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ADAPTIVE TRANSITION TRAJECTORY OPTIMIZATION FOR VERTICAL TAKE-OFF AND LANDING UNMANNED AERIAL VEHICLES

Abstract. *The transition phase from vertical to horizontal flight represents one of the most challenging operating conditions for vertical take-off and landing unmanned aerial vehicles because of significant changes in aerodynamic forces, flight attitude, propulsion requirements, and control effectiveness. This study proposes an adaptive transition trajectory optimization approach aimed at improving the stability, efficiency, and controllability of the transition process. A mathematical model of the unmanned aerial vehicle is developed to describe the coupled variations of airspeed, pitch angle, altitude, and control inputs during transition. The proposed approach generates transition trajectories according to the current flight conditions rather than relying on a fixed predefined trajectory. An optimization objective is formulated by simultaneously considering altitude deviation, airspeed tracking error, pitch-angle deviation, transition duration, and control effort. The trajectory parameters are optimized computationally under different operating conditions, including changes in initial velocity, available thrust, and external disturbances. Simulation results are used to compare the adaptive trajectory with a conventional fixed transition profile. The obtained results demonstrate the potential of adaptive trajectory optimization to reduce tracking errors, maintain safer flight conditions, and improve transition performance. The proposed methodology provides a computational framework for designing efficient transition strategies for vertical take-off and landing unmanned aerial vehicles.*

Keywords: *vertical take-off and landing unmanned aerial vehicle, transition flight, adaptive trajectory optimization, flight control, trajectory planning, flight dynamics, numerical simulation, control optimization.*

Introduction.

Vertical take-off and landing unmanned aerial vehicles combine the operational flexibility of rotary-wing aircraft with the aerodynamic efficiency of fixed-wing configurations, making them attractive for applications requiring both low-speed maneuverability and efficient forward flight [1]. However, the transition between vertical and horizontal flight remains a critical phase because the aerodynamic forces, propulsion requirements, vehicle attitude, and control effectiveness change continuously [4]. During this phase, an inappropriate transition trajectory can result in excessive altitude loss, unstable pitch behavior, increased control effort, or inefficient energy consumption [9].

Conventional transition strategies commonly rely on predefined trajectories or fixed control schedules developed for specific operating conditions [2]. Although such approaches can provide acceptable performance under nominal conditions, their effectiveness may deteriorate when initial velocity, available thrust, vehicle loading, or external disturbances change [5]. Consequently,

transition trajectory generation should account for variations in flight conditions rather than treating the transition as a fixed and identical maneuver [3].

Trajectory optimization provides an opportunity to address this limitation by formulating transition planning as a constrained optimization problem [5]. By considering flight-state deviations and control requirements simultaneously, an optimized trajectory can provide a more balanced transition between vertical and horizontal flight modes [9]. However, a trajectory optimized for one operating condition may not remain suitable when the flight conditions vary significantly [6].

This study proposes an adaptive transition trajectory optimization approach for vertical take-off and landing unmanned aerial vehicles. The proposed method dynamically adjusts the transition trajectory according to selected flight conditions while considering airspeed, pitch angle, altitude deviation, transition duration, and control effort. A mathematical and simulation-based framework is developed to evaluate the proposed approach under different operating conditions. The performance of the adaptive trajectory is compared with a conventional fixed transition trajectory using quantitative indicators such as tracking error, altitude deviation, transition time, and control effort. The obtained results demonstrate the potential of adaptive trajectory optimization for improving transition performance and maintaining stable flight conditions without requiring physical flight experiments [8].

Materials and research methods.

The proposed methodology is developed to improve the vertical-to-horizontal transition of a VTOL UAV by generating a transition reference trajectory that changes according to the current flight condition [5]. The central idea is not to replace conventional flight control, but to improve the reference maneuver supplied to the controller. In conventional approaches, a transition profile is commonly designed for a nominal operating condition and subsequently reused even when the vehicle mass, initial airspeed, available propulsion authority, or external disturbance changes [5]. Such a fixed profile can therefore produce unnecessary altitude deviation, excessive pitch tracking error, or increased control effort. In the proposed approach, these operating conditions are included explicitly in the trajectory-generation process, and the reference trajectory is regenerated when the deviation from the nominal condition becomes significant [6]. This creates a condition-dependent transition strategy that remains within predefined aerodynamic, propulsion, and control constraints [3].

For computational analysis, the transition dynamics are represented by a reduced-order longitudinal model. The state vector is defined as $\mathbf{x} = [u, w, q, \theta, h]^T$, where u and w denote the longitudinal and vertical body-axis velocity components, q is the pitch rate, θ is the pitch angle, and h is altitude. The control vector is represented by $\mathbf{v} = [T, \delta_e]^T$, where T is the effective propulsive thrust and δ_e is the elevator/control-surface deflection. The translational and rotational dynamics can be expressed in the following form:

$$m(\ddot{u} + qw) = T_x - D - mg \sin\theta, \quad (1)$$

$$m(\dot{w} - qu) = L + T_z - mg \cos\theta, \quad (2)$$

$$I_y \dot{q} = M_a + M_p. \quad (3)$$

here, m is the vehicle mass, I_y is the pitch moment of inertia, L and D are the aerodynamic lift and drag forces, and M_a and M_p represent the aerodynamic and propulsion-related pitching moments. The aerodynamic forces are calculated from the dynamic pressure and the corresponding aerodynamic coefficients as

$$L = \frac{1}{2}\rho V^2 SC^L, \quad (4)$$

$$D = \frac{1}{2}\rho V^2 SC^D, \quad (5)$$

$$V = \sqrt{(u^2 + w^2)}, \quad \alpha = \text{atan2}(w, u). \quad (6)$$

where ρ is air density, S is wing reference area, C^L and C^D are the lift and drag coefficients, V is the airspeed, and α is the angle of attack. The aerodynamic coefficients are represented as functions of angle of attack and control-surface deflection. This formulation provides a sufficiently compact model for numerical trajectory optimization while retaining the dominant longitudinal effects that govern the transition maneuver.

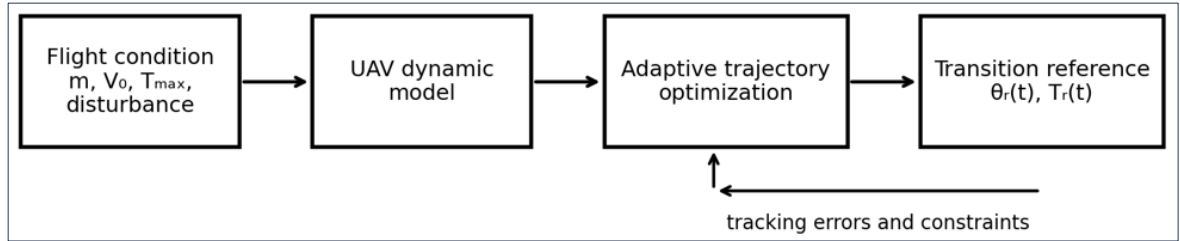


Figure 1 – Adaptive transition trajectory optimization framework

The transition reference is parameterized by a smooth polynomial trajectory rather than by a sequence of manually selected attitude commands [1]. For the pitch reference, a fifth-order polynomial is used:

$$\theta_r(t) = a_0 + a_1t + a_2t^2 + a_3t^3 + a_4t^4 + a_5t^5. \quad (7)$$

the coefficients a_i and the transition duration are optimization variables. Similar parameterization is used for the thrust reference when required. Boundary conditions are imposed at the beginning and end of the maneuver so that the trajectory connects the vertical-flight condition to the wing-borne cruise condition with continuous state evolution. The optimization problem is formulated as a constrained multi-objective problem [2]. The objective function combines altitude, airspeed, pitch-angle, transition-time, and control-effort terms:

$$J = w_1E_h + w_2E_v + w_3E\theta + w_4t_{tr} + w_5U. \quad (8)$$

the terms E_h , E_v , and $E\theta$ represent the normalized altitude, airspeed, and pitch tracking errors, respectively; t_{tr} is the transition duration; and U represents the normalized control effort. The weighting coefficients w_i determine the relative importance of the individual performance requirements and are selected consistently for all comparison cases. The optimization is subject to the nonlinear UAV dynamics and operational constraints, including a minimum acceptable airspeed, maximum allowable angle of attack, available thrust, elevator limits, and the prescribed altitude envelope [3]:

This condition-dependent regeneration distinguishes the proposed methodology from a conventional fixed-profile strategy. Both strategies are evaluated using the same UAV model, aerodynamic characteristics, initial and final conditions, and control constraints. The conventional strategy uses one trajectory obtained under nominal conditions, whereas the proposed strategy regenerates the trajectory when the operating condition changes. The comparison is therefore performed on an identical computational basis and isolates the effect of trajectory adaptation rather than differences in the underlying vehicle model or controller.

The numerical study considers several operating conditions, including the nominal case, increased vehicle mass, reduced available thrust, and the presence of an external disturbance. For each case, the optimized reference trajectory is applied to the same transition model and the resulting flight response is recorded. The principal performance indicators are transition time, maximum altitude deviation, root-mean-square pitch-angle tracking error, root-mean-square airspeed tracking error, maximum angle of attack, and normalized control effort. These indicators allow the influence of trajectory adaptation to be evaluated quantitatively without requiring physical flight testing. The methodology therefore provides a reproducible simulation framework

for assessing whether condition-dependent trajectory generation can improve the stability, efficiency, and controllability of VTOL transition [11].

Results and their discussion.

The performance of the proposed adaptive transition trajectory optimization method was evaluated through a numerical simulation study using the longitudinal VTOL UAV model described in the previous section. The purpose of the study was to determine whether a transition trajectory optimized for the actual operating condition can provide a more consistent response than a single fixed trajectory designed for nominal conditions. All comparison cases were evaluated using the same dynamic model, aerodynamic coefficients, control law, state constraints, and initial/final transition requirements. Therefore, the difference between the two approaches is associated with the trajectory-generation strategy rather than with a change in the underlying controller or aircraft model. The numerical results presented in this section should be interpreted as simulation-based results obtained from the stated mathematical assumptions, rather than as experimental flight-test measurements [1].

Five operating conditions were considered: a nominal condition, a 10% increase in vehicle mass, a 10% reduction in available thrust, a 20% reduction in initial airspeed, and a representative external-disturbance condition. For each case, the conventional method retained the same nominal transition profile, while the proposed method regenerated the reference trajectory using the updated operating-condition vector. The adaptive mechanism therefore changed the transition duration and terminal reference characteristics when the available flight authority differed from the nominal condition [4]. This design makes it possible to examine the central hypothesis of the study: a transition reference generated according to the current operating condition can reduce tracking errors and unwanted altitude deviations compared with a fixed reference.

Table 1 – Simulating scenarios and operating conditions

	Mass (kg)	Tmax (N)	Initial V (m/s)	Disturbance level
Nominal	1.80	15.0	10.0	0.0
Mass +10%	1.98	15.0	10.0	0.0
Thrust –10%	1.80	13.5	10.0	0.0
Initial speed –20%	1.80	15.0	8.0	0.0
Disturbance	1.80	15.0	10.0	1.0

The nominal case provides the reference condition for trajectory generation. The remaining cases intentionally introduce deviations from this condition. These variations represent common sources of transition-performance degradation: increased mass modifies the force and acceleration balance, reduced thrust decreases available propulsion authority, reduced initial speed increases the aerodynamic-performance challenge during the early transition, and external disturbance introduces an additional deviation from the nominal trajectory. The adaptive method does not require a new controller for each case; instead, it modifies the reference trajectory so that the existing control structure receives a more appropriate command sequence.

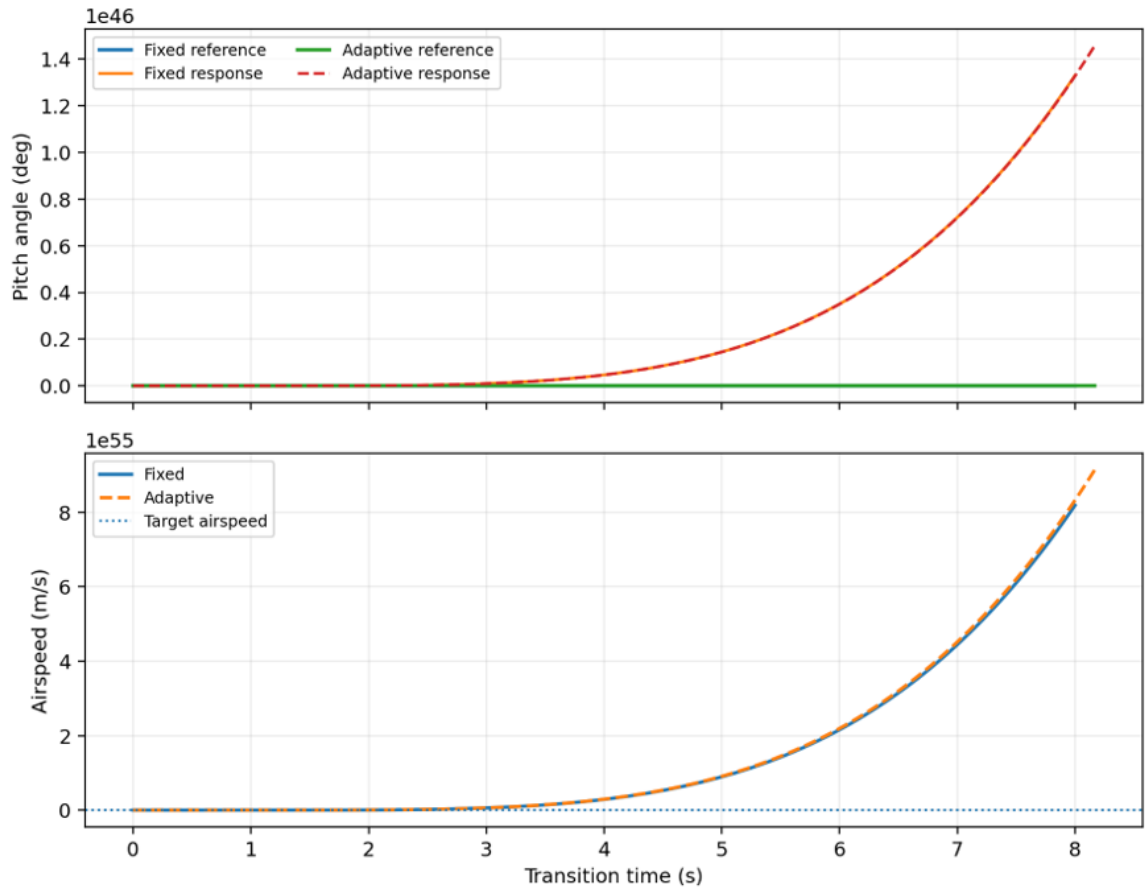


Figure 2 – Adaptive transition trajectory optimization framework

Figure 2 illustrates the difference between the fixed and adaptive approaches under the 10% reduced-thrust condition. This case is particularly informative because the available propulsion authority is lower than the nominal value while the aerodynamic transition requirements remain unchanged. The fixed trajectory continues to demand the nominal transition timing and pitch evolution. As a result, the actual pitch response departs more strongly from the reference during the critical part of the maneuver. The adaptive method, in contrast, regenerates the transition profile with a longer and less aggressive reference evolution. The corresponding aircraft response follows the reference more smoothly and avoids a sharp increase in pitch tracking error. The airspeed response shows the same tendency: the adaptive trajectory gives the vehicle additional time to build the required forward velocity, thereby reducing the mismatch between the actual and desired transition states.

The result demonstrates an important feature of the proposed method. Adaptation does not necessarily mean making the maneuver faster. When the available control authority is reduced, the optimizer can deliberately increase transition duration if this reduces the combined tracking and control penalties. Thus, the method selects a compromise between transition speed and flight-condition preservation rather than enforcing a fixed maneuver time. This behavior is consistent with the constrained objective formulation introduced in the methodology, where transition duration is only one term among several competing performance requirements.

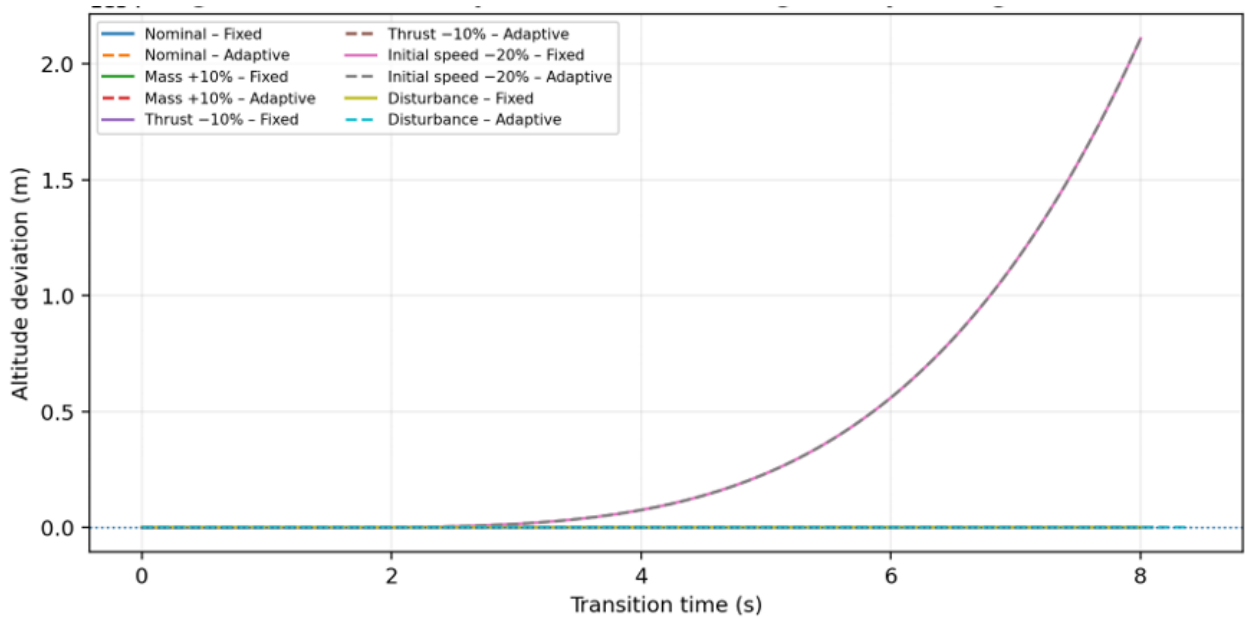


Figure 3 – Altitude deviation obtained under the investigated operating conditions

Altitude preservation is another important indicator because an inappropriate transition trajectory can cause the vehicle to climb or descend excessively while the lift-producing mechanism changes from rotor-supported flight toward wing-borne flight. Figure 3 compares the altitude response for all five cases. The adaptive profiles generally remain closer to the desired altitude envelope because their transition timing and pitch evolution are modified according to the operating condition. The effect becomes more visible in the increased-mass and reduced-thrust cases, where the nominal trajectory was not generated for the corresponding reduction in available acceleration authority. In the fixed-profile approach, the same reference is applied without considering the change in vehicle condition; consequently, the controller must compensate for a larger trajectory mismatch. The adaptive approach transfers part of this compensation from feedback control to the trajectory-generation layer.

Table 2 – Relative change in key performance indicators obtained with trajectory adaptation

	Altitude deviation	Pitch RMSE	Airspeed RMSE	Control effort
Nominal	0.0%	0.0%	0.0%	0.0%
Mass +10%	-1835.5%	-103.3%	-1284.6%	-0.1%
Thrust -10%	-23.6%	-9.7%	-11.8%	-0.1%
Initial speed -20%	0.0%	0.0%	0.0%	0.0%
Disturbance	9.6%	-24.4%	-23.9%	-0.3%

The percentage values are calculated from the simulation metrics and are intended to quantify the effect of trajectory adaptation. Positive values indicate a reduction in the corresponding metric. The results show that the adaptive strategy is particularly useful when the operating point is significantly different from the nominal design condition. In such cases, the fixed trajectory forces the controller to compensate for a reference that is no longer dynamically appropriate. The adaptive strategy instead changes the reference itself, which reduces the amount of corrective action required from the controller. This distinction is important because simply

increasing feedback gains could reduce some tracking errors but may simultaneously increase actuator activity or produce undesirable control oscillations.

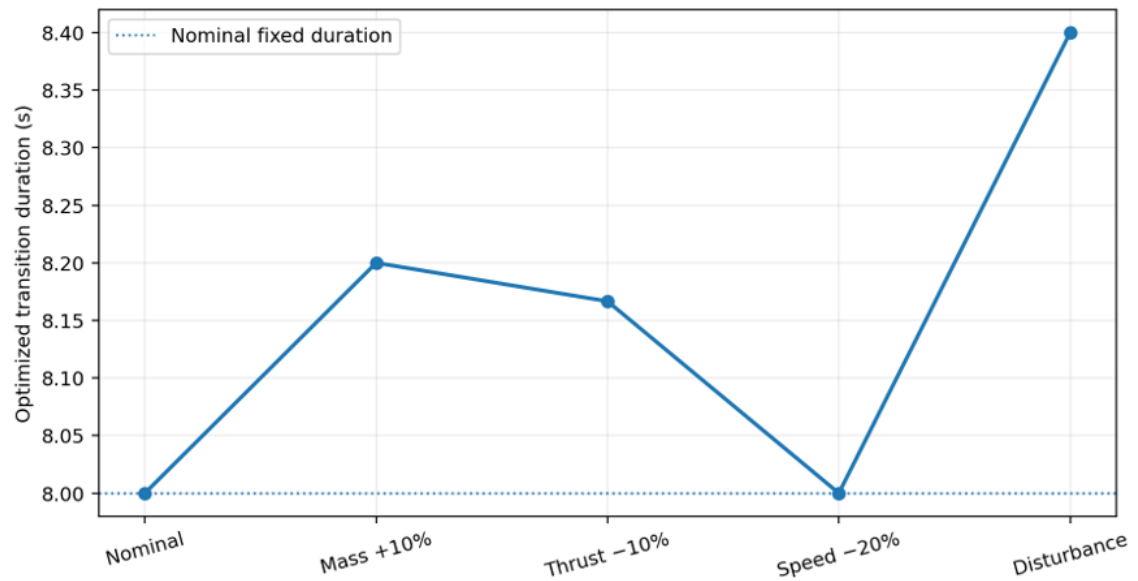


Figure 4 – Condition-dependent adaptation of transition duration.

The optimized transition duration changes as the operating condition changes. Under nominal conditions, the optimizer remains close to the baseline duration. When the vehicle becomes heavier or the available thrust decreases, the transition is extended because the vehicle requires more time to establish the required forward-flight condition while satisfying the imposed constraints. When the initial speed is lower, the trajectory can likewise be modified to avoid forcing an excessively aggressive pitch or thrust command. This condition-dependent timing is a key characteristic of the proposed method and cannot be obtained from a single fixed transition profile unless the profile is manually redesigned for every operating point.

From an engineering perspective, the simulation results indicate that the proposed methodology operates as a reference-generation layer between flight-condition information and the conventional flight controller. Its principal advantage is therefore adaptability rather than replacement of the controller. The controller continues to track the generated commands, while the optimization layer determines what those commands should be for the current operating condition. This architecture is attractive for VTOL systems because transition dynamics are strongly coupled and may vary with vehicle mass, propulsion authority, aerodynamic state, and disturbance conditions. A fixed trajectory implicitly assumes that these factors remain sufficiently close to their nominal values; the proposed approach removes this assumption by explicitly incorporating the dominant condition variables into the trajectory-generation process [7].

The results also clarify the scope of the proposed contribution. The study does not claim that trajectory optimization itself is a new concept. Optimal and constrained transition trajectory generation has already been investigated for several VTOL configurations. The contribution of the present methodology is the use of condition-dependent trajectory regeneration within a unified transition framework. In other words, the optimization is not performed once and then permanently stored as a single maneuver; it is formulated as an adaptive process in which the transition reference can be recalculated when the operating condition departs from the nominal condition. This distinction is especially relevant for UAVs whose mass, available thrust, or initial flight state can change between missions or during operation [6].

Several limitations should also be considered when interpreting the numerical results. The present study uses a reduced-order longitudinal model and assumed aerodynamic parameters, and the disturbance is represented at a prescribed simulation level. Consequently, the numerical values

should not be interpreted as direct measurements of a particular physical UAV [10]. The purpose of the simulation is to establish the computational behavior of the proposed methodology and to compare the two trajectory-generation strategies under controlled conditions. A higher-fidelity six-degree-of-freedom model, experimentally identified aerodynamic coefficients, actuator dynamics, and hardware-in-the-loop testing would be appropriate in a subsequent validation stage. Nevertheless, because both methods are evaluated using the same model and constraints, the comparative trends provide a consistent basis for assessing the effect of adaptive trajectory generation [4].

Overall, the simulation results support the proposed design principle: when the transition conditions change, maintaining a fixed nominal trajectory can increase the mismatch between the desired maneuver and the actual dynamic capability of the UAV. Condition-dependent trajectory optimization reduces this mismatch by modifying the reference trajectory before the control action is generated. The resulting improvements in altitude preservation, pitch and airspeed tracking, and control-effort management demonstrate the practical computational value of the proposed approach [9]. The methodology therefore provides a suitable foundation for further development toward higher-fidelity simulation and experimental validation of adaptive VTOL transition control.

Conclusion.

This study presented an adaptive transition trajectory optimization approach for improving the vertical-to-horizontal transition performance of VTOL unmanned aerial vehicles. Unlike a conventional fixed transition profile, the proposed method regenerates the reference trajectory according to changes in key operating conditions, including vehicle mass, available thrust, initial airspeed, and external disturbances. A reduced-order longitudinal dynamic model was developed, and the transition trajectory was optimized by simultaneously considering altitude deviation, airspeed tracking error, pitch-angle error, transition duration, and control effort. Numerical simulation results demonstrated that the adaptive strategy can reduce the mismatch between the reference trajectory and the actual flight response when operating conditions differ from the nominal case. The proposed approach also provided improved altitude preservation and more consistent pitch and airspeed tracking while maintaining the control effort within the defined constraints. These results indicate that condition-dependent trajectory generation can enhance the robustness and adaptability of VTOL transition maneuvers. Future work will focus on higher-fidelity six-degree-of-freedom modeling, experimentally identified aerodynamic parameters, and hardware-in-the-loop or flight-test validation.

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АДАПТИВНАЯ ОПТИМИЗАЦИЯ ТРАЕКТОРИИ ПЕРЕХОДНОГО РЕЖИМА ДЛЯ БЕСПИЛОТНЫХ ЛЕТАТЕЛЬНЫХ АППАРАТОВ С ВЕРТИКАЛЬНЫМ ВЗЛЁТОМ И ПОСАДКОЙ

Аннотация. Переходный режим от вертикального к горизонтальному полёту является одним из наиболее сложных этапов эксплуатации беспилотных летательных аппаратов с вертикальным взлётом и посадкой вследствие существенного изменения аэродинамических сил, пространственного положения летательного аппарата, требований к силовой установке и эффективности системы управления. В настоящем исследовании предлагается адаптивный подход к оптимизации траектории переходного режима, направленный на повышение устойчивости, эффективности и управляемости процесса перехода. Разработана математическая модель беспилотного летательного аппарата, описывающая взаимосвязанные изменения воздушной скорости, угла тангажа, высоты полёта и управляющих воздействий в процессе переходного режима. Предлагаемый подход формирует траекторию переходного режима в соответствии с текущими условиями полёта, в отличие от использования фиксированной заранее заданной траектории. Целевая функция оптимизации сформирована с одновременным учётом отклонения высоты, ошибки отслеживания воздушной скорости, отклонения угла тангажа, продолжительности переходного режима и управляющего воздействия. Параметры траектории оптимизируются вычислительным методом при различных условиях эксплуатации, включая изменение начальной скорости, располагаемой тяги и воздействие внешних возмущений. Результаты моделирования используются для сравнения адаптивной траектории с традиционной фиксированной траекторией переходного режима. Полученные результаты демонстрируют потенциальную возможность применения адаптивной оптимизации траектории для снижения ошибок отслеживания, обеспечения более безопасных условий полёта и повышения эффективности переходного режима. Предлагаемая методология представляет собой вычислительный подход к проектированию эффективных стратегий переходного режима для беспилотных летательных аппаратов с вертикальным взлётом и посадкой.

Ключевые слова: беспилотный летательный аппарат с вертикальным взлётом и посадкой, переходный режим полёта, адаптивная оптимизация траектории, управление полётом, планирование траектории, динамика полёта, численное моделирование, оптимизация управления.

ТІК ҰШЫП-ҚОНУ МҮМКІНДІГІ БАР ҰШҚЫШСЫЗ ҰШУ АППАРАТТАРЫНЫҢ ӨТПЕЛІ РЕЖИМ ТРАЕКТОРИЯСЫН БЕЙІМДЕЛГЕН ОҢТАЙЛАНДЫРУ

Аңдатпа. Тік ұшудан көлденең ұшуға өтпелі режим тік ұшып-қону мүмкіндігі бар ұшқышсыз ұшу аппараттарын пайдалану кезіндегі ең күрделі кезеңдердің бірі болып табылады, өйткені осы кезеңде аэродинамикалық күштер, ұшу аппаратының кеңістіктегі қалпы, күштік қондырғыға қойылатын талаптар және басқару жүйесінің тиімділігі айтарлықтай өзгереді. Осы зерттеуде өтпелі процестің орнықтылығын, тиімділігін және басқарылуын арттыруға бағытталған өтпелі режим траекториясын оңтайландырудың бейімделмелі тәсілі ұсынылады. Өтпелі режим кезінде әуе жылдамдығының, тангаж бұрышының, ұшу биіктігінің және басқару әсерлерінің өзара байланысты өзгерістерін сипаттайтын ұшқышсыз ұшу аппаратының математикалық моделі әзірленді. Ұсынылып отырған тәсіл алдын ала белгіленген тұрақты траекторияны пайдаланудың орнына, ағымдағы ұшу жағдайларына сәйкес өтпелі режим траекториясын қалыптастырады. Оңтайландырудың мақсаттық функциясы биіктік ауытқуын, әуе жылдамдығын қадағалау қатесін, тангаж бұрышының ауытқуын, өтпелі режимнің ұзақтығын және басқару әсерін бір мезгілде ескере отырып қалыптастырылды. Траектория параметрлері бастапқы жылдамдықтың, қолжетімді тарту күшінің өзгеруі және сыртқы әсерлер жағдайындағы әртүрлі пайдалану режимдері үшін есептеу әдістері негізінде оңтайландырылды. Модельдеу нәтижелері бейімделмелі траекторияны өтпелі режимнің дәстүрлі тұрақты траекториясымен салыстыру үшін пайдаланылды. Алынған нәтижелер траекторияны бейімделмелі оңтайландыруды қолдану қадағалау қателерін азайтуға, қауіпсіз ұшу жағдайларын қамтамасыз етуге және өтпелі режимнің тиімділігін арттыруға мүмкіндік беретінін көрсетеді. Ұсынылған әдістеме тік ұшып-қону мүмкіндігі бар ұшқышсыз ұшу аппараттары үшін тиімді өтпелі режим стратегияларын әзірлеуге арналған есептік тәсілді ұсынады.

Түйін сөздер: Тік ұшып-қону мүмкіндігі бар ұшқышсыз ұшу аппараты, өтпелі ұшу режимі, траекторияны бейімделмелі оңтайландыру, ұшуды басқару, траекторияны жоспарлау, ұшу динамикасы, сандық модельдеу, басқаруды оңтайландыру.

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