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Minimal-learning-parameter based simplified adaptive neural back-stepping control of flexible air-breathing hypersonic vehicles without virtual controllers

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ABSTRACT

In this paper, a novel adaptive neural control methodology is addressed for a flexible air-breathing hypersonic vehicle (FAHV) by a fusion of improved back-stepping and a minimal-learning-parameter (MLP) scheme. To facilitate the control design, the vehicle dynamics is decomposed into the altitude subsystem and the velocity subsystem. Different from the traditional back-stepping design, in this paper, the virtual control laws for the altitude dynamics are artificial intermediate variables required only for analytic purpose while only the final actual controller is needed to be implemented. For each subsystem, only one neural network is employed to approximate the lumped uncertainty. Moreover, by the merit of the MLP technique, only one learning parameter is required for neural approximation in each subsystem. The novel contribution with respect to the existing literatures is that the proposed control strategy is concise and the computational load is low. Finally, the effectiveness of the exploited control approach is verified by simulation results in the presence of uncertain parameters.

1. Introduction

As witnessed by the success of NASA's scramjet-powered X-43A, air-breathing hypersonic vehicles (AHVs) have drawn renewed attention since they can provide a reliable and cost-efficient access to near space for both civilian and military applications. However, the guidance and control systems design for AHVs still presents a set of challenges, which is stemmed from the complexity, nonlinearity, coupling and uncertainty of the vehicle dynamics [1–3]. Besides, the slender geometry of vehicle structure usually results in notable flexible effects [4–6]. Thus, this special generic vehicle must be viewed as a flexible structure and vehicles of this kind are notoriously difficult systems to be controlled.

Recently, numerous control methodologies have been investigated only using the longitudinal dynamic model [5,6] of flexible AHVs (FAHVs) due to the enormous complexity of vehicle dynamics. For the longitudinal dynamics of FAHVs, fault-tolerant control [7–9], robust control [10,11], sliding mode control (SMC) [12,13], linear parameter varying (LPV) control [14,15], active disturbance rejection control (ADRC) [16,17] and trajectory linearization control (TLC) [18,19] are presented, while taking into account the flexible effects or ignoring them. It is well-known that the altitude dynamics of FAHVs can be rewritten as a strict-feedback formulation with unmatched uncertainties [20,21]. For such strict-feedback system, back-stepping is regarded as a powerful methodology for the design of tracking and regulation strategies. For a nth order nonlinear system, there exist n steps of tedious and complex analysis according to the recursive design process of back-stepping. At the first $n-1$ steps, the key idea of back-stepping is to consider some of the states as "virtual controllers" and design for them intermediate control laws. At the last one step, the actual controller is achieved. Both the $n-1$ virtual controllers and the final actual one are required to be implemented. Besides, the traditional back-stepping control suffers a problem of "explosion of terms" which is caused by the repeated differentiations of virtual control laws. To tackle such problem, dynamic surface control (DSC) [22,23] and differentiators [24,25] are applied. Though these technologies can avoid the tedious analytic computations of time derivatives of virtual controllers, additional adaptive parameters (i.e., the states of filter and differentiator) have to be introduced, which may further increase the computational cost. Another shortcoming of back-stepping control is that its robustness is needed to be enhanced via advanced approaches such as parameter projection estimations [1,3] and disturbance observers [26,27].

Improved control strategies with excellent robustness performance can be achievable if the unknown nonlinearities are approximated by intelligent systems such as neural networks (NNs) and fuzzy systems [28–31]. Thus, intelligent control has been an important aspect for hypersonic flight control owing to its

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Nomenclature

m	vehicle mass
ρ	density of air
$\bar{q}$	dynamic pressure
S	reference area
h	altitude
V	velocity
γ	flight-path angle
θ	pitch angle
α	angle of attack ($\alpha=\theta-\gamma$)
Q	pitch rate
T	thrust
D	drag
L	lift
M	pitching moment
I_{yy}	moment of inertia
$\bar{c}$	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
$\beta_i(h,\bar{q})$	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
$\mathbf{R}^n$	n-dimensional Euclidean space
$\mathbf{R}$	the set of all real numbers
$\Vert\bullet\Vert$	the 2-norm of a vector
$\vert\bullet\vert$	the absolute value of a scalar

ability of uncertainty approximation [32,33]. From a practical perspective, we should pay much attention to the computational load owing to the large amount of NN nodes. High computational costs will lead to certain time delays for the control system, which may further cause notable controlling errors since the FAHV flights at hypersonic speed. Hence, lots of efforts have been made to reduce the computational burden by decreasing the required NNs and adaptive parameters. For the velocity subsystem of an FAHV, a traditional strategy [34] is studied by employing two different NNs to estimate the unknown function and control gain. Different from [34], the NNs are utilized to directly approximate the developed back-stepping controllers instead of the unknown nonlinearities [35]. As a result, only one NN is required in each subsystem of the FAHV model. To reduce the computational load, the minimal-learning-parameter (MLP) scheme [22] is applied to regulate the maximum norm instead of the elements of the ideal weight vectors. Moreover, one MLP based adaptive neural control method is addressed without back-stepping [36]. Compared with the previous literatures, both the NNs and learning parameters of that paper are less.

In this paper, to simplify the control structure and reduce the numbers of NNs and online parameters, an attempt is made to propose a novel MLP based neural back-stepping control methodology for the longitudinal dynamic model of an FAHV. For the altitude dynamics, a novel neural back-stepping controller is exploited without virtual control laws. All the virtual controllers are artificial intermediate states required only for stability analysis such that only the final actual controller is needed to be implemented. Meanwhile, the problem of “explosion of terms” is avoided. To reduce the computational load, the NNs are employed to approximate the lumped unknown nonlinearities. Furthermore, by utilizing the MLP algorithm to estimate the norm rather than the elements of NN's weight vector, the required learning parameters are reduced greatly. Finally, the efficacy of the proposed strategy is tested via simulation studies. The special contributions of this paper are summarized as follows:

1. Different from the traditional back-stepping control schemes [19,24,34], there is no need to implement the virtual controllers in this paper. All the virtual control laws are artificial intermediate states required only for analytic purpose. Only the final actual control effort, being independent on the virtual controllers, is needed to be performed. Thus, the proposed control structure is quite concise. Meanwhile, the problem of “explosion of terms” is eliminated.
2. Compared with the improved neural back-stepping control methodologies [34,35], the explored controller possesses lower computational loads and better practicality. In this paper, only two NNs are utilized to approach the lumped uncertainties. With the MLP scheme, only two learning parameters are required for neural approximation. Moreover, the strict assumption [34–36] that the unknown control gains have to be strictly positive is avoided in this paper.

The remainder of this paper is outlined as follows. The problem formulation is presented in Section 2. Section 3 shows the control design process. The simulation studies are made in Section 4 and the conclusions are proposed in Section 5.

2. Problem formulation

2.1. Model description

The adopted longitudinal dynamic model of an FAHV is developed by Bolender and Doman [5]. The longitudinal sketch and force map of the FAHV are shown in Fig. 1. It is supposed that the FAHV presented in Fig. 1 has unity depth into the paper and that air behaves as if it is a perfect gas (i.e., the ratio of specific heats is a constant) [1]. The equations of motion are derived using Lagrange's equations. Moreover, the flexible effects are included in this model by viewing the vehicle as a single flexible structure with mass-normalized mode shapes. The equations of motion of