# Intelligent Control for Electric-Vertical Take Off and Landing (e-VTOL) Aircraft

Mohammad Zaheed Elahi Kahooker
and
Dr. Hugh H.-T. Liu

University of Toronto Institute for Aerospace Studies
Flight Systems and Control Lab

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# Outline

Figure 1: BETA Aircraft ALIA-250 e-VTOL in forward flight [1]

# 1. Motivation

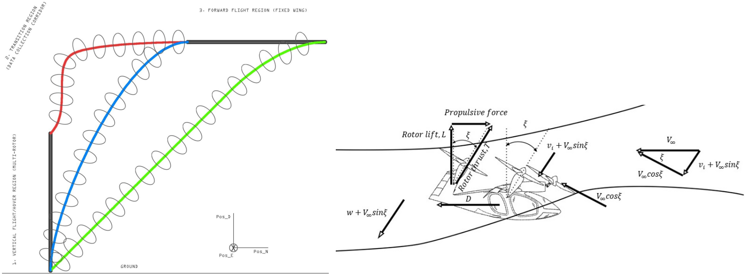
- In recent years there has been a growing interest in the possibilities of aerial mobility using Electric Vertical Takeoff and Landing, or e-VTOL aircraft. These vehicles combines feature from Fixed-Wing and Rotor-wing vehicles.
- e-VTOL aircraft combine the maneuvering capabilities of multi-rotors with the greater range and endurance as well as flight speeds of fixed-wing aircraft
- We aim to develop a customized e-VTOL aircraft flight simulator built from existing obsolete fixed-wing simulator hardware. Further, our mission is to connect this modified flight simulator to research on aspects of operation or control of e-VTOL aircraft.

# 2. Introduction

- Recent advancement in the electric-Vertical Take off and Landing (e-VTOL) aircraft sector brings the question of whether the technology will be fully autonomous, or remotely piloted, or with actual crew onboard.
- There are inherent challenges in operation of such aircraft configurations:
  - Propellers wake interactions.
  - Lack of flight test data.
  - Non-linearities in thrust, drag, and actuation.
- One of the flight regimes requiring further investigation was the transition from hovering to forward flight.
- In this regime, the vehicle moves from a helicopter hover in still air and gains forward speed to transition to fixed wing

# 2. Introduction

- An example of transition regime is shown in the diagram below:



(a) Different transition regimes for e-VTOL (b) Velocities and Force Distribution on e-VTOL during transition

Figure 2: e-VTOL Transition: Tilt-rotor example

# 2. Introduction

- e-VTOL aircraft, due to their hybrid configuration, need rethinking.
- They exhibit aerodynamics interaction between propellers, fuselage, and operate in regimes shared between a helicopter and fixed-wing aircraft.
- Some of the common challenges for e-VTOL vehicles are:
  - Rotor-fuselage and rotor-wings interactions.
  - Lack of empirical data from flight tests.
  - Challenging control characteristics:
    - Control degradation after rotor failures;
    - transition region between fixed-wing and helicopter motion;
    - rotor tilting mechanism, to mention a few.

# 3. Literature Distribution

## *3.1 Intelligent Control for Transition Flight*

Many of literature rely on model-based methods and have shortcomings if the models are not accurately representative. Making our case for Intelligent Control for transition flight promising.

- 250 papers surveyed.
- 28 papers of high relevance.
- divided into categories below:

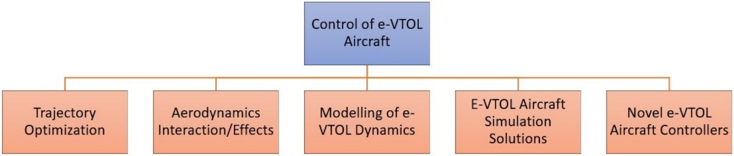


Figure 3: Distribution of Literature
for e-VTOL Control [2], [3], [4], [5], [6], [7], [8]

# 4. Thrust and Lift requirements for e-VTOL

## *4.1 Example: Tiltrotor e-VTOL Aircraft*

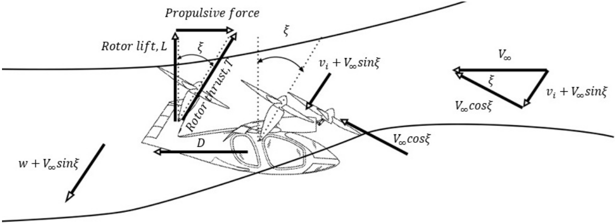


Figure 3: Velocity and Forces on Tilt-rotor e-VTOL [9]

### Specifications and flight condition:

Table 1: Specifications for Example Tilt-rotor e-VTOL Aircraft [1]

| $m\ (kg)$ | $S\ (m^2)$ | $b\ (m)$ | $\bar{c}\ (m)$ | $CL_{\alpha_0}\ (NACA-2412)$ | $\rho\ (\frac{kg}{m^3})$ | $W\ (N)$ |
|---|---|---|---|---|---|---|
| 2000 | 24 | 15 | 1.6 | 0.20 | 1.225 | 20000 |

# 4.1 Example: Tiltrotor e-VTOL Aircraft

$$L_{wing} = \frac{1}{2}\rho V_{\infty}^{2} S C_{L\alpha=0} \tag{1}$$

$$T_{vertical} = W cos(\xi) \tag{2}$$

$$T_{horizontal} = W sin(\xi) \tag{3}$$

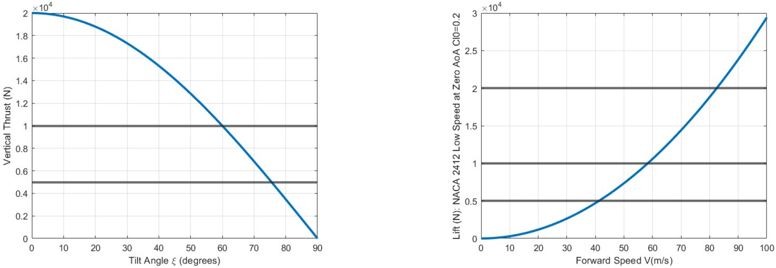


Figure 4: Propeller Lift and Wing Lift

To sustain the weight, we need about $V = 85m/s$.
Assuming forward acceleration $a = 9.81\frac{m}{s^2}$ and no drag. to get to 85 m/s it will take 9 seconds approximately. Meaning:

$$V = at + V_0 = 9.81t \tag{4}$$

Lift equation will be modified with respect to time:

$$L_{wing} = \frac{1}{2}\rho(9.81t)^2 SC_{L\alpha=0} \tag{5}$$

Similarly, we assume 10 seconds to deploy to fully horizontal e-VTOL configuration, this gives a tilting rate of 9 degrees/sec, giving:

$$\xi = \dot{\xi}t = 9t \tag{6}$$

Vertical thrust will be modified with respect to time as:

$$T_{vertical} = Wcos(\xi t) = Wcos(9t) \tag{7}$$

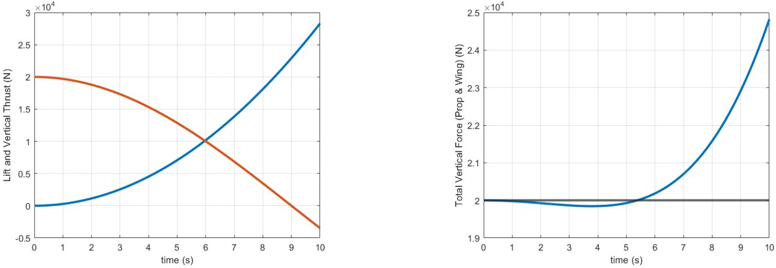
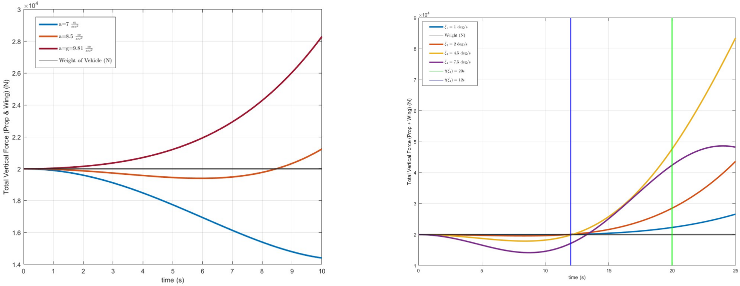


Figure 5: Wing Lift and Vertical Thrust Combined Effects

Finally, the combined effort will be given:

$$L_{total} = T_{vertical} + L_{wing} \tag{8}$$



(a) $L_{total}$ for various accelerations: 10s transition time

(b) $L_{total}$ for various tilting rates $\dot{\xi}$

Figure 5: Forward Acceleration Effect and Tilt-rate Effects on Lift

- Following conclusions can be drawn from above investigation:
  - Forward acceleration impacts wing lift.
  - Tilting rate impact loss of lift for combined propeller + wing.
  - Nonlinear effects.

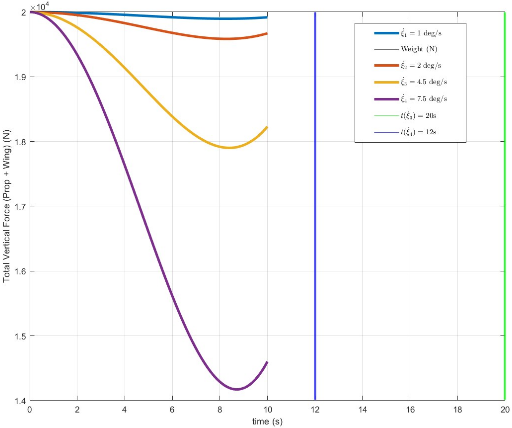


Figure 6: Detailed View $L_{total}$ for various tilting rates $\dot{\xi}$

# 5. Momentum Analysis of e-VTOL Aircraft in Transition

## *5.1 Induced velocity $v_i$ in Forward Flight*

From momentum studies for helicopters [9] we have:

$$T = 2\dot{m}v_i = 2(\rho A U)v_i \tag{9}$$

Or:

$$T = 2\rho A v_i \sqrt{(V_\infty cos\xi)^2 + (V_\infty sin\xi + v_i)^2} \tag{10}$$

We re-arrange in terms of hover condition, $T = 2\rho A {v_h}^2$

$$v_i = \frac{{v_h}^2}{\sqrt{(V_\infty cos\xi)^2 + (V_\infty sin\xi + v_i)^2}} \tag{11}$$

Define following parameters:
In-flow ratio $\lambda$and tip-speed ratio (advance ratio) $\mu$:

$$\lambda = \frac{V_\infty sin\xi + v_i}{\Omega R} \quad \text{and} \quad \mu = \frac{V_\infty cos\xi}{\Omega R} \tag{12}$$

Therefore arriving at

$$\lambda = \frac{V_{\infty} sin\xi}{\Omega R} + \frac{v_i}{\Omega R} = \mu tan\xi + \lambda_i \tag{13}$$

These equations modify the thrust equation shown earlier in terms of in-flow ratios:

$$\lambda_i = \frac{{\lambda_h}^2}{\sqrt{\lambda^2 + \mu^2}} \tag{14}$$

Where we have hover inflow ratio $\lambda_i = \sqrt{C_T/2}$. The solution for in-flow ratio will be:

$$\lambda = \mu tan\xi + \frac{C_T}{2\sqrt{\lambda^2 + \mu^2}} \tag{15}$$

Which can be solved for $\lambda$numerically. Results for different disk Angle of Attack (or tilt angle in case of e-VTOL aircraft) are shown in next page:

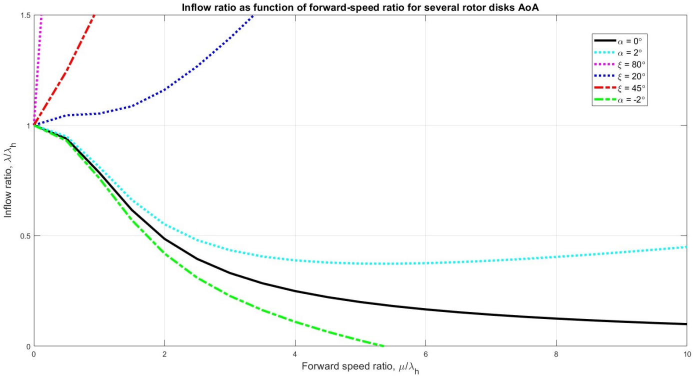


Figure 7: Inflow ratio vs. Forward speed ratio: Helicopter vs. Tilt-rotor e-VTOL

- Nonentities of induced in-flow ratio resulting in non-linearity of thrust distribution.
- strong dependence on AoA or tilt angle.

## 5.2 Intelligent Control Based on Learning from Data

We showed two examples of nonentities in developing a model for our e-VTOL vehicle. There are additional factors that can cause additional modelling complexities for the e-VTOL configuration:

- Wing Drag: Drag Coefficient $C_d$ can vary significantly from nominal value due to multiple propellers on-wing.
- interference effects between propellers, wing, fuselage.
- Tilting mechanism, it's acceleration $\ddot{\xi}$ will result in counter pitch-up moment of the e-VTOL vehicle air frame, introducing additional AoA to the inflow equation.
- Overlap of in-flows: due to propellers proximity to each other.

This is where we believe we would see a promising data-driven approach that can demonstrate safe close-loop performance using learning based control.

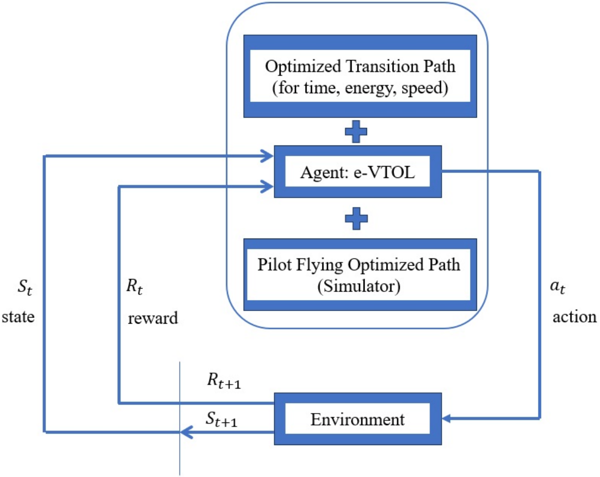


Figure 8: Intelligent Control learning from fusion of data and model

# 6. Development of e-VTOL Flight Simulator

As a stepping stone towards our research, two important milestones were to happen to provide us assurance that our FSC Simulator can be a suitable platform:

- Be able to use MATLAB/Simulink for visualization of aircraft states;
- re-activate the FSC Simulator to make it suitable for e-VTOL aircraft.

For the first step, I focused on development of basic aircraft visualization on MATLAB/Simulink, and the Research Civil Aircraft Model (RCAM a twin-engine Fixed-Wing transport category aircraft [10] [11]) plus MATLAB/Simulink Aerospace Blockset for visualization of aircraft states was constructed.

# 6. Development of e-VTOL Flight Simulator

- Cost-effective: We took elements of the existing fixed-wing setup and built an e-VTOL type simulator around it.
- Uses X-Plane for visualization, Air Manager for instrumentation, Matlab/Simulink for research.
- Built to resemble modern e-VTOL cockpit.

Figure 9: FSC e-VTOL Simulator Setup based on RCAM

# 6. Development of e-VTOL Flight Simulator

## *6.1 Simulator Block Diagram*

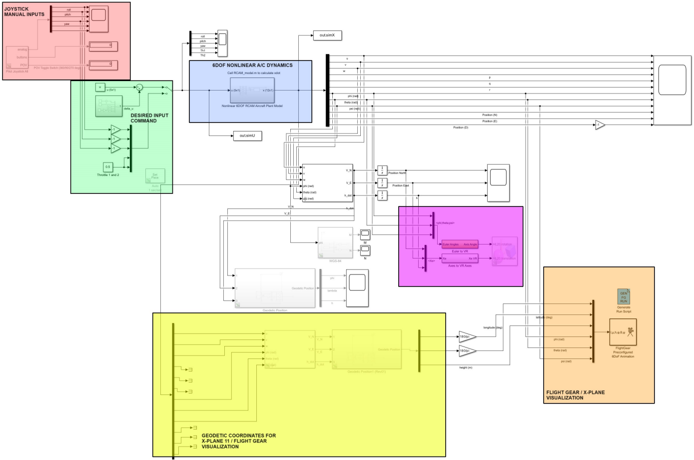


Figure 10: Intelligent Control Learning from fusion of data and model

# 6. Development of e-VTOL Flight Simulator

## *6.2 Simulator System Architecture*

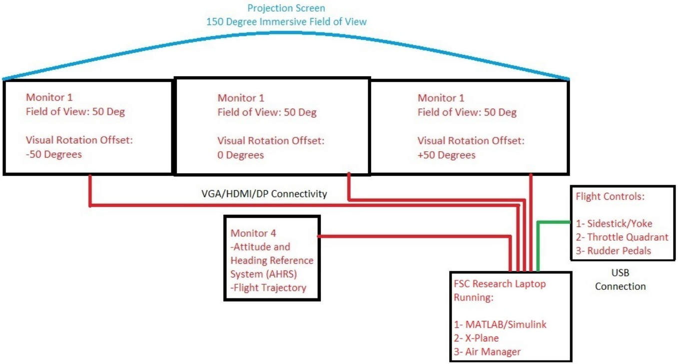


Figure 11: Architecture for Proposed e-VTOL Simulator based on FSC Simulator

# 6. Development of e-VTOL Flight Simulator

## *6.3 Open Loop Simulation*

With equal thrust command on $Th_1$ and $Th_2$ and initial cruise velocity of $u_0 = 85\frac{m}{s}$ we have following open loop response for $t_{sim} = 180s$:

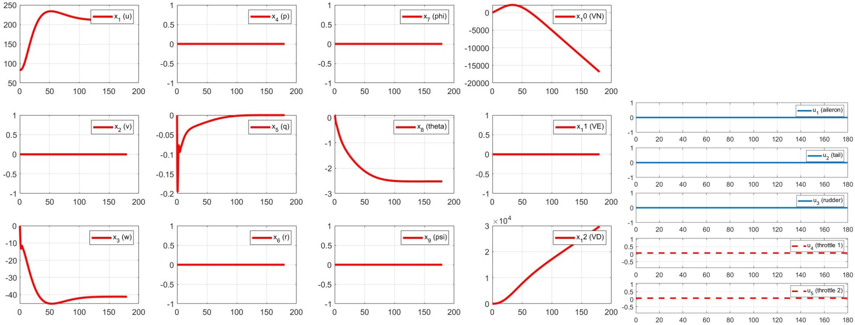


Figure 12: Open Loop Response to equal throttle command

# 6. Development of e-VTOL Flight Simulator

## *6.4 Open Loop Simulation*

Simulating a roll and pitch command by pilot between $t_0 = 0s$ and $t_0 = 40s$ we have following open loop response will be:

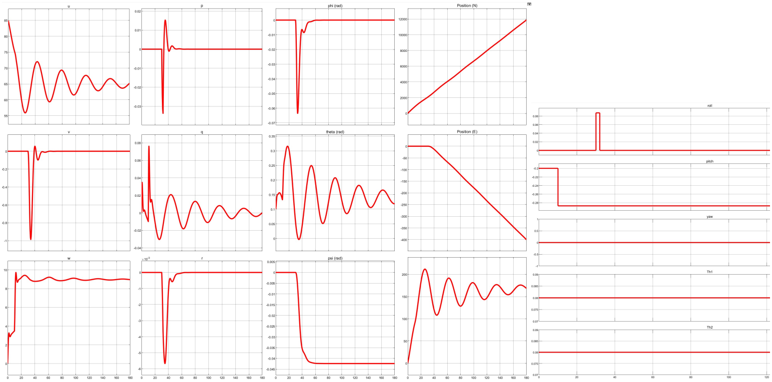


Figure 13: Open Loop Response to equal throttle command

# 7. Conclusion

- Nonlinear RCAM Simulator implemented.
- Phase 1: FSC Simulator Modification.
- Learning-Based Intelligent Control research.
- Problem of Transition Flight of e-VTOL identified.
- Upcoming:
    - Phase 2: Preparation of e-VTOL Flight Simulator.
    - Refining problem description.
    - Learning Based Intelligent Control vs. existing controllers.

# References I

[1] Electric VTOL News, “Beta Technologies ALIA-250,” Vertical Flight Society, 2022. [Online]. Available: https://evtol.news/beta-technologies-alia)

[2] D. Thompson, “Robust control of an evtol through transition with a gain scheduling lqr controller,” Ph.D. dissertation, 2020.

[3] R. Zheng, Y. He, Z. Liu, L. Yang, and F. Gu, “Mode Transition Control of Dual Tilt Rotor Unmanned Aerial Vehicle based on Dynamic Analysis,” in *2020 Chinese Control And Decision Conference (CCDC)*, 2020, pp. 1528–1533.

[4] J. Hyun, M. Jang, T. A. Nguyen, and J.-W. Lee, “Transition Control Planning and Optimization for a Boxed-wing e-VTOL Tiltrotor vehicle using Trim Analysis,” in *2023 International Conference on Unmanned Aircraft Systems (ICUAS)*, 2023, pp. 1128–1135.

# References II

[5] E. Enenakpogbe, J. F. Whidborne, and L. Lu, “Control of an eVTOL using Nonlinear Dynamic Inversion,” in *UKACC 13th International Conference on Control (CONTROL)*, 2022, pp. 158–164.

[6] T. Lombaerts, J. Kaneshige, S. Schuet, B. Aponso, K. Shish, and G. Hardy, “Dynamic Inversion-based Full Envelope Flight Control for an e-VTOL Vehicle using a unified framework,” 2020.

[7] S. Qu, S. W. Zhu, Guoming, and S. S.-M. Swei, “LPV Model-based Adaptive MPC of an e-VTOL Aircraft during Tilt Transition Subject to Motor Failure,” *International Journal of Control, Automation and Systems*, pp. 339–349, 2023.

[8] Z. Wang, S. Mao, Z. Gong, C. Zhang, and J. He, “Energy Efficiency Enhanced Landing Strategy for Manned e-VTOLs using L1 Adaptive Control,” *Symmetry*, vol. 13, no. 11, 2021. [Online]. Available: https://www.mdpi.com/2073-8994/13/11/2125

# References III

[9] J. G. Leishman, *Principles of Helicopter Aaerodynamics*. Cambridge University Press, 2006.

[10] C. Lum, “Building a MATLAB/Simulink Model of an aircraft: The Research Civil Aircraft Model - RCAM,” YouTube, 2020. [Online]. Available: https://www.youtube.com/watch?v=m5sEln5bWuM

[11] S. B. Jean-François Magni and J. Terlouw, *Robust Flight Control: A Design Challenge*. Springer Berlin/Heidelberg, 1997.