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Progress in control approaches for hypersonic vehicle

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The controller design for hypersonic vehicle is critical and challenging because of the inherent couplings between the propulsion system and the airframe dynamics, as well as the presence of strong flexibility effects. Many researchers have investigated various strategies to mitigate the coupling by means of robust design methods. This paper reviews the recent research efforts to promote the capability of control design for hypersonic vehicle. Methodologies such as robust control, adaptive control, sliding mode control and other hybrid methods have made significant progresses in hypersonic control. Then, the main challenges of control approaches for hypersonic vehicle are systematically analyzed in detail.

hypersonic vehicle, robust control, adaptive control, fuzzy control, sliding mode control, inherent coupling

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1 Introduction

The need for a reliable and cost-effective access to space for both civilian and military applications has spurred a renewed interest in hypersonic vehicle, as witnessed by the success of NASA's scramjet-powered X-43A, a substantial experimental vehicle that flew in 2004 and 2005, and the very recent flight of the US Air Force's X-51 scramjet engine demonstrator.

Controller designing is a key issue in making air-breathing hypersonic flight feasible and efficient [1–3]. Dynamics of hypersonic vehicles is highly nonlinear, coupled and partly unpredictable due to the facts such as strong nonlinearity and high flight altitude, which makes the system modeling and flight control extremely challenging [4, 5].

Owing to the dynamics' enormous complexity, the longitudinal dynamics equations developed by Bolender and Doman [6, 7] are employed for the modeling, control design and simulation of hypersonic vehicles by most researchers. Compared with traditional flight vehicles, the longitudinal model of hypersonic vehicle is known to be unstable, non-minimum phase with respect to the regulated output and affected by significant model uncertainty. Therefore hypersonic vehicles are extremely sensitive to changes in atmospheric conditions as well as physical and aerodynamic parameters. It is essential to guarantee stability for the system and provide a satisfying control performance to improve the safety and reliability [8, 9].

Conventionally, the research on flight control design for this class of vehicles primarily deals with mitigating the effect of structural flexibility on vehicle stability and control performance by means of linear robust design methods for linearized models [10, 11]. A linearized model is established around a trim point for a nonlinear, dynamically coupled simulation model of the hypersonic vehicle, thus the linear controller can be designed in a neighborhood of the operating point. In this way, the linear control theories, such as decentralized control, linear quadratic regulator approach

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(LQR), gain scheduling method, etc., are investigated to accomplish the difficulties in the control design. In recent years, contributions have begun to address the design of nonlinear controllers for nonlinear vehicle models as well [12–14]. Owing to the non-linearity and the coupling, many researchers have taken the dynamics information into consideration for controller design to provide good control performance.

The rest of the paper is organized as follows. Firstly, we describe the recent research efforts to promote the capability of control design for hypersonic vehicle and handle different kinds of control related problems. Then, based on the review of dozens of reseach papers, the main challenges of control design for hypersonic vehicle are summarized and systematically analyzed. In the conclusion, some basic principles are put forward to provide an insightful source for the researchers and scholars.

2 Hypersonic vehicle controllers

2.1 Robust controller

Any sensible control design for nonlinear systems must provide robustness against (possibly large) parametric uncertainty due to the flexible dynamics of hypersonic vehicle, which is one of the severe challenges for control of hypersonic vehicles. Satisfactory results obtained using linear state-feedback control naturally raise the question of whether a robust linear observer may suffice to supplement incomplete knowledge of the states in the presence of model uncertainty. As a result, many robust control strategies have been investigated to answer this question [15].

Rehman et al. [16] introduced a robust control scheme involving feedback linearization and mini-max optimal control methods for a general class of systems with parametric uncertainties. The anti-windup augmentation in ref. [17] with a two-stage process was shown to provide effective performance. By designing a robust dynamic output-feedback controller which does not rely on asymptotic state reconstruction, Pete et al. [18, 19] overcame the inevitable limitation of a linear observer. Furthermore, an alternative approach to robust output-feedback design without state estimation was presented and shown to provide an increased level of performance.

Lisa et al. [20] developed an improved robust/adaptive nonlinear controller that does not depend explicitly on the model coefficients. They focused on counteracting the exponentially non-minimum phase behavior of the rigid-body flight-path angle (FPA) dynamics in ref. [21]. Furthermore, with this method as a basis they designed an inner-loop control in ref. [22], in which model uncertainties were dealt with by adaptive control, whereas small-gain arguments were employed for stability analysis. This methodology guarantees robust performance in spite of the model uncertainty.

2.2 Adaptive controller

Adaptive control algorithms have given hope to a new level of flight vehicle robustness previously unachievable with traditional control methods. However, the conventional model reference adaptive control scheme is very sensitive to time-delay, especially if one attempts to adapt fast. This has consequently led to a new paradigm for design of adaptive controllers.

Travis et al. [23] proposed an adaptive controller using only the equivalence ratio and the elevator deflection as control inputs. It was designed by neglecting the flexible effects and their coupling with the vehicle dynamics, but was evaluated with the latter as well as time-delays. Simulation results have demonstrated that this adaptive scheme may be capable of improving performance when compared to a non-adaptive mixed-μ design with similar objectives. Cotting et al. [24] presented four different aircraft models of varying handling qualities levels as a test data-set to determine if an adaptive controller could recover level 1 handling qualities on a piloted, simulated aircraft in a degraded state. It addressed the incorporation of rate-limits and constraints on the aerodynamic control surface, as well as the adoption of anti-windup schemes to alleviate the burden on the guidance system. The adaptive Kriging controller was investigated by Xu et al. [25]. Considering the non-linearity of the dynamics, the nominal feedback was included in the controller while Kriging system was used to estimate the uncertainty. And an adaptive inverse controller proposed by Wang et al. [26] adopted an improved extended minimal resource allocation network (EMRAN) to accelerate the convergence of the adaptive inverse filter without loss of real-time performance. Andrea et al. [27] proposed an integrated adaptive guidance and control, which comprises a robust adaptive nonlinear inner-loop controller and a self-optimizing guidance scheme.

2.3 Fuzzy controller

Fuzzy strategies have drawn much attention owing to their unique characteristic concerning nonlinear control problems, which showed satisfactory performance in simulation [28, 29]. Hu et al. [30] proposed a fuzzy guaranteed cost state-feedback control method for the tracking problem of the longitudinal dynamics of an FAHV model with a constructed a Takagi-Sugeno (T-S) fuzzy model. Jiang et al. [31] employed the T-S fuzzy system to approximate the nonlinear near-space-vehicle (NSV) attitude dynamics and then developed the actuator-fault model, which was demonstrated superior to some existing fault-tolerant control (FTC) schemes in nonlinear systems due to its independence from fault detection and isolation (FDI) mechanisms. Then the FTC problem was expanded to T-S fuzzy systems with actuator time-varying faults [32].

Luo et al. [33] introduced the fuzzy logic into the characteristic modeling by dividing the whole restriction range into several subspaces. With the same whole restriction range the fuzzy dynamic characteristic modeling decreased the time of convergence and at the same time made the attitude angle tracing more precise and robust. Li et al. [34] constructed a fuzzy adaptive controller by combining the fuzzy dynamic characteristic model with adaptive control. The controller needed no prior knowledge of system model and less parameters to tune, allowing engineers to operate it in a simple, straightforward manner. Hu et al. [35] investigated a multi-objective robust controller for an air-breathing hypersonic vehicle that was developed with EFPM to approximate the nonlinear longitudinal model of an aircraft with different flight conditions.

2.4 Sliding mode controller

The sliding mode control (SMC) method provides a systematic approach to the problem of maintaining stability and consistent performance in spite of imprecise modeling due to the advantage of its insensitive response to model uncertainties and disturbances. However, the pure sliding mode control presents drawbacks that include large control authority requirements and chattering, which can be overcome by coupling it with an online parameter estimation scheme.

Xu et al. [36] combined the estimator-based solution with the standard SMC to design an adaptive sliding mode controller, which avoids the chattering phenomenon and can track the step commands in velocity and altitude in spite of parameter uncertainties. Then a continuing effort to develop practical methods for control design using sliding method was made. Zong et al. [37] proposed a multiple-input–multiple-output (MIMO) quasi-continuous high order sliding mode (HOSM) controller in order to reduce the chattering and provide higher accuracy in the meantime, which led to the final HOSM controller-observer synthesis design that requires only partial state variables available for measurement. Hu et al. [38] developed an adaptive sliding mode controller based on the tracking error model. The proposed controller can drive the error dynamics onto the predefined sliding surface in a finite time, and guarantee the property of asymptotical stability without the information of upper bound of uncertainties as well as perturbations. Ronald el al. [39] investigated a pseudo-sliding mode flight control design in the frequency domain, based on the sliding mode control theory.

2.5 Hybrid controller

There is always a trade-off between performance and robustness in control design for systems with uncertainties and disturbances, which is much more significant in hypersonic vehicle control due to inherent characteristic. Among the different approaches in the hypersonic vehicle control literature, we can divide the available robust hypersonic vehicle control approaches into two subcategories: linear model based and nonlinear model based, and then it is possible to design the controller with a combined method by taking advantages of both of them.

Du et al. [40, 41] presented a proportional-derivative (PD) correction partial-feedback-functional-link-network (PFFLN) control method for hypersonic vehicle with dynamical uncertainties. The control law consisted of a nonlinear generalized predictive controller (NGPC), a PD-correction PFFLN control adjustment, and an adaptive robust control (RC) item. Cheng et al. [42, 43] put forward a online support vector regression (SVR) compensated nonlinear generalized predictive control method for the attitude stabilization system of hypersonic vehicle, which demonstrated good robustness and disturbance attenuation ability compared with nominal NGPC and radial basis function (RBF) neural network (NN) schemes. Other strategies such as back-stepping [44, 45], neural network [46, 47], time-varying notch filter (TVNF), small-gain theorem, or other newly developed techniques have also been combined with traditional output feedback methods to obtain the goal: stability, performance, and robustness.

3 Challenging issues

Although the approaches aforementioned have provided robust performance under significant changes in flight conditions and fuel level in experimental simulation [16–47], it is far from satisfactory. There are three main concerns we should take into consideration in reaching our goal to provide satisfactory design of guidance and control systems for hypersonic vehicle: stability, performance, and robustness. However, none of the existing schemes can meet these requirements, or some of them can just meet them with a simplified model. So there are some fundamental and essential issues in control designs that are worth probing further despite the great progresses we have made in the last several years. The typical challenges of controller design for hypersonic vehicles can be generalized as the following eight aspects: input/output coupling, unstable/non-minimum phase, parameter variation, flexible modes, control constraints, tightly integrated airframe engine configuration, little knowledge about aero-thermodynamic effects of hypersonic speeds, and lack of adequate flight and ground test data.

3.1 Robustness

Robustness is a key issue for a reliable controller for hypersonic vehicle, including the stability robustness and the performance robustness [48]. A significant portion of the research in controller design for hypersonic vehicles has focused on adaptive and robust control formulations [16–22]. Despite the fact that the robust controller constitutes a significant improvement (none of these schemes has been completely implemented in a real hypersonic vehicle) over the observer-based design, there is still room for improvement. The analyst and designer must deal with significant uncertainties and the unique configuration of the vehicle produces strong aerodynamic-propulsion-aeroelastic couplings, in which researches have not yet been completely quantified. A more sophisticated design based on adaptive control or other newly developed methods may alleviate the need of satisfactory tracking capabilities by providing a robust controller.

3.2 Reconfigurable control allocation

To meet range safety requirements in the event of failure, it is necessary to take the problem of fault-tolerant control design for flight critical components into consideration. The use of redundant components, such as actuators, can improve the reliability of the overall system, but the redundancy alone may not provide sufficient failsafe capability to meet safety requirements [49, 50]. A reconfigurable control allocation algorithm can surely enhance the reliability of the system and play an important role in the event of component failure. To address changes in the vehicle dynamics that arise from the failed actuators, research into reconfigurable control allocation was performed in refs. [31, 32] by utilizing the fuzzy method. In the process of control design, particular emphasis should be placed on the reconfiguration capability of control allocation.

3.3 Intelligent control

Design of efficient autonomous intelligent controllers for unmanned aerial vehicles (UAV) has been investigated in recent years, and a lot of efforts have been made to enhance the effectiveness of intelligent control [51, 52]. As we have known from the aforementioned literature, the idea of intelligence has been introduced into hypersonic control [36–39, 45–47]. Many researchers have combined the intelligent methods with conventional tools to improve the effectiveness of control design for hypersonic vehicles and have made significant achievements. However, it is far from satisfaction and we still have a long way to go. Bio-inspired intelligence has the advantages of strong robustness and distributed computing mechanism [53]. Although the current study in this field is still in the experimental and preliminary application stage, the bio-inspired intelligent methods have shown a great potential in control related issues and may provide us new ideas for future work. The intelligent control architecture for hypersonic vehicle composed of intelligent controller, intelligent actuator and intelligent sensors is a necessity not just a possibility.

3.4 Integrated control design

The complex interactions between elements of a hypersonic vehicle will require a tightly integrated design process to achieve the optimal performance necessary to meet space access mission objectives. This was recognized early by McRuer in 1991, and in his paper [54], the necessity of an integrated control design (that is, addressing simultaneously propulsion and aerodynamics) was advocated. Many investigators have proposed various strategies to mitigate the coupling by means of robust design methods. However, less emphasis has been focused on integrated control design. The adaptive guidance and control scheme presented in ref. [27] constituted a preliminary step towards the definition of a truly integrated flight control architecture for hypersonic vehicles, but further investigation is necessary in the future.

4 Conclusions

In recent years, control technologies in hypersonic vehicle have been developing with an amazingly rapid speed. This paper reviewed the state of the art in hypersonic vehicle control design, and analyzed the main problems in this field, such as input/output coupling, unstable/non-minimum phase, parameter variation, flexible modes, etc. We attempted to provide an insightful source for the researchers and scholars interested in this new and challenging field. As a result, suggestions to exploring new ideas for hypersonic vehicle control were put forward, which include robustness, reconfigurable allocation control, intelligence control and integrated control design. The exact realization of advanced control technologies can provide a series of novel breakthroughs for the intelligence, integration and advancement of hypersonic vehicle systems.

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