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 rotor 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.

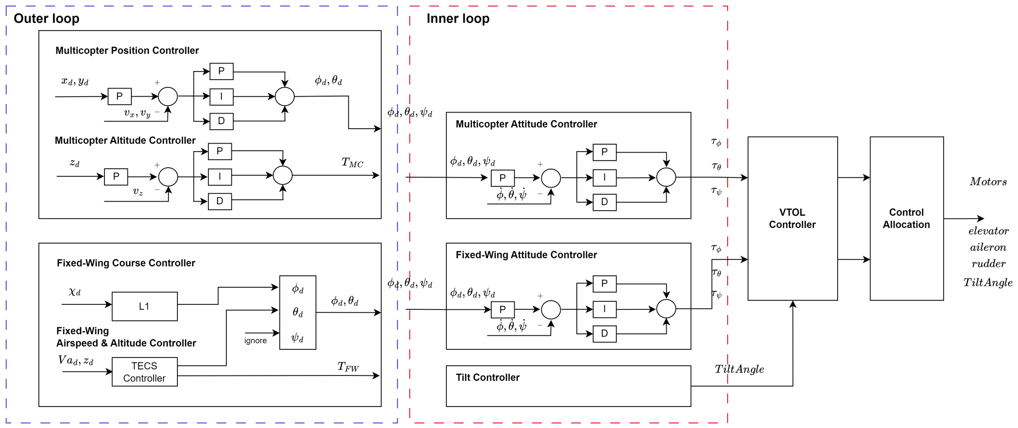

Figure 1. PX4 VTOL Control Structure

2. 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.

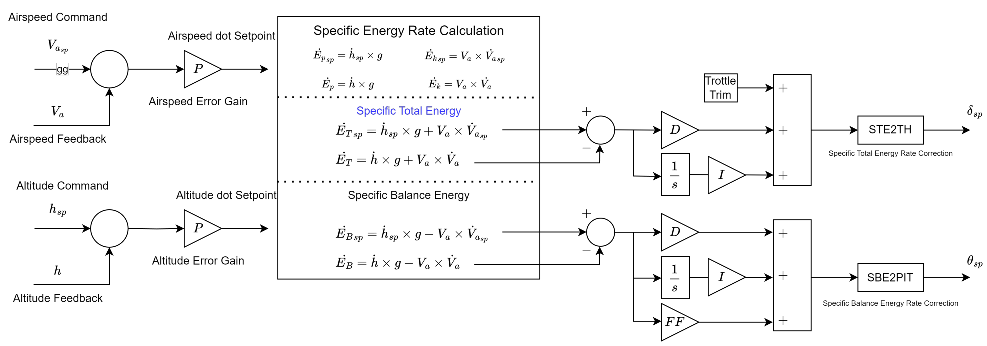

Figure 2. PX4 TECS Control Structure

2.1. Transition Phase Operation

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

- **Open-Loop Tilt Angle Control:** The autopilot tilts the rotors to a predefined angle without real-time feedback, assuming a smooth transition but lacking adaptability to aerodynamic changes or disturbances.
- **Linear Weighting of Control Outputs:** Control authority shifts from rotor-based to fixed-wing surfaces based on airspeed, with linear weighting applied. The transition completes when a predefined speed (e.g., 15 m/s) is reached, activating TECS in fixed-wing mode to manage airspeed and altitude.

2.2. Limitations of TECS Implementation

The transition strategy and subsequent TECS activation present several challenges:

- **Inadequate Dynamic Modeling During Transition:** The open-loop tilt control and linear weighting neglect the aircraft's nonlinear dynamics, such as rotor-wing interactions, leading to uncontrolled altitude loss. While airspeed reaches the transition threshold, altitude control is absent, resulting in subsidence.
- **Delayed TECS Activation After Forward Transition:** TECS activates only after the transition, managing total specific energy rate as: Errors (e.g., altitude loss) accumulated during transition persist until TECS engages, delaying corrective action.
- **Fixed-Gain TECS Limitations:** After forward transition, TECS uses fixed gains to compute control commands. These fixed gains fail to adapt to rapid state changes or accumulated errors, hindering effective altitude and airspeed correction.

TECS is Total Energy Control System The specific potential energy rate, defined as $\mathrm{SER}_{\mathrm{potential}} = g\dot{h}$ (where g is gravitational acceleration and $\dot{h}$ is altitude rate), remains unmanaged during this phase:

$$\mathrm{SER}_{\mathrm{potential}} = g\dot{h} \tag{1}$$

$$\mathrm{SER}_{\mathrm{total}} = \mathrm{SER}_{\mathrm{kinetic}} + \mathrm{SER}_{\mathrm{potential}} = v\dot{v} + g\dot{h} \tag{2}$$

where v is airspeed and $\dot{v}$ is airspeed rate. Errors (e.g., altitude loss) accumulated during transition persist until TECS engages, delaying corrective action.

TECS method can written by :

$$\delta_{\mathrm{sp}} = \left(D(\dot{E}_{T_{\mathrm{sp}}} - \dot{E}_T) + I \int (\dot{E}_{T_{\mathrm{sp}}} - \dot{E}_T)\, dt + T_{\mathrm{cruise}} \right) \frac{1}{\dot{E}_{T,\max} - \dot{E}_{T,\min}} \tag{3}$$

$$\delta_{\mathrm{sp}} = \left\{ D\left(\dot{E}_{B_{\mathrm{sp}}} - \dot{E}_B\right) + I \int \left(\dot{E}_{B_{\mathrm{sp}}} - \dot{E}_B\right) dt \right\} \frac{1}{v_a \cdot g} \tag{4}$$

where $\mathrm{SER}_{\mathrm{dist}} = v\dot{v} - g\dot{h}$ is the specific energy distribution rate, k_θ is the proportional gain, and $k_{I\theta}$ is the integral gain.

2.3. Proposed Improvement: Neural Network-Based Adaptive TECS

Since TECS is inactive during the transition phase, the proposed approach focuses on enhancing its performance post-transition. A simple neural network dynamically adjusts TECS gains based on the aircraft's state (e.g., altitude error, airspeed, pitch rate), enabling faster correction of accumulated errors. This method aims to minimize altitude loss and stabilize flight parameters after transition, offering a practical solution to the limitations of fixed-gain TECS in open-source autopilots.

The following sections will detail the adaptive gain tuning methodology, present simulation results, and discuss implications for tiltrotor eVTOL control.

3. Neural Network-Based Gain Tuning Methodology

The proposed methodology leverages a simple neural network to enable real-time adaptive tuning of TECS gains, addressing the dynamic challenges of tiltrotor eVTOLs during the transition phase. This approach aims to enhance control performance by dynamically adjusting gains based on the aircraft's current flight state, thereby mitigating altitude loss and improving stability.

The methodology consists of the following steps:

This approach differs from traditional TECS by replacing static gains with a dynamic, state-dependent tuning mechanism. The simplicity of the neural network ensures computational efficiency, making it feasible for real-time implementation on resource-constrained autopilot systems. The methodology builds on prior work in adaptive control [**?**] and neural network applications in flight control [**?**], tailoring these concepts to the unique needs of tiltrotor eVTOLs.

4. Results

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation as well as the experimental conclusions that can be drawn.

4.1. Subsection

4.1.1. Subsubsection

Bulleted lists look like this:

- First bullet;
- Second bullet;
- Third bullet.

Numbered lists can be added as follows:

1. First item;
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3. Third item.

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All figures and tables should be cited in the main text as Figure 3, Table 1, etc.

Figure 3. This is a figure. Schemes follow the same formatting.

Table 1. This is a table caption. Tables should be placed in the main text near to the first time they are cited.

Title 1	**Title 2**	**Title 3**
Entry 1	Data	Data
Entry 2	Data	Data [1]

[1] Tables may have a footer.

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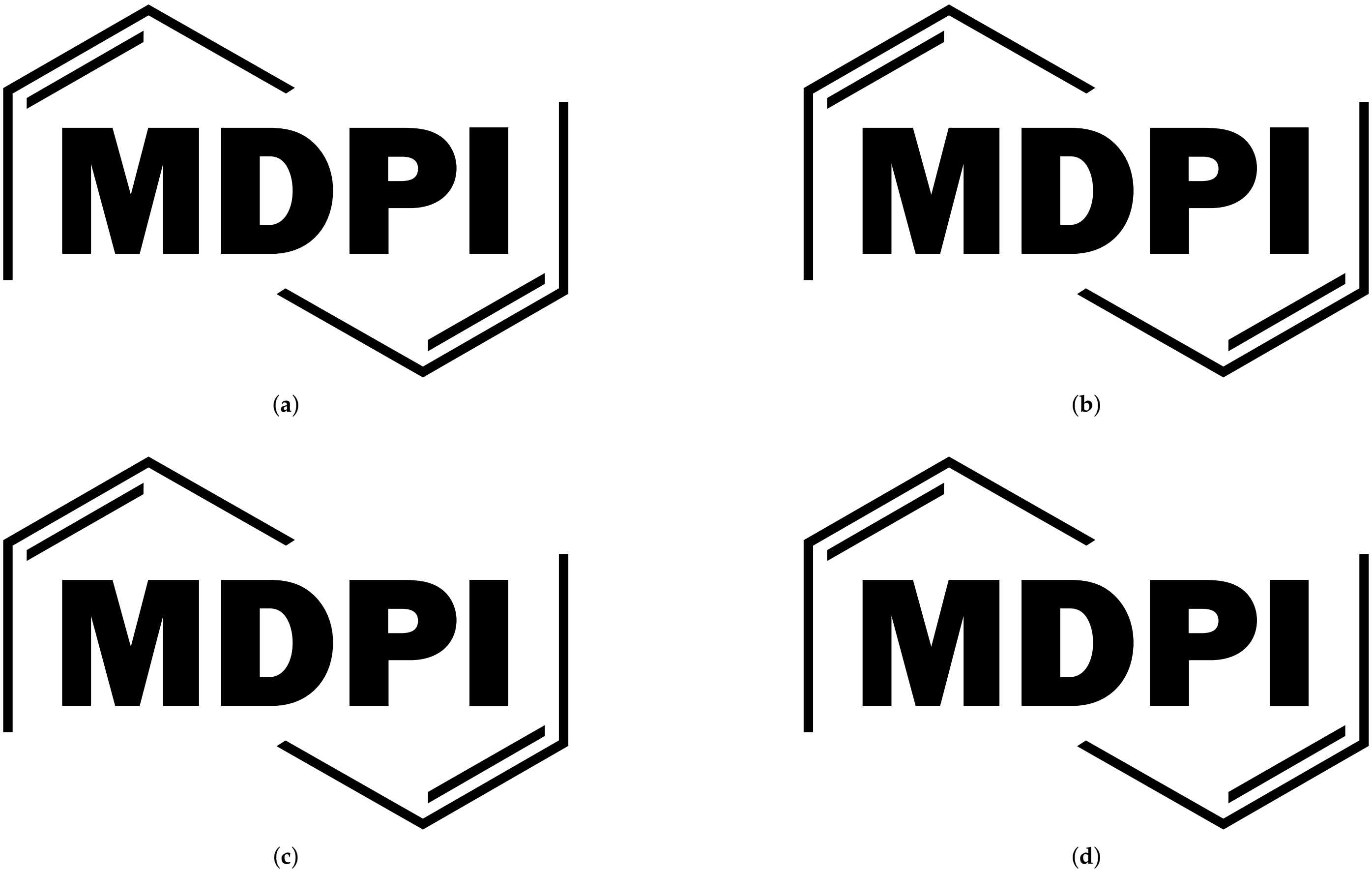

Figure 4. This is a wide figure. Schemes follow the same formatting. If there are multiple panels, they should be listed as: (**a**) Description of what is contained in the first panel. (**b**) Description of what is contained in the second panel. (**c**) Description of what is contained in the third panel. (**d**) Description of what is contained in the fourth panel. Figures should be placed in the main text near to the first time they are cited. A caption on a single line should be centered.

Table 2. This is a wide table.

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Entry 2	Data	Data	Data
	Data	Data	Data

* Tables may have a footer.

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4.3. Formatting of Mathematical Components

This is the example 1 of equation:

$$a = 1, \tag{5}$$

the text following an equation need not be a new paragraph. Please punctuate equations as regular text.

This is the example 2 of equation:

$$a = b + c + d + e + f + g + h + i + j + k + l + m + n + o + p + q + r + s + t + u + v + w + x + y + z \tag{6}$$

Please punctuate equations as regular text. Theorem-type environments (including propositions, lemmas, corollaries etc.) can be formatted as follows:

Theorem 1. *Example text of a theorem.*

The text continues here. Proofs must be formatted as follows:

Proof of Theorem 1. Text of the proof. Note that the phrase "of Theorem 1" is optional if it is clear which theorem is being referred to. □

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Authors should discuss the results and how they can be interpreted from the perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

6. Conclusions

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7. Patents

This section is not mandatory, but may be added if there are patents resulting from the work reported in this manuscript.

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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

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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)*.
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