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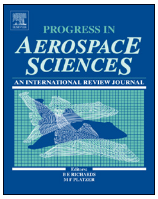

Review and prospect of guidance and control for Mars atmospheric entry

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ABSTRACT

The Mars atmospheric entry phase plays a vital role in the whole Mars exploration mission-cycle. It largely determines the success of the entire Mars mission. In order to achieve a pin-point Mars landing, advanced entry guidance and control is essential. This paper systematically summarizes the past development and current state-of-art of Mars entry guidance and control technologies. More specifically, the Mars entry process and main technical challenges are first introduced. Second, the guidance and control technologies adopted in the past successful Mars landing mission are reviewed in detail. Next, current state-of-art and recent developments of guidance and control for Mars atmospheric entry are summarized at length. The advantages and disadvantages of the various existing methods are analyzed. Lastly, supposing future Mars pin-point landing missions as the potential project application goals, a more comprehensive outlook and prospect for the next-generation Mars entry guidance and control technologies are described.

Contents

Abbreviations: AFL, astrobiology field laboratory; MER-B, Opportunity; CG, center of gravity; MSL, Mars science laboratory; CGT, command generator tracker; MSMSG, multiple sliding mode surface guidance; DEKF, desensitized extended kalman filter; MSR, Mars sample return; DOF, degree-of-freedom; MOLA, Mars orbiter laser altimeter; DSN, deep space network; MOPSO, multi-objective particle swarm optimization; EAGLE, evolved acceleration guidance logic for entry; MPF, Mars Pathfinder; EDL, entry, descent and landing; NASA, National Aeronautics and Space Administration; ESA, European Space Agency; NLP, non-linear programming; ETPC, entry terminal point controller; NNSMVSC, neural network-based sliding mode variable structure control; GNC, guidance, navigation and control; NPC, nonlinear predictive controller; HERRO, human exploration using real-time robotic operations; PC, polynomial chaos; IMU, inertial measurement unit; PD, proportional-differential; KKT, Karush–Kuhn–Tucker; PEDALS, parametric entry, descent, and landing synthesis; L/D, lift-to-drag ratio; PWM, pulse-width-modulation; LQR, linear quadratic regulator; RCS, reaction control system; Mars-GRAM, Mars global reference atmospheric model; SAMIC, structured adaptive model inversion control; MCD, Mars climate database; SMVSC, sliding mode variable structure control; MEDLI, MSL entry, descent, and landing instrument; SOPSO, single objective particle swarm optimization; MER, Mars Exploration Rovers; UHF, ultra-high frequency; MER-A, Spirit

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1. Introduction

1.1. Past Mars landing mission overview

As the nearest neighbor of planet Earth, Mars has attracted more attention than other planets for decades. In order to obtain the first-hand scientific data of Mars topography and chemical composition, landing a vehicle on the surface of Mars and performing in situ exploration is a prerequisite. Since the 1970s humans commenced Mars landing exploration missions. So far, more than two-thirds of the Mars missions ended in failure, and only seven spacecraft successfully landed on the surface of Mars [1].

The Mars-2, launched by the Soviet Union in 1971, is the first spacecraft that reached the surface of Mars, although it finally crashed on the Martian surface. Mars-3 and Mars-6 also succeeded in reaching the surface of Mars in 1971 and 1973 respectively, but their transmissions soon stopped after landing [2]. NASA launched the Viking-1 and Viking-2 in 1976, and both successfully landed on the surface of Mars [3–6]. Subsequent NASA Mars missions, such as Mars Pathfinder (MPF) [7–17], Mars Exploration Rovers (MER) (including Spirit (MER-A) and Opportunity (MER-B)) [18–24], Phoenix [28–35], and Mars Science Laboratory (MSL) [36–44], incorporated the Mars entry, descent and landing (EDL) technologies qualified by the Viking missions and succeeded in landing on Mars. The European Space Agency (ESA) launched the Mars Express in 2003, and its lander probe Beagle-2 successfully landed north of the equator of Mars, but it fell silent after landing [45–47]. Future Mars landing missions include ESA's ExoMars [48,49], NASA's astrobiology field laboratory (AFL) [50] and Mars sample return (MSR) [51–54], which are expected to be launched between 2016 and 2024.

All Mars landers, except for recent MSL/Curiosity, have flown an unguided ballistic atmospheric entry and adopted the so-called first-generation of landing systems, which aimed at safely landing on Mars without considering the scientific value of landing sites. The next-generation landing system, often called pin-point landing systems, will have the capability of autonomously and safely landing on hazardous sites with high scientific value pre-selected by scientists [55,56]. While the first-generation systems generated a landing uncertainty ellipse in the order of 500 km by 100 km, the next-generation aims for a precision in the order of 10 km, and even down to 100 m [57].

1.2. Mars atmospheric entry phase

Mars entry, descent and landing (EDL) commences at the Mars atmosphere interface with a velocity of around Mach 25 and ends with a safe touchdown, which includes the atmospheric entry phase, the parachute descent phase and the powered descent phase [58]. Fig. 1 shows the sequence of events for a future representative Mars EDL baseline scenario. The entry, descent and landing phases are crucial for a Mars landing exploration mission, which directly determines the success of the entire mission [59–62]. As the extremely important sub-phase of EDL, the Mars atmospheric entry phase begins when the vehicle reaches the Mars atmospheric boundary (about 125 km altitude) and ends at deployment of the supersonic parachute, which lasts about 4 minutes and suffers the worst aerodynamic heating environment during all three sub-phases of EDL [42,59]. The entry vehicle's velocity is reduced from 4–7 km/s to about 400 m/s during the Mars atmospheric entry phase. Therefore this phase is also called hypersonic entry phase [63–66]. The 99% of initial kinetic energy will be consumed during the atmospheric entry phase, and the peak overload and peak heat flux also happen in this phase, which present a huge challenge to designing aerodynamic deceleration, structure and thermal protection system [67–70].

In order to simplify the entry guidance and control system design and enhance the entry reliability, the closed-loop guidance and control systems were not adopted in the previous missions except for the recent MSL/Curiosity [59,72,73]. Most Mars entry vehicles adopted ballistic entry, and there was no aerodynamic lift used in the guidance and control operations. Therefore, the entry and landing error caused by the accumulated navigation error,

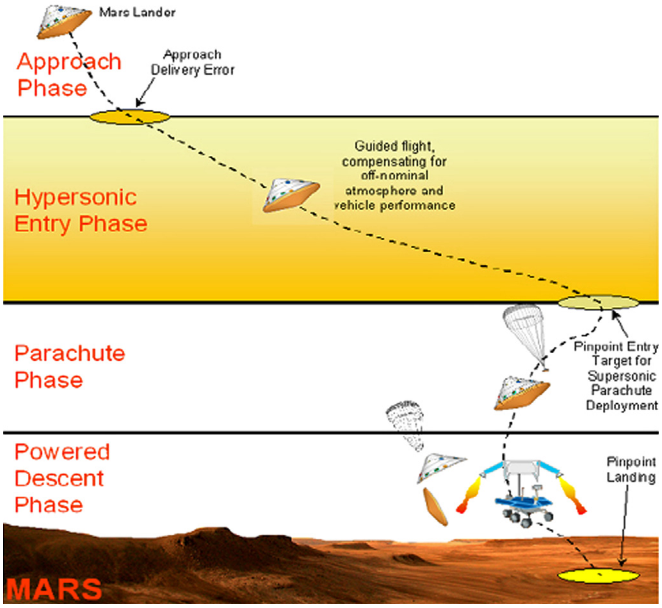

Fig. 1. Representative entry, descent, and landing scenario [71].