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Structured model-following neuro-adaptive design for attitude maneuver of rigid bodies

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ABSTRACT

A new structured model-following adaptive approach is presented in this paper to achieve large attitude maneuvers of rigid bodies. First, a nominal controller is designed using the dynamic inversion philosophy. Next, a neuro-adaptive design is proposed to augment the nominal design in order to assure robust performance in the presence of parameter inaccuracies as well as unknown constant external disturbances. The structured approach proposed in this paper (where kinematic and dynamic equations are handled separately), reduces the complexity of the controller structure. From simulation studies, this adaptive controller is found to be very effective in assuring robust performance.

1. Introduction

The rigid body attitude control problem has been the subject of extensive investigation because of its application to spacecraft attitude maneuvers, underwater vehicles and various aspects of robot manipulators, etc. For example, spacecrafts, in particular, are required to achieve highly accurate large attitude maneuvers. Moreover, this needs to be done in the presence of parameter uncertainties in the system dynamics as at any point of time the inertia matrix is usually not known exactly because of variation in payload distribution, consumption of fuel, etc. In addition, dynamic systems are also influenced by unwanted inputs (disturbances) and the controller should be sufficiently capable of addressing this issue as well. A good rigid body attitude control design should address these issues.

The control design process for attitude maneuvers requires rigid body attitude dynamics, which in turn demands an appropriate selection of attitude kinematic parameters. A survey paper (Shuster, 1993) presents various available kinematic parameters along with their associated properties. It is well known (which is also intuitively obvious) that a three-parameter attitude representation is a minimal representation. However, such a representation invariably suffers from the issue of singularity (Shuster, 1993), which restricts the range of its effective usage in attitude maneuver problems. Quaternions/Euler parameter representations, on the other hand is a four parameter representation (Costic & Dawson, 2001; Shuster, 1993; Sidi, 1997; Wie, 1998; Wie & Barba, 1985) and it does not suffer from this problem. However, an alternative representation, namely Modified Rodrigues Parameter (MRP) (Schaub & Junkins, 1995; Shuster, 1993), has appeared in the literature, which provides a continuous single-valued and analytic representation of rotation. MRP representation is preferred in this paper because only three parameters are involved as compared to four parameters in the quaternion representation. It is well known that the MRPs have a singularity at $\pm 360^\circ$, and hence, any rotation can be described except a complete revolution back to the original orientation. However, note that if used in conjunction with its "shadow set", the MRP representation has the ability to go beyond this limit as well. This is possible because whenever the MRP parameters lead to singularity, their shadow parameters do not. An interested reader can see Schaub and Junkins (1995) for more details. This advantage of the MRP representation can be exploited to execute large attitude maneuvers. In fact, various approaches towards the problem of attitude control have used MRPs in representing the attitude kinematics (Akella, 2001; Junkins, Akella, & Robinett, 1997; Wallsgrove & Akella, 2005).

The design of effective control systems for attitude maneuvers of rigid bodies is a fairly complex task as a result of coupled nonlinear system dynamics. A number of nonlinear control design techniques have been attempted in the literature to tackle various aspects of the attitude control problem. For example, attempts have been made to design effective controllers taking into account the effect of control saturation (Boskovic, Li, & Mehra, 2001). Attitude tracking controllers have also been designed without the requirement of angular velocity feedback (Akella, 2001; Costic &

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Dawson, 2001). The problem of robustness of the controller to parameter uncertainties and to disturbance torques has been addressed as well (Boskovic et al., 2001; Junkins et al., 1997; Wallsgrove & Akella, 2005). A relatively recent paper (Wallsgrove & Akella, 2005) has proposed a variable-structure approach combined with Lyapunov analysis to ensure attitude stabilization in the presence of disturbance torques. In fact, Lyapunov analysis-based control design algorithms employing both quaternions and MRPs have been employed in various nonlinear control design methods proposed in the literature (Akella, 2001; Boskovic et al., 2001; Wallsgrove & Akella, 2005; Wen & Delgado, 1991; Wie & Barba, 1985). Another innovative idea is the concept of energy shaping control (Wisniewski & Kulczycki, 2005).

A popular method of nonlinear control design is the technique of dynamic inversion (Enns, Bugajski, Hendrick, & Stein, 1994), which is essentially based on the philosophy of feedback linearization. This relatively simple approach leads to asymptotic stability of the tracking error. Another advantage is that it leads to a closed-form solution of the control variable. However, some of the critical drawbacks of this approach include the issue of stability of internal dynamics (Enns et al., 1994; Wallner & Well, 1998) and its sensitivity to modeling errors and parameter inaccuracies. Calise and his co-workers have proposed to augment the dynamic inversion technique with neural networks (trained online using a Lyapunov-based approach) so that the inversion error is canceled out (Hovakimyan, Nardi, Calise, & Lee, 2001; Kim & Calise, 1997; Leitner, Calise, & Prasad, 1997). This augmented technique makes the dynamic inversion method more robust to modeling and parameter inaccuracies and hence, makes it a very useful technique. At this point, it may be pointed out that a nice idea of augmenting linear controllers with a neural network-based adaptive design has appeared in the literature as well (Sharma & Calise, 2005). However, this design is a bit conservative, since the baseline controller relies on the linearized plant dynamics, which can only be an approximation of the original nonlinear dynamics.

To address the issue of the unknown parametric uncertainty as well as modeling inaccuracy, an alternate model-following approach has been reported (Balakrishnan & Haung, 2001). The idea in this paper is to design an adaptive "extra control" online, which needs to be added to a baseline controller. The key feature is that it can be augmented with "any" baseline controller (which may or may not be designed on the basis of dynamic inversion). This approach was developed further (Padhi, Unnikrishnan, & Balakrishnan, 2007). This reference presented a more systematic approach to address the same issue. In this approach, the idea is to capture the unknown function generated due to modeling inaccuracies and parameter uncertainties by a neural network (trained online) and use it in computing a modified (adaptive) controller directly from the updated plant model. Note that this approach is valid for nonaffine nonlinear systems as well.

In this paper, the generic theory proposed in Padhi et al. (2007) is developed further to account for a structured form of system dynamics, where the kinematics and dynamics parts are treated separately. Since kinematic equations are not effected by modeling errors and external inputs directly, the complexity of the controller structure and training process is reduced by such a structured approach. Next, this newly developed approach is used in conjunction with a dynamic inversion-based nominal controller and MRP attitude representation in order to design a large angle attitude maneuver of rigid bodies (e.g. satellites). To test the robustness of the approach presented, the attitude dynamics is assumed to have uncertainties in the moment of inertia matrix. Moreover, an unknown constant disturbance is also assumed for a finite duration of time, which can arise because of solar pressure variations, atmosphere drag, etc. From simulation studies, this adaptive controller is found to be very effective in achieving the required objective.

Rest of the paper is organized as follows: Section 2 contains an overview of the rigid body model and the goals to be achieved by the controller. Section 3 contains the generic theory, both for the nominal as well as for the model-following adaptive controller design. Section 4 discusses the problem specific equations. Section 5 describes the simulation results. Appropriate conclusions of this research are drawn in Section 6.

2. System dynamics and problem statement

The problem of attitude maneuver of rigid bodies is considered here, with the assumption that actuators are available to provide torques about three mutually perpendicular axes in the body-fixed frame. In the body-fixed frame, Euler's rotational equations of motion is given by (Akella, 2001)

$$I\dot{\omega} = \omega^{\times} I\omega + (U + \Gamma_D) \tag{1}$$

where ω, U and $\omega^{\times}$ are defined as follows:

$$\omega \triangleq [\omega_1 \;\; \omega_2 \;\; \omega_3]^{\mathrm{T}}, \quad U \triangleq [u_1 \;\; u_2 \;\; u_3]^{\mathrm{T}}, \quad \omega^{\times} \triangleq \begin{bmatrix} 0 & \omega_3 & -\omega_2 \\ -\omega_3 & 0 & \omega_1 \\ \omega_2 & -\omega_1 & 0 \end{bmatrix} \tag{2}$$

where ω_1, ω_2 and ω_3 are the angular velocities about its principal axes and u_1, u_2, u_3 are torques (controls) acting on the rigid body about its principal axes whose mass moment of inertia is given by the matrix $I = [I_{ij}]$, $i, j = 1, 2, 3$. Note that the inertia matrix is not supposed to be known perfectly. Moreover, the term Γ_D signifies that the rigid body is subjected to unwanted disturbance torques as well, which are "unknown" (but assumed to be constant in this paper).

In this paper, the MRP vector $\sigma(t) = [\sigma_1(t) \; \sigma_2(t) \; \sigma_3(t)]^{\mathrm{T}}$ has been used to designate the attitude kinematics of the rigid body, where σ_1, σ_2 and σ_3 represent the MRP coordinates (Schaub & Junkins, 1995; Shuster, 1993). This is motivated from the fact that the representation of attitude dynamics using the MRP vector is nonsingular about the principal axis up to ±360°, and hence, large attitude maneuvers are possible. The kinematic differential equation in terms of the MRP vector is given by

$$\dot{\sigma} = \Omega(\sigma)\omega \tag{3}$$

where

$$\Omega(\sigma) = \frac{1}{4}\begin{pmatrix} 1 + \sigma_1^2 - \sigma_2^2 - \sigma_3^2 & 2(\sigma_2\sigma_1 + \sigma_3) & 2(\sigma_1\sigma_3 - \sigma_2) \\ 2(\sigma_2\sigma_1 - \sigma_3) & 1 - \sigma_1^2 + \sigma_2^2 - \sigma_3^2 & 2(\sigma_2\sigma_3 + \sigma_1) \\ 2(\sigma_3\sigma_1 + \sigma_2) & 2(\sigma_3\sigma_2 - \sigma_1) & 1 - \sigma_1^2 - \sigma_2^2 + \sigma_3^2 \end{pmatrix}$$

Eqs. (1)–(3) govern the nonlinear dynamics of the rotational motion. Before proceeding further it is worth mentioning that there is a need to introduce two different notations in synthesizing the adaptive control design proposed in this paper. The subscript "*d*" stands for the "desired dynamics", which is essentially the dynamic of the nominal model (model having the nominal value of parameters and no disturbance torque acts on it). The actual dynamics, on the other hand, may contain parameter uncertainties and possible disturbance torques as well. The variables in the actual dynamics do not have any subscript.

In this paper, the goal is to execute attitude maneuvers for rigid bodies in the presence of parameter inaccuracies as well as possible constant disturbance torques. To achieve this objective, the control design should ensure that $[\sigma^{\mathrm{T}} \; \omega^{\mathrm{T}}]^{\mathrm{T}} \to [\sigma^{*\mathrm{T}} \; 0]^{\mathrm{T}}$ with the evolution of time from an initial condition $[\sigma^{\mathrm{T}}(0) \; \omega^{\mathrm{T}}(0)]^{\mathrm{T}} = [\sigma_0^{\mathrm{T}} \; 0]^{\mathrm{T}}$. To achieve this objective, a structured model-following adaptive control design procedure is presented in this paper, which has two