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Nonlinear Dynamic Inversion of a Flexible Aircraft

Ryan James Caverly * **Anouck R. Girard** *
Ilya V. Kolmanovsky * **James Richard Forbes** **

* *Department of Aerospace Engineering, University of Michigan, 1320 Beal Avenue, Ann Arbor, MI 48109, USA (emails: caverly@umich.edu, anouck@umich.edu, ilya@umich.edu.)*
** *Department of Mechanical Engineering, McGill University, 817 Sherbrooke Street West, Montreal, Quebec, Canada H3A 0C3 (email: james.richard.forbes@mcgill.ca)*

Abstract: This paper investigates the use of dynamic inversion for the attitude control of a flexible aircraft. Input-output feedback linearization-based dynamic inversion is used to linearize the angular velocity and forward translational velocity equations of motion. A proportional-integral-derivative (PID) controller based on the direction cosine matrix (DCM) that describes the attitude of the aircraft is used, in addition to a proportional-integral (PI) controller to maintain a desired airspeed. Numerical simulations are performed using the proposed dynamic inversion controller, as well as more practical implementations of the controller that include saturated control inputs and no knowledge of the aircraft's flexible states. In simulation, the practical controllers successfully stabilize a flexible aircraft with reasonable control surface deflections.

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1. INTRODUCTION

Dynamic inversion has been shown to be an efficient control method for aircraft, due to its ability to transform nonlinear equations of motion into linear equations over large operating regimes (Enns et al., 1994). Dynamic inversion is a nonlinear control technique that is equivalent to input-output feedback linearization (Sastry and Isidori, 1989; Hovakimyan et al., 2005). As the performance limits of aircraft continue to expand, lighter and consequently more flexible aircraft are produced. This flexibility has been modeled (Tuzcu et al., 2007; Patil et al., 1999; Caverly and Forbes, 2015) and incorporated into the dynamic inversion control framework (Gregory, 2001; Dillsaver et al., 2013). However, the work of Gregory (2001) and Dillsaver et al. (2013) only consider the longitudinal dynamics of a flexible aircraft. There exists literature on the use of dynamic inversion for attitude control of flexible spacecraft (Tafazoli and Khorasani, 2004; Malekzadeh et al., 2010), which contains techniques that can be used as inspiration for the dynamic inversion of a flexible aircraft.

The novel contribution of this work includes the design and analysis of a controller that employs dynamic inversion for attitude and airspeed control of flexible aircraft. In particular, the use of dynamic inversion with practical constraints on the number of measured states and on the magnitude of the control inputs is considered. As proposed in Tafazoli and Khorasani (2004), dynamic inversion of the angular velocity equation of motion is performed. The dynamic inversion presented in this paper differs from that in Tafazoli and Khorasani (2004) by the inclusion of the aircraft's forward velocity in the dynamic inversion process, which allows for the linearization of the aircraft's angular velocity and forward velocity equations of motion. A proportional-integral-derivative attitude control law based on the direction cosine matrix (DCM) is considered along with a proportional-integral (PI) control law for airspeed control. The proposed dynamic inversion controller is implemented in simulation on a flexible high-altitude long-endurance (HALE) aircraft. More practical forms of the proposed controller are also implemented, which include limits on the allowable control surface deflections, no knowledge of the flexible coordinates in the dynamic inversion process, and both control surface deflection limits and no knowledge of flexible coordinates.

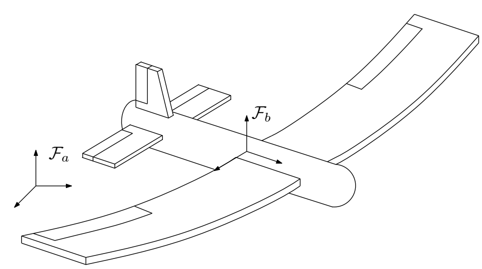

Fig. 1. Visualization of a flexible aircraft with body frame $\mathcal{F}_b$ and inertial frame $\mathcal{F}_a$.

The remainder of this paper proceeds as follows. A presentation of the equations of motion of a flexible aircraft is included in Section 2. Section 3 includes the dynamic inversion framework used to control the attitude of a flexible

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aircraft. Numerical simulations of the proposed controller and variations of the proposed controller are presented in Section 4, followed by concluding remarks in Section 5.

2. DYNAMIC MODEL

Consider the flexible aircraft shown in Fig. 3 whose equations of motion are

$$\mathbf{M}\dot{\boldsymbol{\nu}} + \mathbf{D}\dot{\mathbf{q}} + \mathbf{K}\mathbf{q} + \mathbf{f}_{\text{non}}(\mathbf{q}, \boldsymbol{\nu}) = \hat{\mathbf{B}} \begin{bmatrix} \boldsymbol{\tau} \\ T \end{bmatrix}, \tag{1}$$

where $\mathbf{q}^{\mathsf{T}} = \begin{bmatrix} \mathbf{r}_a^{cw^{\mathsf{T}}} & \mathbf{c}^{ba^{\mathsf{T}}} & \mathbf{q}_e^{\mathsf{T}} \end{bmatrix}$ are the generalized coordinates, $\boldsymbol{\nu}^{\mathsf{T}} = \begin{bmatrix} \dot{\mathbf{r}}_a^{cw^{\mathsf{T}}} & \boldsymbol{\omega}_b^{ba^{\mathsf{T}}} & \dot{\mathbf{q}}_e^{\mathsf{T}} \end{bmatrix}$ are the augmented generalized velocities, $\mathbf{r}_a^{cw}$ is the position of the center of mass of the aircraft relative to an unforced particle w expressed in the inertial frame $\mathcal{F}_a$, $\mathbf{c}^{ba}$ is a column matrix that contains the nine entries of the DCM that describes the attitude of the aircraft relative to $\mathcal{F}_a$, $\mathbf{q}_e$ are the elastic coordinates used to describe the elastic deformation of aircraft, $\boldsymbol{\omega}_b^{ba}$ is the angular velocity of the aircraft relative to $\mathcal{F}_a$ expressed in the body frame $\mathcal{F}_b$. The matrix $\mathbf{M} = \mathbf{M}^{\mathsf{T}} > 0$ is the mass matrix, $\mathbf{D}$ is the damping matrix, $\mathbf{K}$ is the stiffness matrix, $\mathbf{f}_{\text{non}}(\mathbf{q}, \boldsymbol{\nu})$ is a column matrix containing nonlinear terms including aerodynamic forces, $\hat{\mathbf{B}}$ is the matrix that distributes the inputs to the dynamic equations, $\boldsymbol{\tau}$ is the body torque input to the aircraft, and T is the thrust input to the aircraft that acts along the longitudinal axis of the aircraft. Although aircraft do not have actuators that can exert an arbitrary body torque, a body torque is considered as a input in this paper for simplicity and to allow for the use of a DCM-based attitude control law. The pitch, roll, and yaw moments can be mapped to the appropriate control surface deflections by solving a control allocation problem (Durham, 1994; Härkegård, 2004; Bodson, 2002). The equation of motion in (1) is rewritten in first-order state-space form as

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}) + \mathbf{G}(\mathbf{x}) \begin{bmatrix} \boldsymbol{\tau} \\ T \end{bmatrix}, \tag{2}$$

where $\mathbf{x}^{\mathsf{T}} = \begin{bmatrix} \mathbf{q}^{\mathsf{T}} & \boldsymbol{\nu}^{\mathsf{T}} \end{bmatrix}$,

$$\mathbf{f}(\mathbf{x}) = \begin{bmatrix} \boldsymbol{\Gamma}\boldsymbol{\nu} \\ \mathbf{f}_r(\mathbf{x}) \\ \mathbf{f}_\omega(\mathbf{x}) \\ \mathbf{f}_e(\mathbf{x}) \end{bmatrix},$$

$$\mathbf{G}(\mathbf{x}) = \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{G}_{r\tau}(\mathbf{x}) & \mathbf{G}_{rT}(\mathbf{x}) \\ \mathbf{G}_{\omega\tau}(\mathbf{x}) & \mathbf{G}_{\omega T}(\mathbf{x}) \\ \mathbf{G}_{e\tau}(\mathbf{x}) & \mathbf{G}_{eT}(\mathbf{x}) \end{bmatrix}, \tag{3}$$

$$\begin{bmatrix} \mathbf{f}_r(\mathbf{x}) \\ \mathbf{f}_\omega(\mathbf{x}) \\ \mathbf{f}_e(\mathbf{x}) \end{bmatrix} = -\mathbf{M}^{-1}\left(\mathbf{D}\dot{\mathbf{q}} + \mathbf{K}\mathbf{q} + \mathbf{f}_{\text{non}}(\mathbf{q}, \boldsymbol{\nu})\right),$$

$$\begin{bmatrix} \mathbf{G}_{r\tau}(\mathbf{x}) & \mathbf{G}_{rT}(\mathbf{x}) \\ \mathbf{G}_{\omega\tau}(\mathbf{x}) & \mathbf{G}_{\omega T}(\mathbf{x}) \\ \mathbf{G}_{e\tau}(\mathbf{x}) & \mathbf{G}_{eT}(\mathbf{x}) \end{bmatrix} = \mathbf{M}^{-1}\hat{\mathbf{B}},$$

$$\boldsymbol{\Gamma} = \text{diag}\{\mathbf{1}, \boldsymbol{\Gamma}_b^{ba}, \mathbf{1}\},$$

and $\dot{\mathbf{c}}^{ba} = \boldsymbol{\Gamma}_b^{ba}\boldsymbol{\omega}_b^{ba}$. As shown in de Ruiter and Forbes (2014), the relationship $\dot{\mathbf{c}}^{ba} = \boldsymbol{\Gamma}_b^{ba}\boldsymbol{\omega}_b^{ba}$ stems from Poisson's equation, $\dot{\mathbf{C}}_{ba} = -\boldsymbol{\omega}_b^{ba^\times}\mathbf{C}_{ba}$, where

$$\mathbf{a}^\times = \begin{bmatrix} 0 & -a_3 & a_2 \\ a_3 & 0 & -a_1 \\ -a_2 & a_1 & 0 \end{bmatrix},$$

for $\mathbf{a} = [a_1 \ a_2 \ a_3]^{\mathsf{T}}$. Defining $\mathbf{C}_{ba}^{\mathsf{T}} = \begin{bmatrix} \mathbf{c}_1^{ba} & \mathbf{c}_2^{ba} & \mathbf{c}_3^{ba} \end{bmatrix}$ and $\mathbf{c}^{ba^{\mathsf{T}}} = \begin{bmatrix} \mathbf{c}_1^{ba^{\mathsf{T}}} & \mathbf{c}_2^{ba^{\mathsf{T}}} & \mathbf{c}_3^{ba^{\mathsf{T}}} \end{bmatrix}$ leads to

$$\boldsymbol{\Gamma}_b^{ba} = \begin{bmatrix} \mathbf{0} & -\mathbf{c}_3^{ba} & \mathbf{c}_2^{ba} \\ \mathbf{c}_3^{ba} & \mathbf{0} & -\mathbf{c}_3^{ba} \\ -\mathbf{c}_2^{ba} & \mathbf{c}_1^{ba} & \mathbf{0} \end{bmatrix}.$$

The matrices in (1) are further expressed as

$$\mathbf{M} = \begin{bmatrix} \mathbf{M}_{rr} & \mathbf{M}_{r\omega} & \mathbf{M}_{re} \\ \mathbf{M}_{r\omega}^{\mathsf{T}} & \mathbf{M}_{\omega\omega} & \mathbf{M}_{\omega e} \\ \mathbf{M}_{re}^{\mathsf{T}} & \mathbf{M}_{\omega e}^{\mathsf{T}} & \mathbf{M}_{ee} \end{bmatrix},$$

$$\mathbf{f}_{\text{non}} = \begin{bmatrix} \mathbf{f}_{\text{non},r} \\ \mathbf{f}_{\text{non},\omega} \\ \mathbf{f}_{\text{non},e} \end{bmatrix},$$

$$\mathbf{D} = \text{diag}\{\mathbf{0}, \mathbf{0}, \mathbf{D}_{ee}\},$$
$$\mathbf{K} = \text{diag}\{\mathbf{0}, \mathbf{0}, \mathbf{K}_{ee}\},$$

where $\mathbf{D}_{ee} = \mathbf{D}_{ee}^{\mathsf{T}} \geq 0$ and $\mathbf{K}_{ee} = \mathbf{K}_{ee}^{\mathsf{T}} \geq 0$.

3. DYNAMIC INVERSION

The output of the system is chosen to be

$$\mathbf{y} = \begin{bmatrix} \boldsymbol{\omega}_b^{ba} \\ \mathbf{1}_2^{\mathsf{T}}\mathbf{C}_{ba}\dot{\mathbf{r}}_a^{cw} \end{bmatrix}, \tag{4}$$

where $\mathbf{1}_2^{\mathsf{T}}\mathbf{C}_{ba}\dot{\mathbf{r}}_a^{cw}$ is the forward velocity of the aircraft, $\mathbf{1}_2^{\mathsf{T}} = [0 \ 1 \ 0]$, $\mathbf{C}_{ba}$ is the DCM that describes the attitude of $\mathcal{F}_b$ relative to $\mathcal{F}_a$, and $\dot{\mathbf{r}}_a^{cw}$ is the velocity of the aircraft's center of mass relative to an unforced particle expressed in $\mathcal{F}_a$. Taking the time derivative of (4) yields

$$\begin{aligned}
\dot{\mathbf{y}} &= \begin{bmatrix} \dot{\boldsymbol{\omega}}_b^{ba} \\ \mathbf{1}_2^{\mathsf{T}}\left(-\boldsymbol{\omega}_b^{ba^\times}\mathbf{C}_{ba} + \ddot{\mathbf{r}}_a^{cw}\right) \end{bmatrix}, \\
&= \begin{bmatrix} \mathbf{f}_\omega(\mathbf{x}) + \mathbf{G}_{\omega\tau}(\mathbf{x})\boldsymbol{\tau} + \mathbf{G}_{\omega T}(\mathbf{x})T \\ \mathbf{1}_2^{\mathsf{T}}\left(-\boldsymbol{\omega}_b^{ba^\times}\mathbf{C}_{ba} + \mathbf{f}_r(\mathbf{x}) + \mathbf{G}_{r\tau}(\mathbf{x})\boldsymbol{\tau} + \mathbf{G}_{rT}(\mathbf{x})T\right) \end{bmatrix}, \\
&= \bar{\mathbf{f}}(\mathbf{x}) + \bar{\mathbf{G}}(\mathbf{x}) \begin{bmatrix} \boldsymbol{\tau} \\ T \end{bmatrix}. \qquad (5)
\end{aligned}$$

where

$$\bar{\mathbf{f}}(\mathbf{x}) = \begin{bmatrix} \mathbf{f}_\omega(\mathbf{x}) \\ \mathbf{1}_2^{\mathsf{T}}\left(-\boldsymbol{\omega}_b^{ba^\times}\mathbf{C}_{ba} + \mathbf{f}_r(\mathbf{x})\right) \end{bmatrix},$$

$$\bar{\mathbf{G}}(\mathbf{x}) = \begin{bmatrix} \mathbf{G}_{\omega\tau}(\mathbf{x}) & \mathbf{G}_{\omega T}(\mathbf{x}) \\ \mathbf{1}_2^{\mathsf{T}}\mathbf{G}_{r\tau}(\mathbf{x}) & \mathbf{1}_2^{\mathsf{T}}\mathbf{G}_{rT}(\mathbf{x}) \end{bmatrix}.$$

Based on the structure of (5) the control input is chosen to be

$$\begin{bmatrix} \boldsymbol{\tau} \\ T \end{bmatrix} = \bar{\mathbf{G}}^{-1}(\mathbf{x})\left(\bar{\mathbf{v}} - \bar{\mathbf{f}}(\mathbf{x})\right), \tag{6}$$

which gives $\dot{\mathbf{y}} = \bar{\mathbf{v}}$, where $\bar{\mathbf{v}}^{\mathsf{T}} = \begin{bmatrix} \mathbf{v}_\omega^{\mathsf{T}} & \mathbf{v}_r^{\mathsf{T}} \end{bmatrix}$. Based on the chosen aircraft inputs and outputs, the matrix $\bar{\mathbf{G}}(\mathbf{x})$ will always be non singular. This may not always be true when using dynamic inversion with a different set of inputs and/or outputs. Substituting (6) into (5) gives

$$\dot{\boldsymbol{\omega}}_b^{ba} = \mathbf{v}_\omega, \tag{7}$$

$$\mathbf{1}_2^{\mathsf{T}}\left(-\boldsymbol{\omega}_b^{ba^\times}\mathbf{C}_{ba} + \ddot{\mathbf{r}}_a^{cw}\right) = \mathbf{v}_r. \tag{8}$$

Equation (7) represents the attitude dynamics, while (8) represents the forward velocity dynamics. A PID control law that incorporates the DCM directly is considered

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