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Immersion and invariance-based control of novel moving-mass flight vehicles

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ABSTRACT

This paper proposes a novel configuration of the moving mass trim control system with a single moving mass and jet thrusters, which increases the control authority of control system while decreasing its volume and weight requirement. As a stepping stone, dynamics model of a moving-mass flight vehicle and control problem of attitude are formulated. Then, an adaptive controller based on the immersion and invariance approach is designed to guarantee asymptotic stability of the closed-loop system, and a slight improvement is developed to simplify the process. Furthermore, the estimator, which estimates aerodynamic coefficients and unmeasurable terms, is designed without certainty equivalence or linear parameterization. Instead, a procedure is provided to add cross terms between the parameter estimates and the plant states. Also, the associated stability proof is constructive and accomplished by the development of a Lyapunov function. In addition to stability proofs, numerical simulation results in different case are presented to illustrate the performance of the proposed schemes.

1. Introduction

Maneuvering reentry vehicle (MaRV) is playing an increasingly important role in future missions for atmospheric reentry. Furthermore, techniques for controlling MaRV have gravitated to systems that deliver larger amounts of control authority. Some studies have suggested that one of the most cost-effective but high-performance methods is a moving-mass control system (MMCS) [1,2]. Compared with traditional control methods (aerodynamic or thruster-based control method), the MMCS offers greater design and cost advantages. The simplicity in conjunction with the unique ability to provide attitude control authority from within the MaRV's protective aeroshell, making MMCS an attractive alternative to those traditional aerodynamic or thruster-based control systems.

The earliest analysis of an MMCS found in the literature was done in 1980 by Anon [3]. In 1984, at the Naval Surface Warfare Center, Regan [4] and his co-workers perform initial studies of the moving-mass trim control system (MMTCS). They devise a MMTCS, which generates a trim angle of attack (AOA) directly from the motion of the mass, to provide the axisymmetric ballistic vehicle with moderate range corrections when it is close to the target. In 1994, Petsopoulos and Regan [1] design a moving-mass roll control system (MMRCS) and investigate its ability to control the roll attitude and trajectory of a fixed-trim reentry vehicle during a typical reentry mission profile. At Sandia National Laboratories, the MMTCS is a by-product of deconing device test (DDT) conducted by White and Robinett [5]. The DDT provides an initial glimpse of effects of principle axis misalignment and center of mass offset on the vehicle's attitude. After a further study, they find that for a fast spinning vehicle, the trim AOA is generated by a principle axis misalignment, while a slow spinning vehicle relies on a center of mass offset to create a trim AOA under aerodynamic force.

On the other hand, the MMCS troubles the internal configuration of the vehicle in return since it offers the system (the whole vehicle) additional products of inertia, which will complicate the dynamic response. In addition, despite that the control authority of the MMCS can be significantly increased as the mass ratio of the moving mass increases, this way also lead to larger additional products of inertia. Moreover, the moving mass can no longer be treated as a particle in the process of dynamic analysis and controller design like previous literatures as the mass ratio of the moving mass increases. This paper proposes a novel MMTCS's configuration with a single moving mass and jet thrusters. The proposed configuration extends the internal moving mass to taking up most of the internal space of vehicle body and accounting for a large part of the whole mass. Hence, the existing internal component can be designed as the moving-mass element, which further decreases the volume and weight requirement of the MMTCS and increases the MaRV's payload capacity. The mass center offset of

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the whole system caused by the motion of moving mass can generate a trim AOA under aerodynamic drag. And the roll channel is controlled by jet thrusters to achieve the desired orientation.

Considering the apparent advantages of the MMCS, comprehensive literature reviews have covered surprisingly much information on the design and performance of these systems over the past decades. Costello investigates main influences on control authority of an internal translating mass system based on a 7-degree-of-freedom model while neglecting the nonlinear terms and perturbation of the dynamics model [6]. Woolsey develops the linear equations of a reentry vehicle with two moving-mass actuators and uses it in conjunction with a quadratic regulator control design procedure to determine control gains [7]. For the drawbacks that linear controller has difficulty in addressing coupling model, the feedback linearization approach has been widely applied to controller design. Ohlmeyer uses the feedback linearized dynamics of the vehicle to deal with the robust nonlinear control problem that designing a finite-horizon, robust integrated guidance-control system for a moving-mass actuated kinetic warhead, which produces the feedback solution with the multi-stepping algorithm [8]. Gao combines the sliding mode controller with the feedback linearization methodology to design the attitude control system of a moving-mass flight vehicle [9]. Zhang uses the fuzzy tree to approximate nonlinear system to avoid that the inverse system is overly dependent on the explicit expression and the accurate mathematical model [10]. Furthermore, in order to deal with large parameter uncertainties, a variety of robust, direct or indirect adaptive controllers have been developed like the adaptive backstepping approach [11], the fuzzy neural network approach [12], and so on. All of the adaptive approaches above invoke certainty equivalence and require a linear parameterization, this only guarantees the estimation error to be bounded but it is hard to reveal its dynamical behavior, which may be unacceptable in terms of the transient response of the closed-loop system. Moreover, increasing the adaptation gain does not necessarily speed-up the response of the system due to the strong coupling between the plant and the estimator dynamics, namely, there is an inherent limitation on the achievable performance. Another issue is that if the adaptive controller runs for infinite time and then freeze the parameter estimate, the resulting controller may be destabilized. In 2003, a new method called Immersion and Invariance (I&I) for (uncertain) nonlinear systems is presented by Astolfi [13,14]. This method relies upon the notions of system immersion and manifold invariance, which are classical tools from nonlinear regulator theory and geometric nonlinear control, but are used from a new perspective. The basic idea of the I&I approach is to achieve the control objective by immersing the plant dynamics into a (possibly lower-order) target system that captures the desired behavior. More precisely, the I&I methodology relies on finding a manifold in state-space that can be rendered invariant and attractive, with internal dynamics a copy of the desired closed-loop dynamics, and on designing a control law that robustly steers the state of the system sufficiently close to this manifold. The advantage is to reduce the controller design problem to other subproblems which, in some instances, might be easier to solve. Hence, this method has been widely applied in aerospace vehicles, such as missile [16], unmanned aerial vehicles [17,18], air-breathing hypersonic vehicle [19], and so on. What's more, the I&I well addresses the foregoing issues of previous adaptive approaches.

For the proposed configuration, the dynamic behavior of the moving mass becomes outstanding because of the high mass ratio, and the dynamical coupling between the body attitude and the motion of actuator mass increases the difficulty of controller design as well. In this paper, the dynamic model of the system and the moving mass of the proposed configuration are investigated first. Then, an adaptive attitude-servo controller is designed based on the I&I theory, which is followed by the stability analysis. Finally, numerical simulations in different scenarios indicate the great performance of the adaptive controller.

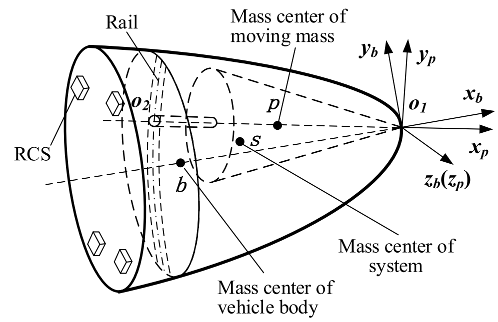

Fig. 1. The scheme of moving mass flight vehicle.

2. Dynamics modeling

2.1. Dynamics model of system

The moving mass flight vehicle is comprised of a main vehicle body and an internal single moving mass which is fixed with the vehicle body at o_1 and can move along the internal rail at o_2. (As shown in Fig. 1.) The motion of the moving mass leads to the mass center offset of the system, which can generate a trim AOA under the action of aerodynamic force. Therefore, the attitude of the flight vehicle can be controlled with the help of jet thrusters. The body coordinate system, moving mass coordinate system and inertial reference coordinate system used to establish dynamics model of flight vehicle is shown in Fig. 1.

In the first place, we build the dynamics model of system. The mass center of moving mass, vehicle body and system are denoted by p, b and s, respectively. Summing the angular momentum of the moving mass and the body with respect to the mass center of system yields the angular momentum of system with respect to the center of mass of system:

$$\begin{aligned}\boldsymbol{H}_s &= \boldsymbol{H}_p + \boldsymbol{H}_b \\ &= \boldsymbol{I}_p \cdot (\boldsymbol{\omega}_b + \boldsymbol{\omega}_{pb}) + \boldsymbol{I}_b \cdot \boldsymbol{\omega}_b + m_p \boldsymbol{r}_{sp} \times \dot{\boldsymbol{r}}_{o_1 p} \\ &\quad + m_b \boldsymbol{r}_{sb} \times \dot{\boldsymbol{r}}_{o_1 b}\end{aligned} \tag{1}$$

where $\boldsymbol{I}_b$ and $\boldsymbol{I}_p$ are inertial tensors of the vehicle body and moving mass about their center of mass, respectively. m_p and m_b are the mass of the moving mass and the vehicle body. $\boldsymbol{\omega}_b$ is the inertial angular velocity vector of the body, and $\boldsymbol{\omega}_{pb}$ is the relative angular velocity of the moving mass with respect to the body. According to the momentum theorem, the derivative of angular momentum of system in the inertial reference coordinate system is given by Eq. (2):

$$\begin{aligned}\frac{d\boldsymbol{H}_s}{dt} &= \frac{d(\boldsymbol{I}_p \cdot \boldsymbol{\omega}_p + \boldsymbol{I}_b \cdot \boldsymbol{\omega}_b)}{dt} + m_p \boldsymbol{r}_{sp} \times \ddot{\boldsymbol{r}}_{o_1 p} + m_b \boldsymbol{r}_{sb} \times \ddot{\boldsymbol{r}}_{o_1 b} \\ &= \sum \boldsymbol{M}_s\end{aligned} \tag{2}$$

$\boldsymbol{\omega}_p$ is the inertial angular velocity vector of the moving mass and $\sum \boldsymbol{M}_s$ is the total external moments acting on the flight vehicle, which can be written as

$$\begin{aligned}\sum \boldsymbol{M}_s &= \boldsymbol{M}_{\text{jet}} + \boldsymbol{r}_{sq} \times \boldsymbol{F}_{\text{aero}} \\ &= \boldsymbol{M}_{\text{jet}} + \boldsymbol{M}_b + \boldsymbol{r}_{sb} \times \boldsymbol{F}_{\text{aero}}\end{aligned} \tag{3}$$

where $\boldsymbol{M}_{\text{jet}}$ is the roll control moment caused by jets and $\boldsymbol{M}_b$ is the vector of aerodynamic moment about the center of mass of the vehicle body. $\boldsymbol{F}_{\text{aero}}$ is the vector of aerodynamic force at the