerial vehicle (UAV). Autonomous vertical flight is a challenging but important task for tactical UAVs to achieve high level of autonomy under adverse conditions. With the SA strategy, we proposed a two stage flight control procedure using two autonomous control subsystems to address the dynamics variation and performance requirement difference in initial and final stages of flight trajectory for a nontrivial nonlinear trirotor mini-UAV model. This control strategy for chosen mini-UAV model has been verified by simulation of hovering maneuvers using software package Simulink and demonstrated good performance for fast SA in real-time search-and-rescue operations.

***Keywords*—**Flight control, trirotor aircraft, situational awareness, unmanned aerial vehicle.

I. Introduction

SITUATION awareness has been formally defined as "the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" [1]. As the term implies, situation awareness refers to awareness of the situation. Grammatically, situational awareness (SA) refers to awareness that only happens sometimes in certain situations.

SA has been recognized as a critical, yet often elusive, foundation for successful decision-making across a broad range of complex and dynamic systems, including emergency response and military command and control operations [2].

The term SA have become commonplace for the doctrine and tactics, and techniques in the U.S. Army [3]. SA is defined as "the ability to maintain a constant, clear mental picture of relevant information and the tactical situation including friendly and threat situations as well as terrain". SA allows leaders to avoid surprise, make rapid decisions, and choose when and where to conduct engagements, and achieve decisive outcomes.

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I. Astrov is with the Department of Computer Control, Tallinn University of Technology, Tallinn 19086, Estonia (corresponding author to provide phone: 372-620-2113, fax: 372-620-2101; e-mail: igor.astrov@dcc.ttu.ee).

A. Pedai is with the Department of Computer Control, Tallinn University of Technology, Tallinn 19086, Estonia (e-mail: andrus.pedai@dcc.ttu.ee).

The tactical unmanned aerial vehicle (TUAV) is one of the key tools to gather the information to build SA for all leaders. The TUAV is the ground maneuver commander's primary day and night system. The TUAV provides the commander with a number of capabilities including:

- Enhanced SA.
- Target acquisition.
- Battle damage assessment.
- Enhanced battle management capabilities (friendly situation and battlefield visualization).

The combination of these benefits contributes to the commander's dominant SA allowing him to shape the battlefield to ensure mission success and to maneuver to points of positional advantage with speed and precision to conduct decisive operations. Some conditions for conducting aerial reconnaissance with TUAVs are as follows.

- Time is limited or information is required quickly.
- Detailed reconnaissance is not required.
- Extended duration surveillance is not required.
- Target is at extended range.
- Threat conditions are known; also the risk to ground assets is high.
- Verification of a target is needed.
- Terrain restricts approach by ground units.

A mini-TUAV offers many advantages, including low cost, the ability to fly within a narrow space and the unique hovering and vertical take-off and landing (VTOL) flying characteristics.

The current state of TUAVs throughout the world is outlined [4]. A novel design of a multiple rotary wing platform which provide for greater SA in the urban terrain is then presented.

Autonomous vertical flight is a challenging but important task for TUAVs to achieve high level of autonomy under adverse conditions. The fundamental requirement for vertical flight is the knowledge of the height above the ground, and a properly designed controller to govern the process.

In [5], a three stage flight control procedure using three autonomous control subsystems for a nontrivial nonlinear helicopter model on the basis of equations of vertical motion for the center of mass of helicopter was proposed. The proposed control strategy has been verified by simulation of hovering maneuvers using software package Simulink and demonstrated good performance for fast SA.

This paper concentrates on issues related to the area of [5], but demonstrates another field for application of these ideas, i.e., research technique using control system modeling and simulation on the basis of equations of motion for the center of mass of small trirotor TUAV for fast SA.

In this paper our research results in the study of vertical flight (take-off and hovering cases) control of small trirotor TUAV which make such SA task scenario as "go-search-find-return" possible are presented.

The contribution of the paper is twofold: to develop new schemes appropriate for SA enhancement using TUAVs by hybrid control of vertical flight of small trirotor TUAVs in real-time search-and-rescue operations, and to present the results of hovering maneuvers for chosen model of a trirotor TUAV for fast SA in simulation form using the MATLAB/Simulink environment.

II. Trirotor TUAV Model

The trirotor TUAV is composed of three rotors. It is clear that one of the advantages of trirotors with respect to quadrotors is that they require one motor less which can lead to a reduction in weight, volume and energy consumption. The two main rotors in the forward part of the trirotor rotate in opposite directions and are fixed to the aircraft frame. The tail rotor can be tilted using a servomechanism.

The dynamics of the trirotor TUAV for the case of low speeds of motion can be represented by the following equations [6]-[7]

$$\ddot{x} = -\tau_4 \frac{\sin\theta}{m} \tag{1}$$

$$\ddot{y} = \tau_4 \frac{\cos\theta \sin\phi}{m} \tag{2}$$

$$\ddot{z} = \tau_4 \frac{\cos\theta\cos\phi}{m} - g \tag{3}$$

$$JW\ddot{\eta} + J\dot{W}\dot{\eta} + W\dot{\eta} \times JW\dot{\eta} = \tau \tag{4}$$

where

$$\eta = (\psi \quad \theta \quad \phi)^T, \tag{5}$$

$$W = \begin{bmatrix} 0 & -\sin\psi & \cos\psi\cos\theta \\ 0 & \cos\psi & \sin\psi\cos\theta \\ 1 & 0 & -\sin\theta \end{bmatrix}, \tag{6}$$

$$\dot{W} = \begin{bmatrix} 0 & -\cos\psi & -\cos\psi\sin\theta - \cos\theta\sin\psi \\ 0 & -\sin\psi & -\sin\psi\sin\theta + \cos\theta\cos\psi \\ 0 & 0 & -\cos\theta \end{bmatrix}, \tag{7}$$

$$\tau = (\tau_1 \quad \tau_2 \quad \tau_3)^T, \tag{8}$$

$$\tau_1 = l_2(f_1 - f_2), \tag{9}$$

$$\tau_2 = -l_1(f_1 + f_2) + l_3 f_3 \cos\alpha, \tag{10}$$

$$\tau_3 = -l_3 f_3 \sin\alpha, \tag{11}$$

$$\tau_4 = f_1 + f_2 + f_3 \cos\alpha, \tag{12}$$

x, y, z are coordinates of center of mass in the earth-frame;
ψ, θ, ϕ are yaw, pitch and roll angles;
α is the tilting angle of third rotor;
$f_i (i = 1,2,3)$ is the thrust generated by the i-th rotor;
l_1 is the distance from the centre of mass to the centre of line between the first and second rotors;
$2l_2$ is the distance between the first and second rotors;
l_3 is the distance from the centre of mass to the third rotor;
J is the inertia matrix;
g is the gravity constant;
m is the mass of the TUAV.

The inputs in (9)-(11) then can be represented in matrix form as

$$\begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{bmatrix} = \begin{bmatrix} l_2 & -l_2 & 0 \\ -l_1 & -l_1 & l_3\cos\alpha \\ 0 & 0 & -l_3\sin\alpha \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix} \tag{13}$$

Then the individual forces in (13) will be

$$\begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix} = -\frac{1}{2} \begin{bmatrix} -\frac{1}{l_2} & \frac{1}{l_1} & \frac{ctg\,\alpha}{l_1} \\ \frac{1}{l_2} & \frac{1}{l_1} & \frac{ctg\,\alpha}{l_1} \\ 0 & 0 & \frac{2}{l_3\sin\alpha} \end{bmatrix} \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{bmatrix} \tag{14}$$

Note that exists an orientation of body frame in which the inertia matrix in (4) simplifies to:

$$J = diag(I_x, I_y, I_z) \tag{15}$$

For simplicity we consider the matrix J in (15) as unit matrix, i.e.

$$J = diag(1,1,1), \tag{16}$$

where $I_x = I_y = I_z = 1kgm^2$.

Substituting (16) into (4), we obtain

$$W\ddot{\eta} + \dot{W}\dot{\eta} + W\dot{\eta} \times W\dot{\eta} = \tau \tag{17}$$

If we apply the properties of vector product to (17), we obtain

$$W\ddot{\eta} + \dot{W}\dot{\eta} = \tau \tag{18}$$

From (18), we have

$$\ddot{\eta} = W^{-1}\tau - W^{-1}\dot{W}\dot{\eta} \tag{19}$$

where

$$W^{-1} = \frac{1}{\cos\theta}\begin{bmatrix} \cos\psi\sin\theta & \sin\psi\sin\theta & \cos\theta \\ -\sin\psi\cos\theta & \cos\psi\cos\theta & 0 \\ \cos\psi & \sin\psi & 0 \end{bmatrix}. \tag{20}$$

We can regroup the three dynamics in (5), (7), (8), (19) and (20) as:

$$\ddot{\psi} = \dot{\theta}tg\theta + \dot{\phi}\sec\theta + \tau_1 tg\theta\cos\psi + \tau_2 tg\theta\sin\psi + \tau_3 \tag{21}$$

$$\ddot{\theta} = -\dot{\phi}\cos\theta - \tau_1\sin\psi + \tau_2\cos\psi \tag{22}$$

$$\ddot{\phi} = \dot{\theta}\sec\theta + \dot{\phi}tg\theta + \tau_1\sec\theta\cos\psi + \tau_2\sec\theta\sin\psi \tag{23}$$

From (1)-(3), (12), and (21)-(23) we can see that the attitude vector $(x \;\; y \;\; z)^T$ for given model of TUAV can be computed.

The numerical values for trirotor TUAV's constant parameters of (1)-(4) for a case of small elevation above sea level are given by [6]:

$$m = 0.5kg,\; l_1 = 0.07m, l_2 = 0.24m, l_3 = 0.33m,\; g = 9.81m/s^2.$$

III. Control System

It is possible to consider the thrusts f_1 and f_2 in (9) as constant functions of time with one value. Hence, we have

$$f_1 = f_2 = const \tag{24}$$

Hence

$$\tau_1 = 0 \tag{25}$$

Combining (10), (12) and (24), we can write

$$\tau_2 = -2f_1(l_1 + l_3) + l_3\tau_4 \tag{26}$$

Then, from (11), (12) and (24), it follows that

$$\tau_3 = l_3 tg\alpha(2f_1 - \tau_4) \tag{27}$$

It is possible to consider the tilting angle α in (10)-(12) as a constant angle. Here, we take

$$\alpha = const \tag{28}$$

With selection of (24)-(28), a complex control problem is now turned into a control problem with using only one collective thrust τ_4 as control input for controlling the coordinate z of altitude with respect to reference input z^0.

The control system configuration to regulate the input variable τ_4 is thus designed, to have the next structure (see Fig. 1)

$$\dot{\tau}_4 = K(t_1(z^0 - z) - t_2\dot{z} - \ddot{z}) \tag{29}$$

where t_1, t_2 are constants to be determined.

It is possible to consider the variable τ_4 as a "fast" function of time. Hence, assuming that $\dot{\tau}_4 \approx 0$, from (29), we find

$$\ddot{z} + t_2\dot{z} + t_1 z = t_1 z^0 \tag{30}$$

The following coefficients of (30) are obtained from [8], for overshooting with value of $\sigma \approx 5\%$

$$t_1 \approx \frac{9}{t_{d_z}^2}, t_2 \approx \frac{3\sqrt{2}}{t_{dz}} \tag{31}$$

where t_{d_z} is desired transition time of coordinate z.

For a hovering flight, angles of roll, pitch, and yaw must be zeros. Therefore, it follows from (3) that

$$\ddot{z}(t) = b\tau_4(t) - g, \tag{32}$$

where

$$b \approx \frac{1}{m}. \tag{33}$$

Differentiating both sides of (32) with respect to time, we obtain

$$\dddot{z}(t) = b\dot{\tau}_4(t) \tag{34}$$

Combining (29) and (34), we have

$$\dddot{z}(t) = bK\,(i_3(t) - \ddot{z}(t)), \tag{35}$$

where

$$i_3(t) = t_1(z^0 - z(t)) - t_2\dot{z}(t). \tag{36}$$

Defining $\ddot{z}(t) = a(t)$ in (35), we obtain

$$\dot{a}(t) = bKi_3(t) - bKa(t) \tag{37}$$

The variable $a(t)$ in (37) can be described in a common way through next expression as indicated in [9]

$$a(t) = (a_0 + \int_0^t e^{-A(\tau)}bKi_3(\tau)d\tau)e^{A(t)}, \tag{38}$$

where

$$A(t) = -\int_0^t bKd\tau \,. \tag{39}$$

Let us consider the behavior of the considered control system (see Fig. 1) for the time t of time interval $t \geq t_{dz}$ during the hovering.

Hence, assuming that $a_0 = 0$, $z^0 - z(t) \approx \Delta z^0$, $\Delta = 0.05$, $\dot{z}(t) \approx 0$, from (38)-(39), we find

$$a(t) = i_3(1 - e^{-bKt}) \tag{40}$$

where

$$i_3(t) \approx t_1 \Delta z^0 \approx const. \tag{41}$$

Assume now that for the desired transition time for control of acceleration $a(t)$ lies in the zone of overshooting with value of $\sigma \approx 5\%$, then, from (40)-(41), it follows that

$$t_{d_{\ddot{z}}} \approx -\frac{\ln(\Delta)}{bK} \tag{42}$$

Therefore, using (33) and (42), and the ratio of coordinate-to-acceleration transition times $N = \dfrac{t_{dz}}{t_{d\ddot{z}}}$ and that $\ln(\Delta) \approx -3$, we obtain

$$K \approx \frac{3Nm}{t_{dz}} \tag{43}$$

IV. Simulation Results

Consider the control of trirotor TUAV model (1)-(3), (21)-(23) for the case of take-off and hovering maneuvers by hybrid constrained system of two control subsystems.

The goal of the following simulations is twofold. First, we verify that these control subsystems are able to control the take-off and hovering trajectories. Second, we observed the effect of enhancing SA because the variety of such trajectory parameters as desired transition times, ratios of coordinate-to-acceleration transition times and heights of hovering easily can be changed the possible take-off and hovering trajectories of trirotor TUAV.

Constant thrust forces of the first and second rotors, constant tilting angle of the third rotor, initial conditions, desired height positions, ratios of coordinate-to-acceleration transition times and desired transition times for control subsystems are chosen to be:

$$f_1 = f_2 = 2.4N,\ \alpha = 89\deg,\ x(0) = y(0) = z(0) = 0m,$$

$$z_1^0 = 3m, z_2^0 = 8m,\ N_1 = 40, N_2 = 15,\ t_{d1} = 3s, t_{d2} = 12s.$$

Simulation results of the offered block scheme with two control subsystems (see Fig. 1) are shown in Figs. 3-6.

Fig. 2 shows the height trajectory of flight control.

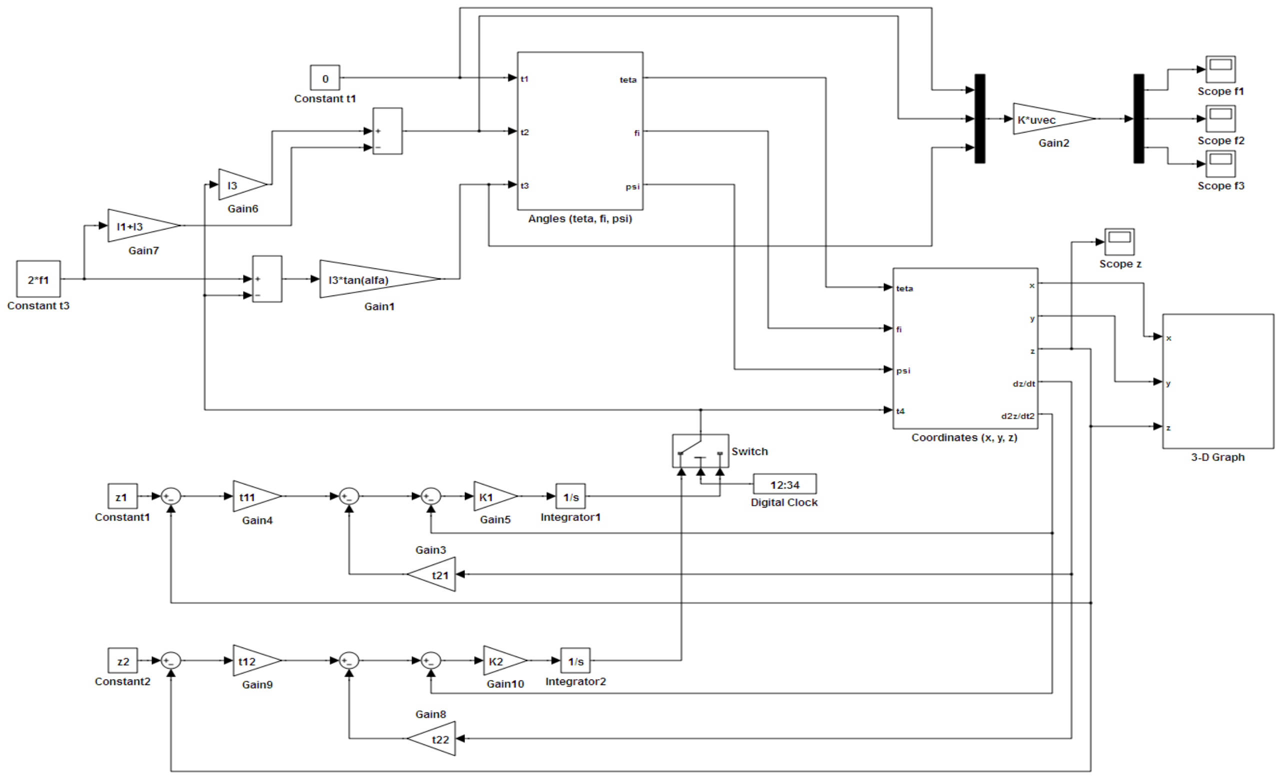

Fig. 1. Block diagram of hybrid control system.

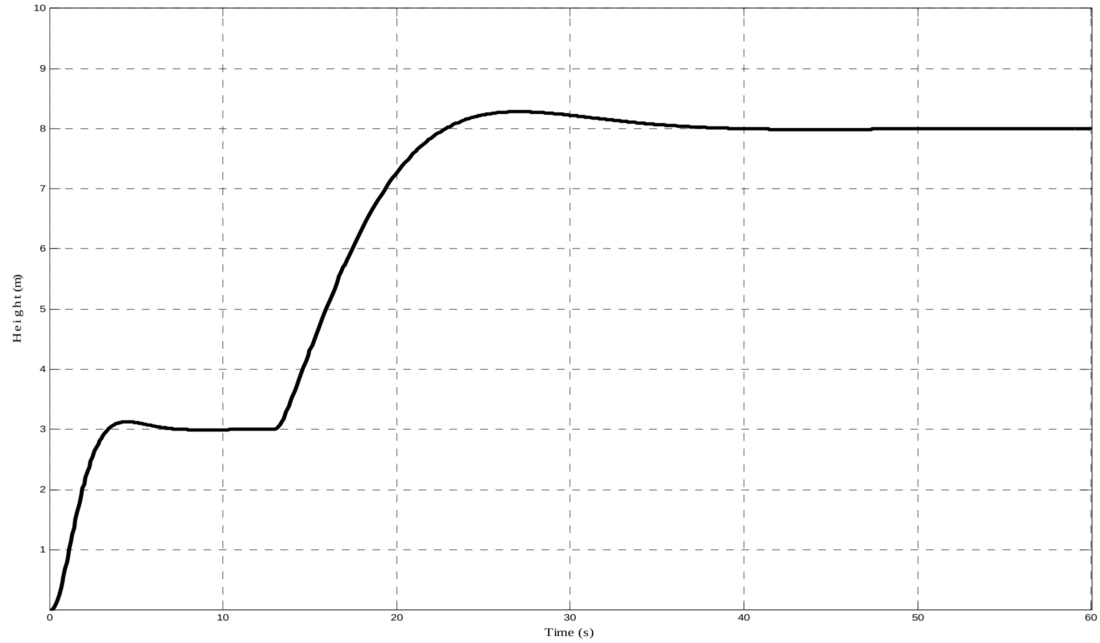

Fig. 2. Trirotor TUAV's height trajectory.

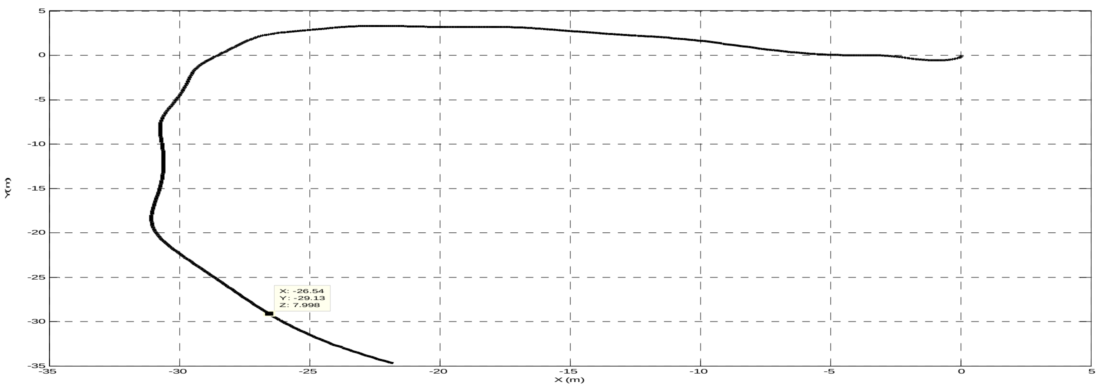

Fig. 3. X-Y view of trirotor TUAV's trajectory.

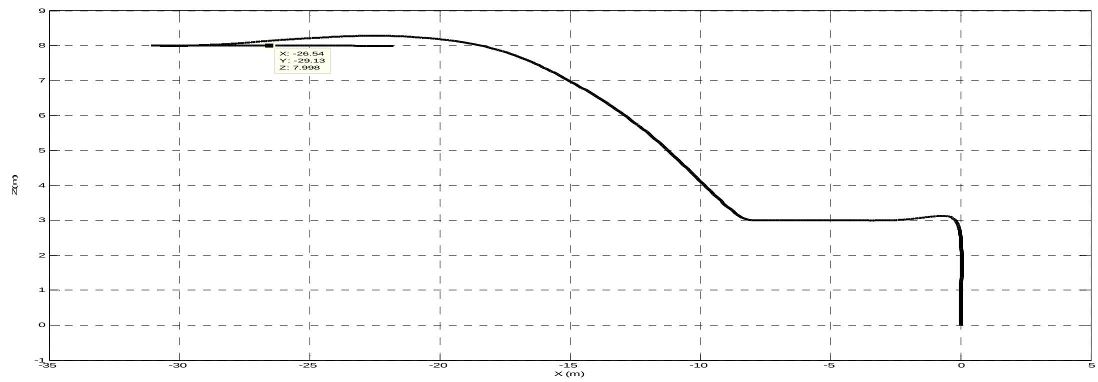

Fig. 4. X-Z view of trirotor TUAV's trajectory.

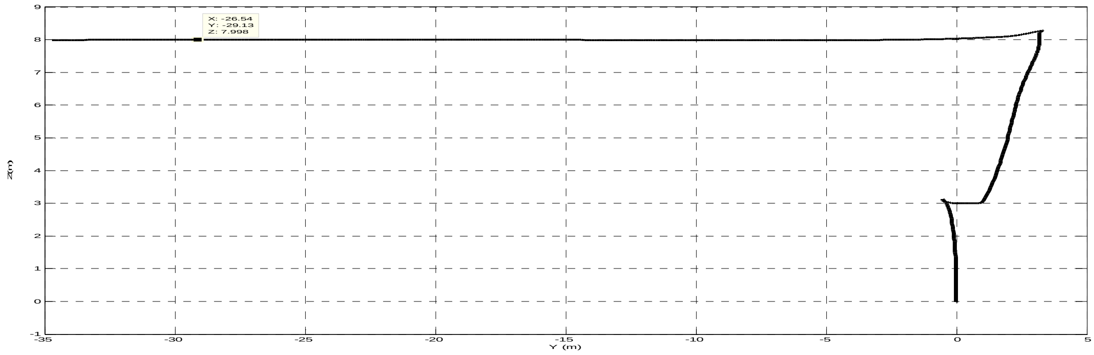

Fig. 5. Y-Z view of trirotor TUAV's trajectory.

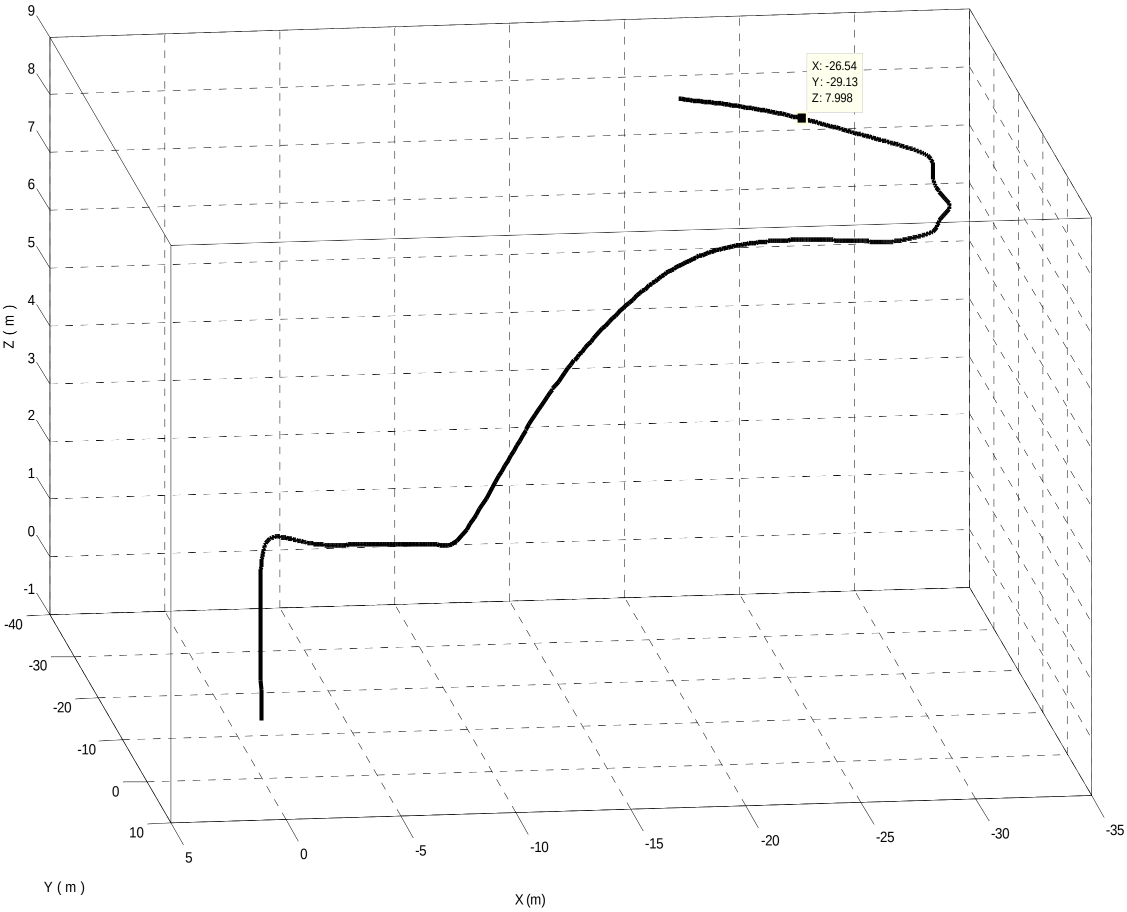

Fig. 6. 3-D motion of the trirotor TUAV.

We simulated the block diagrams of subsystems as parts of hybrid control system and take into account that the full take-off and hovering trajectories were separated into initial and final phases with boundary point in the first lag position.

Some advantages of this example are as follows.

- Possibility to consider a terrain restriction in the places of hovering.
- Smooth trajectory of flight and possibility of lag in two different selected height positions.
- Using of two control subsystems to control the take-off and hovering trajectories of flight.

These results support the theoretical predictions well and demonstrate that this research technique would work in real-time flight conditions.

V. Conclusions

A new research technique is presented in this paper for enhanced SA in possible TUAV's missions.

The need for highly reliable and stable hovering for VTOL class TUAVs has increased morbidly for critical situations in real-time search-and-rescue operations for fast SA.

For fast, stable and smooth hovering maneuvers, we proposed a two stage flight strategy, which separates the flight process into initial and final phases. Two control schemes are designed for this flight strategy. The effectiveness of the proposed two stage flight strategy has been verified in field of flight simulation tests for chosen model of the trirotor TUAV using software package Simulink.

From the simulation studies of flight tests, the following can be observed:

- The block diagram of flight control is very useful for graphic representation of the flight trajectory.
- The received control subsystems are autonomous and completely shared in time.
- The trajectory tracking display forms give a researcher an immediate view of a trirotor TUAV motion with a range of such trajectory parameters as transition times, ratios of coordinate-to-acceleration transition times and heights of hovering. This allows us to investigate the sensitivity of the hybrid control system, providing a medium for such development and evaluation and enhancing the researcher's understanding of hovering maneuvers.

Although many of the details inevitably relate with this particular system, there is sufficient generality for this research technique to be applied to others models of TUAVs during hovering maneuvers.

From the applications viewpoint, we believe that this two stage flight strategy using flexible and effective hybrid control furnish a powerful approach for enhancing SA in applications to VTOL class TUAVs.

Future work will involve further validation of the performance of the proposed research technique and exploring other relevant and interesting TUAV's missions.

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