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High-order tracking differentiator based adaptive neural control of a flexible air-breathing hypersonic vehicle subject to actuators constraints

Xiangwei Bu [a,*], Xiaoyan Wu [a], Mingyan Tian [b], Jiaqi Huang [a], Rui Zhang [a], Zhen Ma [a]

[a] *Air and Missile Defense College, Air Force Engineering University, Xi'an 710051, China*
[b] *95486 People's Liberation Army Troops, Chengdu 610077, China*

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ABSTRACT

In this paper, an adaptive neural controller is exploited for a constrained flexible air-breathing hypersonic vehicle (FAHV) based on high-order tracking differentiator (HTD). By utilizing functional decomposition methodology, the dynamic model is reasonably decomposed into the respective velocity subsystem and altitude subsystem. For the velocity subsystem, a dynamic inversion based neural controller is constructed. By introducing the HTD to adaptively estimate the newly defined states generated in the process of model transformation, a novel neural based altitude controller that is quite simpler than the ones derived from back-stepping is addressed based on the normal output-feedback form instead of the strict-feedback formulation. Based on minimal-learning parameter scheme, only two neural networks with two adaptive parameters are needed for neural approximation. Especially, a novel auxiliary system is explored to deal with the problem of control inputs constraints. Finally, simulation results are presented to test the effectiveness of the proposed control strategy in the presence of system uncertainties and actuators constraints.

1. Introduction

Air-breathing hypersonic vehicles (AHVs) have been regarded as a reliable and cost-effective access to near space for both civilian and military applications [1,2], as witnessed by the success of NASA's scramjet-powered X-43A and X-51A. As a key issue in making AHV feasible and efficient, the flight control design is critical and challenging owing to the substantial couplings between the propulsion system and the airframe dynamics, as well as the presence of noticeably flexible effects and aerodynamic uncertainties. It is well known that all the control systems must be robust to the system uncertainties and couplings [3,4], especially to the ones mentioned above.

Because of the enormous complexity of the vehicle dynamics, only the longitudinal dynamic models of AHVs have been developed and adopted for controller design [5,6]. A trajectory linearization control (TLC) strategy with robust performance is proposed for the longitudinal dynamics of a flexible AHV (FAHV) based on the extended state observer (ESO) [7]. Furthermore, by applying ESO to estimate the model uncertainties, the advantage of that control scheme over the basic TLC is demonstrated by simulation results. In [8], a linear parameter varying (LPV) switching tracking control method is addressed for an FAHV on the basis of a polytopic LPV model that is newly constructed to represent the complex dynamics of FAHV via Jacobian linearization and tensor-product model transformation approach. To eliminate the undesired chattering phenomenon usually encountered in the traditional sliding mode control (SMC), the high order SMC methodology is studied for the longitudinal dynamics of FAHV [9]. In [10], an observer-based fault-tolerant controller is devised for an AHV subject to actuator faults and limited measurements of states. Unfortunately, the flexible effects are ignored in that study.

Back-stepping is a powerfully direct method of control design for uncertain nonlinear systems. By decomposing the vehicle dynamics into the respective velocity subsystem and altitude subsystem, and further formulating the altitude subsystem as strict-feedback form, output-feedback controllers are proposed for the longitudinal dynamics of FAHV via back-stepping [11,12]. To enhance the robustness of back-stepping control, various techniques are studied. In [13–15], an improved back-stepping control strategy is presented for AHV using parameter projection scheme. Hence that control algorithm has a strong ability of disturbance rejection since it does not depend explicitly on the aerodynamic coefficients. Based on the results of [16], a novel

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[*] Corresponding author. Tel.: +86 18691971775.
E-mail address: buxiangwei1987@126.com (X. Bu).

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Nomenclature

m	vehicle mass
ρ	density of air
$\overline{q}$	dynamic pressure
S	reference area
h	altitude
V	velocity
γ	flight-path angle
θ	pitch angle
α	angle of attack (α=θ-γ)
Q	pitch rate
T	thrust
D	drag
L	lift
M	pitching moment
I_{yy}	moment of inertia
$\overline{c}$	aerodynamic chord
z_T	thrust moment arm
Φ	fuel equivalence ratio
δ_e	elevator angular deflection
N_i	ith generalized force
$N_i^{\alpha_j}$	jth order contribution of α to N_i
N_i^0	constant term in N_i
$N_2^{\delta_e}$	contribution of δ_e to N_2
$\beta_i(h,\overline{q})$	ith trust fit parameter
η_i	ith generalized elastic coordinate
ζ_i	damping ratio for elastic mode η_i
ω_i	natural frequency for elastic mode η_i
$C_D^{\alpha^i}$	ith order coefficient of α in D
$C_D^{\delta_e^i}$	ith order coefficient of δ_e in D
C_D^0	constant coefficient in D
$C_L^{\alpha^i}$	ith order coefficient of α in L
$C_L^{\delta_e}$	coefficient of δ_e contribution in L
C_L^0	constant coefficient in L
$C_{M,\alpha}^{\alpha^i}$	ith order coefficient of α in M
$C_{M,\alpha}^0$	constant coefficient in M
$C_T^{\alpha^i}$	ith order coefficient of α in T
C_T^0	constant coefficient in T
h_0	nominal altitude for air density approximation
ρ_0	air density at the altitude h_0
$\tilde{\psi}_i$	constrained beam coupling constant for η_i
c_e	coefficient of δ_e in M
$1/h_s$	air density decay rate

nonlinear disturbance observer (NDO) is devised to estimate the model uncertainties, which ensures that the proposed control approach can provide robust tracking of velocity and altitude commands in the presence of parametric uncertainties [17]. Moreover, a novel hybrid control framework that combines NDO and back-stepping is presented for an FAHV [11,12].

Neural network (NN) has been demonstrated to be an effective tool for nonlinearity approximation. Improved control can be achievable if the unknown nonlinearities of FAHV model are approximated by NN. Thus several back-stepping controllers that incorporate NNs are addressed for FAHV [18,19]. To simplify the back-stepping design, dynamic surface control [20] is performed to avoid the tedious analytic computations of time derivatives of virtual controllers. Furthermore, an improved design of neural back-stepping control based on singularly perturbed system is proposed for AHV [21], which eliminates the problem of “explosion of terms”. More specially, the NN is applied to approximate the developed back-stepping controller rather than the unknown nonlinearity [22]. Also the problem of “explosion of terms” is avoided in that work. Noticing that the computational ability of computer or hardware is limited, it is of great significance to reduce the complexity especially the computational burden of control law. In [23], with a strict assumption that the control gains are positive and bounded, only one NN is required for estimating the lumped uncertainty in the altitude subsystem. Meanwhile, also the complexity design of back-stepping is avoided. Besides, the minimal-learning parameter (MLP) scheme [20] is introduced to adjust the norm of NN's weight vector. In this way, the computational burden is reduced evidently.

One of the practical issues in the flight control design is that the control inputs cannot be implemented owing to actuator saturation. Noting that the outputs of actuator are constrained for physical limitations, the closed-loop system may encounter performance limitations or even lose stability theoretically if the values of desired control laws are over the maximal or minimum bound that can be provided by actuators. Therefore, it is necessary to investigate high-reliability control methodology extensively taking into account input constraint [24–26]. In [15], auxiliary systems are constructed to deal with the magnitude constraints on actuators and states. The uniformly ultimately boundedness of that control scheme is guaranteed for the closed-loop system by compensating error and desired control law. Similar compensation method is also utilized to tackle the magnitude and rate limitations on the control inputs [24]. Though an improved neural controller [24] is designed for the altitude subsystem to reduce the computational load, it is worth mentioning that one has to invoke two different NNs to respectively approximate the unknown function and control gain of the velocity subsystem. In [20], a robust adaptive neural controller is presented for an FAHV with input constraint and aerodynamic uncertainty. Specially, only one NN is needed to estimate the lumped uncertainty of velocity subsystem in that paper. Furthermore, based on MLP scheme, only one parameter is required to be regulated in the altitude uncertainty approximation in spite of the complicated design process of back-stepping.

The motivation of this paper is to develop a novel neural controller for a constrained FAHV. The dynamic model of FAHV is decomposed into two functional subsystems including the velocity subsystem and the altitude subsystem. By converting the altitude subsystem into the normal output-feedback formulation, there is no need of complex back-stepping design. Then a novel adaptive neural controller is addressed for the altitude subsystem. For the newly generated states, a high-order tracking differentiator (HTD) is used to estimate them. To minimize the computational cost of neural approximation, the MLP scheme is employed to regulate the norm of weight vector rather than its elements. Similar neural controller is presented for the velocity subsystem. To deal with the constraints on actuators, novel auxiliary systems are exploited to compensate the desired controllers, which makes sure that the semi-globally uniformly bounded stability of closed-loop system can be still achieved even when the physical limitations are in effect. Finally, simulation results for an FAHV are provided to show the efficacy of the proposed controller. The main advantages of the approach presented herein include:

1. The effect of actuator saturation is successfully eliminated by a novel design of auxiliary error compensation, which guarantees the stability of closed-loop system, as well as the boundedness of velocity and altitude tracking errors even when the actuators are saturated.