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Adaptive attitude control of spacecraft using neural networks

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Abstract

An adaptive control technique can be applicable to reorient spacecraft with uncertain properties such as mass, inertial and various misalignments. A nonlinear quaternion feedback controller is chosen as a baseline attitude controller. A linearly added adaptive input supported by neural networks to the baseline controller can estimate and eliminate the uncertain spacecraft property adaptively. The normalized input neural networks (NINNs) are examined for reliable computation of the adaptive input. The newly defined learning rules of the neural networks are established appropriately for a spacecraft. To prove the stability of the closed-loop dynamics with the control law, Lyapunov stability theory is considered. As a result, the proposed approach results in the uniform ultimate boundedness in tracking error and robustness of the chattering and the singularity problems.

Keywords: Adaptive control; Neural networks; Spacecraft attitude control

1. Introduction

High resolution earth observation spacecraft usually requires high precision attitude control capability to accomplish given mission objectives. However, the uncertainties in the spacecraft system actuated by conventional fixed-gain PID controller and external disturbances in general introduce steady state error and undesirable phase during large angle maneuvers [1]. The error ultimately affects precise attitude control performance. In practical applications, for example, the system inertia can be considered as uncertainty to account for changes in overall system configuration, for example, fuel consumption, out-gassing, etc. One potential approach to handle the model uncertainty is adaptive control. Adaptive control parameterizes the uncertainty in terms of certain unknown parameters, and attempts to employ feedback strategy to learn these parameters during the operation of the system.

Slotine and DiBenedetto developed an adaptive controller including the Gibbs parameters to compensate model uncertainty [2]. A nonlinear adaptive control algorithm in the presence of inertia uncertainties was developed [3]. This algorithm has a singularity problem so that the nonlinear controller forces the output to zero when the denominator of the control law is zero. Naturally, it induces a chattering problem. As an enabling nonlinear control theory, the feedback linearization technique has been applied to a wide variety of systems. A direct adaptive control strategy for a spacecraft with uncertain moment of inertia based on the feedback linearization was proposed by Sheen and Bishop [4]. Most adaptive control methods have been restricted to

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the systems with linear unknown parameters. Furthermore, the feedback linearization-based attitude control and momentum management of spacecraft is dependent on the initial conditions due to singularity problem [5]. Mathematically, the singularity problem corresponds to the case when the denominator of the control law becomes zero. The denominator in the nonlinear control form, for example, includes angular rate or attitude [6]. If angular rate or attitude is zero, then the denominator may become zero. If the absolute value of the denominator goes down to a certain level, then most of the controller produces no control signal. Unfortunately, this approach introduces the chattering problem.

The uncertainties in the spacecraft are in general nonlinear caused by various sources [1]. The system considered in this paper is subject to uncertain function, not parametric uncertainty. Since the neural network was demonstrated as a universal smooth function approximator [7], extensive studies have been conducted for diverse applications, especially pattern recognition, identification, estimation, and control of dynamic systems [8–12]. Application was made to adaptive control using neural networks for a general serial-link rigid robot arm [13]. The structure of the neural network controller is derived by filtered error approach. Calise et al. have extensively worked on the control and estimation of aircrafts and helicopters using neural network [14–16]. Adaptive output feedback control using a high-gain observer and radial basis function neural network were proposed for nonlinear systems represented by input–output models [17]. Also, a nonlinear adaptive flight control system was designed by backstepping [11] and neural network controller.

In this paper, to avoid singularity and chattering problem, the linearization technique is not considered, and the well-known quaternion feedback law [18] is chosen as the baseline controller. The three-layered neural network is augmented to the baseline controller to estimate and remove the unknown terms. The learning rules of the neural network are based on new weight updates, which are specifically designed for a spacecraft attitude control system. This is a new result different from the general update law. Therefore, the adaptive neural network-based quaternion control law can be claimed to provide much flexibility for implementation in generic spacecraft systems. Furthermore, for more reliable computation, normalized input neural network (NINN) is considered. The importance of the input data normalization is emphasized because of various benefits gained for the function approximation [19,20]. This paper is organized in five sections. First, the equations of motion of a rigid spacecraft with multiple CMGs are introduced. Then, the NINN is introduced. An adaptive control law with a new update law for spacecraft with uncertainty is followed. In the next section, the stability analysis is presented. Finally, the proposed method is demonstrated using numerical simulation study.

2. Spacecraft dynamics model

Consider a spacecraft installed with one variable speed control moment gyro which has been widely studied in the past couple of decades (see Fig. 1). The gimbal inertia matrix and flying wheel inertia matrix based on the gimbal frame orientation are denoted as I_g and I_d, respectively. The angular velocity vectors of the gimbal frame and the flying wheel are defined as $\dot{\gamma}_g$, $\boldsymbol{\varpi}_g$ with respect to the gimbal frame orientation, respectively. The angular velocity vector of the spacecraft with respect to the body frame can be derived from the gimbal frame coordinate system such that

$$\boldsymbol{\omega} = C\boldsymbol{\omega}_g \tag{1}$$

where $\boldsymbol{\omega}_g$ is the angular vector based on the gimbal frame coordinate, and C denotes the associated direction cosine matrix.

The total angular momentum of the rigid spacecraft is then represented by

$$\boldsymbol{h} = \boldsymbol{h}_s + \boldsymbol{h}_g + \boldsymbol{h}_d \tag{2}$$

where $\boldsymbol{h}_s$ corresponds to the angular momentum vector of the spacecraft, and $\boldsymbol{h}_g$, $\boldsymbol{h}_d$ represent the angular momentum vectors of the gimbal frame and the flying wheel, respectively. Equations of motion of the spacecraft system from Euler's equation are described as

$$\dot{\boldsymbol{h}} = \boldsymbol{u}_e \tag{3}$$

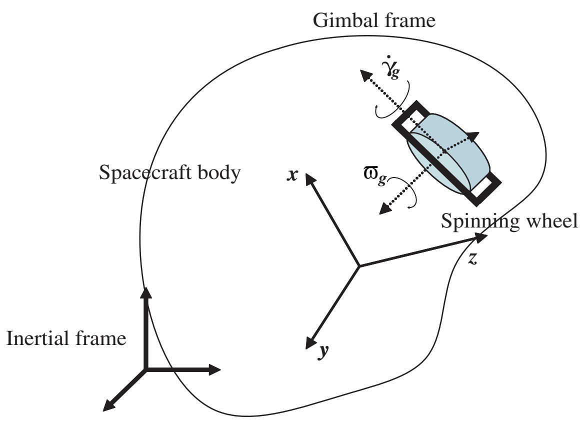

Fig. 1. Coordinate definition of spacecraft with one VSCMG.