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Control Loss Recovery Autopilot Design for Fixed-Wing Aircraft

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Abstract:

In this paper a loop-shaping design approach is investigated for distressed fixed-wing aircraft experiencing control loss due to surface or power failure. An accurate nonlinear model of the aircraft dynamics is utilized to obtain a target aircraft behavior in the emergency situation, for which a loop-shaping controller is designed to balance performance and robustness, and to decouple different command channels. A rudder servoactuator jam scenario is presented as an example where it is seen that the autopilot recovers level flight and responds well to fly-by-wire commands from the operator.

Keywords: Loop-shaping, loss of control, surface jam, power loss, autopilot design, numerical simulation.

1. INTRODUCTION

Many aviation accidents have been caused by the sudden or gradual loss of control of the aircraft (Belcastro & Foster, 2010). Such loss of control may be caused by mechanical failures, human factors or environmental conditions. The first one includes control surface and engine failures and will physically limit the power and flight envelope of the aircraft, perhaps causing it to fly in unusual attitudes. The second and third factors are also important since pilot error and atmospheric conditions have been determined to be responsible for many accidents in aviation history (Gero, 2013).

Significant research effort has been devoted in literature to classifying aircraft loss of control accidents, as well as intervention mechanisms for preventing or recovering from mechanical failure, human errors and environmental factors (Belcastro, et al., 2014). Many of the recovery type approaches targeted are white-box methods in the sense that the designer looks at the aircraft dynamics, proposes a specific solution for a specific problem, and comes up with a specific intervention strategy (Yu & Jiang, 2012). This approaches poses some problems and sources of error however, since classical approaches to aircraft modelling and controller design make many assumptions and simplification to achieve decoupling of longitudinal and lateral channels, as well as linear approximations of the dynamics. (Etkin & Reid, 1996), (Nelson, 1998), (Stevens & Lewis, 2003), (Blakelock, 1991).

In an emergency control loss situation however, the aircraft will most probably exhibit a highly coupled dynamics and designs based on classical assumptions may not be optimal or even valid (Gill, et al., 2015). The situation deteriorates quite rapidly, perhaps within seconds in such control loss scenarios so if it is desired that the aircraft return to its near uncoupled and linear behavior, the burden must be shifted to an automated control system. This requires the controller to handle the system as a whole, and not separately in the longitudinal and lateral direction. This calls for a multi-input multi-output design, preferably with good robustness properties.

While multi-input multi-output robust flight controller designs are not uncommon for missile (Choi, et al., 2012), helicopter (Yang & Liu, 2003) and multirotor systems (Liu, Li, Kim, & Zhong, 2014) , they are found in fewer numbers for fixed wing aircraft since it is much practical to design individual controllers for separate channels (Nelson, 1998), (Blakelock, 1991). Unfortunately a loss of control scenario will likely render the standard approaches to separate the channels invalid since the aircraft may end up being in an unusual attitude with one or more of its four user inputs (throttle, aileron, elevator, rudder) being unavailable for recovering the aircraft.

In this paper we design a multi-input multi-output robust controller for a distressed aircraft experiencing some common loss of control scenarios. Alternative to a white-box approach requiring deep analysis of the aircraft dynamics for each such scenario, we take a black-box approach focusing only on input-output effects. This makes the control design methodology similar to each case, despite the physical meaning of the scenarios and their implication on the flight dynamics may be substantially different. The prosed controllers are verified using numerical simulations, hardware-in-the-loop tests, as well as actual flight tests with unmanned aerial vehicles.

2. MATHEMATICAL MODEL OF THE AIRCRAFT

The non-linear model of the aircraft dynamics is derived from basic Newtonian mechanics. For a rigid body, the total force and moment equations are:

$$\mathbf{F} = m\left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{\Omega} \times \mathbf{V}\right) \tag{1}$$

$$\mathbf{M} = \frac{\partial (\mathbf{I} \cdot \mathbf{\Omega})}{\partial t} + \mathbf{\Omega} \times (\mathbf{I} \cdot \mathbf{\Omega}) \tag{2}$$

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These equations express the motion of a rigid body relative to an inertial reference frame. $\mathbf{V} = [\,u\ v\ w\,]^T$ is the velocity vector at the center of gravity, $\mathbf{\Omega} = [\,p\ q\ r\,]^T$ is the angular velocity vector about the center of gravity, $\mathbf{F} = [\,F_x\ F_y\ F_z\,]^T$ is the total external force vector, and $\mathbf{M} = [L\ M\ N\,]^T$ is the total external moment vector. **I** is the inertia tensor of the rigid body, which is defined as

$$\mathbf{I} = \begin{bmatrix} I_{xx} & -J_{xy} & -J_{xz} \\ -J_{yx} & I_{yy} & -J_{yz} \\ -J_{zx} & -J_{zy} & I_{zz} \end{bmatrix} \tag{3}$$

The coefficients of the matrix **I** are the moments and products of inertia of the rigid body and they are constant for a frame of reference fixed to the aircraft. A manipulation of equations (1)-(2) yields

$$\frac{\partial \mathbf{V}}{\partial t} = \frac{\mathbf{F}}{m} - \mathbf{\Omega} \times \mathbf{V} \tag{4}$$

$$\frac{\partial (\mathbf{I} \cdot \mathbf{\Omega})}{\partial t} = \mathbf{M} - \mathbf{\Omega} \times (\mathbf{I} \cdot \mathbf{\Omega}) \tag{5}$$

from where a state-space model may be derived. The body-axes elements of linear and rotational velocities can be selected as the state variables for the model, whereas the body-axes components of the external forces and moments are the inputs to the model. A problem is that these inputs are in fact reliant upon the state variables so further steps are necessary to couple these back to the forces and moments. Nevertheless, using appropriate manipulations one could arrive at a non-linear state space model as follows:

$$\dot{\mathbf{x}} = \mathbf{f}\,(\mathbf{x}, \mathbf{F}(t), \mathbf{M}(t)\,) \tag{6}$$

with:

$$\mathbf{F} = \mathbf{g}_1(\mathbf{x}(\mathrm{t}), \mathbf{u}(\mathrm{t}), \mathbf{v}(\mathrm{t}), \mathrm{t}) \tag{7}$$

$$\mathbf{M} = \mathbf{g}_2(\mathbf{x}(\mathrm{t}), \mathbf{u}(\mathrm{t}), \mathbf{v}(\mathrm{t}), \mathrm{t}) \tag{8}$$

These equations may be blended into a compact expression

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}(\mathrm{t}), \mathbf{u}(\mathrm{t}), \mathbf{v}(\mathrm{t}), \mathrm{t}) \tag{9}$$

with state vector **x**, input vector **u**, disturbance vector **v**, and time t. The state vector **x** ordinarily embodies three linear and three angular velocities from **V** and **Ω**, but it is helpful to add six additional variables characterizing the attitude and location of the aircraft for obtaining a solution of the system. Specifically, the spatial orientation of the aircraft is essential for working out the gravitational force, the altitude is required for the computation of aerodynamic and engine forces both of which are influenced by air density that is a function of the aircraft's altitude. The position of the aircraft with regards to Earth is useful for tasks including evaluating flight trajectories of autopilot designs. In practice, it is often easier to utilize airspeed, angle of attack and sideslip angle rather than the linear velocity components so that

$$\mathbf{x} = [V\ \alpha\ \beta\ p\ q\ r\ \psi\ \theta\ \phi\ x_e\ y_e\ H\,]^T \tag{10}$$

in terms of which the state space equations can be derived (Rauw, 2001). For solving the abovementioned differential equations one should acquire the force and moment values $\mathbf{F} = [\,F_x\ F_y\ F_z\,]^T$ and $\mathbf{M} = [L\ M\ N\,]^T$ which are dependent upon of numerous mass and geometry variables, the engine model, in addition to the input commands. These forces and moments are handily stated by using stability derivatives, which represent the influence of various crucial parameters of a given force or moment value. For example the longitudinal aerodynamical force is expressed as

$$\begin{aligned} F_x &= C_{X_0} + C_{X_\alpha}\alpha + C_{X_{\alpha^2}}\alpha^2 + C_{X_{\alpha^3}}\alpha^3 \\ &+ C_{X_q}\frac{q\bar{c}}{V} + C_{X_{\delta_r}}\delta_r + C_{X_{\delta_f}}\delta_f + C_{X_{\alpha\,\delta_f}}\alpha\,\delta_f \end{aligned} \tag{11}$$

where C_{X_0}, C_{X_α}, $C_{X_{\alpha^2}}$, $C_{X_{\alpha^3}}$, C_{X_q}, $C_{X_{\delta_r}}$, $C_{X_{\delta_r}}$, $C_{X_{\alpha\,\delta_f}}$ are the stability derivatives capturing the effect of their multiplying term on F_x. Equations for F_y, F_z, L, M, N may be written likewise in terms of their related stability derivatives (Rauw, 2001). A fast computer realization of the mathematical equations just outlined is essential for developing the flight control system and for performing numerical validations. To achieve this goal the mathematical software MATLAB and its graphical environment Simulink were chosen for this study.

3. CONTROLLER DESIGN

The first step in controller design is to determine a target safe flight condition achievable under the failure experienced by the aircraft. The flight controller will attempt to drive the aircraft to this condition and then offer the option the pilot one of the following options: 1) take over manual control of the plane or 2) continue a fly-by-wire travel by providing only reference commands to the autopilot, which will transform these into real actuator commands.

Let us denote the normal aircraft dynamics of the form

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u}, \mathbf{v}, t) \tag{12}$$

$$\mathbf{y} = \mathbf{h}(\mathbf{x}, \mathbf{u}, \mathbf{v}, t) \tag{13}$$

where the output vector **y** represents the variables to be managed by the flight controller in response to reference commands from the pilot. Assume at time $t = t_L$ the aircraft experiences a problem and control is lost. Depending on the problem experienced by the aircraft, the flight dynamics, the inputs available for control and the outputs to be controlled may be different than those in normal flight for $t > t_L$, which we will denote by

$$\dot{\mathbf{x}} = \bar{\mathbf{f}}(\mathbf{x}, \bar{\mathbf{u}}, \mathbf{v}, t) \tag{14}$$

$$\bar{\mathbf{y}} = \bar{\mathbf{h}}(\mathbf{x}, \bar{\mathbf{u}}, \mathbf{v}, t) \tag{15}$$

As an example consider a rudder servoactuator failure that leaves the rudder stuck at $\delta_{\mathrm{r,stuck}} = 10°$ and unusable for the rest of the flight. From the moment of failure, the aircraft dynamics can be represented by

$$\begin{aligned} \dot{\mathbf{x}} &= \bar{\mathbf{f}}(\mathbf{x}, \bar{\mathbf{u}}, \mathbf{v}, t) \\ &= \mathbf{f}(\mathbf{x}, \mathbf{u}, \mathbf{v}, t)|_{\mathbf{u}=[\bar{\mathbf{u}},\delta_{r,\mathrm{stuck}}]=[F_{\mathrm{thrust}},\delta_e,\delta_a,\delta_{r,\mathrm{stuck}}]} \end{aligned} \tag{16}$$