Automatica 45 (2009) 1668–1678

Contents lists available at ScienceDirect

Automatica

journal homepage: www.elsevier.com/locate/automatica

On-line robust trajectory generation on approach and landing for reusable launch vehicles[☆]

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ARTICLE INFO

Article history:
Received 10 September 2007
Received in revised form
9 November 2008
Accepted 19 March 2009
Available online 29 April 2009

Keywords:
Reusable launch vehicle
Motion primitive
Neighboring optimal control
Adaptive techniques
Robustification
Neighboring feasible trajectory existence theorem
Trajectory robustness theorem

ABSTRACT

A major objective of next generation reusable launch vehicle (RLV) programs includes significant improvements in vehicle safety, reliability, and operational costs. In this paper, novel approaches that can deliver an RLV to its landing site safely and reliably are proposed. Trajectory generation on approach/landing (A&L) for RLVs using motion primitives (MPs) and neighboring optimal control (NOC) is first discussed. In this stage, the proposed trajectory generation approach is based on an MP scheme that consists of trims and maneuvers. From an initial point to a given touchdown point, all feasible trajectories that satisfy certain constraints are generated and saved into a trajectory database. An optimal trajectory can then be found off-line by using Dijkstra's algorithm. If a vehicle failure occurs, perturbations are imposed on the initial states of the off-line optimal trajectory, and it is reshaped into a neighboring feasible trajectory on-line by using an NOC approach. If the perturbations are small enough, a neighboring feasible trajectory existence theorem (NFTET) is then investigated and its proof is provided as well. The approach given in the NFTET shows that a vehicle with stuck effectors can be recovered from failures in real time. However, when the perturbations become large, for example, in severe failure scenarios, the NFTET is no longer applicable and often the vehicle cannot be recovered from such failures. A new method is then used to deal with this situation. The NFTET is now extended to the trajectory robustness theorem (TRT). According to the TRT and its proof, a robustifying term is introduced to compensate for the effects of the linear approximation in the NFTET. The upper bounds with respect to input deviation are adaptively adjusted to eliminate their uncertainty. In order to obtain best performance, σ-modification is employed. The simulation results verify the excellent robust performance of this method.

1. Introduction

The increased demand for commercial and military utilization of space is a substantial driver for the development of new technologies to improve space vehicle economics. Reusable launch vehicles (RLVs) have the potential to increase space launch efficiencies far beyond those achieved by current systems.

Second generation (and future generation) RLVs may eventually take the place of the space shuttles, but not before scientists perfect the technologies that make RLVs safer, more reliable, and less expensive than the shuttle fleet. To achieve this goal, a variety of RLV trajectory design approaches have recently been proposed. Generally, an RLV mission is composed of four major flight phases: ascent, re-entry, terminal area energy management (TAEM), and approach and landing (A&L). Some results on trajectory generation in ascent and re-entry phases were presented in Doman (2004). Some methods of trajectory planning for TAEM were presented in Burchett (2004), Grantham (2003) and Hull, Gandhi, and Schierman (2005). A few trajectory design approaches at the A&L phase were discussed in Barton and Tragesser (1999), Cox, Stepniewski, Jorgensen, Saeks, and Lewis (1999), Hull et al. (2005), Kluever (2004), Schierman, Hull, and Ward (2002), Schierman, Hull, and Ward (2003) and Schierman et al. (2004).

A&L is a critical flight phase that brings the unpowered vehicle from the end of the TAEM phase to runway touchdown. Hull et al. (2005) addressed the on-line trajectory reshaping problem for RLVs during the TAEM and A&L phases of re-entry flight. In Kluever (2004) a guidance scheme that employs a trajectory-planning algorithm was developed for the A&L phase of an unpowered RLV. The trajectory planning scheme computed a

[☆] This work was supported with AFRL/AFOSR grant No. F33615-01-2-3154. In addition the work was supported by DAGSI and the University of Dayton Graduate School Dean's Summer Fellowship. The material in this paper was partially presented at the 31st Annual Dayton–Cincinnati Aerospace Science Symposium, 2007 American Control Conference, and 46th IEEE Conference on Decision and Control. This paper was recommended for publication in revised form by Associate Editor Shuzhi Sam Ge under the direction of Editor Miroslav Krstic.

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doi:10.1016/j.automatica.2009.03.017

reference flight profile by piecing together several flight segments that were defined by a small set of geometric parameters. A feasible reference profile that brings the vehicle from its current state to a desired landing condition was obtained by iterating on a single geometric parameter. The flight-path angle at the start of the flare was selected as the iteration variable. Open- and closed-loop guidance commands were readily available once the reference trajectory was obtained. In Schierman et al. (2002) the authors proposed an optimum-path-to-go (OPTG) algorithm, which was a general framework to perform the on-line trajectory-command generation task. The methodology was applied to the X-33 RLV for the A&L, and a Monte Carlo simulation analysis was used to demonstrate the benefits of the approach. However, this approach did not effectively adjust to drastically altered vehicle dynamics caused by more serious problems, such as locked control surfaces or vehicle damage. In Schierman et al. (2003), an improvement on the OPTG algorithm was presented. The new OPTG approach eliminated these problems by referencing a database of precomputed, verified solutions. During flight, the OPTG routine chose a feasible trajectory for the failed vehicle while an adaptive guidance system made corrections for errors or disturbances. Schierman et al. (2004) presented a fault-tolerant autonomous landing system for a re-entry RLV with flight-test results of the new OPTG methodology. The results indicated that for more severe, multiple control failures, control reconfiguration, guidance adaptation, and trajectory reshaping were all needed to recover the mission. An autolanding trajectory design for the X-34 Mach 8 vehicle was presented in Barton and Tragesser (1999). The techniques facilitate rapid design of reference trajectories. The trajectory of the X-34 based on the shuttle approach and landing design were from steep glideslope, circular flare, and exponential flare to shallow glideslope. In Cox et al. (1999), a neural network autolander for the X-33 prototype RLV was developed. The autolander was based on a new linear quadratic adaptive critic algorithm. It was implemented by an array of Functional Link Neural Networks and was trained by a modified Levenberg–Marquardt method.

The goal of this paper is to develop new approaches that can deliver an RLV to its landing site safely and reliably, recover the vehicle from some failures, and avoid mission abort as much as possible. A motion primitive (MP) scheme is proposed to generate A&L trajectories off-line under nominal condition. A feasible trajectory database under nominal conditions for the RLV at the A&L phase is constructed. When the vehicle experiences a failure, neighboring optimal control (NOC) is then used to generate a neighboring feasible trajectory in real time to recover it from the failure. Failures considered in this paper correspond to the case of a stuck effector. When the perturbations applied during NOC implementation are small enough and hence linear approximation is applied, a neighboring feasible trajectory existence theorem (NFTET) is investigated and its proof is provided as well. When the perturbations become large, for example, in severe failure scenarios, NFTET is no longer applicable and often the vehicle cannot be recovered from such failures. A new method is used to deal with this situation and the robustness of the RLV system is then enhanced. The NFTET is now extended to the TRT — trajectory robustness theorem. Its proof will also be provided later. This approach has at least three advantages over existing trajectory planning methods. First, it uses MP to generate an off-line feasible trajectory database that will be easily to create a new database for a new initial point. Second, it finds an off-line optimal trajectory using Dijkstra's algorithm instead of the traditional optimal control method so that NOC promises to find an on-line neighboring feasible trajectory. Third, a novel robustification approach is introduced to enhance the robustness of the system and hence an RLV with severe failure might be recovered in real time.

Section 2 introduces a motion primitive (MP) scheme and shows how to generate feasible trajectories in the A&L phase based on the MP scheme. Section 3 shows that the trajectory retargeting can recover the vehicle from some failures in real time by using an NOC approach. Section 4 discusses how to enhance the robustness of NOC using adaptive bounds with respect to input deviation. Some results and discussions are given in Section 5. The conclusions are drawn in Section 6.

2. Trajectory generation on approach and landing using motion primitives

This section will first introduce the point-mass equations of motion for the A&L problem of an RLV and then briefly describe the MP scheme. After that, how to generate feasible trajectories using an MP scheme is discussed (Jiang & Ordóñez, 2007; Jiang, Ordóñez, Bolender, & Doman, 2006).

2.1. Point-mass equations of motion

For an unpowered RLV during A&L, the discussion is restricted only to flight in the longitudinal plane. The gliding flight in a vertical plane of symmetry is then defined by the following point-mass equations (Jiang et al., 2006; Kluever, 2004; Miele, 1962):

$$\dot{V} = \left(-\frac{D}{W} - \sin\gamma\right) g, \tag{1}$$

$$\dot{\gamma} = \left(\frac{L}{W} - \cos\gamma\right) \frac{g}{V}, \tag{2}$$

$$\dot{h} = V \sin\gamma, \tag{3}$$

$$\dot{x} = V \cos\gamma, \tag{4}$$

where V is the vehicle velocity, γ is the flight-path angle, h is the altitude, x is the downrange, g is the gravitational acceleration, W is the vehicle weight, $L = \bar{q}SC_L$ is the lift, and $D = \bar{q}SC_D$ is the drag, where $\bar{q}$ is the dynamic pressure, S is the aerodynamic reference area of the vehicle, and C_L and C_D are the lift and drag coefficients, respectively. The dynamic pressure $\bar{q} = \rho V^2/2$, where the air density ρ at altitude h is approximated using an exponential model $\rho = \rho_0 e^{-\beta h}$, where ρ_0 is the air density at sea level and β is the atmospheric density scale.

Generally, the lift coefficient C_L is a linear function of α, where α is the angle of attack and the drag coefficient C_D is a quadratic function of C_L, namely, $C_L = C_{L0} + C_{L\alpha}\alpha$ and $C_D = C_{D0} + KC_L^2$, where C_{L0} is the lift coefficient at zero angle of attack, $C_{L\alpha}$ is the lift slope coefficient, C_{D0} is the drag coefficient at zero lift, and K is a coefficient relative to induced drag. Substituting the C_L expression into C_D gives it as a function of α, namely, $C_D = k_{D0} + k_{D1}\alpha + k_{D2}\alpha^2$, where k_{D0}, k_{D1}, and k_{D2} are resulting coefficients with respect to α.

The constraints at touchdown are

$$\dot{h}_{TDmin} \le \dot{h}_{TD} \le \dot{h}_{TDmax}, \tag{5}$$

$$V_{TDmin} \le V_{TD} \le V_{TDmax}, \tag{6}$$

where $\dot{h}_{TD}$ is the sink rate at touchdown, $\dot{h}_{TDmin}$ and $\dot{h}_{TDmax}$ are its minimum and maximum values, respectively, V_{TD} is the touchdown velocity, and V_{TDmin} and V_{TDmax} are its minimum and maximum values, respectively.

In the state Eqs. (1)–(4), V, γ, h, and x are the four state variables and α is the control variable.

2.2. Motion primitives

A motion plan consists of two classes of MPs (Frazzoli, 2002). The trajectory generation in this paper involves transitioning from one class of MPs to the other. The first class of MPs is a special class of trajectories, known as trims. A trim is a steady-state or quasi-