Project Assignment
Nonlinear and Adaptive Control of Advanced Aerospace Systems
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Introduction

The goal of the project is to design an adaptive flight controller for the provided 3DOF aircraft model. The aircraft model does not correspond to a real production aircraft, but is a somewhat realistic model (albeit simplified and tweaked to ensure controllability.) The model to be considered is the one given in equations (1.14) and (1.15) of the lecture notes. Equation (1.14) of the notes is given below for completeness:

$$
\begin{aligned}
m\dot{V}_T &= T\cos\alpha - D(\alpha) - mg\sin(\theta-\alpha) \\
\dot{\alpha} &= q - \frac{1}{mV_T}\left[T\sin\alpha + L(\alpha) + L_\delta - mg\cos(\theta-\alpha)\right] \\
\dot{\theta} &= q \\
J_y\dot{q} &= M_A(\alpha) + M_{A,\delta}
\end{aligned}
$$

The term L_δ stands for the lift generated by the aerodynamic control surfaces, which has been extrapolated from the lift due to the airframe, $L(\alpha)$. The goal is to control the Mach number

$$M_\infty = \frac{V_T}{a_0}$$

where a_0 is the local speed of sound, and the flight-path angle

$$\gamma = \theta - \alpha$$

A simple relationship between airspeed and Mach number is assumed, which neglects the influence of altitude (that is the speed of sound has been considered constant.) Also, the dynamic pressure

$$\bar{q} = \tfrac{1}{2}\rho_0 V_T^2$$

is computed by assuming a constant air density, ρ_0. Aerodynamics forces and moments, as well as thrust, are generated via look-up tables. All model parameters and look-up tables are found in the parameter file `model_parameters_3DOF.mat`. The range of validity of the model is as follows:

$$M_\infty \in [0.5, 2]\,, \qquad \alpha \in [-10, 10] \text{ deg}$$

Please, note that all angles and surface deflections in the modes are expressed in radiants, degrees are never used.

The model has a redundant set of actuators, namely the throttle, δ_T, to control airspeed and a pair of aerodynamic effectors, a canard, δ_c, and an elevator, δ_e. The admissible ranges of deflections for the aerodynamic surfaces and the throttle are

$$\delta_c \in [-20, 20] \text{ deg}, \quad \delta_e \in [-30, 30] \text{ deg}, \quad \delta_T \in [0, 1.5]$$

Note that the throttle cannot take on negative values, hence $T \geq 0$ for the considered range of α. Vehicle deceleration can only be attained using drag by setting $\delta_T = 0$ (the model does not include speed brakes.) The control-design model for the aerodynamic control forces and moments is given by

$$\begin{pmatrix} L_\delta \\ M_{A,\delta} \end{pmatrix} = \bar{q}\boldsymbol{B}\begin{pmatrix} \delta_c \\ \delta_e \end{pmatrix}$$

whereas the control-oriented model for thrust is given as

$$T = \bar{q}\left[C_T^{\alpha}\alpha + C_T^0\right]\delta_T$$

where C_T^{α}, C_T^0 are coefficients to be estimated. Similarly, the control-oriented models for lift, drag and pitching moment are given as follows

$$\begin{aligned}
L(\alpha) &= \bar{q}\left[C_L^0 + C_L^{\alpha}\alpha\right] \\
C_D(\alpha) &= \bar{q}\left[C_D^0 + C_D^{\alpha}\alpha + C_D^{\alpha^2}\alpha^2\right] \\
C_{M_A}(\alpha) &= \bar{q}\left[C_{M_A}^0 + C_{M_A}^{\alpha}\alpha\right]
\end{aligned}$$

where the coefficients (to be estimated as well) have been normalized to remove the effective surface area S (see the modeling section in the notes.) Note that the explicit dependence on Mach number of the above forces and moment has not been included in the control-design model. However, these forces/moment do depend on Mach number (as seen from the look-up tables), which means that the above coefficients will change as a function of M_∞.

The simulink file `Jet_model_3DOF.slx` contains all relevant blocks to be used for simulation, namely the 3-DOF model of the dynamics, the generation of forces and moments via look-up tables, and various conversions. Feel free to explore the blocks and familiarize yourself with the model. The files `model_parameters_3DOF.mat` and `initial_conditions_3DOF.mat` must be loaded before loading the file `Jet_model_3DOF.slx` to ensure that all model parameters and initial conditions are in the workspace.

Project Synopsis

The project shall proceed along these steps:

1. Download and unzip the file `Nonlinear_aircraft_model_{3DOF}.zip` from the file repository.

2. Familiarize yourself with the nonlinear model. Use Chapter 1 of the notes as reference.

3. Perform a basic systems identification of the control oriented models for lift, drag, thrust and pitching moment using the provided range for M_∞ and α. This will give you an idea of the range of variability of the coefficients $C_T^0, C_T^{\alpha}, C_L^0, C_L^{\alpha}, C_D^0, C_D^{\alpha}, C_D^{\alpha^2}$, $C_{M_A}^0, C_{M_A}^{\alpha}$ to be estimated by the adaptive controllers. When doing so, set $\delta = 0$ to avoid producing lift and moment due to aerodynamic surfaces.

4. Implement the adaptive controller for the airspeed following Section 3.2 of the notes, or provide your own solution. Note that the solution explained in class did not make use of the anti-windup modification, hence feel free to implement a basic direct adaptive controller without anti-windup. The reference trajectory to be followed for M_∞ is the step input provided in the file `Jet_model_3DOF.slx`. To test the airspeed controller, you may want to isolate the airspeed dynamics from the rest of the model by taking α and θ (or γ and θ) as constant external signals.

5. Design an adaptive controller for the pitch dynamics by adapting the results of Section 3.3 to the simpler model

$$\dot{\theta} = q$$
$$J_y \dot{q} = M_A(\alpha) + M_{A,\delta}$$

Use the elevator as the main actuator for the pitch dynamics. As for the inverse model, use $\alpha_{\text{ref}} = 0$ and a constant $\gamma_{\text{ref}} \in [-5, 5]$ deg, hence $\theta_{\text{ref}} = \gamma_{\text{ref}}$, $q_{\text{ref}} = 0$. Feel free to use a second-order shaping filter to generate a smooth reference for $\gamma_{\text{ref}}(t)$, hence for $\theta_{\text{ref}}(t)$ and $q_{\text{ref}}(t)$. Again, use an attitude controller with or without MRAC modification (the one presented in class did not make use of the MRAC modification presented in the notes.) To test the attitude controller, you may want to isolate the pitch dynamics from the rest of the model by taking α and V_T (or α and M_∞) as constant external signals.

6. Using the canard as an auxiliary actuator, design an adaptive controller to stabilize the dynamics of the angle-of-attack to $\alpha_{\text{ref}} = 0$, using the same method developed in Section 4.2 of the notes for the vertical velocity. Note: Since $T \geq 0$ and $C_L^\alpha > 0$ the terms $T \sin \alpha$ and $\bar{q} C_L^\alpha \alpha$ provide useful dissipation, and shall not be canceled using the available control. Recall that the canard has a limited control authority.

7. Combine the three controllers and test the design on the full nonlinear models. Feel free to push the limits of the controller by modifying the command trajectories.

Things to keep in mind:

- Recall that all inputs are saturated in the nonlinear model. Likely, only the saturation on the throttle will be active during simulations. If your inputs saturate and drive the closed-loop system into unstable behavior, try to lower the value of the gains. It is a good idea to remove the saturation first, so the behavior of the closed-loop systems can be analyzed without worrying about saturation-induced instability.

- When simulating the nonlinear model, it is important to choose appropriately the integration algorithm and the parameters of the solver. Do not settle for the automatic choice provided by Simulink. A stiff algorithm may be needed to prevent numerical instabilities. Treat the solver algorithms for what they are: nonlinear algorithms with their pros and cons. Be aware of the possibility of numerical instability.

What to Write in Your Report

The report must be concise, yet informative. Do not show *all* your work, but do explain and describe any modification you have made to the solutions provided in your notes. Add a table with the values of all the gains of the controller. If something does not work as expected, provide your explanation why this is happening. Do not include your simulink files, only a report in PDF format. Make sure to include your name in the report.