Article

Real-Time Adaptive TECS Gain Tuning Using Neural Networks for Tiltrotor eVTOL

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Abstract: Tiltrotor electric Vertical Take-Off and Landing (eVTOL) aircraft encounter significant control challenges during the transition from hover to forward flight, particularly when using open-source autopilot systems like PX4. During this phase, the autopilot employs open-loop tilt angle control and linear weighting of rotor and fixed-wing control outputs, neglecting the aircraft's nonlinear dynamics and resulting in altitude loss. After the transition, when Total Energy Control System (TECS) activates in fixed-wing mode, its fixed gains fail to rapidly correct accumulated errors, exacerbating altitude subsidence. This paper proposes a novel approach to enhance TECS performance after forward transition by dynamically adjusting its gains in real-time using a simple neural network. By adapting gains based on the aircraft's state, this method minimizes altitude loss and stabilizes airspeed and pitch attitude more effectively. Simulation results demonstrate that the neural network-based adaptive TECS significantly reduces altitude subsidence and improves flight stability compared to static gain configurations. This research provides a practical solution to enhance the control performance of tiltrotor eVTOLs, addressing limitations in open-source autopilots and supporting their application in urban air mobility.

Keywords: Tiltrotor eVTOL; TECS; neural networks; adaptive gain tuning; (List three to ten pertinent keywords specific to the article; yet reasonably common within the subject discipline.)

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1. Introduction

The development of electric Vertical Take-Off and Landing (eVTOL) aircraft, particularly those with tiltrotor configurations, has gained significant attention due to their potential in urban air mobility and logistics. These hybrid aircraft integrate the vertical lift capabilities of helicopters with the forward flight efficiency of fixed-wing airplanes, necessitating advanced control systems to manage the transition from hover to cruise modes [1].

Open-source autopilot systems, such as PX4, are widely adopted for their accessibility and flexibility. TECS, introduced by Lambregts in 1983 [?], manages total energy—combining kinetic and potential energy—to regulate airspeed and altitude via coordinated throttle and elevator inputs. While effective for fixed-wing aircraft, its application to tiltrotor eVTOLs requires adaptation to address the unique dynamics of the transition phase. Previous studies have validated adaptive TECS strategies for fixed-wing aircraft [?] and proposed modifications for unmanned aerial vehicles [?], yet these approaches have not been explored during the transition phase of tiltrotor eVTOLs.

In PX4, the transition phase relies on open-loop tilt angle control and linear weighting of multicopter and fixed-wing control outputs, which neglects nonlinear dynamics and leads to altitude loss. TECS activates only after the transition, in fixed-wing mode, where its fixed gains fail to promptly correct errors accumulated during the transition. This study proposes a real-time adaptive TECS gain tuning framework using a simple neural network to address these limitations after forward transition. The neural network dynamically adjusts TECS gains based on the aircraft's current state (e.g., altitude error, airspeed, pitch rate), aiming to minimize altitude loss and ensure rapid stabilization of airspeed and pitch attitude. This approach provides a practical alternative to designing a complex transition control system.

The paper is structured as follows: Section 2 analyzes the transition phase of open-source autopilots and the limitations of TECS implementation. Section 3 details the neural network-based gain tuning methodology. Section 4 presents simulation results comparing the adaptive TECS with conventional methods. Section 5 concludes with implications and future research directions. Through this work, we aim to enhance the reliability and efficiency of control systems for next-generation eVTOL platforms. This study addresses the critical gap in tiltrotor eVTOL control by introducing a neural network-based adaptive TECS framework, offering a novel solution to the challenges of post-transition instability neglected by existing open-source autopilot systems.

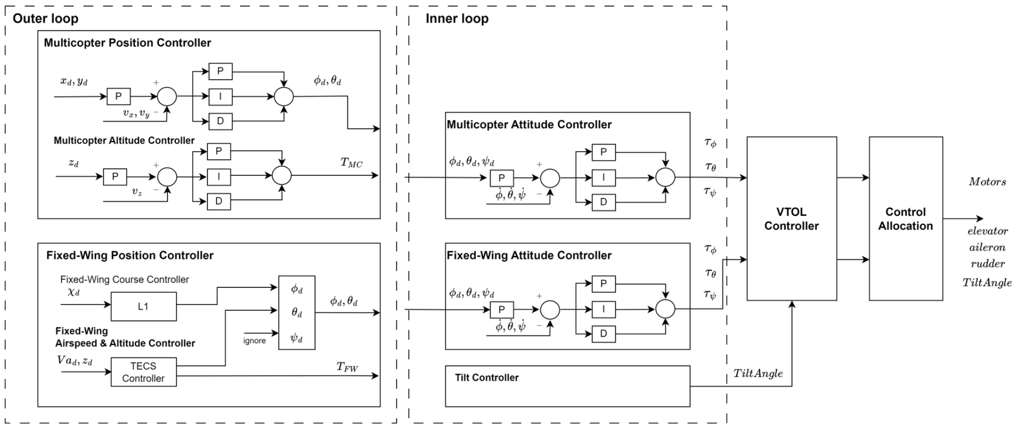

Figure 1. PX4 VTOL Control Structure

2. Literature Review

2.1. *Analysis of Open-Source Autopilot Transition Phase*

Open-source autopilot systems, such as PX4, support a variety of unmanned aerial vehicles (UAVs), including tiltrotor eVTOLs. However, their transition logic from hover to forward flight relies on simplified strategies that inadequately address the complex dynamics of hybrid aircraft. While TECS has proven effective for fixed-wing aircraft, its application to tiltrotor eVTOLs during the transition phase remains underexplored, necessitating adaptive strategies as proposed in this study.

2.1.1. Transition Phase Operation

The transition phase in open-source autopilots involves two key mechanisms:

- Open Loop Tilt Angle Control
  The front rotor of the tilt rotor tilts to a certain angle to achieve airspeed during the transition. Once the transition starting speed (BLENDED_ASPD) is reached, the transition algorithm begins. Until transition completion airspeed, tilt angle keep particular tilt an-

gle(VT_TILT_TRANS). When the transition completion speed (TRANSITION_ASPD) is reached, the switch to fixed-wing mode starts.

- Linear Weighting of Control Outputs
  At this point, the outputs for attitude control of the fixed-wing and rotary-wing are divided based on the current airspeed with weighting applied. Once the transition completion speed (TRANSITION_ASPD) is reached, the output of the fixed-wing control takes over completely.

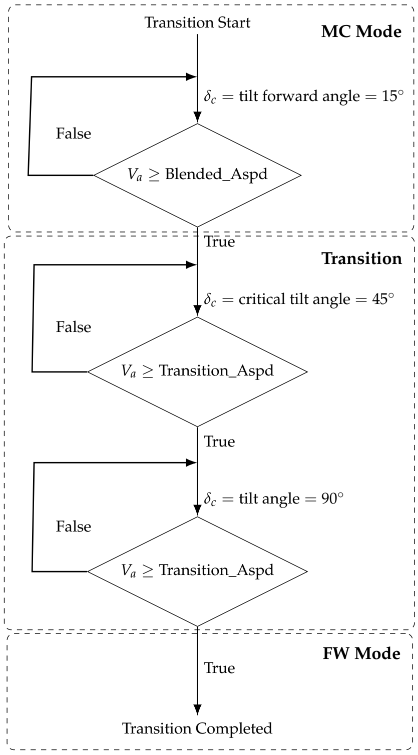

Figure 2. Flowchart for the Transition Process in Flight Modes

In the transition phase, the open-source method does not consider the aircraft's nonlinear dynamics, such as rotor tilt angle changes, which can lead to altitude loss and instability post-transition.

2.2. Total Energy Control System (TECS)

The Total Energy Control System (TECS) is a control strategy used in aircraft to manage their total energy, which consists of potential energy ($E_P = mgh$) and kinetic energy ($E_K = \frac{1}{2}mv^2$). TECS regulates airspeed and altitude by coordinating throttle and pitch inputs: throttle adjusts the total energy, while pitch controls the distribution of energy between altitude and speed.

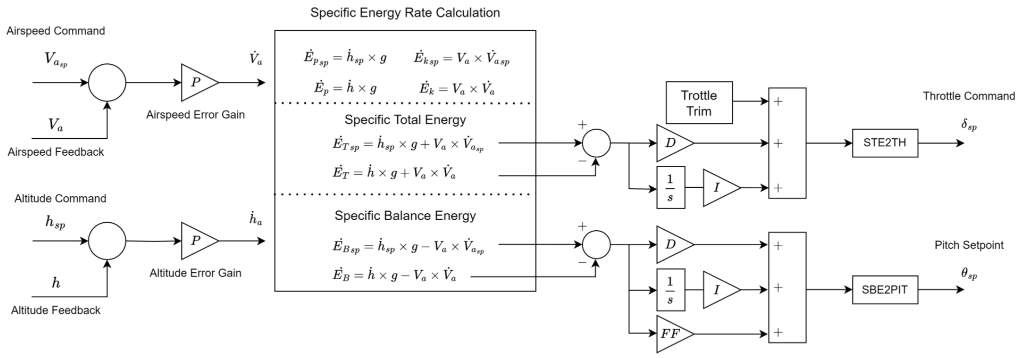

Figure 3. PX4 TECS Control Structure

In the Open-Source autopilot framework, TECS remains inactive during the transition phase of tiltrotor eVTOLs and only activates once the aircraft fully enters fixed-wing mode.

2.2.1. TECS Control Structure

TECS manages two primary functions:

- Total Energy Control: Adjusts throttle to regulate the total specific energy rate ($\dot{E}_T = \dot{E}_P + \dot{E}_K$), where:
  - $\dot{E}_P = \dot{h}g$ (potential energy rate, linked to altitude change),
  - $\dot{E}_K = v\dot{v}$ (kinetic energy rate, linked to speed change).
- Balance Energy Control: Adjusts pitch to control the balance specific energy rate ($\dot{E}_B = \dot{E}_P - \dot{E}_K$), ensuring proper energy distribution between altitude and airspeed.

The setpoints for these energy rates are defined as:

$$\dot{E}_{T_{\rm sp}} = \dot{h}_{\rm sp}g + v_a\dot{v}_{a_{\rm sp}}, \quad \dot{E}_{B_{\rm sp}} = \dot{h}_{\rm sp}g - v_a\dot{v}_{a_{\rm sp}} \tag{1}$$

where $\dot{h}_{\rm sp}$ is the desired altitude rate, v_a is the current airspeed, and $\dot{v}_{a_{\rm sp}}$ is the desired airspeed rate.

The control outputs—thrust ($\delta_{\rm sp}$) and pitch ($\theta_{\rm sp}$)—are calculated as:

$$\delta_{\rm sp} = \left(D_T(\dot{E}_{T_{\rm sp}} - \dot{E}_T) + I_T\int(\dot{E}_{T_{\rm sp}} - \dot{E}_T)\,dt + T_{\rm cruise}\right)\frac{1}{\dot{E}_{T,\max} - \dot{E}_{T,\min}} \tag{2}$$

$$\theta_{\rm sp} = \left(D_B(\dot{E}_{B_{\rm sp}} - \dot{E}_B) + I_B\int(\dot{E}_{B_{\rm sp}} - \dot{E}_B)\,dt + ff_B\dot{E}_{B_{\rm sp}}\right)\frac{1}{v_a g} \tag{3}$$

where:

- D_T, I_T: Derivative and integral gains for specific total energy rate,
- D_B, I_B: Derivative and integral gains for specific balance energy rate,
- ff_B: Feedforward gain,
- $T_{\rm cruise}$: Cruise thrust,
- $\dot{E}_{T,\max} = g \times$ max_climb_rate, $\dot{E}_{T,\min} = g \times$ max_descent_rate: Limits on energy rates.

For tiltrotors, the transition phase introduces unique dynamics, such as rotor tilt angle changes, which affect the balance between $\dot{E}_P$ and $\dot{E}_K$. Fixed gains, as used in PX4's default TECS, fail to adapt to these rapid changes, resulting in delayed altitude recovery and instability post-transition.

3. Methodology

3.1. Neural Network-Based Gain Tuning Methodology

To address the limitations of static TECS gains in managing the nonlinear dynamics of tiltrotor eVTOLs during the post-transition phase, this study introduces a real-time gain tuning methodology using a single-layer feedforward neural network. The approach dynamically adjusts the proportional (K_p) and integral (K_i) gains of TECS based on key flight states—such as altitude error, airspeed deviation, and pitch rate—thereby reducing altitude loss and enhancing stability immediately after transitioning to fixed-wing mode, while offering a computationally efficient solution for open-source autopilot systems.

3.1.1. Why Use a Neural Network?

Immediately after the transition to fixed-wing mode, the aircraft experiences residual effects from the transition phase, such as aerodynamic shifts and thrust vector changes. Fixed gains cannot adequately respond to these variations, leading to poor altitude control. A neural network enables real-time adaptation by learning and adjusting gains based on current errors (e.g., altitude and energy rate deviations), offering a robust solution for open-source platforms like PX4.

3.1.2. Neural Network Design

The proposed neural network is a simple two-layer feedforward network:

- **Inputs**:
  - Proportional error: $e_p(k) = \dot{E}_{\mathrm{sp}}(k) - \dot{E}(k)$,
  - Integral error: $e_i(k) = \sum \int e_p(k)\, dt$.
- **Outputs**:
  - Adjusted gains $K_p(k)$ and $K_i(k)$, computed using a sigmoid activation function:

$$f(x) = \frac{2(1 - e^{-x \cdot Y_g})}{Y_g(1 + e^{-x \cdot Y_g})} \tag{4}$$

  where $x(k) = K_p(k)e_p(k) + K_i(k)e_i(k)$, and Y_g is a tuning parameter shaping the sigmoid curve in figure 4.

The control input $u(k) = f(x)$ drives the TECS outputs (thrust and pitch), with gains updated dynamically.

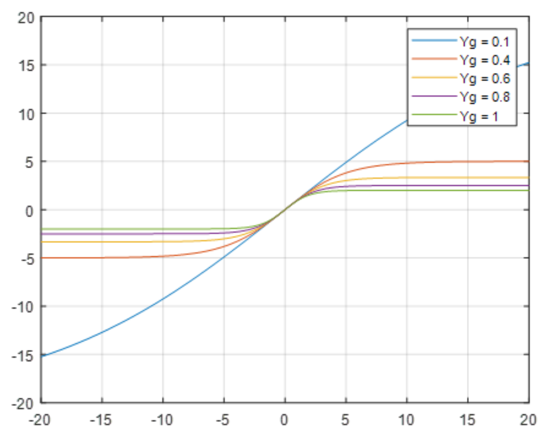

Figure 4. Sigmoid function shapes for different Y_g values

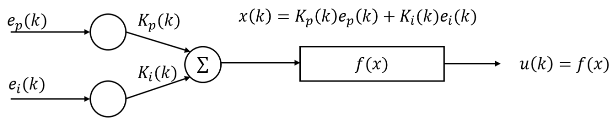

Figure 5. Neural network block diagram for adaptive TECS gain tuning

3.2. Tuning Process

The gains are tuned using the steepest descent method to minimize the cost function:

$$J(k) = \frac{1}{2}(\dot{E}_{\mathrm{sp}}(k) - \dot{E}(k))^2 \tag{5}$$

The update rules are:

$$K_p(k+1) = K_p(k) - \eta_p \frac{\partial J(k)}{\partial K_p(k)}, \quad K_i(k+1) = K_i(k) - \eta_i \frac{\partial J(k)}{\partial K_i(k)} \tag{6}$$

with partial derivatives:

$$\frac{\partial J(k)}{\partial K_p(k)} = -e_p(k) \cdot f'(x(k)) \cdot e_p(k), \quad \frac{\partial J(k)}{\partial K_i(k)} = -e_p(k) \cdot f'(x(k)) \cdot e_i(k) \tag{7}$$

where $f'(x) = \frac{4e^{-x \cdot Y_g}}{(1+e^{-x \cdot Y_g})^2}$, and η_p, η_i are learning rates.

This method replaces static gains with a dynamic, state-dependent tuning mechanism, ensuring computational efficiency for real-time implementation on autopilot systems.

3.3. Implementation and Validation

The proposed method will be implemented and tested using PX4 simulations, focusing on the post-transition phase in fixed-wing mode. Performance will be evaluated by comparing altitude stability and recovery time against the default fixed-gain TECS.

4. Model

4.1. Aircraft Model

In simulation, we focus on longitudinal dynamics, including altitude, airspeed, and pitch attitude control. The aircraft model used in the simulation is a tiltrotor eVTOL with the following parameters:

Physical Properties	
Symbol	**Value**
m	5.22 kg
J_x	1.229 kg·m²
J_y	0.1702 kg·m²
J_z	0.8808 kg·m²
J_{xz}	0.9343 kg·m²
S_{wing}	0.75 m²
b	2.10 m
$\bar{c}$	0.3571 m

Table 1. Physical Properties

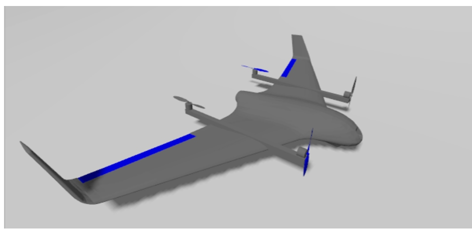

Figure 6. Tiltrotor Gazebo model

Figure 7. Aircraft Model Parameters and Tiltrotor Gazebo Model

where m is the mass, J_x, J_y, J_z, J_{xz} are the moments of inertia, S_{wing} is the wing area, b is the wing span, and $\bar{c}$ is the mean aerodynamic chord. The aerodynamic coefficients are also provided in Table 1.

Aerodynamic Coefficients

Symbol	Value
C_{L_0}	0.0867
C_{L_α}	4.02
C_{L_q}	3.8954
$C_{L_{\delta_e}}$	0.278
C_{D_0}	0.0197
C_{D_α}	0.0791
$C_{D_{\alpha^2}}$	1.06

Symbol	Value
C_{D_q}	0.0
$C_{D_{\delta_e}}$	0.0633
C_{m_0}	0.0302
C_{m_α}	-0.126
C_{m_q}	-1.3047
$C_{m_{\delta_e}}$	-0.206

Table 2. Aerodynamic Coefficients of the Aircraft Model

The aerodynamic coefficients are provided in Table 1. The lift, drag, and moment coefficients are defined as:

where C_{L_0} is the lift coefficient at zero angle of attack, C_{L_α} is the lift coefficient per unit angle of attack, C_{L_q} is the lift coefficient per unit pitch rate, $C_{L_{\delta_e}}$ is the lift coefficient per unit elevator deflection, C_{D_0} is the drag coefficient at zero angle of attack, C_{D_α} is the drag coefficient per unit angle of attack, $C_{D_{\alpha^2}}$ is the drag coefficient per unit angle of attack squared, C_{D_q} is the drag coefficient per unit pitch rate, $C_{D_{\delta_e}}$ is the drag coefficient per unit elevator deflection, C_{m_0} is the moment coefficient at zero angle of attack, C_{m_α} is the moment coefficient per unit angle of attack, C_{m_q} is the moment coefficient per unit pitch rate, and $C_{m_{\delta_e}}$ is the moment coefficient per unit elevator deflection.

$$L = \frac{1}{2}\rho v^2 S C_L, \quad D = \frac{1}{2}\rho v^2 S C_D, \quad M = \frac{1}{2}\rho v^2 S C_m \tag{8}$$

where L is the lift force, D is the drag force, M is the pitching moment, ρ is the air density, v is the airspeed, and S is the wing area.

4.2. Control System

The control system for the tiltrotor eVTOL consists of the following components:

- **Multicopter Attitude Control**: PID controllers for roll, pitch, and yaw control in Multicopter mode.
- **Multicopter Altitude Control**: PID controller for altitude control in Multicopter mode.
- **Fixed-Wing Attitude Control**: PID controller for attitude control in Fixed-Wing mode.
- **TECS**: Total Energy Control System for airspeed and altitude regulation.

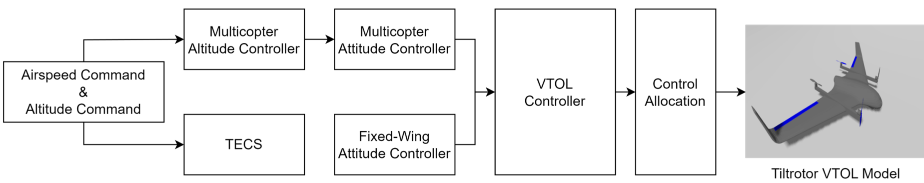

Figure 8. Control System Diagram

The control system diagram is shown in Figure 8.

In simulation, we focus on longitudinal dynamics, including altitude, airspeed, and pitch attitude control.

5. Simulation Results

5.1. Simulation Setup

The simulation environment used MATLAB Simulink. The aircraft model was integrated with the neural network-based adaptive TECS gain tuning method, replacing the default fixed gains. The simulation focused on the post-transition phase, with the aircraft transitioning from multicopter to fixed-wing mode at a predetermined airspeed. The initial condition is derived from the transition phase; thus, parameters governing this phase were carefully defined to establish the simulation conditions.

To ensure realistic and optimal performance, specific parameters were set for both the Vertical Take-Off and Landing (VTOL) transition and the Total Energy Control System (TECS) gain tuning. The VTOL parameters, which dictate the transition dynamics from multicopter to fixed-wing mode, include the critical tilt angle, transition thrust, blended airspeed, transition airspeed, and tilt rate. These values were selected based on typical configurations for tiltrotor electric VTOL (eVTOL) aircraft. Similarly, the TECS parameters, including learning rates, sigmoid shaping factors, and initial gains, were chosen to optimize the neural network's adaptability and ensure stability during gain tuning. Table 3 provides a detailed summary of these parameters and their values used in the simulation.

Table 3. Simulation Parameters for VTOL Transition and TECS Gain Tuning

Parameter	**Value**
VTOL Parameters	
Critical Tilt Angle	50 degrees
Transition Thrust	0.35
Blended Airspeed (BLENDED_ASPD)	8 m/s
Transition Airspeed (TRANSITION_ASPD)	15 m/s
TECS Parameters	
η_{ste} (STE Learning Rate)	0.000001
η_{sbe} (SBE Learning Rate)	0.000001
γ_g^{ste} (STE Sigmoid Parameter)	0.3
γ_g^{sbe} (SBE Sigmoid Parameter)	0.2
Initial K_p^{ste} (STE Proportional Gain)	0.8
Initial K_i^{ste} (STE Integral Gain)	0.02
Initial K_p^{sbe} (SBE Proportional Gain)	1.2
Initial K_i^{sbe} (SBE Integral Gain)	0.20

The VTOL parameters, such as Trnsition Thrust ,blended airspeed (BLENDED_ASPD), and transition airspeed (TRANSITION_ASPD) are critical for ensuring a smooth and stable transition phase. These are complemented by the TECS parameters, which enable the neural network to dynamically adjust gains in response to altitude and energy rate errors. The values presented in Table 3 were implemented in the simulation to evaluate the performance of the proposed adaptive TECS gain tuning method.

5.2. TECS State Response

Figure 9 show the altitude and airspeed responses across the entire simulation period (0-100 sec), respectively. The neural network-based TECS demonstrates significantly faster altitude recovery compared to the PX4 fixed-gain TECS, while both methods exhibit similar airspeed stabilization.

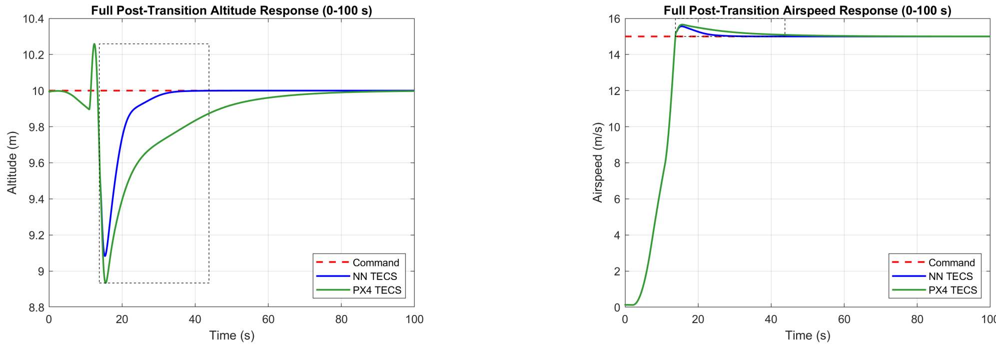

Figure 9. TECS State Response: Altitude and Airspeed Comparison.

5.3. Flight Mode

In Figure 10, we illustrate the transition from multicopter mode to fixed-wing mode, where TECS is activated in fixed-wing mode.

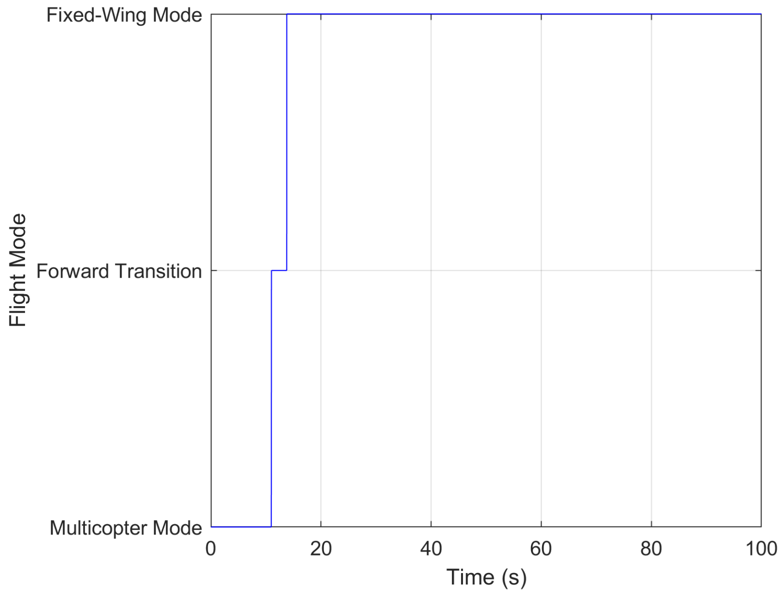

Figure 10. Flight Mode Transition: Multicopter to Fixed-Wing Mode.

In figure 10, 13.8 seconds is the time when the aircraft enters the fixed-wing mode. The transition phase is critical for the aircraft's stability and performance, and the neural network-based TECS gain tuning method significantly improves the aircraft's response during this phase.

5.4. Energy Rate Error Response

The energy rate error response is shown in Figure 11,12 . The neural network-based TECS demonstrates faster error reduction, leading to improved altitude and airspeed recovery and stability.

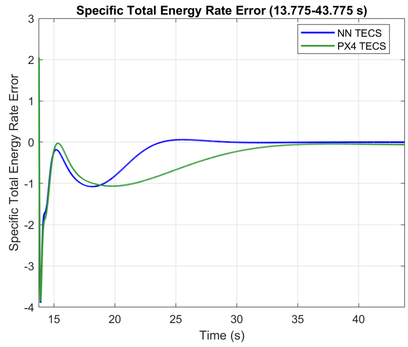

Figure 11. Specific Total Energy Rate Error (STE)

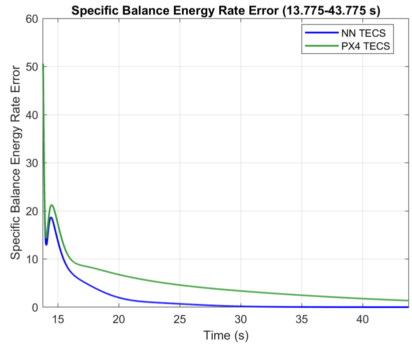

Figure 12. Specific Balance Energy Rate Error (SBE)

5.5. TECS Control Outputs

Figure 13 and Figure 14 present the thrust and pitch outputs of the TECS control system, respectively. These plots illustrate the control inputs applied post-transition, highlighting the neural network's ability to adjust these outputs for improved stability.

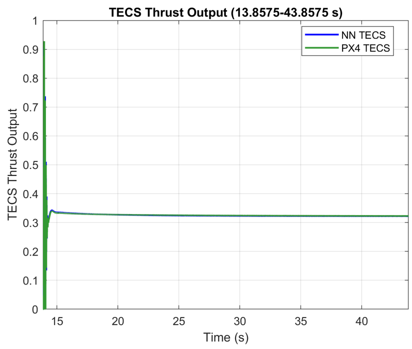

Figure 13. Thrust Output

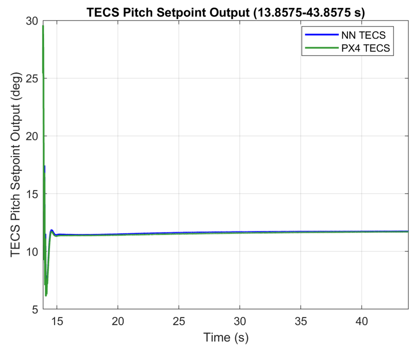

Figure 14. Pitch Output

5.6. TECS Gain Tuning

The TECS gain tuning process is illustrated in Figure 15, 16. The neural network dynamically adjusts the proportional and integral gains based on the altitude and energy rate errors, leading to improved performance during the post-transition phase.

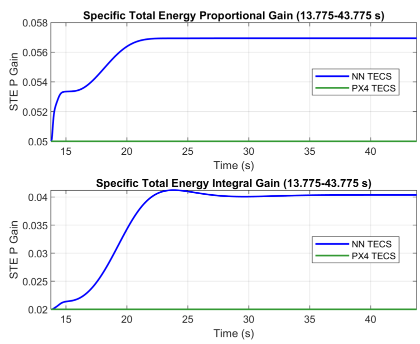

Figure 15. Total Energy Gain

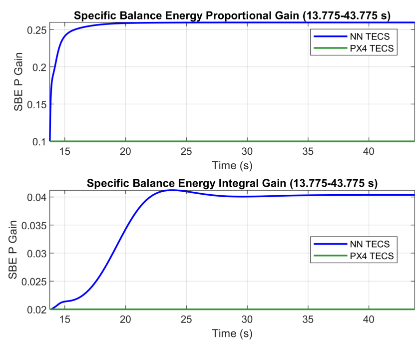

Figure 16. Balance Energy Gain

The gain tuning process is critical for ensuring the TECS can adapt to the changing dynamics of the aircraft during the transition phase. The neural network's ability to learn and adjust these gains in real-time significantly enhances the overall performance of the TECS.

5.7. Sensitive Analysis

The neural network-based adaptive TECS gain tuning method was tested under various conditions to evaluate its robustness and sensitivity to different flight states. The results demonstrate consistent performance across different scenarios, highlighting the method's adaptability and reliability.

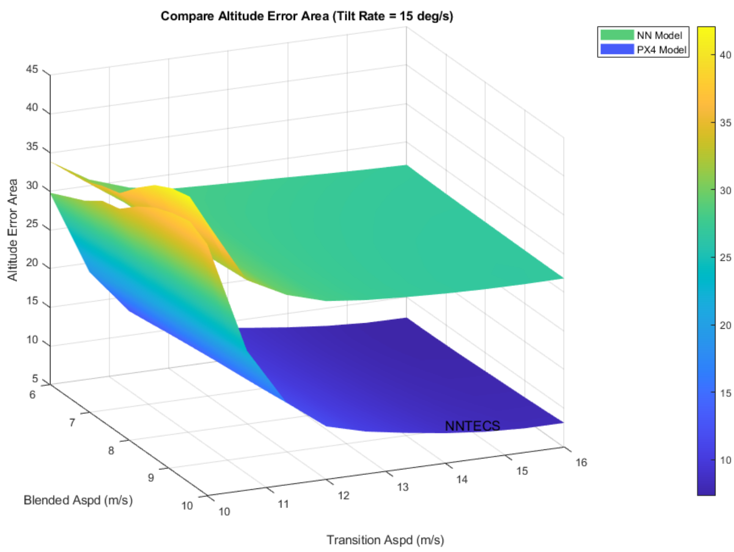

Figure 17. Sensitive Analysis: Neural Network TECS Performance under Different Flight States.

6. Discussion

7. Conclusions

This section is not mandatory, but can be added to the manuscript if the discussion is unusually long or complex.

8. Patents

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, X.X. and Y.Y.; methodology, X.X.; software, X.X.; validation, X.X., Y.Y. and Z.Z.; formal analysis, X.X.; investigation, X.X.; resources, X.X.; data curation, X.X.; writing—original draft preparation, X.X.; writing—review and editing, X.X.; visualization, X.X.; supervision, X.X.; project administration, X.X.; funding acquisition, Y.Y. All authors have read and agreed to the published version of the manuscript.", please turn to the CRediT taxonomy for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

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Data Availability Statement: We encourage all authors of articles published in MDPI journals to share their research data. In this section, please provide details regarding where data supporting reported results can be found, including links to publicly archived datasets analyzed or generated during the study. Where no new data were created, or where data is unavailable due to privacy or ethical restrictions, a statement is still required. Suggested Data Availability Statements are available in section "MDPI Research Data Policies" at https://www.mdpi.com/ethics.

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Abbreviations

The following abbreviations are used in this manuscript:

MDPI	Multidisciplinary Digital Publishing Institute
DOAJ	Directory of open access journals
TLA	Three letter acronym
LD	Linear dichroism

Appendix A

Appendix A.1

The appendix is an optional section that can contain details and data supplemental to the main text—for example, explanations of experimental details that would disrupt the flow of the main text but nonetheless remain crucial to understanding and reproducing the research shown; figures of replicates for experiments of which representative data are shown in the main text can be added here if brief, or as Supplementary Data. Mathematical proofs of results not central to the paper can be added as an appendix.

Table A1. This is a table caption.

Title 1	**Title 2**	**Title 3**
Entry 1	Data	Data
Entry 2	Data	Data

Appendix B

All appendix sections must be cited in the main text. In the appendices, Figures, Tables, etc. should be labeled, starting with "A"—e.g., Figure A1, Figure A2, etc.

References

1. Author 1, T. The title of the cited article. *Journal Abbreviation* **2008**, *10*, 142–149.
2. Author 2, L. The title of the cited contribution. In *The Book Title*; Editor 1, F., Editor 2, A., Eds.; Publishing House: City, Country, 2007; pp. 32–58.
3. Author 1, A.; Author 2, B. *Book Title*, 3rd ed.; Publisher: Publisher Location, Country, 2008; pp. 154–196.
4. Author 1, A.B.; Author 2, C. Title of Unpublished Work. *Abbreviated Journal Name* year, *phrase indicating stage of publication (submitted; accepted; in press)*.
5. Title of Site. Available online: URL (accessed on Day Month Year).
6. Author 1, A.B.; Author 2, C.D.; Author 3, E.F. Title of presentation. In Proceedings of the Name of the Conference, Location of Conference, Country, Date of Conference (Day Month Year); Abstract Number (optional), Pagination (optional).
7. Author 1, A.B. Title of Thesis. Level of Thesis, Degree-Granting University, Location of University, Date of Completion.