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Development Of Tools And Methods For Autonomous Fixed-wing UAV Research

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Introduction

Autonomous systems like a fixed-wing Unmanned Aerial Vehicle/System (UAV/S) operate based on high-level Guidance and Navigation algorithms and low-level control (GNC) laws. A challenge for both academics and professional engineers is the testing of all the software and hardware that must work together to carry out a given autonomous mission [1]. Software-In-The-Loop(SITL) simulations run the autopilot codes in a completely simulated environment. The Hardware-In-The-Loop(HITL) simulation in contrast is carried out by running the autopilot code in the actual target hardware that will be used in the actual UAV. Even when the software and hardware are deemed appropriate, their application can result in unrealistic and unreliable outcomes due to inadequate prior information about the target vehicle's dynamic behaviour [1]. This necessitates the development of higher fidelity simulations and means of obtaining such models before the autopilot can be tested. To compound the problems, flight testing of such fixed-wing UAVs can often be an expensive and a high-risk routine. This is due to the risk of crashes or loss of the vehicle due to GNC-failure. In this study, to aid the researchers, we aim to exploit both Free/Open Source and Commercial off-the-shelf software tools and hardware to develop a test bench that is adequate for the types of stated tasks.

Aims & Objectives

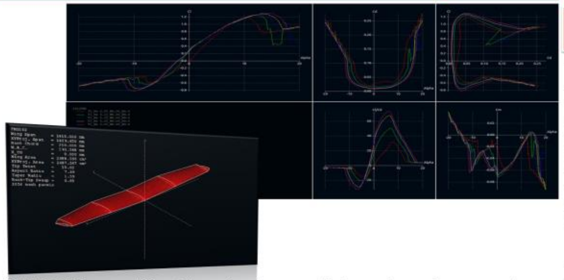
The primary aim of this project is to develop a Test-Bench to aid with autonomous fixed-wing UAV research on a target Flight Controller and compare the simulation results with real-world flight data. To achieve that, the following objectives need to be realised:

Create an X-Plane model of a target airframe.
- Analyse the airframe aerodynamics in XFLR5.
- Build an analytical model of the airframe in Simulink.
- Setuo SITL & HITL test environments.
- Compare the results

Test Bench Setup & Results

FMS SkyTrainer 182 RC Airplane [2] was used as the target airframe. Through the use of PlaneMaker on X-Plane 10 [3], an X-Plane model was created for this aircraft. The aerodynamic data were obtained through the use of XFLR5 [4] for low Re (50k to 250k). A 12 state 6 DOF MATLAB/Simulink based model [5] was created. Pixhawk PX4 Autopilot [6] was used to control the X-Plane model through QGroundControl [6].

XFLR 5 Modelling



XFLR 5 [4] was utilised to estimate essential aerodynamic parameters (Re Range between 50k & 250k).

Mathematical Modelling

The Forces & Moments acting on the UAV and associated Flight Dynamics parameters were modelled with appropriate first order ODE's.

$$\begin{pmatrix}\dot{p}_n\\ \dot{p}_e\\ \dot{p}_d\end{pmatrix} = \begin{pmatrix} c_\theta c_\psi & s_\phi s_\theta c_\psi - c_\phi s_\psi & c_\phi s_\theta c_\psi + s_\phi s_\psi \\ c_\theta s_\psi & s_\phi s_\theta s_\psi + c_\phi c_\psi & c_\phi s_\theta s_\psi - s_\phi c_\psi \\ -s_\theta & s_\phi c_\theta & c_\phi c_\theta \end{pmatrix} \begin{pmatrix}u\\ v\\ w\end{pmatrix}$$

$$\begin{pmatrix}\dot{u}\\ \dot{v}\\ \dot{w}\end{pmatrix} = \begin{pmatrix} rv - qw \\ pw - ru \\ qu - pv \end{pmatrix} + \frac{1}{m}\begin{pmatrix}f_x\\ f_y\\ f_z\end{pmatrix},$$

$$\begin{pmatrix}\dot{e}_0\\ \dot{e}_1\\ \dot{e}_2\\ \dot{e}_3\end{pmatrix} = \frac{1}{2}\begin{pmatrix} 0 & -p & -q & -r \\ p & 0 & r & -q \\ q & -r & 0 & p \\ r & q & -p & 0 \end{pmatrix}\begin{pmatrix}e_0\\ e_1\\ e_2\\ e_3\end{pmatrix}$$

$$\begin{pmatrix}\dot{p}\\ \dot{q}\\ \dot{r}\end{pmatrix} = \begin{pmatrix} \Gamma_1 pq - \Gamma_2 qr \\ \Gamma_5 pr - \Gamma_6 (p^2 - r^2) \\ \Gamma_7 pq - \Gamma_1 qr \end{pmatrix} + \begin{pmatrix} \Gamma_3 l + \Gamma_4 n \\ \frac{1}{J_y} m \\ \Gamma_4 l + \Gamma_8 n \end{pmatrix}$$

$$\begin{pmatrix}\dot{\phi}\\ \dot{\theta}\\ \dot{\psi}\end{pmatrix} = \begin{pmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \frac{\sin\phi}{\cos\theta} & \frac{\cos\phi}{\cos\theta} \end{pmatrix}\begin{pmatrix}p\\ q\\ r\end{pmatrix}$$

where

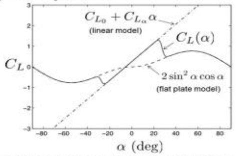
$$\Gamma_1 = \frac{J_{xz}(J_x - J_y + J_z)}{\Gamma}, \quad \Gamma_2 = \frac{J_z(J_z - J_y) + J_{xz}^2}{\Gamma}, \quad \Gamma_3 = \frac{J_z}{\Gamma},$$
$$\Gamma_4 = \frac{J_{xz}}{\Gamma}, \quad \Gamma_5 = \frac{J_z - J_x}{J_y}, \quad \Gamma_6 = \frac{J_{xz}}{J_y},$$
$$\Gamma_7 = \frac{(J_x - J_y)J_x + J_{xz}^2}{\Gamma}, \quad \Gamma_8 = \frac{J_x}{\Gamma}, \quad \Gamma = J_x J_z - J_{xz}^2.$$

Use of a blending function to model a higher fidelity aerodynamics:

$$F_{\text{lift}} = \frac{1}{2}\rho V_a^2 S\left[C_L(\alpha) + C_{L_q}\frac{c}{2V_a}q + C_{L_{\delta_e}}\delta_e\right]$$
$$F_{\text{drag}} = \frac{1}{2}\rho V_a^2 S\left[C_D(\alpha) + C_{D_q}\frac{c}{2V_a}q + C_{D_{\delta_e}}\delta_e\right]$$
$$C_L(\alpha) = (1-\sigma(\alpha))\underbrace{\left[C_{L_0} + C_{L_\alpha}\alpha\right]}_{\text{linear model}} + \sigma(\alpha)\underbrace{\left[2\,\text{sign}(\alpha)\sin^2\alpha\cos\alpha\right]}_{\text{flat-plate model}}$$

$$\sigma(\alpha) = \frac{1 + e^{-M(\alpha-\alpha_0)} + e^{M(\alpha+\alpha_0)}}{\left(1 + e^{-M(\alpha-\alpha_0)}\right)\left(1 + e^{M(\alpha+\alpha_0)}\right)}$$

blending function



Forces acting on the UAV were modelled based on the summation of all forces originating from gravity, propulsion and aerodynamic forces acting on the UAV:

$$\begin{pmatrix}f_x\\ f_y\\ f_z\end{pmatrix} = \begin{pmatrix} -mg\sin\theta \\ mg\cos\theta\sin\phi \\ mg\cos\theta\cos\phi \end{pmatrix} + \frac{1}{2}\rho V_a^2 S\begin{pmatrix} C_X(\alpha) + C_{X_q}(\alpha)\frac{c}{2V_a}q + C_{X_{\delta_e}}(\alpha)\delta_e \\ C_{Y_0} + C_{Y_\beta}\beta + C_{Y_p}\frac{b}{2V_a}p + C_{Y_r}\frac{b}{2V_a}r + C_{Y_{\delta_a}}\delta_a + C_{Y_{\delta_r}}\delta_r \\ C_Z(\alpha) + C_{Z_q}(\alpha)\frac{c}{2V_a}q + C_{Z_{\delta_e}}(\alpha)\delta_e \end{pmatrix} + \frac{1}{2}\rho S_{\text{prop}} C_{\text{prop}}\begin{pmatrix} (k_{\text{motor}}\delta_t)^2 - V_a^2 \\ 0 \\ 0 \end{pmatrix}$$

The UAV's DC motor's steady state torque generation calculated from the voltage supplied :

$$Q_m = K_Q\left[\frac{1}{R}(V_{in} - K_V\Omega) - i_0\right]$$

$R \triangleq$ resistance of the motor windings
$K_Q \triangleq$ motor torque constant
$K_V \triangleq$ back-emf voltage constant
$i_0 \triangleq$ zero-torque or no-load current

Wind modelling using the Dryden Model [7]:

$$H_u(s) = \sigma_u\sqrt{\frac{2V_a}{L_u}}\frac{1}{s + \frac{V_a}{L_u}} \qquad H_v(s) = \sigma_v\sqrt{\frac{3V_a}{L_v}}\frac{\left(s + \frac{V_a}{\sqrt{3}L_v}\right)}{\left(s + \frac{V_a}{L_v}\right)^2} \qquad H_w(s) = \sigma_w\sqrt{\frac{3V_a}{L_w}}\frac{\left(s + \frac{V_a}{\sqrt{3}L_w}\right)}{\left(s + \frac{V_a}{L_w}\right)^2}$$

gust description	altitude (m)	$L_u = L_v$ (m)	L_w (m)	$\sigma_u = \sigma_v$ (m/s)	σ_w (m/s)
low altitude, light turbulence	50	200	50	1.06	0.7
low altitude, moderate turbulence	50	200	50	2.12	1.4
medium altitude, light turbulence	600	533	533	1.5	1.5
medium altitude, moderate turbulence	600	533	533	3.0	3.0

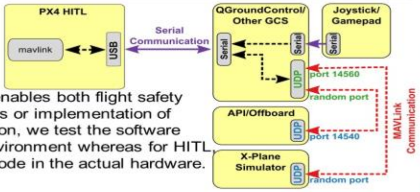
Calculation of the wind vector, adjusted airspeed vector, airspeed, angle of attack and side slip:

$$\mathbf{V}_w^b = \begin{pmatrix}u_w\\ v_w\\ w_w\end{pmatrix} = \mathcal{R}_v^b(\phi,\theta,\psi)\begin{pmatrix}w_{n_s}\\ w_{e_s}\\ w_{d_s}\end{pmatrix} + \begin{pmatrix}u_{w_g}\\ v_{w_g}\\ w_{w_g}\end{pmatrix} \qquad \mathbf{V}_a^b = \begin{pmatrix}u_r\\ v_r\\ w_r\end{pmatrix} = \begin{pmatrix}u - u_w\\ v - v_w\\ w - w_w\end{pmatrix}$$

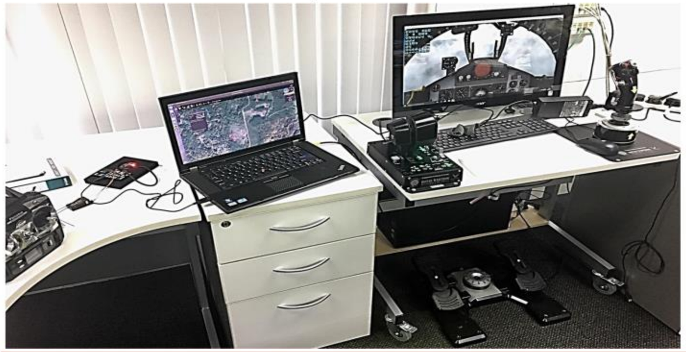
$$V_a = \sqrt{u_r^2 + v_r^2 + w_r^2}$$
$$\alpha = \tan^{-1}\left(\frac{w_r}{u_r}\right)$$
$$\beta = \sin^{-1}\left(\frac{v_r}{\sqrt{u_r^2 + v_r^2 + w_r^2}}\right)$$

SITL/HITL Simulation

The Pixhawk 4 Autopilot and the PX4 Flight Code [6] can be altered and tested through the QGroundControl [6] application and X-Plane prior to real flight tests. This enables both flight safety and rapid testing of new codes or implementation of algorithms. In the SITL situation, we test the software running within a computer environment whereas for HITL simulation, we run the flight code in the actual hardware.

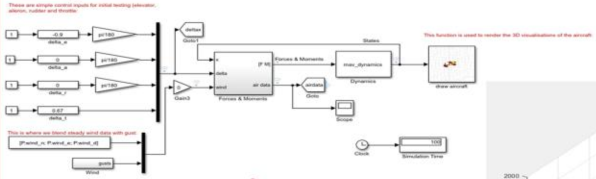


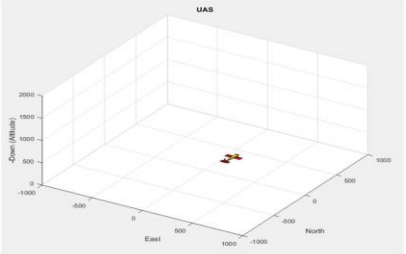
The system's architecture [6] can be seen in the above image. This setup was implemented in the lab using one machine running X-Plane 10, another machine running QGroundControl and a Pixhawk 4 Flight Controller. The following picture shows our HITL test bench in action. While it is possible to use one machine to run all the different software modules. However, that was avoided as a dedicated Flight Simulation machine ensure smoother operations for such resource intensive tasks.

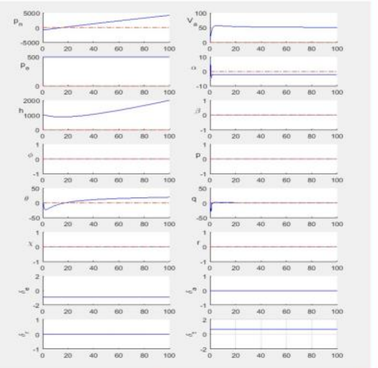


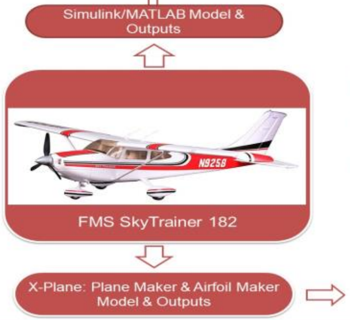
Simulink & X-Plane Simulations

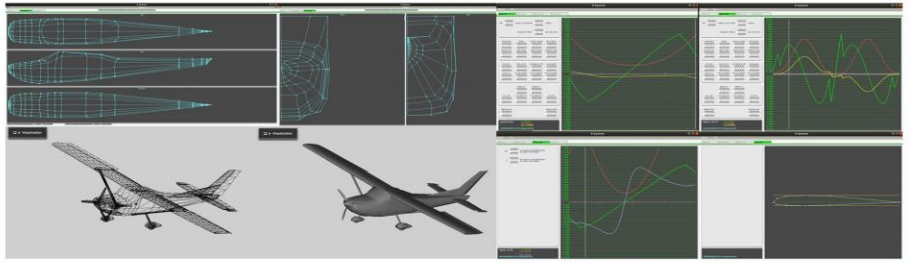
Through the use of s-function blocks, the mathematical models have been converted into a Simulink simulation of the target UAV:











Conclusion & Future Work

The goal was to setup the simulation environments for appropriate SITL and HITL simulations. The methods presented here work with limitations. For example, great care has been taken interfacing X-Plane with either Simulink or Pixhawk to avoid mismatches of simulation time-steps. Also, the Pixhawk PSP doesn't support the communication protocols used by QGroundControl. Even if these shortcomings won't be overcome, this test-bench is a powerful tool for carrying out Parameter Estimation/System Identification tasks and testing Guidance Navigation & Control (GNC) algorithms on simulated models of the target airframe. The developed Simulink model and X-Plane model can be used to predict flight data that can later be contrasted against the real flight data from real flight tests of the FMS SkyTrainer 182. This aids with both safety of the flying platform and refinement of simulation models from flight data.

Upon the completion of real-world flight tests and data acquisition, the predictions from this test bench and its individual modules (X-Plane and Simulink model) can be checked for their respective accuracies. Although we cannot alter X-Plane's source code, we will be able to improve our Simulink/MATLAB simulation fidelity as all relevant modules of that simulation has been coded by us in the form of S-Functions [5] based on our mathematical modelling.

References

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