Aerodynamic Analysis and Development for UAV Dynamics and Control Law Synthesis

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Abstract

- **The goal of this capstone project is to develop a reliable process for modelling the aerodynamics of a known stable airframe, and consequently develop a theoretical control system based on the modelled dynamic behaviours.**
- **To verify the validity of our developed process, an analysis between the simulated and experimental aerodynamics was performed to determine the effectiveness of CFD methods at capturing the dynamics of a UAV.**
- **A comparative analysis of the theoretical control law to the open sourced ArduPilot control software was completed via experimental flight testing to verify the efficacy and performance of the developed control law.**

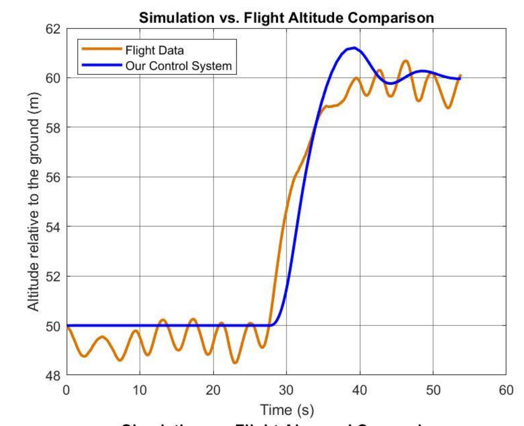
Introduction

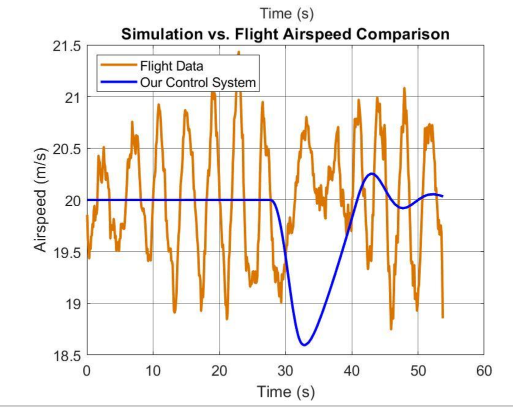
- During the initial design phase of an aircraft, simulations are the preferred method to test a design prior to prototyping. This project explores the errors associated with using different methods to achieve a simulated model a UAV.
- It is necessary to investigate how modelling errors and assumptions in every step can affect the result. This will help users acknowledge constraints in developing a trustworthy process to synthesize a control law.
- There are currently no existing methods through CFD that result in an exact dynamic model of a UAV. Being able to identify errors and assumptions in this process is crucial to learn how to best accommodate them in future processes.

Flight Data Analysis

- Flight plans were created using ArduPilot for autonomous flights.
- Three flight states investigated:
  1. Straight level flight
  2. Banking
  3. Altitude increases and decreases
- Flight data used for two purposes:
  1. Compare control system performance with real life behavior
  2. Validate CFD and OpenVSP coefficients

Flight plan with 2x straight and level sections and 1xbanking section





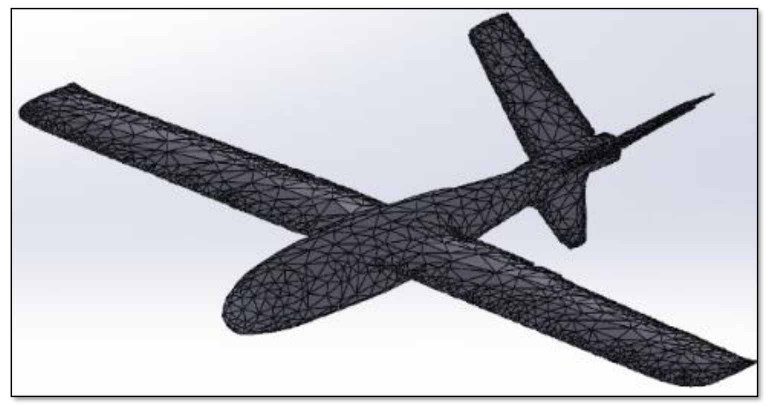
Discussion

- Obtained stability and control derivatives describing a statically stable airframe using OpenVSP and CFD; however, the modelling of moments varies.
- A combination of dynamic coefficients from OpenVSP and CFD have been used based on their respective limitations in estimating viscous effects and dynamic stability. OpenVSP value errors are a consequence of poor drag modelling and numerical error, resulting in poor convergence and numerical solutions that are sensitive to geometry changes. CFD errors are mostly attributed to the spatial discretization error which can be reduced and quantified through a grid convergence study.
- The aerodynamic coefficients from OpenVSP and CFD were compared to the UAV's performance in experimental flights with similar simulated dynamics. As the control system approaches its boundary speeds of 17m/s and 22m/s, the altitude and speed holds become less accurate due to the system operating in conditions further away from our plant linearization states. This issue can be solved using gain scheduling for transitioning between different flight regimes.

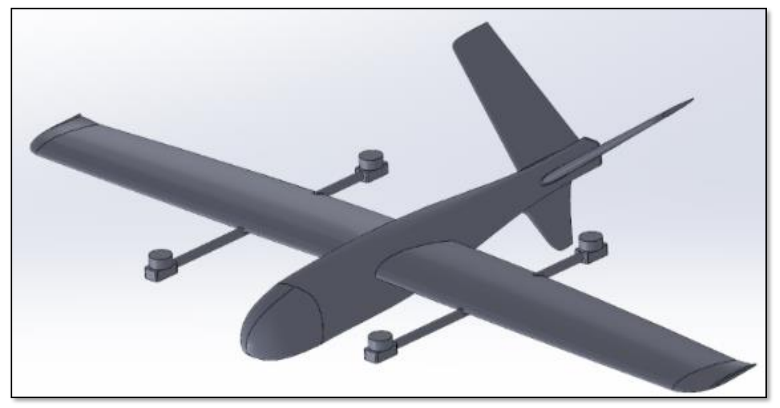
Computational Fluid Dynamics

Decimated 3D Scan

The first step to generating a CFD mesh is to have a CAD model of the UAV. An optical 3D scan of the UAV was completed, to which the point cloud data was adapted to an STL mesh of the craft.



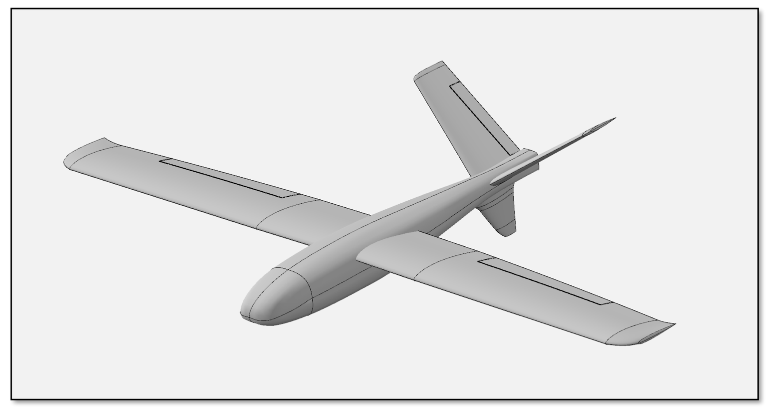
SolidWorks CAD



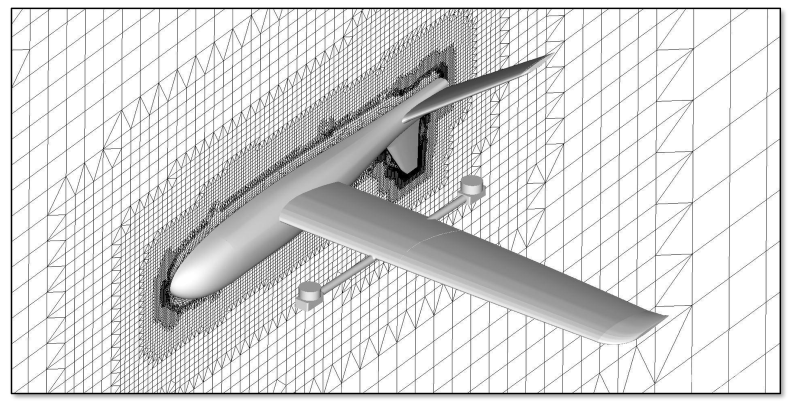
Clean CAD parts were developed from the STL model using lofts with preservation of cross-sectional geometry. Multiple models were created to depict various control surface deflections.

OpenVSP Analysis

Aerodynamic analysis was performed on OpenVSP to obtain stability and control derivatives of the UAV using vortex lattice method (VLM).



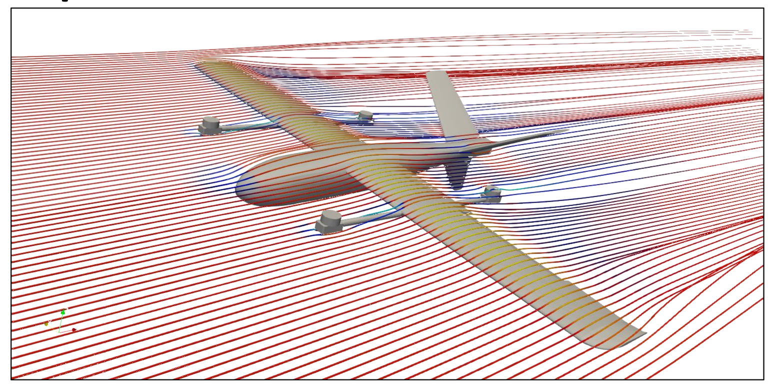
Pointwise Volume Mesh



Cadence Pointwise software was used to mesh five CAD models depicting each case of control surface deflection. The volume mesh was propagated from the UAV surface using voxel blocks for maximum cell orthogonality.

OpenFOAM Results in Paraview

Flow simulated over UAV in OpenFOAM using simpleFoam solver with Spalart-Allmaras turbulence model to determine aerodynamic coefficients. The average y+ value for each case was ~50 to target the log-law region of the boundary layer (30 < y+ < 300)



Conclusions

- Open VSP's panel method is highly divergent when modelling aircraft dynamics due to component buildup errors and complex 3D panel geometry errors. VLM provided stable and controllable aircraft dynamics comparable to actual aircraft dynamics.
- CFD obtained coefficients proved to supplement the OpenVSP dynamics with a theoretically more accurate dynamic model. CFD was most valuable in the modelling of nonlinear aerodynamic coefficients as a function of the angle of attack and sideslip angle where the OpenVSP dynamics approximate them as linear. The dynamic rates of change were only able to be modeled through OpenVSP due to the computational cost to compute these coefficients in CFD, which remains its greatest drawback.
- The simulated MIMO control scheme proved robust and capable of managing roll attitude, altitude, and airspeed within our flight regime. The simulated control system, designed for cruise airspeeds of 17m/s-22m/s, can reject lateral disturbances of more than 30° and can manage altitude changes of more than +/- 150m, which is larger than our legal flight window.

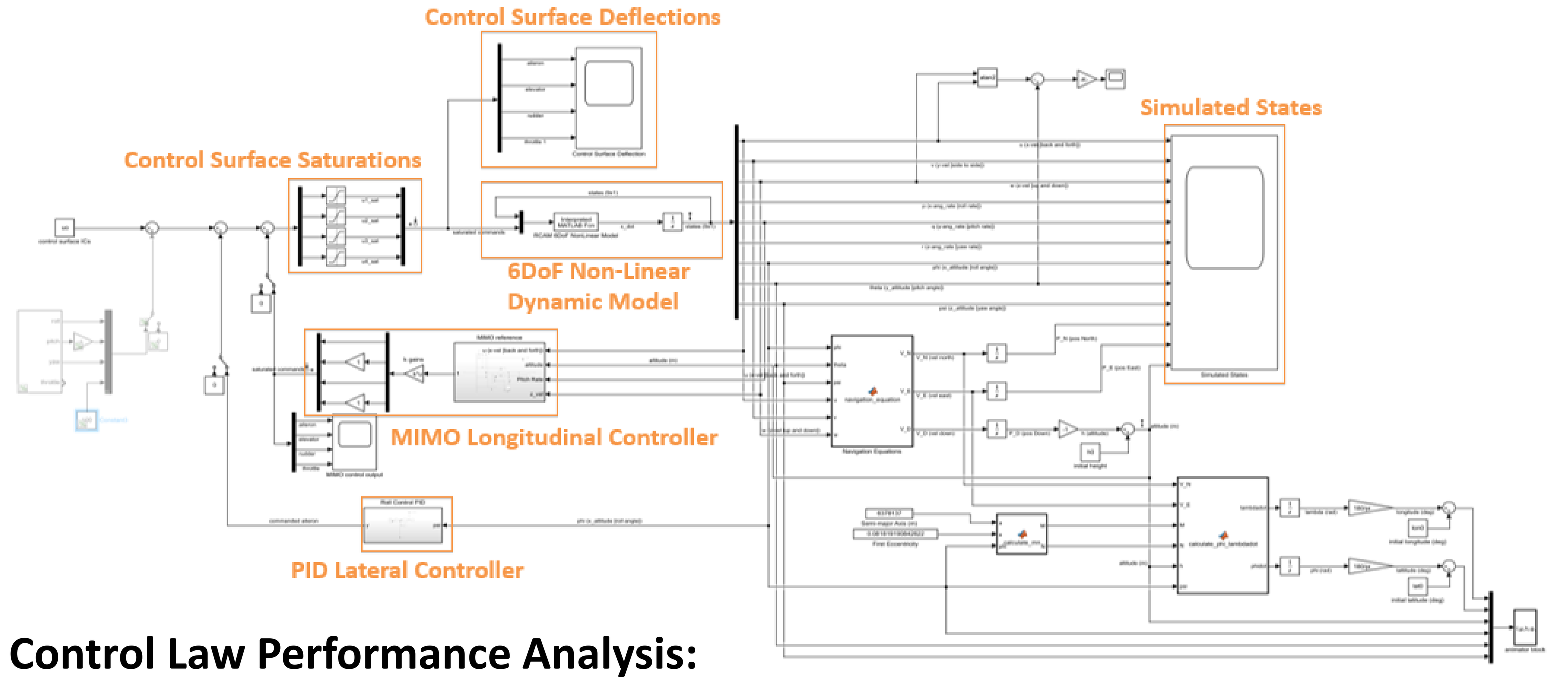
Dynamic Model and Control Law Synthesis

Dynamic Model:

- Our dynamic model was built based off Garteur's Research Civil Aircraft Model (RCAM), which simulated the dynamics of a Boeing 757.

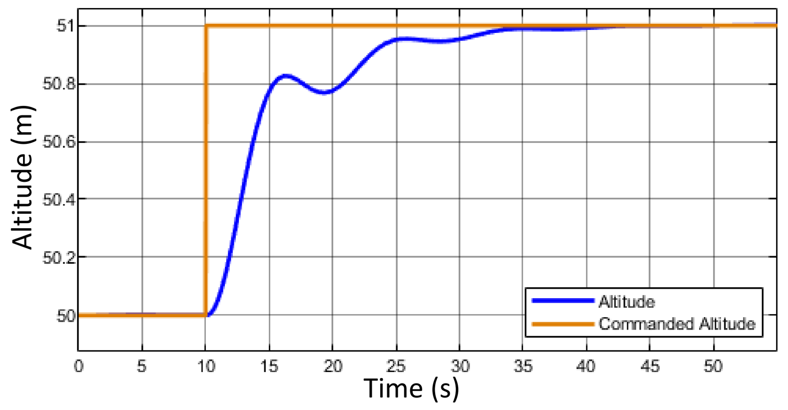
Control Law Synthesis:

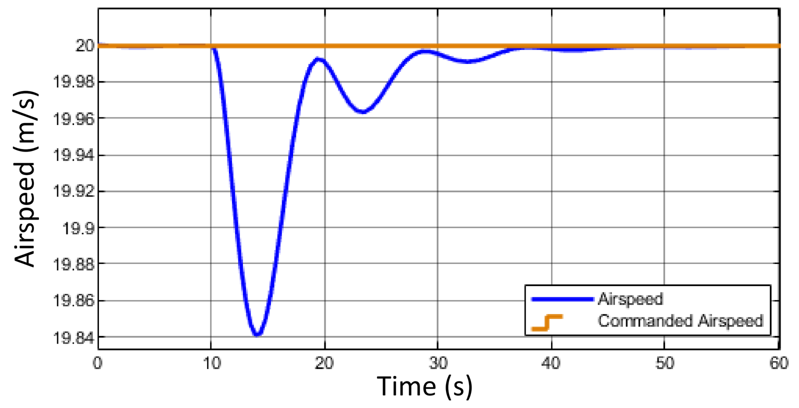
- The goal is to derive an experimental control law for altitude control, speed management, and disturbance rejection in the cruising flight regime.
- The architecture we proceeded with is one multivariable controller to manage altitude & speed (longitudinal dynamics) and one PID controller to manage the bank angle (lateral dynamics) of the UAV.



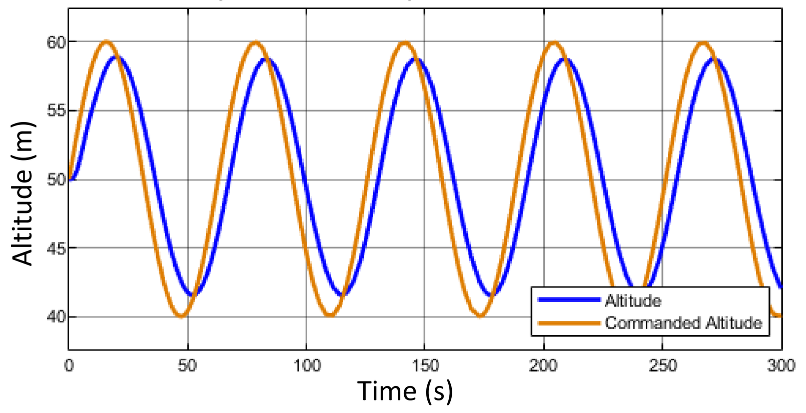
Control Law Performance Analysis:

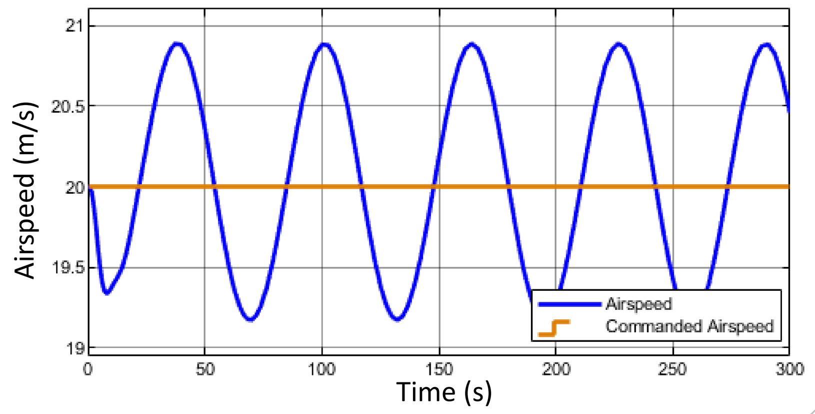
- For the longitudinal multivariable controller, we will be analyzing its performance by the settling time for altitude changes and the corresponding airspeed response. The step response to an altitude change is shown below. In the example below, the settling time is 22.1 seconds, and the airspeed is maintained as commanded within 20% tolerance bands.





- In addition, we tested this control system to see how it responds to a sinusoid altitude reference. The response shows that the control system is responsive and stable, even for faster dynamic requirements.





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