INDI Control Techniques and Automatic Landing Procedures

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Introduction: Advancements in UAVs

- Fixed-wing tricycle gear UAVs gained popularity for long-distance efficiency and versatility.
- Automation of takeoff and landing is crucial for operational efficiency and safety.
- Challenges in implementing ATOL due to the vulnerability of light aircrafts to environmental factors and uncertain aircraft models.
- INDI control strategy offers advantages: reduced reliance on models.

Literature Review: Advancements in Flight Control Techniques for UAVs: INDI and NDI

- Classical linear control techniques are limited to **small-range operations,** leading to potential instability with expanded operational range.
- Gain scheduling commonly used to compensate for non-linearities but is time-consuming and expensive.
- **Nonlinear Dynamic Inversion** (NDI) avoids gain-scheduling, offers improved performance, easier reuse, and coping with changing models.
- NDI drawback: model mismatches and measurement errors affecting performance and stability.
- **Incremental Nonlinear Dynamic Inversion** (INDI) developed to address NDI limitations.

Nonlinear Dynamic Inversion

NDI provides a systematic approach to control systems as linear by canceling system dynamics. This is done by finding a direct relation between the desired output and the input and inverting it to get the control law

To illustrate, consider the aircraft's angular rates, which can be expressed using the following equation:

$$J\dot{\omega} + \omega \times J\omega = M = M_a + M_c$$

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$$J\dot{\omega} + \omega \times J\omega = M = \boxed{M_a + M_c}$$

$$J\dot{\omega} + \omega \times J\omega = M_a + (M_c)_\delta \delta$$

To find the control law, replace $\dot{\omega}$ by the pseudo-control input v and invert to find the actual control variable:

$$\delta = \left(M_c\right)_\delta^{-1}\left(Jv + \omega \times J\omega - M_a\right)$$

Incremental Nonlinear Dynamic Inversion

Incremental Nonlinear Dynamic Inversion

Rather than calculating the total deflection of the control surfaces during each execution, it is possible to compute only the increments of the control surface deflections. To accomplish this, we write the previous equation as Taylor series expansion:

$$
\begin{aligned}
\dot{\omega} = {} & J^{-1}(M_{a0} - \omega_0 \times J\omega_0 + M_{c0}) \\
& + \frac{\partial}{\partial \omega}[J^{-1}(M_a - \omega \times J\omega + M_{c]}))]_{\omega=\omega_0,\delta=\delta_0}(\omega - \omega_0) \\
& + \frac{\partial}{\partial \delta}[J^{-1}(M_a - \omega \times J\omega + M_c)]_{\omega=\omega_0,\delta=\delta_0}(\delta - \delta_0)
\end{aligned}
$$

Incremental Nonlinear Dynamic Inversion

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$$\dot{\omega} = \dot{\omega_0} + \frac{\partial}{\partial \delta}[J^{-1}M_c]_{\omega=\omega_0,\delta=\delta_0}(\delta - \delta_0)$$

Incremental Nonlinear Dynamic Inversion

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$$\dot{\omega} = \dot{\omega_0} + \frac{\partial}{\partial \delta}[J^{-1}M_c]_{\omega=\omega_0,\delta=\delta_0}(\delta - \delta_0)$$

Assuming a linear relation between control deflection and control moment :

$$\dot{\omega} = \dot{\omega_0} + J^{-1}(M_c)_\delta d\delta$$

Replacing the angular acceleration with the pseudo-control input ($\dot{\omega} = v$):

$$d\delta = (M_c)_\delta^{-1} J(v - \dot{\omega_0})$$

Methodology :

Airframe Measurement

Methodology :

XFLR5
Analysis

Methodology :

Simulink
Analysis

Methodology :

Results and Discussion

Methodology :

Airframe Measurement

XFLR5 Analysis

Simulink Analysis

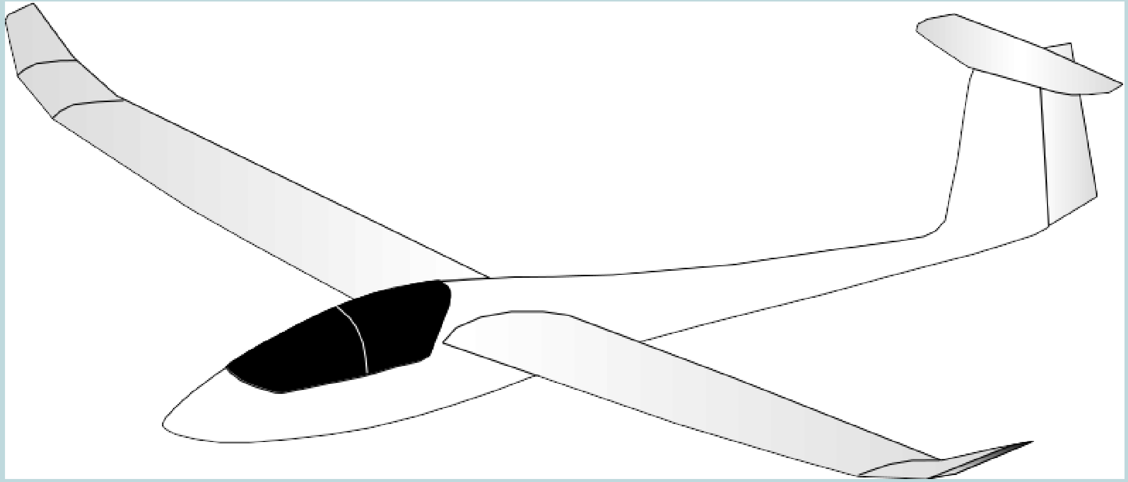
Results and Discussion

Airframe Measurement:

The plane used for this research is the FUNCUB XL ND made by Multiplex. It is a versatile high-wing aerobatic aircraft designed for RC model flying. The plane was altered to include an on-board computer, sensors, batteries, and other necessary equipment. The manufacturer has provided the following technical specifications:

XFLR5 Analysis :

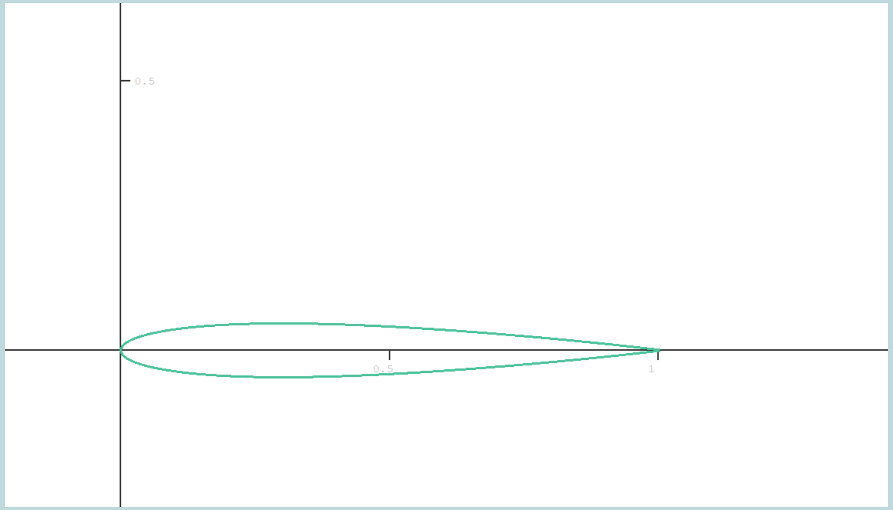
XFLR5 is a tool that analyzes airfoils, wings, and planes that operate at low Reynolds Numbers. It can use the XFOIL code for airfoil analysis and can also predict stability and control derivatives, which are crucial for modeling. To create an aircraft model, the following steps are taken



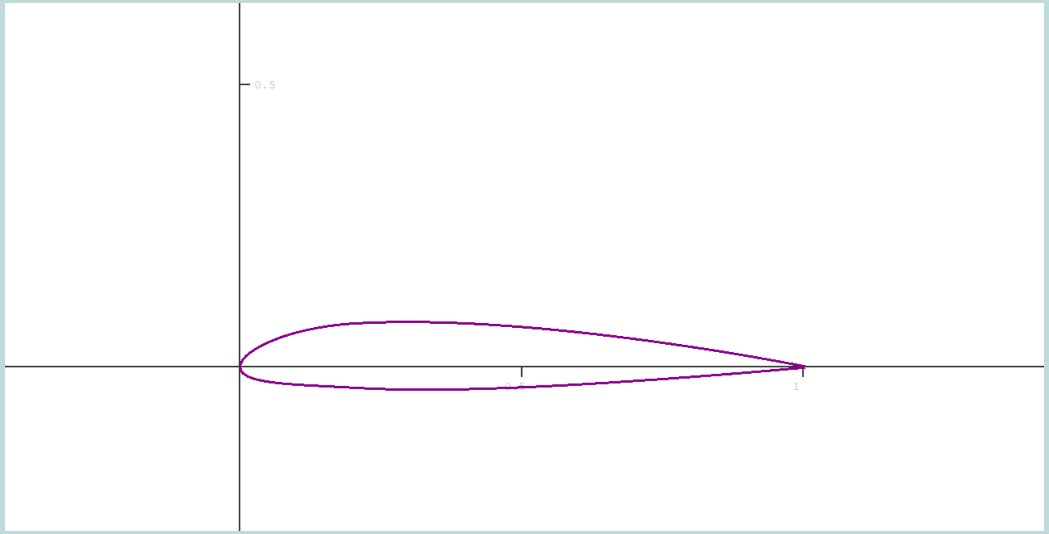
XFLR5 Analysis :

a) Airfoil Creation:

The two primary foils were the NACA 2212 (main wing), NACA 0010 (for the horizontal and vertical stabilizers) and they were modified according to the thickness and camber of the actual model.



NACA 0010



NACA 2212

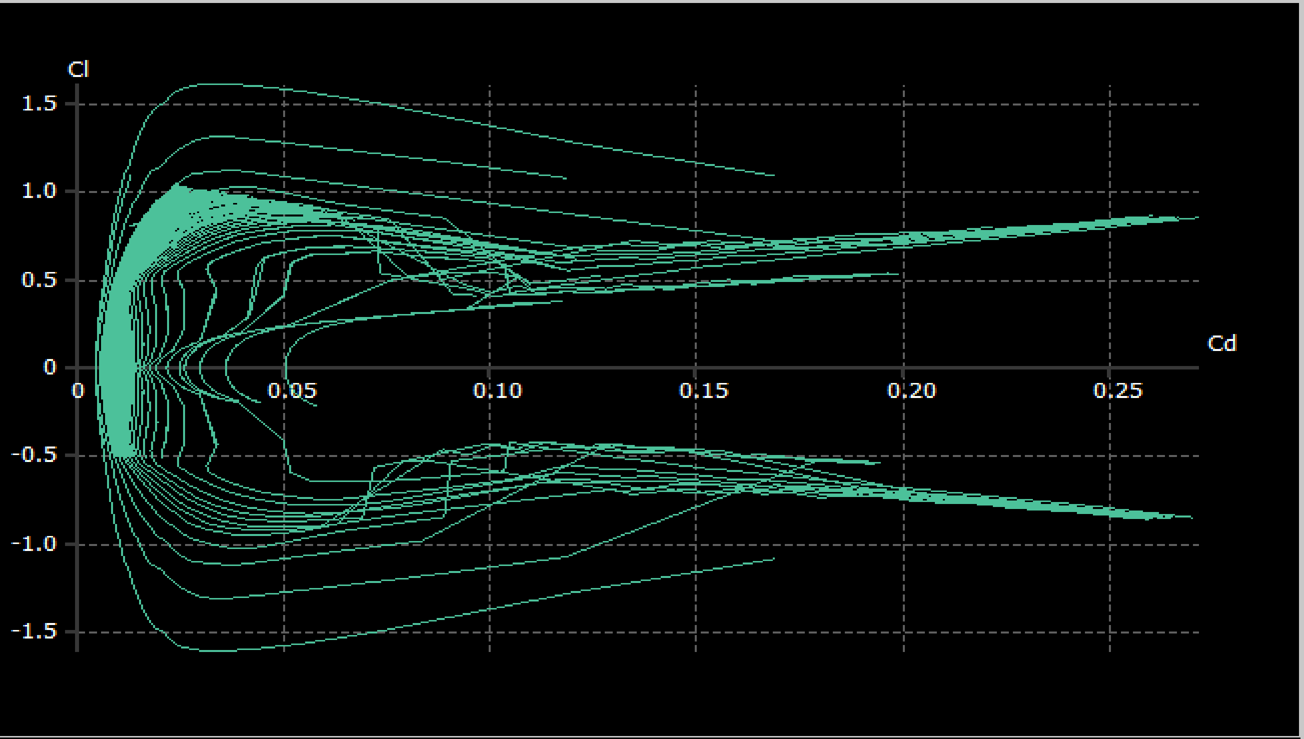
XFLR5 Analysis :

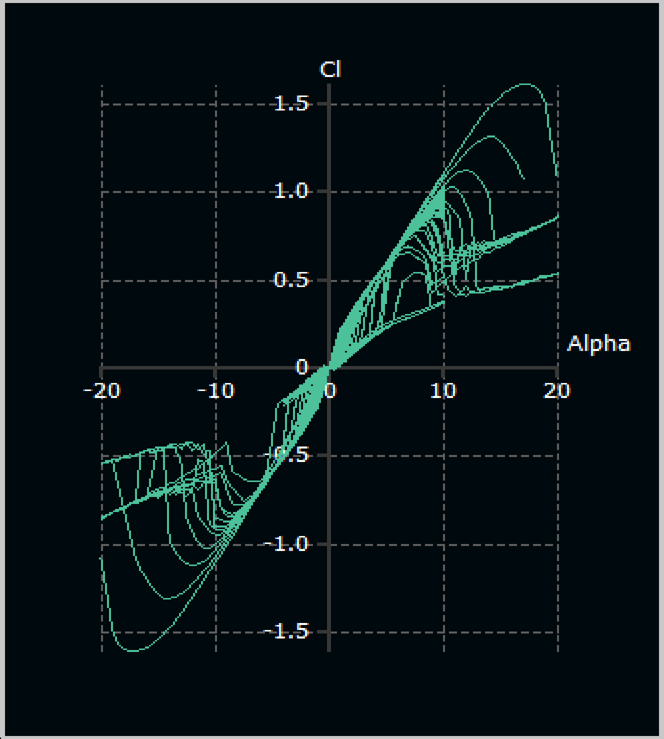
b) Airfoil Analysis:

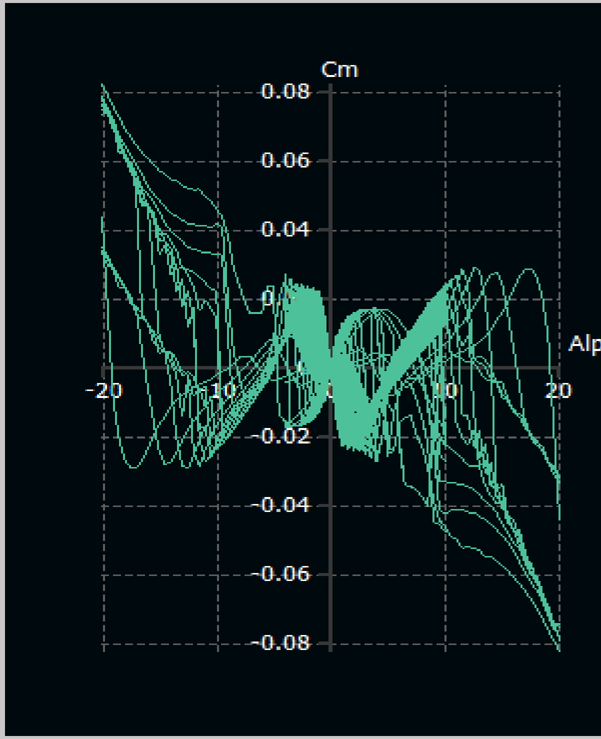
To gather all the necessary aerodynamic data on the identified airfoils and their variants, a 2D analysis was conducted on these airfoils. Initially, a batch analysis was performed for a range of Reynolds numbers from 10,000 to 500,000, with alpha varying from -20 to 20 in 0.5-degree increments

NACA 0010

NACA 2212







NACA 0010
T1_Re0.005_M0.00_N9.0
T1_Re0.010_M0.06_N9.0
T1_Re0.010_M0.00_N9.0
T1_Re0.015_M0.00_N9.0
T1_Re0.015_M0.06_N9.0
T1_Re0.020_M0.06_N9.0
T1_Re0.020_M0.00_N9.0
T1_Re0.022_M0.00_N9.0
T1_Re0.022_M0.06_N9.0
T1_Re0.030_M0.00_N9.0
T1_Re0.030_M0.06_N9.0
T1_Re0.040_M0.00_N9.0
T1_Re0.040_M0.06_N9.0
T1_Re0.050_M0.00_N9.0
T1_Re0.050_M0.06_N9.0
T1_Re0.060_M0.00_N9.0
T1_Re0.060_M0.06_N9.0
T1_Re0.070_M0.00_N9.0
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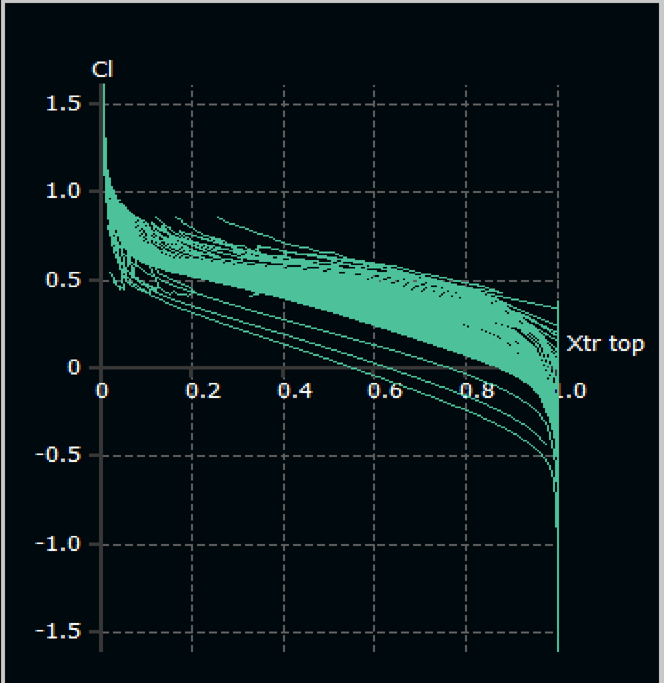
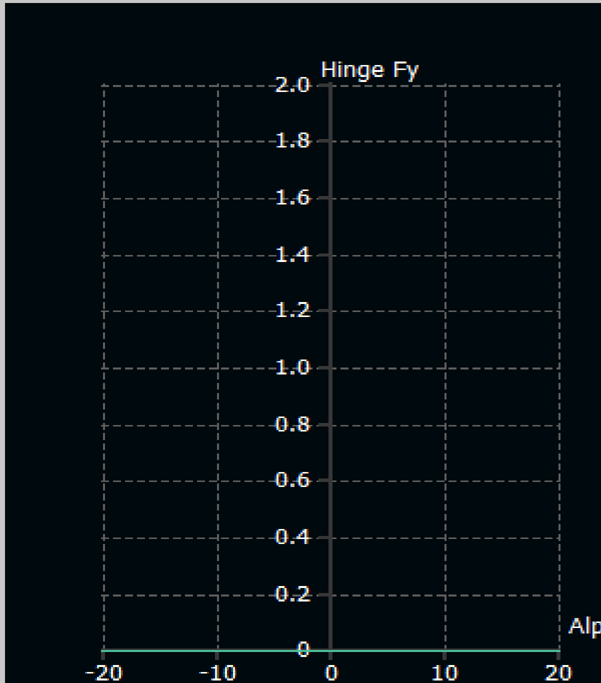
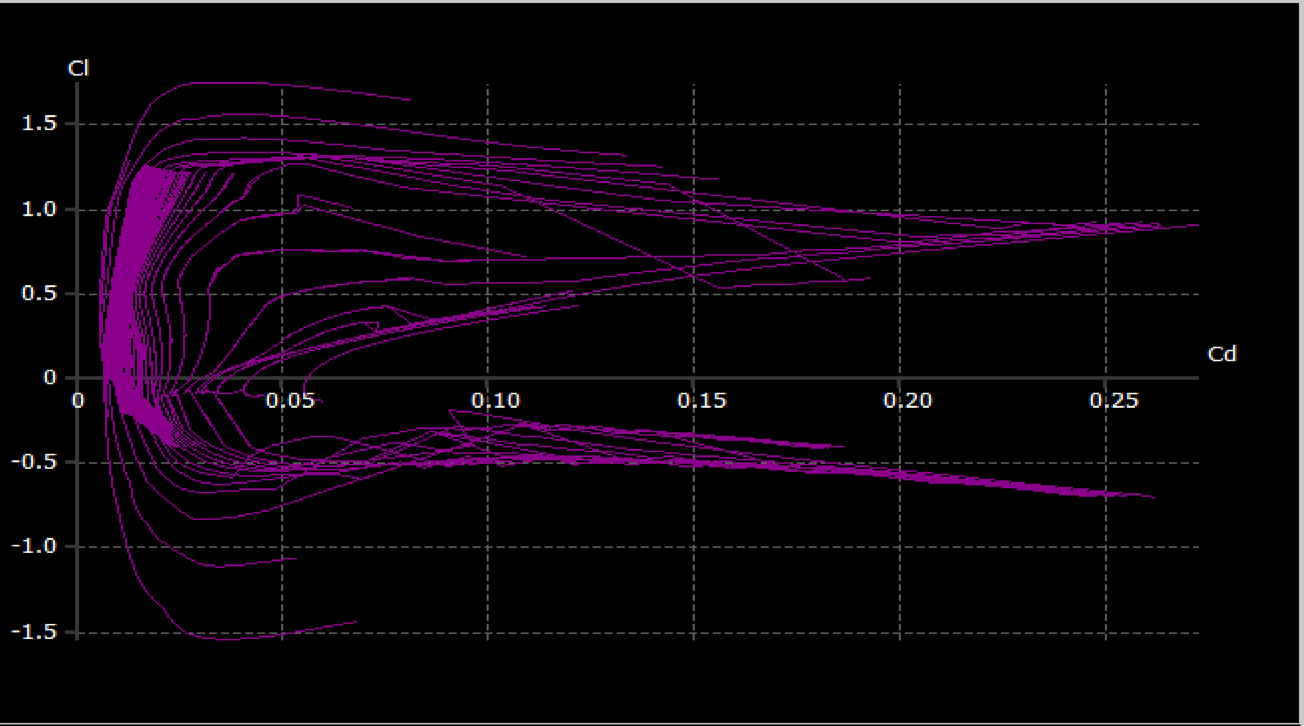
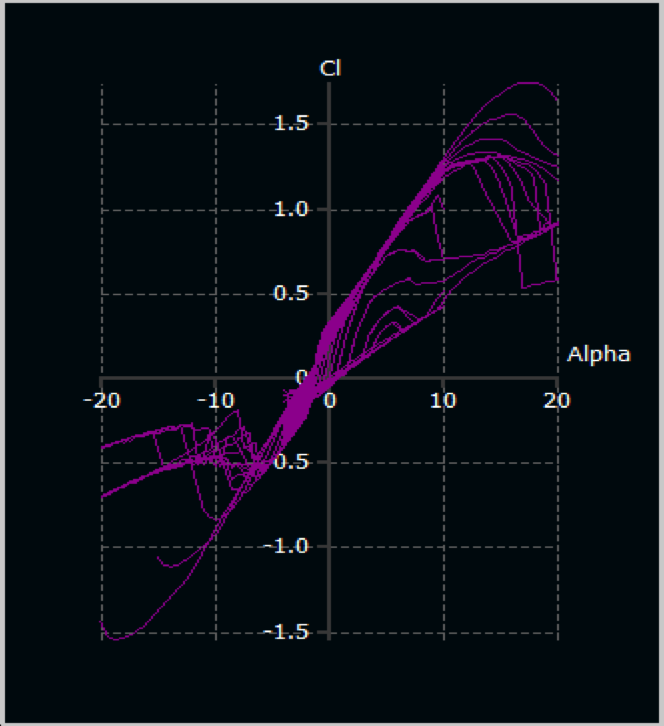
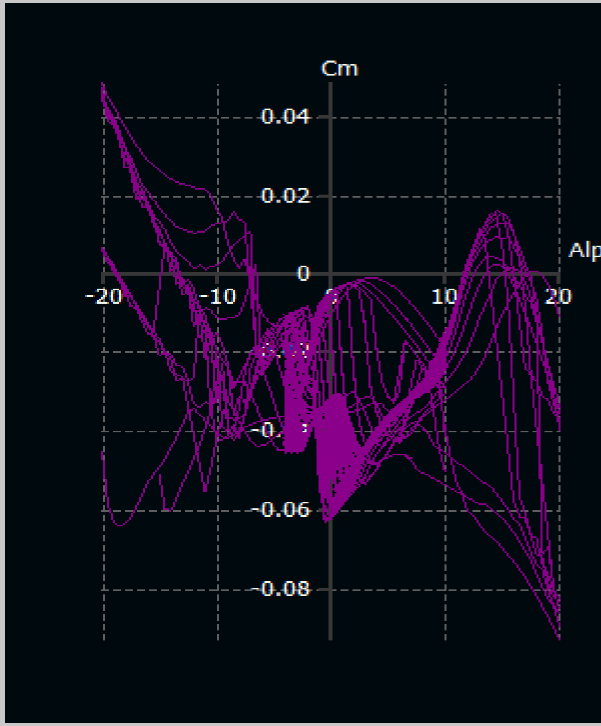
T1_Re0.080_M0.00_N9.0
T1_Re0.080_M0.06_N9.0











NACA 2212

- T1_Re0.005_M0.00_N9.0
- T1_Re0.010_M0.06_N9.0
- T1_Re0.010_M0.00_N9.0
- T1_Re0.015_M0.00_N9.0
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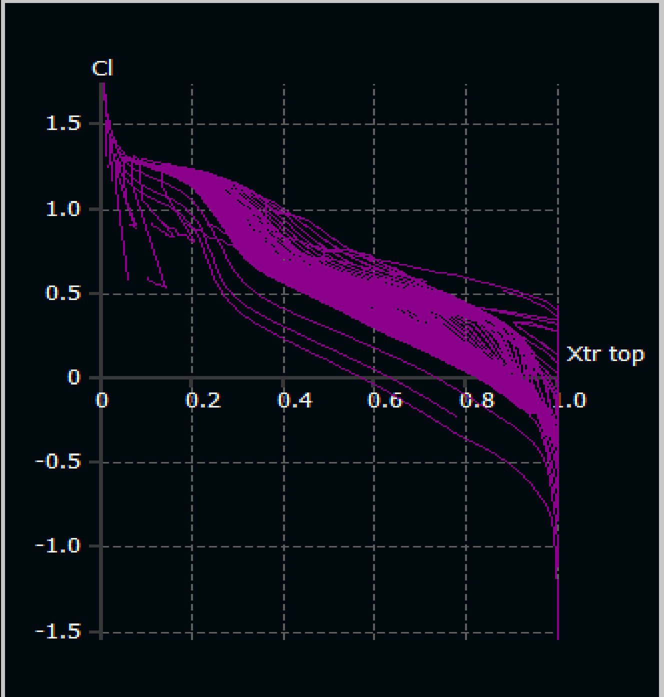
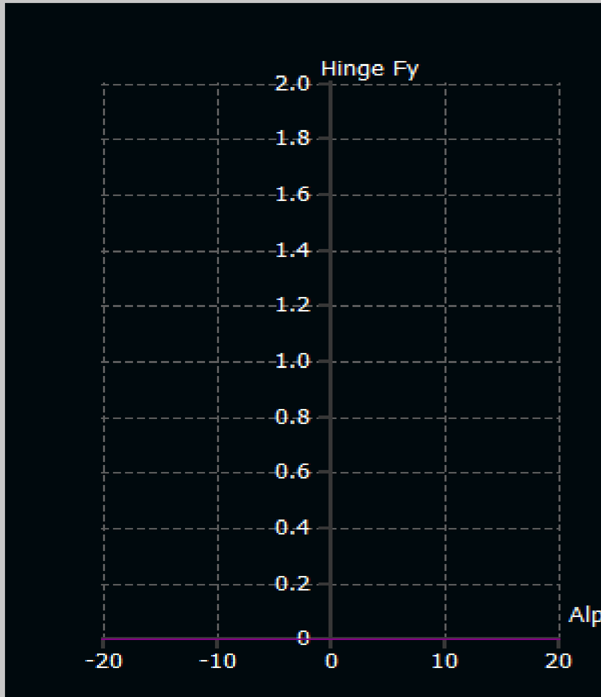
- T1_Re0.030_M0.06_N9.0
- T1_Re0.040_M0.00_N9.0
- T1_Re0.040_M0.06_N9.0
- T1_Re0.050_M0.00_N9.0
- T1_Re0.050_M0.06_N9.0
- T1_Re0.060_M0.00_N9.0
- T1_Re0.060_M0.06_N9.0
- T1_Re0.070_M0.00_N9.0
- T1_Re0.070_M0.06_N9.0
- T1_Re0.080_M0.00_N9.0
- T1_Re0.080_M0.06_N9.0
- T1_Re0.090_M0.00_N9.0





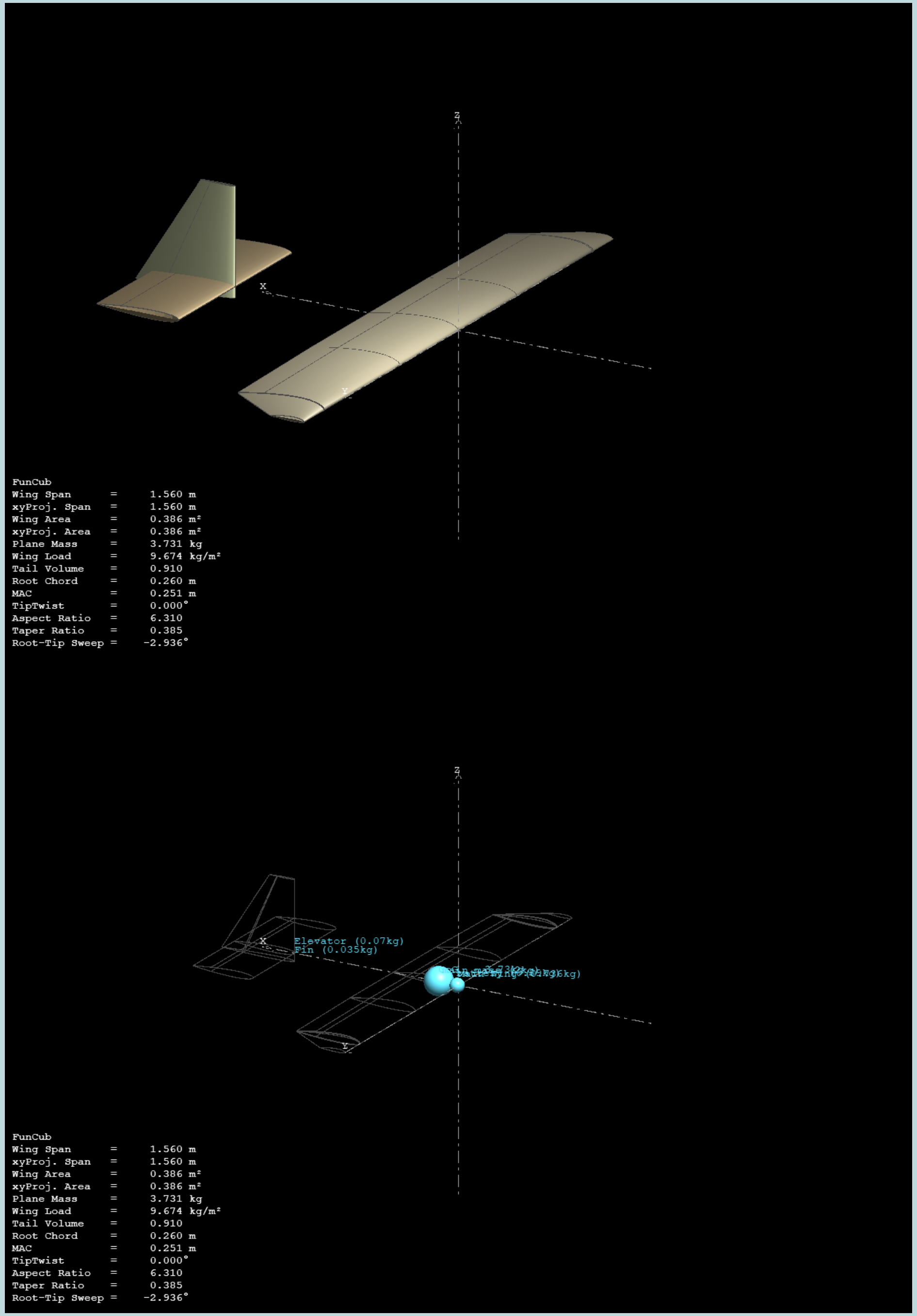
XFLR5 Analysis :

c) Plane modelling:

After generating the airfoils and conducting a 2D viscous analysis on them, a 3D model of the plane was created. After that, the following analyses were run on the 3d model :

- Performance analysis
- Stability Analysis

These produce the control and stability derivatives required for the Simulink model



Simulink Model:

The control structure comprises four loops, namely the position control, velocity control, attitude control, and angular rate control, which are arranged in a cascaded structure. The NDI control approach is used to design the position and attitude control loops, since the kinematics equations, both rotational and translational , do not have any coefficients that rely on the specific model. On the other hand, the INDI control approach is used for the flight path and angular rate control loops due to the presence of model uncertainties.

Simulink Model:

a) Position control loop: The aim is to track the trajectory reference accurately. This loop generates the desired references for χcmd and γcmd.

b) Velocity control loop: It aims to steer the aircraft towards the reference values of $[V, \chi, \gamma]$ref given in the first loop. It generates the necessary commands, such as αcmd and µcmd, for the attitude control loop. Moreover, it generates the required thrust command to follow the velocity reference V.

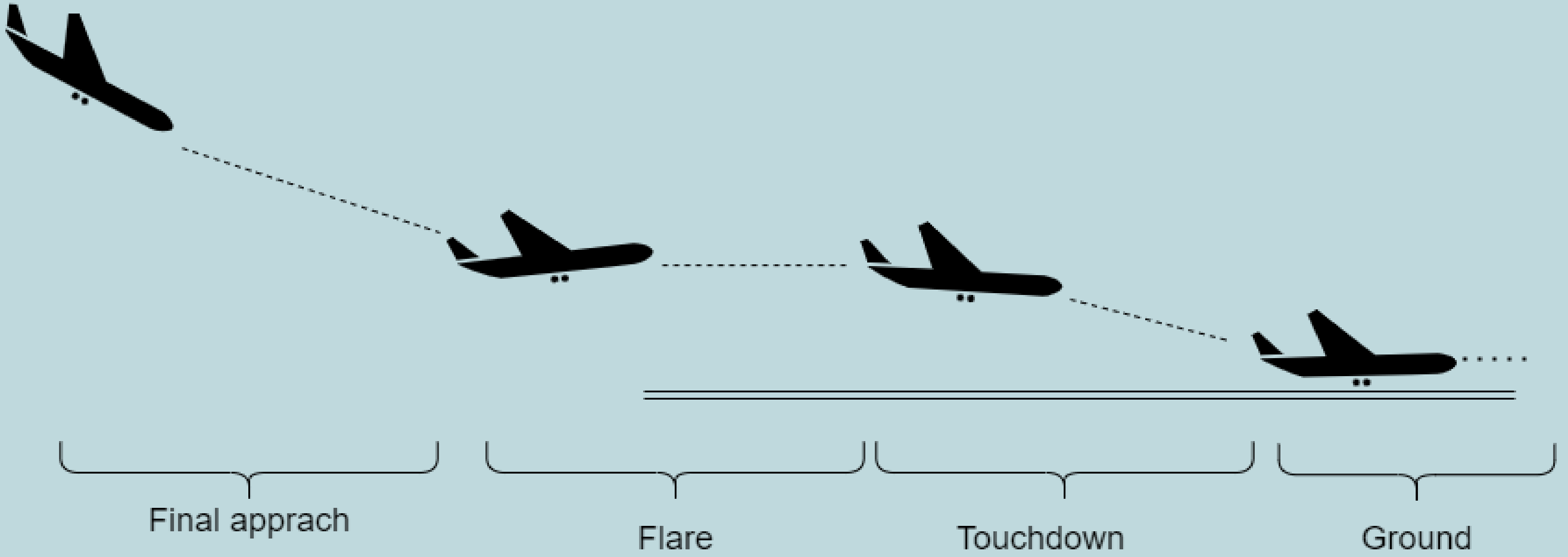
Simulink Model:

c) Attitude control loop: The objective is to follow the reference values given by the velocity control loop and to generate the desired angular rates $[p, q, r]$cmd, which will be fed to the angular rate loop.

d) Angular rate control loop: It is responsible for tracking the desired rates set by the attitude control loop. Its main purpose is to send the necessary command to the actuators in order to achieve the desired objective

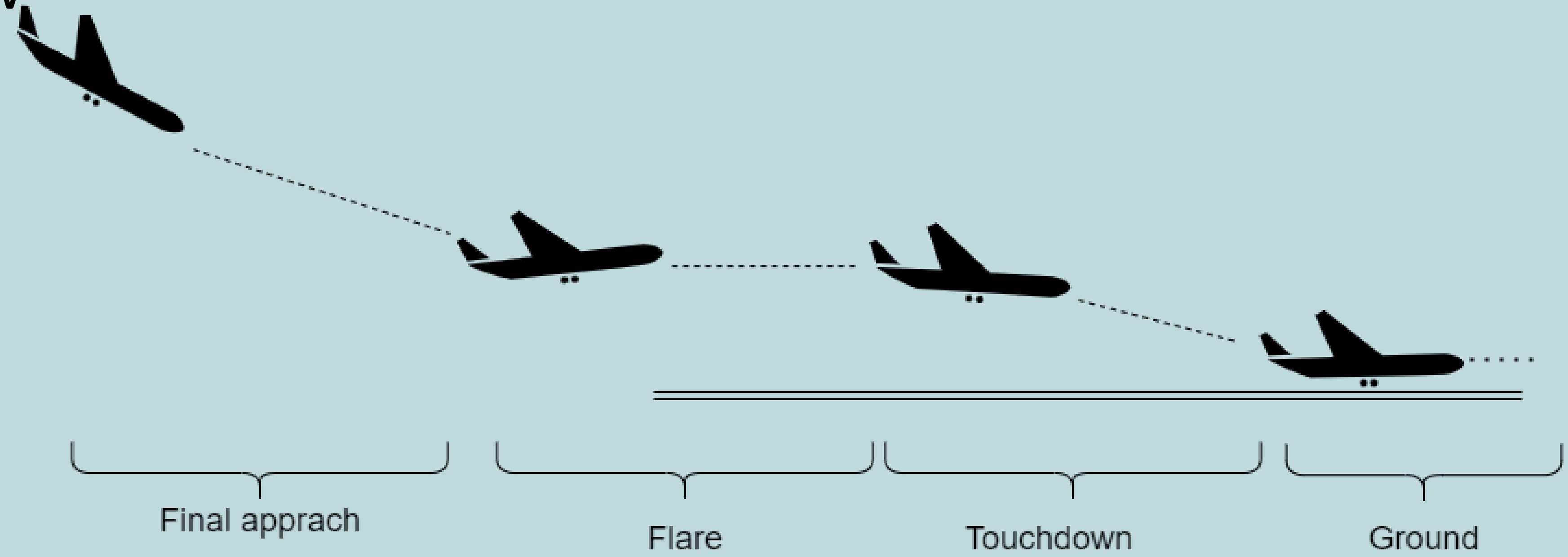
Automated Landing phases and challenges :

The primary difficulty in controlling the motion of an aircraft during automatic landing lies in the imbalance between the number of quantities that need to be regulated and the available actuators. Specifically, maintaining airspeed (VA),the sink rate ($\dot{h} \approx \alpha$), and pitch angle (θ) within acceptable ranges with only two actuators, thrust and elevator



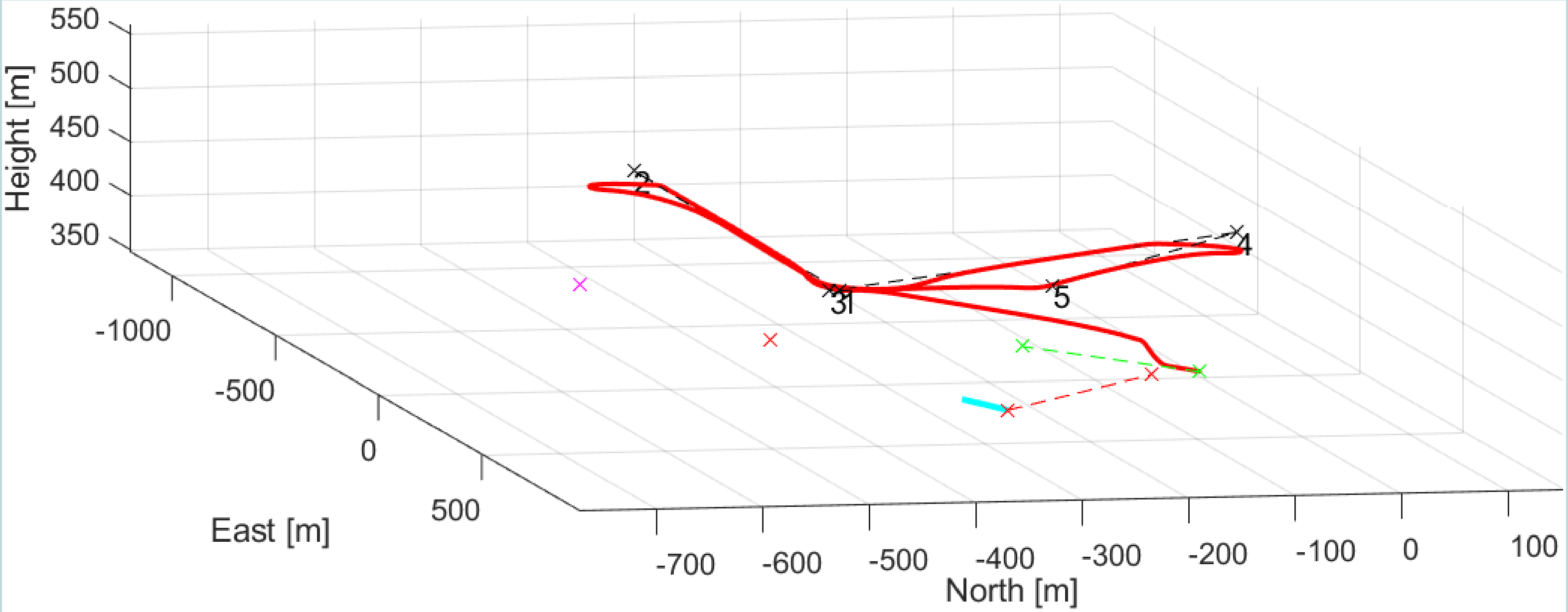
Automated Landing phases and challenges :

During the flare, the conflicting control goals regarding the values of θ, γ, and VA are especially evident. In order to improve tracking, it has been suggested to add feed-forward terms to control laws. $\dot{\gamma}$ can be added to the second term of the velocity control law, $\dot{\alpha}$ can be added to the second term of the attitude control law and $\dot{q}$ to the rate control law



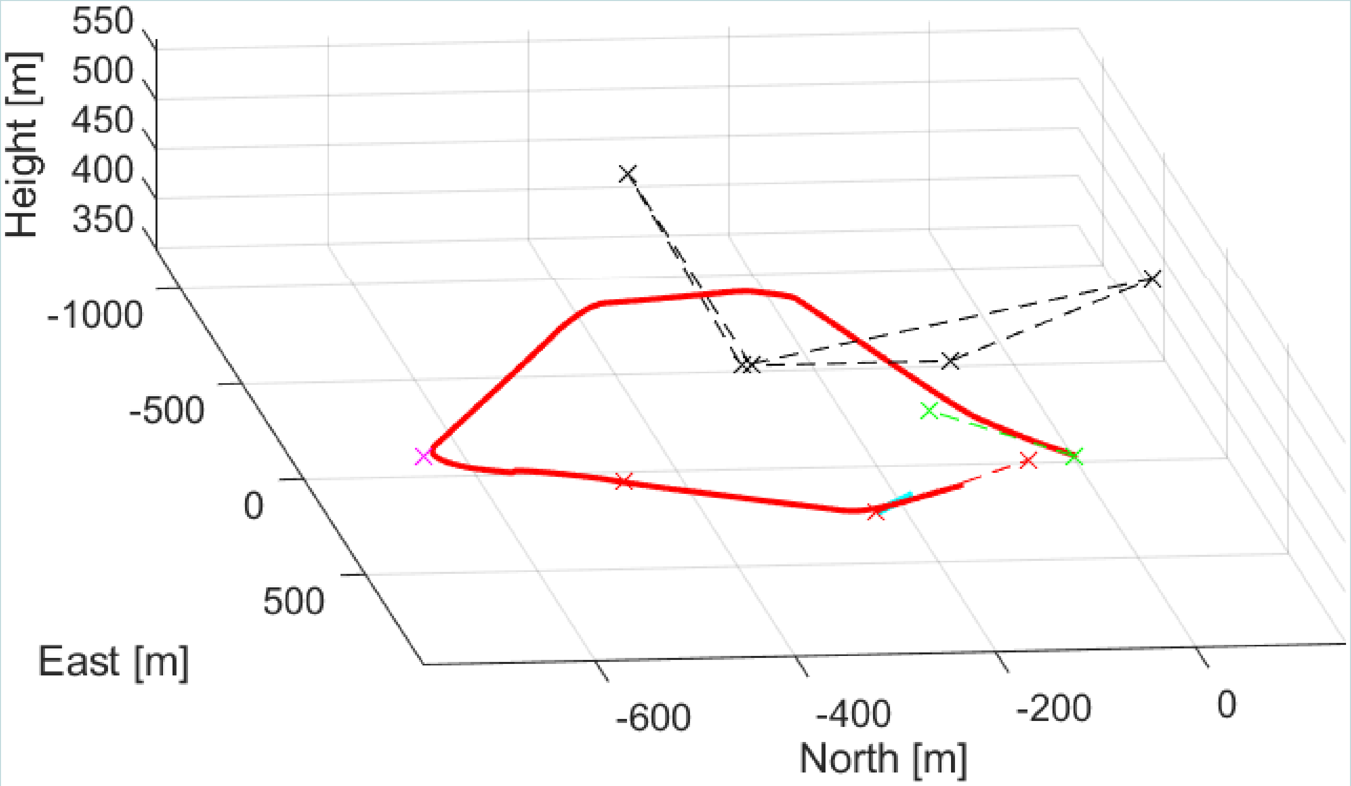
Results and Discussion :

The figure depicts a waypoint follower routine that initiates takeoff from point 1 on the ground and then cruises to point 5. It is clear that the aircraft can adeptly track the specified reference path.



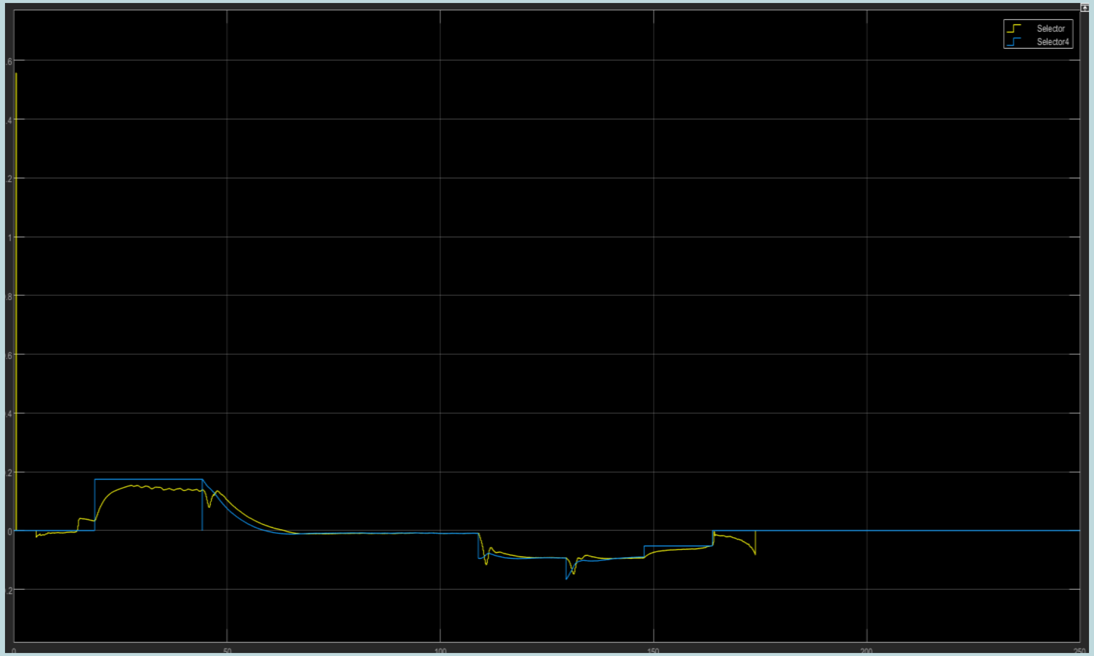
Results and Discussion :

The process of takeoff and landing, along with a brief cruising phase in between, is shown in the recorded procedure depicted in the figure below

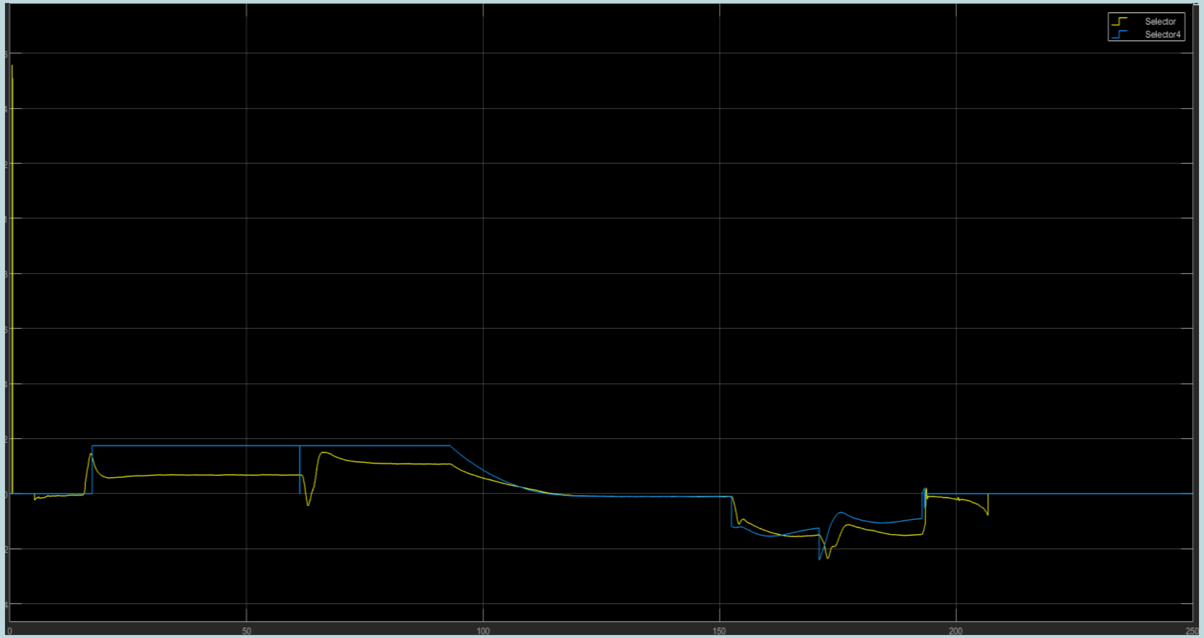


Results and Discussion :

The impact of incorporating the feedforward terms on the flare process is showcased by comparing the reference nominal value of the flight path angle γ with the corresponding actual value of the signal



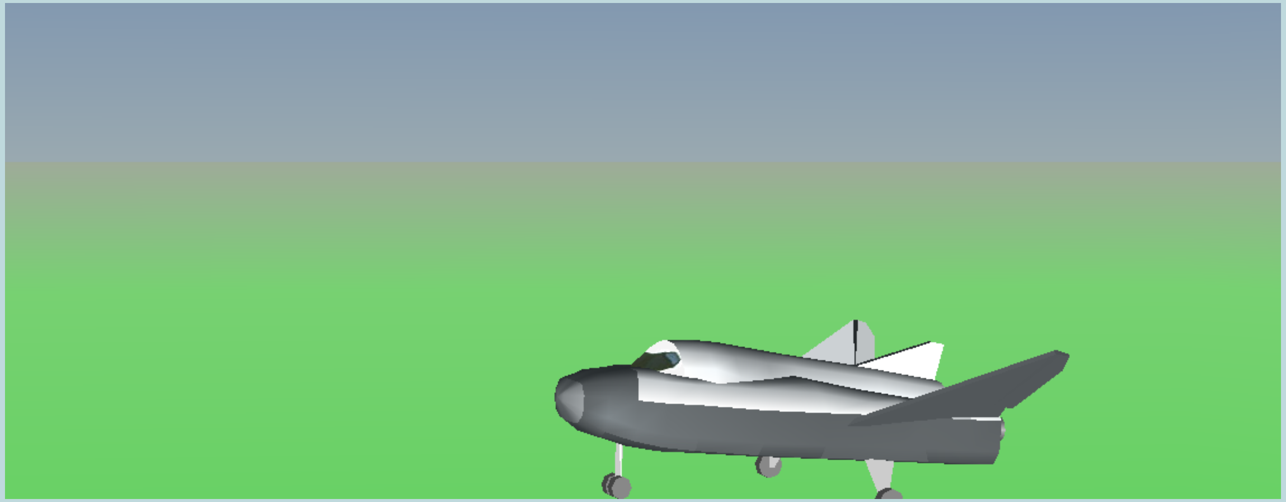
With feedforward terms



Without feedforward terms

Conclusion:

This study demonstrates the successful implementation of an INDI-based flight controller for automated aircraft operations during landings, tailored explicitly for nosewheel aircraft. Moreover, by incorporating feedforward terms, the gamma tracking during the flare phase of the landing process is significantly improved. The presented guidance and control concepts are rigorously validated through various flight simulations.



Future Work

The next crucial step in advancing this research would be the validation of the control system through HIL simulations and flight tests. This will ultimately pave the way for the successful implementation of automated takeoff and landing operations for the target airframe, contributing to the advancement of UAV technologies and their applications in various industries.