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Neuro Robust Adaptive Descending Control of Space Vehicles

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Abstract: Accurate descending control is crucial to ensure safe operation of space exploration vehicles. This work investigates automatic trajectory tracking control of space vehicles during landing phase. A set of algorithms for adjusting vehicle heading angle, heading speed and altitude are derived using adaptive robust and neural network control techniques. It is shown that with the proposed control algorithms, external disturbances and coupled dynamics inherent in the system are effectively compensated. Simulations on various flight conditions also confirm the effectiveness of the proposed methods.

1. INTRODUCTION

Trajectory tracking control represents one of the most important enabling technologies for future space exploration. Autonomous rendezvous and docking are essential to ensure safe operation of autonomous space missions (Fig. 1). The challenging issue related to the design of space vehicle flight control system is that the vehicle operates in the wide range of environments, from the sea-level atmosphere to the near vacuum of space. The resultant system dynamics of the vehicle are highly nonlinear and strongly coupled with uncertainties and disturbances, which calls for high performance control schemes. There have been several applications involving landing spacecraft or rendezvous with celestial objects. Many of the applications have undergone challenging breakthroughs in addressing tracking from one location to another. Some of these applications involved autonomous guidance, navigation, and control operations during the landing phase, where the landing accuracy and relative landing velocity were addressed. Examples of these occurrences are Guelman and Harel, power-limited soft landing on an asteroid under the gravitational effect while neglecting drag, Jensen, who dealt with the kinematics of rendezvous maneuver based on proportional navigation techniques, and Yuan and Hsu, who investigated a spacecraft rendezvous flight via a modified proportional navigation scheme. Based on certain assumptions, various control approaches, such as model-based control, nonlinear inverse control, VSC control and fuzzy based control (and others) have been proposed.

This work is concerned with trajectory tracking control of flight vehicles during the reentry (descending) phase. Since flight condition changes rapidly during this process, it is important to maintain the vehicle's lateral, longitudinal and vertical motions along the desired command. A 3D nonlinear model is considered in which modelling uncertainties and nonlinearities are explicitly addressed. Based on most typical situations related to system uncertainties, a set of control algorithms are derived. It is shown that under the assumed conditions, the proposed control schemes are able to achieve good tracking performance. The remainder of the paper is organized as follows. Section 2 details the system model and formulates the problem under consideration, and section 3 develops the trajectory control algorithms and conduct stability analysis. Section 4 presents some simulation results and finally section 5 offers the conclusion of the study.

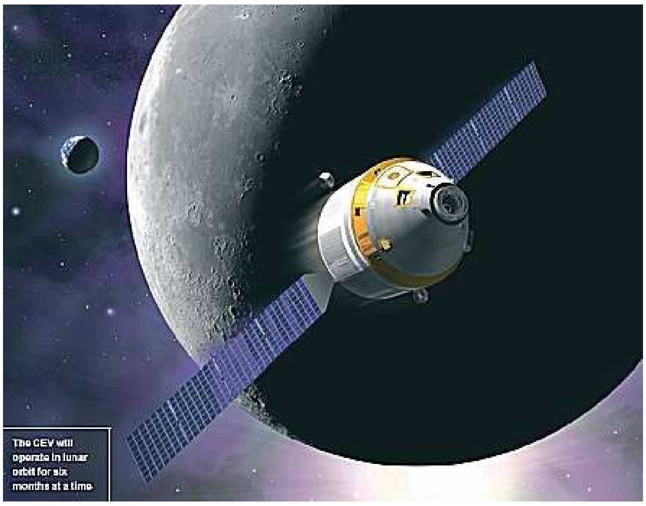

Fig. 1. A crew exploration vehicle lunar operation

2. PROBLEM FORMULATION

A fundamental requirement for safe and reliable space vehicle operation (such as docking with a celestial object or space station) is that the approaching speed of the vehicle must be well controlled so that it is driven to zero at the time of touchdown. This means that the commanded acceleration of the active vehicle in both the direction normal to the line of sight (LOS) and the direction along the LOS must reduce to zero as the space vehicle lands on a celestial object. For this reason, this work is focused on the following three-dimensional system equations

$$\begin{aligned} \ddot{r} &= f_r(r,\dot{r},\theta,\phi,\dot{\theta},\dot{\phi}) + g_r u_r + \Delta f_r(r,\dot{r},\theta,\dot{\theta},\phi,\dot{\phi},t) \\ \ddot{\theta} &= f_\theta(r,\dot{r},\theta,\phi,\dot{\theta},\dot{\phi}) + g_\theta u_\theta + \Delta f_\theta(r,\dot{r},\theta,\dot{\theta},\phi,\dot{\phi},t) \\ \ddot{\phi} &= f_\phi(r,\dot{r},\theta,\phi,\dot{\theta},\dot{\phi}) + g_\phi u_\phi + \Delta f_\phi(r,\dot{r},\theta,\dot{\theta},\phi,\dot{\phi},t) \end{aligned} \tag{1}$$

where r is the distance from the spacecraft to the celestial object, θ and ϕ are the azimuth and pitch angles with respect to the celestial body, as illustrated in Fig. 2. The nonlinear functions in the equations are defined as follows,

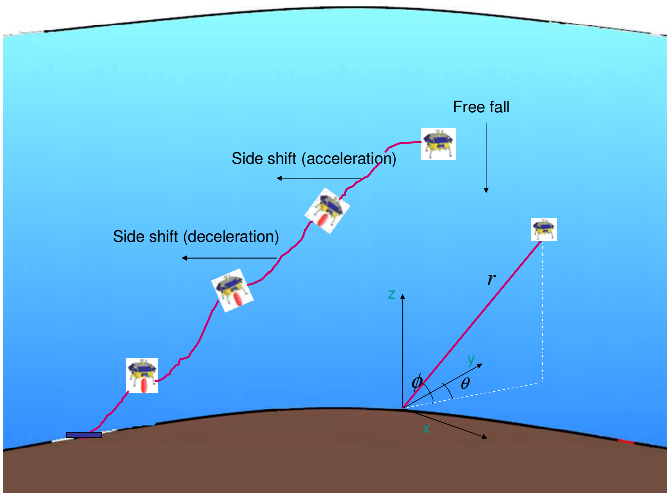

Fig. 2 The geometry for landing phase

$$\begin{aligned} f_r(\cdot) &= r\dot{\phi}^2 + r\dot{\theta}^2\cos^2\phi - \mu/r^2 \\ &\quad -\beta\sqrt{\dot{r}^2+\left(r\dot{\theta}\cos\phi\right)^2+\left(r\dot{\phi}\right)^2}\cdot\left(w_1 r^{-2}+w_2 e^{-kr}\right)\times\dot{r} \\ f_\theta(\cdot) &= 2\dot{\theta}\dot{\phi}\tan\phi - 2\dot{r}\dot{\theta}/r \\ &\quad -\beta\sqrt{\dot{r}^2+\left(r\dot{\theta}\cos\phi\right)^2+\left(r\dot{\phi}\right)^2}\cdot\left(w_1 r^{-2}+w_2 e^{-kr}\right)\times r\dot{\theta}\cos\phi \\ f_\phi(\cdot) &= -2\dot{r}\dot{\phi}/r - \dot{\theta}^2\cos\phi\sin\phi \\ &\quad -\beta\sqrt{\dot{r}^2+\left(r\dot{\theta}\cos\phi\right)^2+\left(r\dot{\phi}\right)^2}\cdot\left(w_1 r^{-2}+w_2 e^{-kr}\right)\times r\dot{\phi} \end{aligned} \tag{2}$$

where μ is the gravitational constant times the mass of the asteroid, w_i $(i=1,2)$ are constants, $\beta > 0$ denotes the drag coefficient. And also g_r, g_θ and g_ϕ are the control gains, u_r, u_θ and u_ϕ are the control inputs, and Δf_r, Δf_θ and Δf_ϕ represent the coupling effects and external disturbances. For later development, we denote

$$F = [f_r \ f_\theta \ f_\phi]^T \tag{3}$$

$$G = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1/r\cos\phi & 0 \\ 0 & 0 & 1/r \end{bmatrix} \tag{4}$$

$$U = [u_r \ u_\theta \ u_\phi]^T \tag{5}$$

$$\Delta F = [\Delta f_r \ \Delta f_\theta \ \Delta f_\phi]^T \tag{6}$$

$$Z = [r \ \theta \ \phi]^T \tag{7}$$

Accordingly, (1) can be expressed in the following compact form

$$\ddot{Z} = F + GU + \Delta F \tag{8}$$

The landing control problem can be stated as follows: Design control algorithms to decrease the relative velocity to zero as the space vehicle approaches to the celestial object and at the same time to maintain the vehicle's relative position (r,θ,ϕ) and velocity ($\dot{r},\dot{\theta},\dot{\phi}$) at the desired value.

3. CONTROL DESIGN

As the first step, we define the vehicle trajectory tracking error

$$e = Z - Z_d \tag{9}$$

and the filtered error variable

$$s = \dot{e} + k_1 e \quad (k_1 > 0) \tag{10}$$

Because of (10), it is seen that the control objective is realized as long as s is driven to zero as time goes by. Therefore, we focus on designing U to stabilize s. From (8) and (10) we have

$$\dot{s} = F + GU + \Delta F - \ddot{Z}_d + k_1\dot{e} \tag{11}$$

Due to the existence of the uncertainties, as lumped by $\Delta F(.)$, traditional model-based control is not applicable. In this work, we design the control scheme based on various available information on $\Delta F(.)$, as assumed in the following cases:

Case 1: $\Delta F(\bullet)$ are negligible.

Case 2: $\Delta F(\bullet)$ are available precisely.

Case 3: $\|\Delta F(\bullet)\| \le c_0 < \infty$, where c_0 is unknown.

Case 4: $\|\Delta F(\bullet)\| \le \rho(\|x\|)$

$$= \gamma_0 + \gamma_1\|x\| + \gamma_2\|x\|^2 + \cdots + \gamma_n\|x\|^n = \sum_{k=0}^{n}\gamma_k\|x\|^k$$

Case 5: $\Delta F(\bullet) = w^T\varphi(\cdot) + \varepsilon$, where $w^T \in R^{3\times l}$, $\varphi(\bullet) \in R^{l\times 1}$, and ε is approximation error which is assumed to be bounded by $\|\varepsilon\| \le E_0 < \infty$.

Case 1 and Case 2 can be dealt with by model based control. Cases 3-5 represent more general situations and will be addressed in what follows by adaptive robust and neuro-adaptive control schemes.

3.1 Adaptive Robust Control Strategy for Case 3

For this case, the following adaptive robust control is proposed,

$$U = G^{-1}(-k_1\dot{e} - k_2 s - F + \ddot{Z}_d + u_c) \quad (12)$$

with

$u_c = -\hat{c}_0 sign(s)$, $\dot{\hat{c}}_0 = \lambda\|s\|$, where $k_2 > 0$, $\lambda > 0$ are control parameters chosen by designer. With the control scheme (12), it is seen that the closed-loop dynamics become

$$\dot{s} = -k_2 s + \Delta F + u_c \quad (13)$$

To show the stability of the scheme, we construct the Lyapunov function candidate

$$V = \frac{1}{2}s^T s + \frac{1}{2\lambda}(c_0 - \hat{c}_0)^2 \quad (14)$$

Which, up using (13), leads to

$$\begin{aligned}\dot{V} &= s^T\dot{s} + (c_0 - \hat{c}_0)(-\dot{\hat{c}}_0)\frac{1}{\lambda} \\ &= s^T(-k_2 s + \Delta f + u_c) + (c_0 - \hat{c}_0)(-\dot{\hat{c}}_0)\frac{1}{\lambda} \\ &\le -k_2 s^T s + \|s\| c_0 + s^T\left(-\hat{c}_0\frac{s}{\|s\|}\right) + (c_0 - \hat{c}_0)\left(-\dot{\hat{c}}_0\frac{1}{\lambda}\right) \quad (15) \\ &= -k_2 s^T s < 0\end{aligned}$$

It then can be concluded that $s \to 0$ (therefore $e \to 0$, and $\dot{e} \to 0$) , as $t \to \infty$, i.e: $r \to r_d, \theta \to \theta_d, \varphi \to \phi_d$ and $\dot{r} \to \dot{r}_d, \dot{\theta} \to \dot{\theta}_d, \dot{\varphi} \to \dot{\phi}_d$ as $t \to \infty$.

3.2 Adaptive Robust Control Strategy for Case 4

In this case we have

$$\rho(\|x\|) = \sum_{k=0}^{n} \gamma_k \|x\|^k = \gamma^T \zeta(\bullet) \quad (16)$$

where $\gamma = [\gamma_0, \gamma_1, \gamma_2, \ldots, \gamma_n]^T$, $\zeta = [1, \|x\|, \|x\|^2, \ldots, \|x\|^n]^T$.

The control scheme is constructed as follows,

$$U = G_z^{-1}(-k_1\dot{e} - k_2 s + u_c - F + \ddot{Z}_d) \quad (17)$$

with $u_c = -\hat{r}^T\zeta(\bullet)\frac{s}{\|s\|}$, $\dot{\hat{\gamma}} = \zeta(\bullet)\|s\|$.

Choose the Lyapunov function candidate as

$$V = \frac{1}{2}s^T s + \frac{1}{2}(\tilde{\gamma}^T\tilde{\gamma}) \quad (18)$$

where $\tilde{\gamma} = \gamma - \hat{\gamma}$, it can be shown that

$$\begin{aligned}\dot{V} &= s^T\dot{s} - (\tilde{\gamma}^T\dot{\hat{\gamma}}) \\ &\le -k_2 s^T s + \|s\|\gamma^T\zeta(\bullet) + s^T u_c + (\gamma - \hat{\gamma})^T(-\dot{\hat{\gamma}}) \\ &= -k_2 s^T s + \|s\|\gamma^T\zeta(\bullet) - s^T(\hat{\gamma}^T\zeta(\bullet)\frac{s}{\|s\|}) + (\gamma - \hat{\gamma})^T(-\dot{\hat{\gamma}}) \\ &= -k_2 s^T s + \tilde{\gamma}^T(\zeta(\bullet)\|s\| - \dot{\hat{\gamma}}) = -k_2 s^T s \le 0 \quad (19)\end{aligned}$$

It is readily concluded that $s \to 0$, then $e \to 0$, and $\dot{e} \to 0$ as $t \to \infty$.

3.3 Neuro-Adaptive Control Strategy for Case 5

This is the most complicated situation in which the uncertain term ΔF is to compensated by the following neural network unit,

$$\Delta F_z = f_{NN} + \varepsilon = w^T\varphi + \varepsilon \quad (20)$$

where $w^T \in R^{3\times l}$, $\varphi(\bullet) \in R^{l\times 1}$ are the optimal weight matrix and basic function vector of the neural network, respectively, and $\|\varepsilon\| \le E_0 < \infty$ is the reconstruction error with unknown upper bound. For this case, we construct the following controller

$$U = G^{-1}(-k_1\dot{e} - k_2 s - F + \ddot{Z}_d + u_c) \quad (21)$$

Where the NN based compensation is given as follows,

$$u_c = -[\hat{w}^T\varphi + u_{rb}] \quad (22)$$

with

$$\hat{w} = \int_0^t \varphi(\bullet)s^T(t)d\tau,\ u_{rb} = [\int_0^t \|s\| d\tau]\mathrm{sgn}(s(t))$$

$$\varphi_i = \frac{1 - e^{-\alpha_i(\|X\|)}}{1 + e^{-\alpha_i(\|X\|)}},\ (X = \begin{bmatrix} r & \dot{r} & \theta & \dot{\theta} & \phi & \dot{\phi}\end{bmatrix}, i = 1, 2, \ldots l).$$

The overall control block diagram is shown in Figure 3. To address the stability, we consider the following Lyapunov function candidate,

$$V = \frac{1}{2}s^T s + \frac{1}{2}tr(\tilde{w}^T\tilde{w}) + \frac{1}{2}(E_0 - \int_0^t \|s\| d\tau)^2 \quad (23)$$

where $\tilde{w} = w - \hat{w}$, it can be shown that

$$\begin{aligned}\dot{V} &= s^T\dot{s} - tr(\tilde{w}^T\dot{\hat{w}}) + (E_0 - \int_0^t \|s\| d\tau)(-\|s\|) \\ &\le -k_2 s^T s + s^T(w^T\varphi(\bullet) + \varepsilon) - s^T(\hat{w}^T\varphi(\bullet)) - s^T u_{rb} \\ &\quad + tr(w - \hat{w})^T(-\dot{\hat{w}}) - (E_0 - \int_0^t \|s\| d\tau)(\|s\|) \\ &= -k_2 s^T s + tr[(w - \hat{w})^T(\varphi(\bullet)s^T - \dot{\hat{w}})] + s^T(\varepsilon - u_{rb}) \\ &\quad -(E_0 - \int_0^t \|s\| d\tau)(\|s\|) \quad (24)\end{aligned}$$

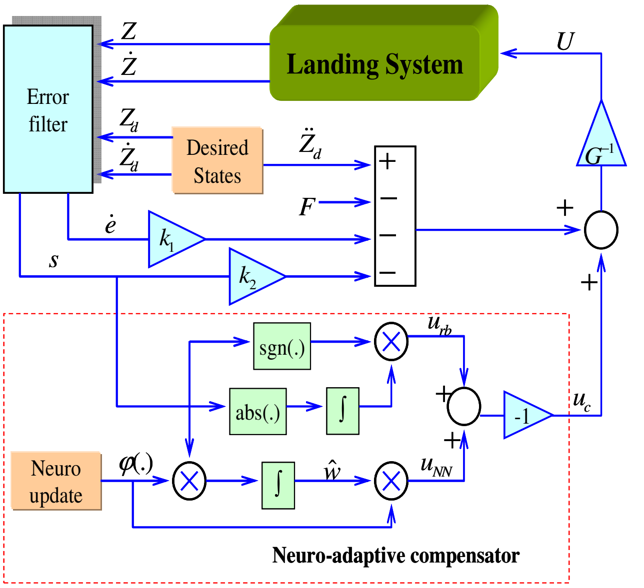

Fig. 3 Block diagram of the proposed neuro-robust adaptive control

Note that $s^T(\varepsilon - u_{rb}) \le (E_0 - \int_0^t \|s\| d\tau)(\|s\|)$, it follows that

$$\dot{V} \le -k_2 s^T s \le 0$$

Thus

$$s \in L_\infty \cap L_2 \cap L_1,\ \hat{w} \in L_\infty$$

We can also show that s is uniformly continuous because $\dot{s} \in L_\infty$ .By Babalart lemma, we conclude that $s \to 0\ as\ t \to \infty$,then $e \to 0$, and $\dot{e} \to 0$, as $t \to \infty$, i.e: $r \to r_d, \theta \to \theta_d, \varphi \to \phi_d$ and $\dot{r} \to \dot{r}_d, \dot{\theta} \to \dot{\theta}_d, \dot{\varphi} \to \dot{\phi}_d$ as $t \to \infty$.

Remarks:

The control scheme, consisting of (21) and (22), has simple structure, and does not involve analytical estimation of the upper bound on the reconstruction error, making the design process simple and easy for implementation easy.

4. SIMULATION

To test the effectiveness of the developed method, a series of simulations are conducted. Some simulations results are presented in this section. The desired trajectory is chosen as

$$r_d = r_a + (r_0 - r_a)e^{-t} - \delta\ (km)$$

$$\theta_d = \theta_f\ (rad)$$

$$\phi_d = \phi_f\ (rad)$$

where r_a denotes the celestial radius, δ is a positive parameter to ensure the vehicle lands on the celestial body in finite time, θ_f and ϕ_f denotes the desired final angle θ and ϕ. The initial conditions for the numerical study are adopted from Guelman and Harel. The system parameters are chosen to satisfy the landing requirements. The parameters and initial states are then given as follows: r_a =10 km, r_0 =200 km, θ_0 =0.2 rad, $\dot{r}_0$ =-5 km/h, $\dot{\theta}_0$ =0.2 rad/h, $\dot{\phi}_0$ =0.6 rad/h, θ_f =0.5 rad, ϕ_f =0.5 rad. The other system and control parameters are $\beta = 0.02$, $\mu = 4000$, $\Delta T = 0.005(\text{sec})$,

$\omega_1 = 1$, $\omega_2 = 1$, $\theta_0 = 0.2rad, \phi_0 = 0.8rad$.

Simulation results are given in Figure 4 – Figure 7, where Figure 4 is a plot of the tracking error for poison, azimuth angle and pitch angle. Figure 5 is the control signals. The tracking process in 2D is shown in Figure 6. Figure 7 is a three-dimensional plot showing the desired and actual motion trajectories of the vehicle during the given operation. Note that although precise descriptions of system dynamics and external disturbances are unavailable, good tracking precision via the proposed neuro-robust adaptive control still maintains with smooth control action and satisfactory orientation and position tracking.

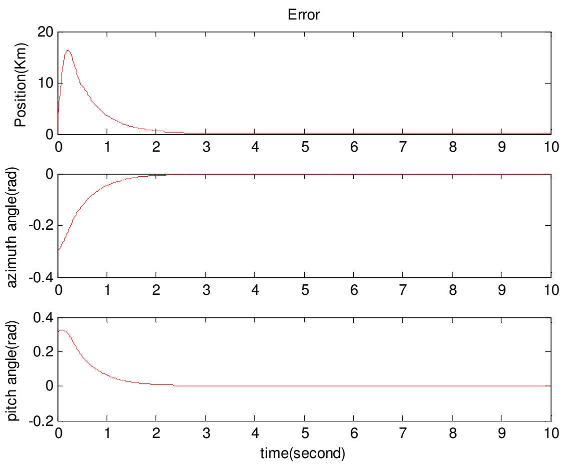

Fig. 4. Tracking errors

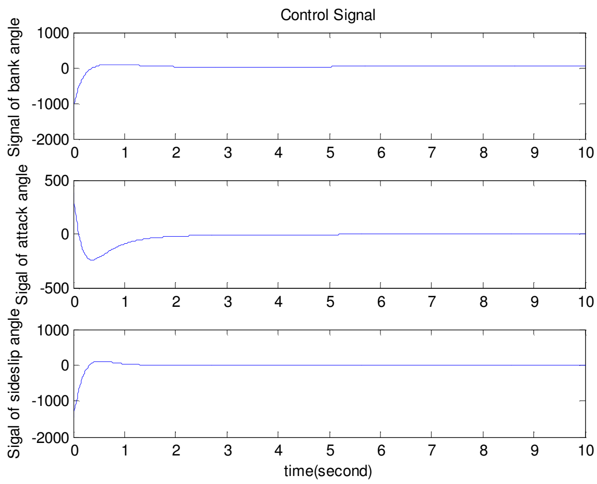

Fig. 5. Control signals

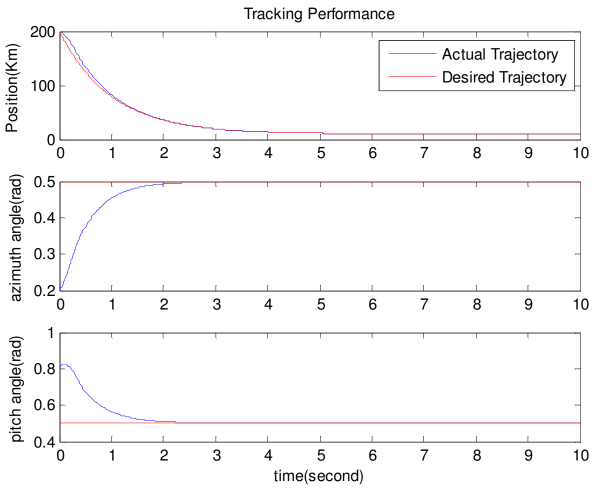

Fig. 6 Tracking process

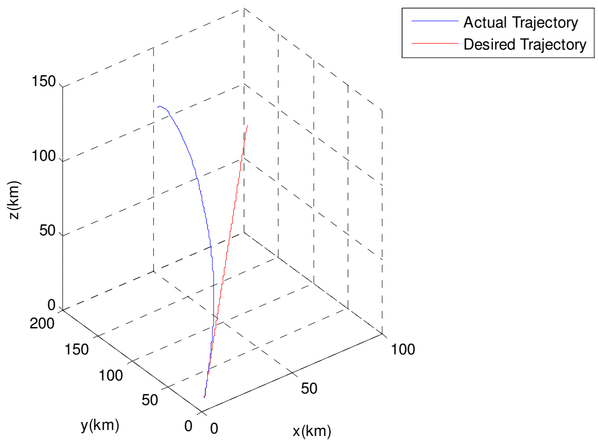

Fig. 7 Three dimensional tracking process

5. CONCLUSION

This work investigated the problem of automatic descending control of space vehicles. A three-dimensional model reflecting system nonlinearities, uncertainties, and coupling effects was used for control design. A set of control algorithms are developed that do not require any detail information on the lumped uncertain term. A numerical example was simulated as a verification of the effectiveness of the proposed control algorithms.

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