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A semi-analytical guidance algorithm for autonomous landing

Paolo Lunghi [a,*], Michèle Lavagna [a], Roberto Armellin [b]

[a] Aerospace Science and Technology Department, Politecnico di Milano, Via La Masa 34, 20156 Milano, Italy
[b] Aeronautics, Astronautics and Computational Engineering Academic Unit, University of Southampton, Highfield Campus, Southampton SO17 1BJ, UK

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Abstract

One of the main challenges posed by the next space systems generation is the high level of autonomy they will require. Hazard Detection and Avoidance is a key technology in this context. An adaptive guidance algorithm for landing that updates the trajectory to the surface by means of an optimal control problem solving is here presented. A semi-analytical approach is proposed. The trajectory is expressed in a polynomial form of minimum order to satisfy a set of boundary constraints derived from initial and final states and attitude requirements. By imposing boundary conditions, a fully determined guidance profile is obtained, function of a restricted set of parameters. The guidance computation is reduced to the determination of these parameters in order to satisfy path constraints and other additional constraints not implicitly satisfied by the polynomial formulation. The algorithm is applied to two different scenarios, a lunar landing and an asteroidal landing, to highlight its general validity. An extensive Monte Carlo test campaign is conducted to verify the versatility of the algorithm in realistic cases, by the introduction of attitude control systems, thrust modulation, and navigation errors. The proposed approach proved to be flexible and accurate, granting a precision of a few meters at touchdown.

Keywords: Autonomous landing; Optimal guidance; Powered descent; Trajectory optimization

1. Introduction

In last years, a renewed interest in planetary exploration has brought to the realization of several missions, especially towards Mars, culminated with the landing of the rover Curiosity in August 2012. Together with Mars, the Moon is a main destination for exploration. The European Space Agency has conducted several studies concerning a possible unmanned lunar lander (Carpenter et al., 2012), while NASA is planning to send humans back to space. ESA will supply the Orion/MPCV European Service Module (ESM) for the 2018 unmanned Exploration-1 Mission, including ground and flight operation support (Marshall and Norris, 2013). Targets for the subsequent manned Exploration-2 and 3 missions are under study, including Near-Earth Asteroids (NEA) and the Moon as possible destinations. Provisions for the construction and delivery of a second ESM have been taken. Recently ESA and the Russian federal space agency, Roscosmos, have signed a formal agreement to work in partnership on the ExoMars programme towards the launch of two missions in 2016 and 2018, with the goal to bring a rover on Mars surface. In addition to mission to planets and their moons there is a strong interest in visiting small bodies as asteroids and comets. A typical high-autonomy scenario is the close approach to a low-gravity object, finalized to either touch and go operations or landing. The ESA Rosetta probe, launched in March 2004, have performed a rendezvous with the comet 67P/Churyumov–Gerasimenko in August 2014. The release of the lander Philae, with the objective to collect and on-board analyze samples of comet's soil, has been successfully performed the next 12th November (Geurts et al., 2014). The

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* Corresponding author.
E-mail addresses: paolo.lunghi@polimi.it (P. Lunghi), michelle.lavagna@polimi.it (M. Lavagna), roberto.armellin@soton.ac.uk (R. Armellin).

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OSIRIS-REx spacecraft, planned by NASA for launch in 2016, will travel to the NEA Bennu, study it in detail, and bring back a sample to Earth (Gal-Edd and Cheuvront, 2014). MarcoPolo-R, a project with similar objectives, has been studied by European Space Agency as M-class candidate mission for the launch in 2022 (Michel et al., 2014). Recently, in the FY2014 budget proposal, NASA has included a plan to robotically capture a small NEA and redirect it safely to a stable orbit in the Earth-moon system where astronauts can visit and explore it (Condon and Williams, 2014). ESA is studying with NASA the AIDA mission including ESA's AIM and NASA's DART spacecraft, to be launched to rendezvous with the Didymos binary asteroid. To be launched in 2020, AIM will rendezvous and release a lander to one of the bodies in 2022 (Cheng, 2013). All the examples mentioned above share the common problem of designing a landing on a celestial body. The landing phase is a critical phase, being usually a single point of failure for the mission success.

During last decades, several improvements in automatic landing precision have been implemented, but the relative uncertainty of the landing dispersion still imposes strict requirements on the landing site selection. On the other hand, scientifically relevant places may be associated with hazardous terrain features or confined in very limited areas; in other cases there is no possibility to completely characterize a predefined landing area with the required accuracy. Moreover, in the case of planetary landing, the short duration of the landing phase, together with telecommunications delays, makes a continuous control from the ground impossible. Even in cases where the long duration of the maneuver allows a certain degree of remote control (such as the case of proximity maneuvers around low gravity bodies) high accuracy is still impossible without an on-board autonomous guidance system (Berry et al., 2013), as well as efficient counteraction to unexpected events or failures, as demonstrated by the uncontrolled bounce of the ESA lander Philae during the recent landing on the comet 67P.

This is why precise and autonomous landing capability is a key feature for the next space systems generation. The system must perform high precision relative navigation, and seek and identify a reachable and safe landing site; then, it needs to recalculate a pinpoint feasible trajectory toward the target. The minimization of the propellant consumption is a goal of every space mission, as it allows a reduction in launch mass or an increase in payload, and thus in the scientific return of the mission. Also, a fuel optimal approach in hazard avoidance computation contributes to maximize the attainable landing area, consequently increasing the chances to find a safe landing site. That is why propellant minimization can be considered as an ideal criterion in divert trajectory design. On the other hand, numerical optimization implies usually heavy computation with no guarantee of convergence.

Different approaches at the problem have been adopted during the years. A trajectory based on a quartic polynomial in time, with no optimization involved, was used during the Apollo missions (Klumpp, 1974). A derivative of the Apollo lunar descent guidance has been still considered in recent years for the Mars Science Laboratory (MSL) (Wong et al., 2002). Various other approaches to obtain both numerical and approximate solutions of the pinpoint landing terminal guidance problem have been proposed over the last few years. In Topcu et al. (2005) the first-order necessary conditions for the problem are developed, and it is shown that the optimal thrust profile has a maximum–minimum–maximum structure. Direct numerical methods for trajectory optimization have been widely investigated, not requiring the explicit consideration of the necessary conditions and with better convergence properties (Betts, 1998). These methods have been used together with Chebyshev pseudospectral techniques, to allow the reduction of the number of the optimization variables (Fahroo and Ross, 2002). Also convex programming has been proposed to guarantee the convergence of the optimization; this approach, coupled with direct collocation methods, has proved that the size of the region of feasible initial states, for which there exist feasible trajectories, can be increased drastically (more than twice) compared to the traditional polynomial-based guidance approaches, but at the price of a higher computational cost (Açikmeşe and Ploen, 2007). This method has been coupled with a minimum-landing-error approach, in order to compute a landing trajectory even in case a feasible solution for the selected landing site is not found (Blackmore et al., 2010).

In the case of asteroids and comets, landing and close proximity operations present some peculiarities, due to their small size and irregular shape. In particular, the gravitational acceleration is very weak and variable in function of the relative position of the spacecraft respect to the target. Due to that, orbits are generally complex and non periodic, and stable only in certain regions (Lara and Scheeres, 2002). Zero Emission Effort/Zero Emission Velocity guidance had been proved to produce a good approximation of the fuel-optimal trajectory in close proximity maneuvers around asteroids (Hawkins et al., 2012), and it has been applied together with high-order sliding mode control to increase robustness to disturbances and unmodeled dynamics (Furfaro et al., 2013a,b).

In this work a guidance algorithm capable to dynamically recompute and correct the landing trajectory during the descent is developed, allowing the on-board choice of the landing site, as required by systems that have to operate in full autonomy. An innovative semi-analytical approach is proposed: the trajectory is parameterized in a polynomial form, depending only on a few parameters that can be efficiently optimized by a simple derivative-free optimization algorithm. Traditional closed-form guidance schemes (such as Apollo guidance, E-guidance) are sub-optimal and do not include explicitly path constraints, potentially leading to infeasible trajectories. On the other hand, fully numerical methods, although extremely flexible in terms of optimality