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Hierarchical Flight Control System for Tilt-Rotor Drones

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ABSTRACT

This paper presents a hierarchical flight control system for tilt-rotor drones. The offered approach performs high-level mission goals by gradually confirming them into machine-level instructions. The learned data from numerous sensors is spread backside to the greater levels for sensitive decision making. Each vertical take-off and landing drone is linked through regular wireless communication rules for accessible multi-agent facility. The proposed flight control system has been effectively employed on several small tilt-rotor drones and validated in some applications. Solutions from waypoint navigation, a probabilistic chase-evasion competition and vision-based object chasing show the capability of the recommended method for intelligent flying drones.

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Introduction

Implementation of smart drones has been done potential because of hi-tech innovations in different areas such as artificial intelligence, flying robotics, wireless communication, and control systems. There is small skepticism that intelligent drones will be employed to autonomously run missions, or embedded in numerous structures, and spread our abilities to identify, mind and action, or replace human attempts in applications where individual action is threatening, unproductive and/or even impossible. Supporting to this impression, proposed study objects to establish numerous autonomous negotiators into integrated and intelligent structures with condensed reasoning and control intricacy, open-mindedness, adaptivity to variations in mission and situation, modularity, and scalability to achieve intricate assignments competently.

Tilt-Rotor vertical take-off and landing (VTOL) or tilt-rotor drones (TRDs) have got distinctive flying abilities such as hover, vertical take-off/landing, and sideslip, which cannot be attained by traditional fixed-wing airplanes [1,2]. These multipurpose mission modes are effective for numerous circumstances as well as reconnaissance, ground target tracking, and tasks with restricted launching space such as a ship deck or in situations that need repeated landings and take-offs (Figure 1) [3]. These types of drones integrating are helicopter technology as fixed-wing aircraft technology.

Figure 1: Tilt-Rotor Bayraktar DİHA Unmanned Aerial Platform (Turkey) [3]

The last time has seen astonishing advancement in TRD study including design and modeling, modern control theory, and avionics [4-11]. But the recent level still drops quickly by applying results to most actual applications and utilizing the detailed abilities of the rotorcraft. Our research has been focused on enhancing the performance of TRDs as participants of a networked intelligent group containing numerous heterogeneous drones. To reach this goal, it is important that every mission control system be able with well-capable autonomy, i.e., abilities to independent sense, mind, plan, and act in expertise with other drones or ground/water-based robots or environments. This article shows the combination of a hierarchical flight management system (FMS) for TRDs that offers autonomy as permitting management among all team participants. The proposed paper presents three control approaches: 1) TRD cascade PID control strategy; 2) the dynamic control allocation strategy (from Ref. [7]), so it adapts to a potential drone configuration change; 3) multi-functional hierarchical FMS strategy [12].

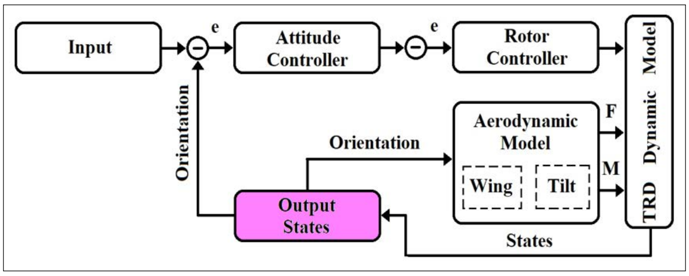

Figure 2: TRD Cascade PID Control Strategy [6]

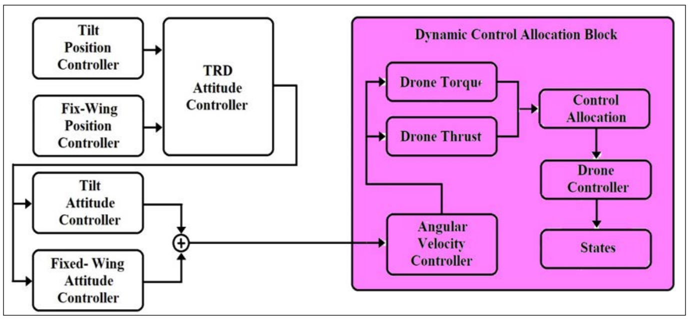

Figure 3: TRD Control Strategy with Dynamic Control Allocation [6]

After determining the TRD dynamic model and calibration of the appropriate aerodynamic coefficients, for the TRD control, the state variables are operated by a PID controller, and Figure 2 appears the block diagram of the control strategy. Forces and moments due to rotors and wind aerodynamics are computed independently.

The general control structure contains two cascade PID controllers, which accept errors from speed and attitude and provide consistent control amounts [5]. The control of TRD is reached by applying the negative feedback [13].

Additionally, the current drone controller offers the off-the-shelf controller for namely this type of drone, it normally needs to load up the appropriate files to represent the required control pull to every single actuator input, which can only carry the drone with a fixed structure. In its place, we employed a possible drone structure change (such as an actuator failure). Consequently, the control diagram becomes like on Ref. [7] (Figure 3).

So, we use up a multi-differential controller as a non-linear model predictive tracking controller (Figure 4).

The former has been successfully validated in various scenarios, as mentioned on Ref. [7]. The last is especially efficient in focusing on nonlinearity, coupling, input, and state saturations.

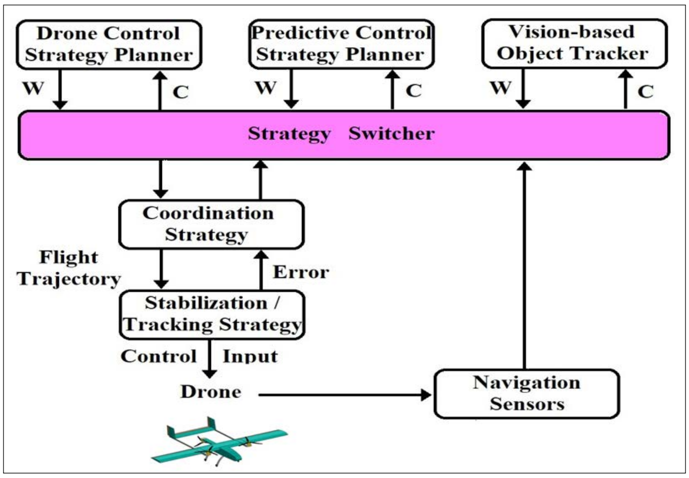

Figure 4: Multi-Functional Hierarchical FMS for TRD: W – Waypoints, C – Conflicts

The low-level drone stabilization strategy is linked to the higher-level strategy planner using vehicle control language (VCL), interface for autonomous agents, human being pilots to control the host drone [12,14]. Every autonomous agent is a piece of a wireless communication network, by which complex assignments could be accomplished in a coordinated way [13,15].

As target problems, the following situations are waypoint navigation, pursuit-evasion, ground target tracking, and vision-based landing [12]. These strategies represent one or more functionalities of the hierarchical multi-agent system. In waypoint navigation, the functionality of the guidance strategy using the VCL structure is underlined. The pursuit-evasion refers to probabilistic logic for strategy switcher, multiagent synchronization on a wireless network, dynamic VCL process, and vision-based detection. The ground target chasing and vision-based landing tests high-speed position tracing control, target detection and identification, and chasing processes of the onboard vision handling unit as strategy planning and switcher [15].

Problem Statement

An intelligent agent functions: 1) constantly identifies dynamically varying environments; 2) to explain apparent data, to resolve tasks and to define suitable reaction; and 3) shows suitably to impact terms in its environment [12]. Built on these properties, we could depict each strategy in the hierarchical FMS shown in Figure 4.

Vigorously altering environments in the world and drone states are seen by different onboard sensors. Motion-related data, which is crucial for UAS control and high-level process, is measured by the onboard navigation sensors such as inertial navigation system (INS) and global positioning system (GPS) [12,13].

Extra sensors such as ultrasonic sensors and laser rangefinders are employed to obtain the environment particular data as well as relative distance from the ground surface, or to identify the other drones in the vicinity of the host drone. A computer vision structure is applied to identify objects of concern based on their colour or form [15].

Figure 4 reveals three types of strategy planners to be applied for every test. The suitable strategy planner for a particular mission is chosen by a strategy switcher.

While the recent status of the world is not totally significant, the world is modelled as a partly detectable Markov decision method. The strategy planner also renews every agent's information, or probability distribution throughout the state space of the world, provided measurement and activity stories, and creates a plan, like a mapping from the agent's principle state to its act set [12]. Pursuit of the optimal strategy is computationally problematic in many challenges, therefore normally optimal strategies are applied in Ref. [12], or the group of rules to seek over is restricted as in Ref. [13]. Processes are usually operated on real-time functioning structures to fulfil fast real-time restrictions.

The strategy planner as well operates communication networks too. Developed from an easy telemetry for data up and down link, the communication performs a crucial function in the real-time management of numerous drones in dynamic environment as a closely coordinated, distributed interacted intelligence. Furthermore, it is necessary to get the care of a high-ranking quality-of-service wireless communication system with negligible expectancy, in the spirit of ambient noise or signal blocking for secure action.

Ultimately, the drone is ordered to go to the planned spots that are processed by the decision-making procedure. In acting so, the UAS ought to be capable to independently drive itself beyond the reference routes or waypoints. Each drone platform is supplied with alleviating controllers. Special action-detection management appears at an extremely rapid level in charge to survive with possibilities, such as revealing and prevention of collisions [15].

Methodology

Tilt-Rotor Drone Onboard Platform

Modern UAS is firmly integrated by mechanical and electronic modules, involving an airframe, navigation sensors, processors, batteries, and extra onboard sensors, targeted at implementing autonomous responsibilities thru nominal interference by a remote human operative. Bayraktar DİHA TRD is made on off-the-shelf remote-controlled drones of numerous ranges and loads. The onboard modules are classified into the pursuits: 1) flight control onboard computer; 2) navigational sensors; 3) communication unit, and 4) onboard power structure (Figure 5) [3,12, 15].

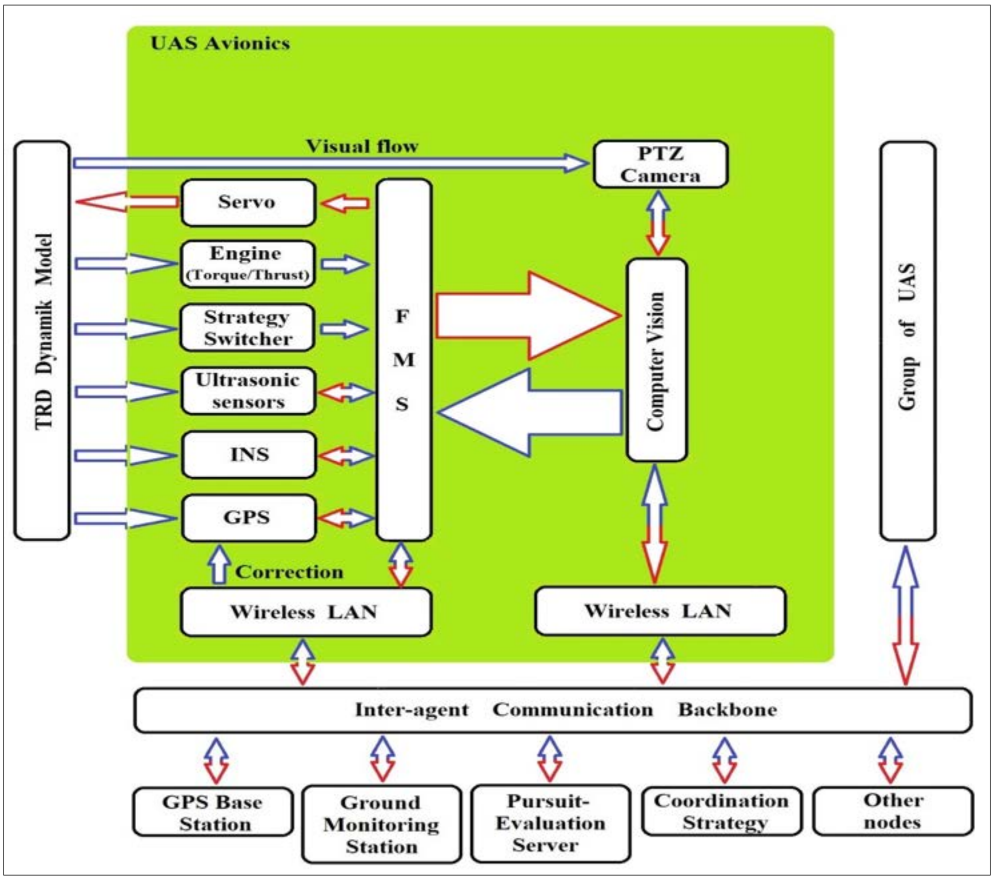

Figure 5: Bayraktar DİHA TRD Platform Architecture

The onboard flight computer is fundamental to the guidance, navigation, and control of the host drone. It is in concern of real-time UAS control, sensor integration, and inter-agent communication. The flight management software system is executed in the real-time operating system. The input to the servo control system is processed at 50 Hz using the flight control algorithms [12].

The navigation system is made over INS and GPS. INS delivers position, velocity, attitude angles and levels at an arbitrarily high rate. A weakness of INS is the boundless fault developing quickly over time. This can be successfully adjusted by an outward locate sensor such as GPS. Due to the matching features of INS and GPS, a grouping of these sensors has enhanced a universal arrangement for UAS. To obtain the setting-specific info such as the relative distance from the ground or nearby objects, laser range detectors, ultrasonic sensors, and vision sensors are treated as well [14].

Bayraktar DİHA TRDs are furnished with an onboard vision handling unit (VHU) and a camera boarded on a tilt platform. The VHU paths indicators of specific model and approximate the virtual flow amongst the camera and the object. For independent take-off and landing, a vision-created sensing estimates the comparative space and slope angles to the indicator on the landing site. The VHU approximate is adapted with navigation data commencing the onboard computer through a sequential tie [15].

Wireless network is employed to realise the remote availability and connectivity amongst numerous agents. The communication stream on the communication connection is labelled in a regulated communication arrangement, which allows the interoperability of airborne and ground-created agents [12].

Tilt-Rotor Drone Dynamics

A TRD is a kindly nonlinear multi-input multi-output (MIMO) system, which is revealed to critical disorder such as its peculiar rotor wake and wind gusts. The modelling of the UAS merits a dedicated exposure and the complete details of the active simulations, beginning which the suggested control rules are constructed, is observed in Ref. [15].

The total dynamics of a TRD are modelled as a set of nonlinear differential equations, which is split into the kinematics (1st two equations) and the system dynamics (the last one) [12]:

$$[\dot{s}^S, \dot{y}^S, \dot{z}^S]^T = R^{B\rightarrow S}[\dot{x}^B, \dot{y}^B, \dot{z}^B]^T, \quad (1)$$

$$\frac{d}{dt}\begin{bmatrix}\phi\\ \theta\\ \psi\end{bmatrix} = \begin{bmatrix}1 & sin\phi\tan\theta & cos\phi\tan\theta\\ 0 & cos\phi & -sin\phi\\ 0 & sin\phi\cos\theta & cos\phi\cos\theta\end{bmatrix}, \quad (2)$$

$$\dot{s}^D(t) = f_c(x^D(t), u(t)), \quad (3)$$

where

$$x = [x^K, x^D]^T \in R^{n_x},$$

$$x^K = [x^S, y^S, z^S, \phi, \theta, \psi]^T$$

$$x^D = \left[u, v, w, p, q, r, a_{1s}, b_{1s}, r_{fb}\right]^T,$$

$$u = \left[u_{a1s}, u_{b1s}, u_{\theta M}, u_{r_{ref}}\right]^T \in R^{n_x}.$$

At this point S and B indicates 3-D and body coordinates. $\dot{x}^B$, $\dot{y}^B$ and $\dot{z}^B$ u,v and w correspondingly, will be treated for notational ease) designate velocity regarding the body-coordinate framework. ϕ, θ, and ψ mean roll, pitch, and yaw, and p,q and r are their rates, correspondingly [15].

The factors a_{1s} and b_{1s} are longitudinal and lateral flap angles, and r_{fb} is the feedback gyro system state [6]. The dynamic model, as in Eq. (3) has four enters. u_{a1s} and u_{b1s} control lateral and longitudinal repeated pitch, correspondingly. The cyclic pitch changes the original pitch of every rotor blade throughout a cycle to vary the trend of the thrust vector. $u_{\theta M}$ is the servosystem response for the main rotor cooperative pitch. The cooperative control changes the pitch of all blades and thus variations the magnitude of the thrust direction. $u_{r_{ref}}$ controls the amount and direction of the rear rotor thrust, which counters the anti-torque of the front rotor and thus controls the heading angle. Anticipated to the intricacy and the ambiguity essential to aerodynamic orders, the dynamic simulation was recognized by using a parametric recognition procedure to a set of test flight statistics. A test data put on frequency curving signals to the instrumented TRD in longitudinal, lateral, pitch and yaw paths in turn, whilst providing the drone's general stability. The UAV reaction is determined by the navigation sensors and transferred to the base station through a wireless link. The verified extent is prepared and then treated by forecast error technique, a time-domain parametric identification approach [11]. The followed model for the last equation (Eq. (3) is a lined time-invariant structure with conditions and responses described beyond. Figure 6 matches the state variables expected by the recognized model, which confirms an adequate match with the real mission data [15].

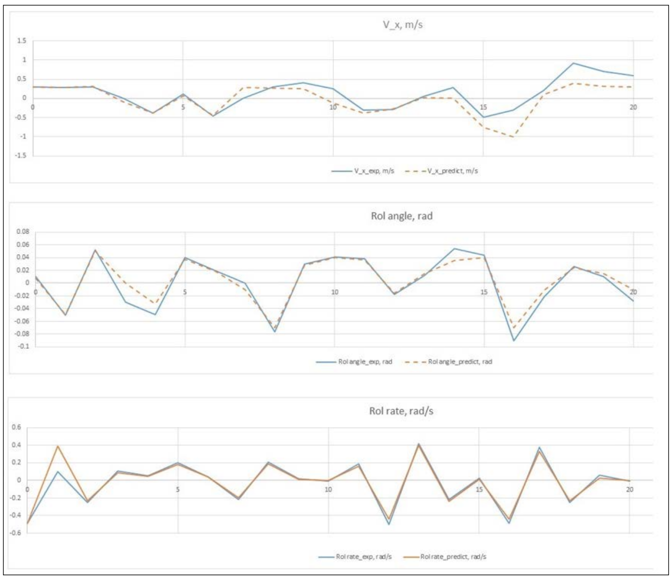

Figure 6: Identification Simulation: Data (Solid) vs. Prediction by the Identified Model (Dotted) during 20 s Experiments

Tilt-Rotor Drone Stabilization and Tracking

In the primary approximate, multiple single-input, single-output (SISO) control loops are aimed across the four inputs of longitudinal / lateral cyclical pitches and main / tail cooperative pitches [12]. This consider has evident benefits in conditions of an easier configuration, basic design practice, and low processing capacity. On the other hand, it acts not present a methodical approach to describe for improbability, disturbance, and dispersion. Furthermore, it has extremely restricted implies to alleviate the coupling among passages.

The suggested controller contains of three loops [14]: 1) deepest attitude controller, 2) mid-loop linear velocity controller, and 3) outer loop attitude controller (Figure 7).

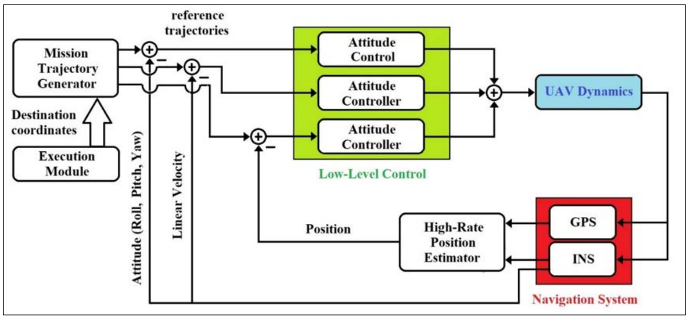

Figure 7: Multi-Loop Controller Architecture [12]

The attitude controller supplies reverse only the difference of the roll and pitch angles from the reduce situation (nonzero angle wanted to conserve a stability), not the noisy angular rates p and q measured by rate gyros. This methodology produces a controller that is easier and further tough to mechanical vibration. The suitable angular feedback gains for roll and pitch channels are established to take appropriate reaction speed and damping ratio [12].

The translational velocity dynamics of little TRDs are unstable through the attitude response only. They must be become stable using velocity response, which is established by a arrangement of root position and step response procedures [12].

For hover control, the position control circles in all 3 (x-, y-, and z) axis are included on important of the linear velocity and attitude response. The position control includes domestic coordinate conversion to reward the heading adjustment. The position gains are located by using the related techniques explained over to the extended TRD dynamics using velocity and attitude response. Lastly, whole acts are combined to remove steady-state faults and cut disparity [12].

Results and Discussion

The vertical and heading dynamics are naturally steady exactly to the interface amongst the inflow and the induced lift. The vertical reaction is advanced by synthetic dampening via destructive velocity reaction. For yaw tracing, the route fault and its integral are consumed back on top of the integral gyro system.

Briefly, the multi-loop PID control law is assumed as the subsequent regular equation [12]:

$$\begin{pmatrix} u_{a1s} = -K_{\phi}\phi - K_{\vartheta}\vartheta - K_y e_y s - K_{Iy}\int e_y s dt, \\ u_{b1s} = -K_{\theta}\theta - K_u u - K_x e_x s - K_{Ix}\int e_x s dt, \\ u_{\theta M} = -K_w w - K_z e_z s - K_{Iz}\int e_z s dt, \\ u_{r_{ref}} = -K_{\Psi}\Psi - K_{I\Psi}\int e_{\Psi} dt, \end{pmatrix} \quad (4)$$

where e_x, s, e_y, s and $e_z s$ indicate the position error, and e_{ψ} indicates the leading error.

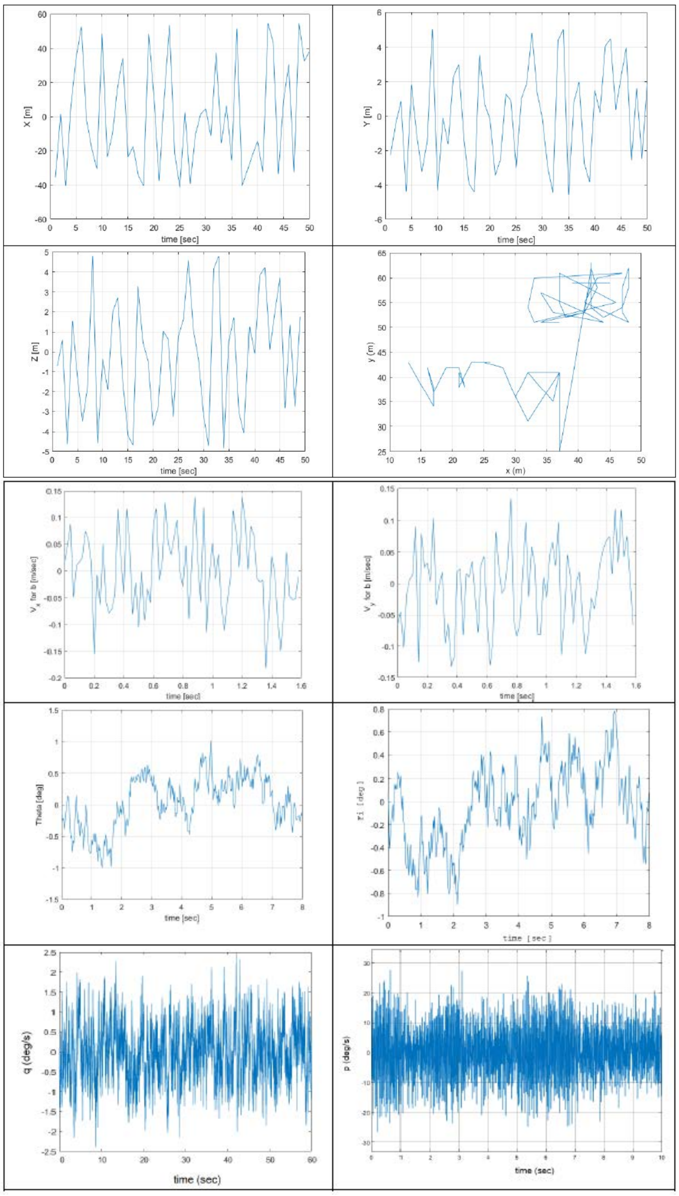

Figure 8: Experiment Result of Autonomous Hover

Figure 8 shows the experiment result of hovering controller tested on Tilt-Rotor Bayraktar DİHA Unmanned Aerial Platform (Turkey) [3]. The RUAV proven a steady and precise control reply through (±0.2; ±0.3; ±0.2 m; ±1.1^0) correctness in (x; y; z; ψ)-axis. Roll, pitch, translational velocity in x and y paths are controlled very well completely.

Earlier, we have shown that the conventional multi-loop control makes rationally fit. In order to advance the following presentation for composite routes by taking into account of nonlinear features, link between modes, and input/state capacity, we similarly reflect a nonlinear model prognostic controller as a chasing deposit.

To each model time, a nonlinear predictive controller calculates a determinate control arrangement, which reduces a cost function, naturally a weighted quadratic sum of positions and inputs completed a finite distance. We used a discretized core model gained from a partly nonlinear continuous time model (with nonlinear force footings and complete nonlinear kinematic equations) [12].

As in Ref. [12] for the inner model, Eq. (2) is discretized to

$$x_{k+1} = f\left(x_k, u_k\right) \triangleq f_d(x_k) + B_d u_k,$$

$$f_d(x_k) \triangleq x_k + T_s f_c(x_k),$$

$$B_d \triangleq T_s B_c, \qquad (5)$$

where T_s is the sample time. For chasing, we describe a cost function as in Ref. [12]:

$$J = \phi(\tilde{y}_N) + \sum_{k=0}^{N-1} L(x_k, \tilde{y}_k, u_k), \qquad (6)$$

$$\phi\left(\tilde{y}_N\right) \triangleq \frac{1}{2}\tilde{y}_N^T P_0 \tilde{y}_N, \qquad (7)$$

$$L\left(x_k, \tilde{y}_k, u_k\right) \triangleq \frac{1}{2}\tilde{y}_K^T Q \tilde{y}_k + \frac{1}{2}x_k^T S x_k + \frac{1}{2}u_k^T R u_k, \qquad (8)$$

where $\tilde{y} \triangleq y_d - y, y = Cx + R^{n_y}, y_d$ is the wanted trajectory, and S is offered to confident the state variables that do not conventional seem in y. By offering an order of Lagrange multiplier vectors $\left\{\lambda_k \in R^{n_x}\right\}_{k=1}^{N}$, as like in Ref. [12]:

$$J = \phi(\tilde{y}_N) + \sum_{k=0}^{N-1} L(x_k, \tilde{y}_k, u_k), + \lambda_{k+1}^T[f(x_k, u_k) - x_{k+1}]. \qquad (9)$$

By defining the Hamiltonian function as

$$H_k = L\left(x_k, \tilde{y}_k, u_k\right) + \lambda_{k+1}^T f(x_k, u_k). \qquad (10)$$

In this case Eq. (6) can be represented as in [12] too:

$$J = \phi(x_N) - \lambda_N^T x_N + \sum_{k=1}^{N-1}\left[H_k - \lambda_N^T x_{N\,k}\right] + H_0. \qquad (11)$$

Meanwhile we need to selected $\left\{u_k\right\}_0^{N-1}$ that reduces *J*, we take a look at the expression for as in Ref. [12]:

$$J = \left[\frac{\partial\phi}{\partial x_N} - \lambda_{Nk}^T\right]dx_N + \frac{\partial H_0}{\partial x_0}dx_0 + \frac{\partial H_k}{\partial \tilde{y}_0}d\tilde{y}_0 + \frac{\partial H_k}{\partial u_0}du_0 + \\ + \sum_{k=1}^{N-1}\left[\left\{\frac{\partial H_k}{\partial x_k} - \lambda_k^T\right\}dx_k + \frac{\partial H_k}{\partial \tilde{y}_k}d\tilde{y}_k + \frac{\partial H_k}{\partial u_k}du_k\right]$$

Picking

$$\lambda_N^T = \frac{\partial\phi}{\partial x_N} - \tilde{y}_N^T P_0 C, \qquad (12)$$

$$\lambda_k^T = + \frac{\partial H_k}{\partial \tilde{y}_k}\frac{\partial \tilde{y}_k}{\partial x_k} = \mathrm{x}_k^T S + \lambda_{k+1}^T \frac{\partial f_k}{\partial x_k} - \tilde{y}^T QC \qquad (13)$$

yields

$$\sum_{k=1}^{N-1}\frac{\partial H_k}{\partial x_k}du_k + \lambda_0^T dx_0 \qquad (14)$$

and

$$\frac{\partial H_k}{\partial x_k} = \mathrm{u}_k^T R + \lambda_{k+1}^T \frac{\partial f_k}{\partial u_k}. \qquad (15)$$

With an primary rate of the input arrangement $\left\{u_k\right\}_0^{N-1}$ gained by means of a nonlinear predictive controller and an assumed $x_0, \left\{x_k\right\}_1^N$ are first calculated using Eq. (5). Then, for $k = N,...,1, \lambda_k$ are calculated recursively using Eq. (12)-(13), and for $k = N,\ldots,1, \lambda_k, \frac{\partial H_k}{\partial u_k}$ are calculated using Eq. (15) and used for the gradient descent. By setting u_k at the opening of the optimization at the iteration count decreases meaningfully [12].

Through an original amount of the input series $\left\{u_k^{(0)}\right\}_0^{N-1}$ acquired via a nonlinear predictive controller and a known $x_0, \left\{x_k\right\}_1^N$ are initially calculated applying expression (5). But then, for $k = N,\ldots,1,\lambda_k$ are computed recursively using expressions (12) and (13), and for $k = N,\ldots,1,\lambda_k, \frac{\partial H_k}{\partial u_k}$ are calculated with expression (15) and employed for the gradient incline. Via setting u_k at the beginning of the optimization at every time step with the u_k of the previous time trial, the iteration count decreases substantially.

Conclusion and Future Work

This article performed a hierarchical TRD flying control system. The UAS dynamics are labelled as a linear model from the test mission data. The tracing control cover is proposed managing the next two procedures: multi-loop PID control and nonlinear model analytical control. The performance of PID controller has been justified in tests that involve a tracing route of reasonable complexity. The nonlinear model predictive control has proved a remarkable tracing presentation in the presence of deep combination and control input capacity at the cost of deeper addition capacity.

The proposed multi-functional flight management system was confirmed in the tracking patterns: waypoint navigation, chasing of a moving objects and autonomous landing. Additional study exertion will be made to enlarge the capability of the flight management system with rich approach planning senses, enlarged robustness, and the broader flight envelope, therefore contraction down the break among existing TRDs and extremely manoeuvrable intelligent drones.

References

1. CH-10 Rainbow-10 Tilt-Rotor VTOL Shipboard Reconnaissance Strike Drone. Available online: https://www.globalsecurity.org/military/world/china/ch-10.htm
2. Yang Sheng, Liu Xuanzun, China reveals CH-10 tilt-rotor drone. Available online: https://www.globaltimes.cn/page/201810/1125359.shtml
3. Bayraktar DİHA - vertical take-off and landing reconnaissance drone can stay aloft for up to 12 hours. Available online: https://building-tech.org/%D0%A1%D0%BE%D0%BE%D0%B1%D1%89%D0%B5%D1%81%D1%82%D0%B2%D0%BE/bayraktar-di%CC%87ha---razvedivatelniy-bespylotnyk-vertykalnogo-vzleta-y-posadky-mozhet-ostavatsya-v-vozdukhe-do-12-chasov
4. Çakıcı F, K Leblebicioglu, Modeling and simulation of a small-sized Tiltrotor UAV, The Journ. of Defense Modeling & Simulation, 9(4), 2012: 335-345. Available online: https://www.researchgate.net/publication/258132199_Modeling_and_simulation_of_a_small-sized_Tiltrotor_UAV
5. H Wang, W Sun, C Zhao, S Zhang, J Han, Dynamic Modeling and Control for Tilt-Rotor UAV Based on 3D Flow Field Transient CFD. Available online: https://www.mdpi.com
6. RS Pessoa, Mathematical Modeling of a Tilt-Rotor Drone, Projeto de Graduacao, Pontifícia Universidade Católica do Rio de Janeiro, Brasil, 2017. Available online: https://www.maxwell.vrac.puc-rio.br/30497/30497.PDF
7. M Mousaei, J Geng, A Keipour, D Bai, S Scherer, Design, Modeling and Control for a Tilt-rotor VTOL UAV in the Presence of Actuator Failure, Proc. of 2022 IEEE/RSJ Int. Conf. on IROS, 4310-4317. Available online: https://arxiv.org/abs/2205.05533
8. WL Brogan, Modern Control Theory, 3rd Ed., Available online: https://dokumen.tips/documents/william-l-brogan-modern-control-theory-3rd-edibookfiorg.html?page=1
9. BL Stenens, FL Lewis, EN Johnson, Aircraft Control and Simulation: Dynamics, Control design, and Autonomous Systems, 3rd Ed., Wiley, 2016.
10. Advanced Avionics Handbook, U.S. Dept. of Transportation, FAA, 2009.
11. M Kayton, WR Friend, Avionics Navigation Systems, 2nd Ed., a Wiley-Intercience Publ., 2006.
12. HJ Kim, DH Shim, A flight control system for aerial robots: algorithms and experiments, Control Engineering Practice 11 (2003), 1389-1400. Available online: https://people.eecs.berkeley.edu/~sastry/pubs/PDFs%20of%20Pubs2000-2005/Pdfs%20of%20Misc.Others/Kim,H.Jin/KimFlightControlSystem2003.pdf
13. N Zosimovych, UAV Autopilot Controller with Test Dynamics Model Platform. XI Int. Sc. and Eng. Conf. IKT-2020, 9-11 Apr., Zhytomyrska Politechnyka Publisher, Zhytomyr, Ukraine, 135-138.
14. Virtual AC system controllers. Available online: https://www.emobility-engineering.com/virtual-ac-system-controllers/ .
15. N Zosimovych, Tilt-Rotor Drone - Flight Control System Design. XXII Int. Scientific and Pract. Conf. Proc. «Modern theories and improvement of world methods», June 06-09, 2023, Helsinki, Finland, 433-440. https://isg-konf.com/uk/modern-theories-and-improvement-of-world-methods/ .