DEVELOPMENT AND TUNING OF A NONLINEAR SIX DOF MODEL AND CONTROLLERS FOR A LARGE UAV

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Abstract

This paper presents development of non-linear six-degree-of-freedom model for a large UAV and simulation of its dynamics during its landing phase. A non-linear six-degree-of-freedom aircraft model was developed using the block available in the Aerosim Aeronautical Simulation Blockset in MATLAB / SIMULINK environment. The aircraft parameter data for a large UAV was taken. The developed model could be used for simulating the dynamics of the UAV with single piston engine and fixed pitch propeller. The following controllers were tuned using the above model to simulate its landing phase. ‘Bank to Aileron’, ‘Airspeed error to Pitch command’, ‘Pitch error to Elevator deflection’, ‘Engine rpm error to Throttle’. The first approach was by conventional techniques using PI and PID controllers. In the next stage fuzzy logic controllers were designed for the above cases. All fuzzy controllers were designed using Mamdani inference system.

Keywords: UAV, 6DOF model, controller tuning

Nomenclature

b = wing span

M = mach number

c = mean aerodynamic chord

MAP = manifold pressure vector
e = wing planform efficiency factor

Meng = engine moment

ht = high throttle

Mprop = propeller moment

klt = low throttle

NGC = navigation guidance and control

kpl = positive large

NL = negative large

ktl = proportional integral and derivative gains

NS = negative small

kpl = positive large

nlt = high throttle

PID = proportional integral derivative

nl = negative large

klt = low throttle

PS = positive small

nl = negative large

PL = positive large

ns = negative small

R = propeller radius

ode = ordinary differential equation.

RPM = rotations per minute

pl = positive large

SISO = single input single output

p, q, r = angular velocities along X, Y and Z-axes

TSL = sea level temperature

ps = positive small

UAV = unmanned aerial vehicle

r = radius of turn

WMM = world magnetic model

t = time

NGC = navigation guidance and control

2-D = two dimensional

DOF = degrees of freedom

1-D = one dimensional

EOM = equations of motion

CD = drag coefficient

FLC = fuzzy logic controller

CD0 = zero-lift drag coefficient

Ieng = engine shaft moment of inertia

Cδf = drag coefficient-lift control (flap) derivative

Iprop = propeller moment of inertia

Cδe = drag coefficient pitch control(elevator)derivative

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In this paper, development of nonlinear six-degree of freedom aircraft model is described. The aircraft model for the UAV was developed using the 6-DOF Aircraft Model (with Body-frame EOM) block from the AeroSim blockset, with the propulsion subsystem modified. Aerosim has got two aircraft model examples, namely Navion (a general aviation airplane) and Aerosonde (a weather-reconnaissance and remote sensing mission UAV). Using these two aircraft models NGC simulations were carried out [1] and [2]. The complete aircraft model blocks available can be customized using aircraft configuration script. Thus, any UAV can be modelled using the aircraft configuration script template available in samples directory under the Aerosim tree. In this project aircraft data for a large UAV was taken. The aircraft configuration script consists of five sections. In section 1, the aerodynamic parameters of the UAV are specified. In section 2 the geometry and aerodynamic performance of the propeller are specified. All engine data is
given at sea level. In section 4, the inertia parameters of the UAV are specified, namely mass, centre of gravity location and moments of inertia. In section 5, the calendar date used by the world magnetic model is specified. When all the parameters of the aircraft configuration script are filled up then it can be saved with a unique name. The internal structure of the complete UAV block is shown in Fig.1. The internal structure of aircraft model has the following subsystems. They are aerodynamic model with linear aerodynamics, propulsion model with piston-engine propulsion and fixed pitch propeller block, inertia model which has weight variation due to fuel consumption, atmosphere model with standard atmosphere, wind gusts and turbulence blocks, Earth model (which provides Earth radius, gravity and magnetic field components at current aircraft location) and equations of motion subsystem with nonlinear equations of motion. In the aerodynamic model the aerodynamic force and moment coefficients are computed using linear combinations of aerodynamic derivatives. The aerodynamic coefficients are computed using the following formulae [3].

\[
\begin{align*}
C_L &= C_{L0} + C_{L\alpha} \alpha + C_{L\delta f} \delta_f + C_{L\delta e} \delta_e \\
&\quad + \left( \frac{c}{2V} \right) \cdot \left( C_{L\alpha \alpha} \alpha^2 + C_{L\alpha q} q^2 \right) + C_{LM} M 
\end{align*}
\]  

(1)
The fuzzy controllers designed are explained. Thus the present work stands as first hand experience in developing a nonlinear six DOF model for a large UAV and do the simulation analysis for the same.

Setting up and Running the UAV Model

When the aircraft configuration script developed was run, a new aircraft configuration file with .mat extension was created. This file name was then used in the complete aircraft block (6 DOF body frame EOM) available in the Aerosim library. In the general-aviation propulsion system block, the power developed by the engine is computed as a function of RPM and MAP. The data available to interpolate power was not adequate. So, the 2-D power lookup table f(RPM, MAP) in the piston engine block was replaced by 1-D power lookup table f(throttle) as shown in Fig. 2. The power output was quite good with the above tuning. The block parameters for the complete aircraft (EOM) block consisted of aircraft configuration file, initial conditions for velocities, angular rates, attitude, position, fuel mass, engine speed, ground altitude, WMM coefficient file, simulation date and sample time.

All the aircraft block parameters were filled up and the UAV model was made ready for simulation. The UAV was given an initial velocity of 35 m/s, initial altitude of 1000 m and all other initial conditions in the block parameters were filled. The model was run in open loop. The simulink model used was as shown in Fig. 3. Before the model was run, the simulation pull-down menu in the open loop simulink model was selected. Then the configuration parameters option was selected. In the configuration parameters the solver type was set to fixed-step. The integration scheme was set to ode4 or ode5 [3]. The fixed step size was set to match the aircraft model sample time, which was 0.005 seconds. The bank response indicated that the spiral mode was unstable. When the model was run with engine OFF the bank angle was zero. Thus, spiral mode instability was due to engine torque. The open loop responses with engine ON and engine OFF were as shown in Fig. 4.

Controller Tuning By Conventional Method

The ‘airspeed to elevator’, ‘bank to aileron’ and ‘engine rpm to throttle’ controllers were tuned using the above model. With these controllers the landing phase of the UAV was simulated. Trim and linearization routine was developed for the developed model based on the already available trim and linearization routine for Aerosonde UAV available in trim directory. The control-
Fig. 2 Inclusion of 1-D power lookup table in the piston engine block

Fig. 3 Simulink model for open loop simulation of the UAV model
ler design using the linear models based on this routine did not give correct results. So, the controllers were tuned by trial and error process. A PI controller was found to be sufficient for bank control. The values of $k_p$ and $k_i$ were found to be 3.5 and 1 respectively. PID controller was implemented for airspeed error to pitch command. The values of $k_p$, $k_i$ and $k_d$ were found to be -4.5, -1 and -0.1 respectively. The pitch error to elevator deflection controller gains were found to be $k_p = 4$, $k_i = 0.87$ and $k_d = 0.4$. A PI controller was found sufficient for ‘engine rpm error to throttle command’. The gains for the controller were found to be $k_p = 0.01$ and $k_i = 0.1$.

**Base Leg and Final Turn Algorithm**

The base leg and final turn was assumed to commence from an altitude of 330 m. The airspeed command was maintained at 35 m/s. The bank command was given as -15 degrees. The engine rpm command was given as 1700 rpm in order to maintain a rate of descent of around 5m/s. The initial conditions were filled in the block parameters and the aircraft configuration file was ‘exptuav’. This phase lasted till 58m, for which the default ground was taken to be 15.58m above mean sea level. The UAV took a radius of turn as 466.5m and descended to an altitude of 58m, where the landing phase started. The responses for the UAV model during base leg and final turn were as shown in Fig. 5.

**Landing Phase Algorithm**

The approach was assumed to start at an altitude of 58m. The airspeed command was kept at 32.5m/s. The bank command was kept at 0 degrees. The engine rpm command was maintained at 2080 rpm. The engine rpm was maintained constant in order to maintain a rate of descent of around 1.8 m/s. The glide slope was assumed to be 3 degrees. The range was assumed to be 800m. The
default ground altitude was 15.58 m. The initial conditions were filled in the block parameters.

The flare was made to commence at an altitude of 19m above mean sea level, by cutting off the elevator control input from the controller and giving a constant elevator deflection of 20 degrees. This was implemented in the simalink model by providing a conditional switch, which monitored the altitude and disconnected the elevator control input when the altitude reached 19m and a constant elevator deflection was given to the elevator. The simulink model for the landing phase of UAV is shown in Fig. 6. The responses for landing phase were as shown in Fig. 7.

**Fuzzy Logic Controller Design**

During the landing phase, the system dynamics is nonlinear and human expertise for landing was available, so FLC for landing was attempted in the place of conventional controllers. All fuzzy logic controllers were SISO systems and were designed using Mamdani inference system. Center of area defuzzification scheme was used for all the controllers. Some of the rules used in the bank to aileron FLC were as follows:

- If bank error is PS then aileron deflection is NS
- If bank error is NL then aileron deflection is PL

Some of the rules used by the airspeed to elevator FLC were as follows:

- If airspeed error is pl then elevator deflection is nl.
- If airspeed error is ps then elevator deflection is ns.

Some of the rules used by the engine rpm to throttle FLC were as follows:

- If rpm error is pl then throttle is ht.
- If rpm error is ps then throttle is lt.
Fig. 6 Simulink model for the landing phase of the UAV

Fig. 7 Landing phase responses for the UAV model
The landing phase responses for the UAV model using FLCs were as shown in Fig. 8. The rule viewers for bank to aileron, airspeed to elevator and engine rpm to throttle were as shown in Figs. 9, 10 and 11 respectively.

Discussion of Results

During base leg and final turn the UAV took a semi-circular descend to come to the landing phase. The heading was linearly decreasing. The radius of turn was calculated using the formula

$$\frac{V_a^2}{(r \cdot g)} = \tan \phi$$

(10)

During glide slope the airspeed was settling to the commanded value of 32.5 m/s. The sink rate was also maintained constant to around 1.8 m/s. At the time of flare the constant elevator deflection had resulted in a gradual decrease in the rate of descent and made the UAV land safely. The airspeed also decreases during flare and its value was below the stall speed of the UAV.

Conclusion

A non-linear 6-DOF model was developed for a large UAV. This will serve as an experience for developing a 6-DOF model for any large UAV with single piston engine and fixed pitch propeller. The developed model was simulated to know its dynamics during landing phase, which can be helpful for pilot assisted landing. The future scope of the project can be the following:

- Manual pilot commands can be provided through the joystick interface block.
Fig. 9 Rule viewer for bank to aileron fuzzy logic controller

Fig. 10 Rule viewer for airspeed to elevator fuzzy logic controller

Fig. 11 Rule viewer for engine RPM to throttle fuzzy logic controller
• Flight parameters from simulation can be sent for visual output by making use of the flight simulator interface blocks.

• Actuator models can be included in the simulation.

• The sensor models can be included to increase the realism of the simulation.

• Trim and linerisation routine can be tuned to give correct results.

• The effect of wind on the dynamics of the UAV can be studied and

• Other UAV missions like waypoint navigation, control and guidance can be simulated.

References


