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Acceleration autopilot for a guided spinning rocket via adaptive output feedback

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ABSTRACT

Uncertainties in control effectiveness, and moment coefficients are among the practical challenges in control of flight vehicles. Adaptive control is known as a proper method to handle uncertain systems, and has been used in numerous applications to improve system performance in the presence of system uncertainties. This paper presents a new method of synthesizing an acceleration autopilot for a guided spinning rocket, which is a class of uncertain, non-square multi-input/multi-output system. Firstly, a nonlinear and coupled six-degree-of-freedom (6-DoF) dynamic model is established, which is used to evaluate the performance of the proposed adaptive autopilot during the whole operating cycle. Secondly, a simple design procedure based on square-up method and linear matrix inequality (LMI) is proposed to design the autopilot, allowing a globally stable adaptive output feedback law to be generated. Finally, the adaptive output feedback autopilot is applied to the nonlinear 6-DoF dynamic model and it is shown to result in stable tracking in the presence of uncertainties.

1. Introduction

Traditional artillery ballistic gun-launched munitions cannot satisfy more and more stringent performance requirements about precision-strike capability, dispersion error reduction and range augmentation required on modern battlefields. Complex guided systems such as missiles can meet these requirements but they remain expensive due to the integration of high quality actuators and sensors. The idea is to develop a guided rocket, which permits to reach a compromise between the low cost of ballistic projectiles and the necessity to have high performance systems with efficient control algorithms.

The guided rocket chosen in this work is a dual-canard controlled, tail-stabilized spinning configuration, which makes use of an existing multiple launch rocket system (MLRS). This one has the advantage of simplifying the structure of the control system, avoiding asymmetric ablation, relaxing the manufacturing error tolerance and improving the penetration ability. It is also easy to implement and does not require the design of a new launch system. However, this kind of configuration has the disadvantages of cross coupling due to the spinning airframe. Besides, uncertainties in control effectiveness, and moment coefficients are among the practical challenges in the control system design. Finally, the actuators are of limited performance, due to the low cost and small size specification.

These disadvantages can be handled by developing a flight autopilot using modern multivariable control method, such as robust control [1,2] and gain-scheduling control [3,4]. The interpolation-based variable gain control method is simple and easy to implement, but this design method lacks a theoretical basis for ensuring good performance of the system throughout the entire operating cycle [5]. For the dual-channel controlled spinning rocket, various autopilots were designed, such as rate loop autopilot [6], attitude autopilot [7], acceleration autopilot [8], and three loop autopilot [9]. However, these related works were carried out under the nominal condition without considering uncertainties which may experience during the whole flight trajectory. Additionally, it is difficult to design an autopilot for a guided spinning rocket with excellent performance using traditional separate channel design method.

Performance degradation in face of reduced control effectiveness and parametric uncertainties was observed even in gain-scheduled robust missile autopilots [1]. However, adaptive control is known as a proper method to deal with these uncertainties, and has been used in numerous applications. Therefore, this paper is to investigate the potential of output feedback adaptive control for improving stability and performance of the spinning rocket autopilot. Adaptive control presents appropriate techniques to control

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autonomous systems with extensive applications during the past decades [10–15]. However, these controllers require that the system states must be measurable, which may not always be possible. For this reason, there has been an increasing motivation to develop an adaptive output feedback controller. Existing classical methods of multi-input and multi-output (MIMO) output feedback adaptive control are applicable for square systems, that is, the plant has the same number of inputs and outputs [16,17]. An output feedback adaptive autopilot for spinning rocket was designed with the assumption of square system [18]. In the design procedure, only the acceleration information was used to construct the autopilot, satisfying the square system assumption. Recently, research in squaring-up methods to deal with non-square systems has gained more interest [19–22].

In this paper, an output adaptive autopilot for a guided spinning rocket is proposed to handle uncertainties in control effectiveness and moment coefficients. The spinning rocket is a typical non-square system, which has two inputs and four outputs. The main challenge that needs to be addressed is the determination of a corresponding square and strictly positive real transfer function. The unique features of this output feedback adaptive controller are a baseline controller that uses a Luenberger observer, a closed-loop reference model, manipulations of a linear matrix inequality, and the Kalman–Yakubovich–Popov (KYP) lemma. Using these features, a simple design procedure is proposed for the adaptive controller, and the corresponding stability property is established.

The remainder of this paper is structured in the following manner. Section 2 develops the nonlinear 6-DoF dynamic model for a dual-canard controlled spinning rocket. Section 3 presents the output feedback adaptive autopilot design. Section 4 demonstrates the performance of the output feedback adaptive autopilot via numerical simulations. Finally, Section 5 concludes this paper.

2. Model formulation

The spinning rocket considered in this paper is an axially-symmetric rolling airframe, as is shown in Fig. 1. Two pairs of canard rotating with the airframe are employed as control surfaces twisting and steering the rocket, and the inertial measurement unit (IMU) is fixed on a roll-stabilized platform to prevent it from spinning with the airframe.

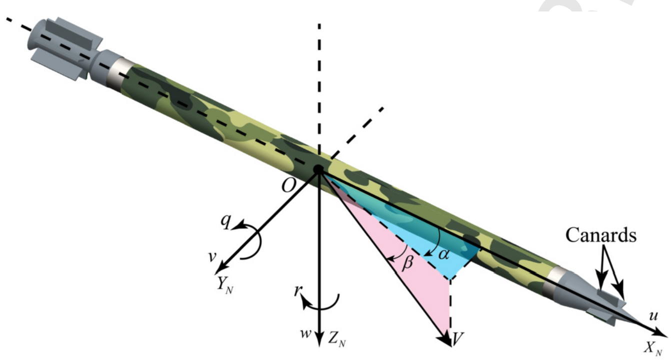


Fig. 1. Sketch of the spinning rocket.

2.1. Coordinate systems

To describe the airframe motion equations, three relevant coordinate systems, Earth coordinate system, rolling body coordinate system, and non-rolling body coordinate system, are defined in the following.

The Earth coordinate system $AXYZ$ is assumed an inertial coordinate frame. A is located at the center of gravity (c.g.) of the rocket at the instant of launch, AX is coincident with the launching direction and in the horizontal plane, AY is orthogonal to AX in the horizontal plane, and AZ is defined by the right-hand rule.

The non-rolling body coordinate system $OX_NY_NZ_N$ can be obtained by rotating the Earth frame $AXYZ$ an yaw angle ψ about the AZ axis and then an pitch angle θ around the subsequent OY_N axis to coincide the OX_N axis with the longitudinal axis of the rocket, as shown in Fig. 2a.

The rolling body coordinate system $OX_BY_BZ_B$ is a spinning frame and is fixed to the rocket. The origin O is at the c.g. of the rocket, OX_B is coincident with the longitudinal axis pointing to the nose, OY_B is orthogonal to OX_B in the symmetrical plane of the rocket, and OZ_B is defined by the right-hand rule. It can be obtained by rotating the non-rolling body coordinate $OX_NY_NZ_N$ an roll angel ϕ about the OX_N axis, as shown in Fig. 2b.

The transformation matrix from Earth frame $AXYZ$ to non-rolling body coordinate $OX_NY_NZ_N$ is

$$
\begin{aligned}
R_A^N &= R(\theta)R(\psi) \\
&= \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \\
&= \begin{bmatrix} \cos\theta\cos\psi & \cos\theta\sin\psi & -\sin\theta \\ -\sin\psi & \cos\psi & 0 \\ \sin\theta\cos\psi & \sin\theta\sin\psi & \cos\theta \end{bmatrix} \qquad (1)
\end{aligned}
$$

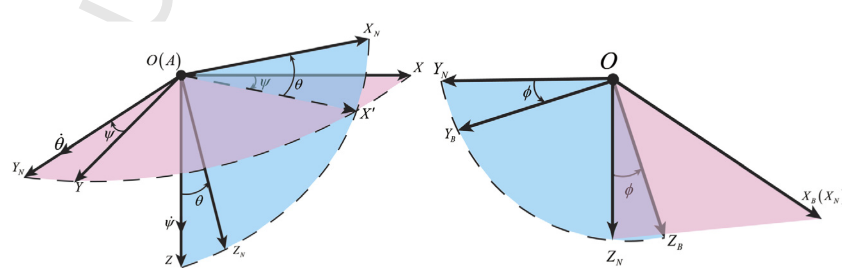
Moreover, the transformation matrix from non-rolling body coordinate $OX_NY_NZ_N$ to rolling body coordinate $OX_BY_BZ_B$ is

$$
R_N^B = R(\phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix} \qquad (2)
$$

2.2. Airframe motion equations

2.2.1. Kinematic equation

The position of the spinning rocket's c.g. is expressed as $(x, y, z)^T$ in the Earth frame, so the velocity of c.g. in Earth frame



(a) Non-rolling body coordinate (b) Rolling body coordinate

Fig. 2. Coordinate systems. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)