G-FOLD: A Real-Time Implementable Fuel Optimal Large Divert Guidance Algorithm for Planetary Pinpoint Landing. Behçet Açıkmeşe, Jordi Casoliva, John M. Carson III, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109, USA. Email: {behcet,Jordi.Casoliva,jmcarson}@jpl.nasa.gov. Lars Blackmore, Space Exploration Technologies, 1 Rocket Rd Hawthorne, CA 90250, USA. Email: lars.blackmore@spacex.com.

Introduction: Spacecraft accumulate large position and velocity errors during the atmospheric entry phase of a planetary mission due to atmospheric uncertainties and limited control authority. The powered descent phase, which is the last phase of Entry, Descent, and Landing (EDL), is when the lander makes a controlled maneuver to correct for these errors. This maneuver must be computed onboard in real-time because the state of the lander cannot be predicted at the start of powered descent phase.

Current state-of-the-art onboard Powered Descent Guidance (PDG) algorithms used in this phase are inherited from the Apollo era. These algorithms do not explicitly optimize fuel usage or prevent landing mission constraints from being violated. As a result they cannot fully utilize the full spacecraft divert capability, and hence significantly limit the landing precision. We developed a new solution methodology and an associated onboard real-time implementable algorithm, called *G-FOLD*, for powered descent guidance for planetary landing, which autonomously generates fuel optimal landing trajectories in real-time. The algorithm is capable of generating any physically feasible large divert PDG trajectory that satisfies mission constraints. It has been used extensively at NASA JPL over the last seven years to perform future Mars lander mission analysis in an automated fashion. It has proved itself to be an essential analysis tool and the fact that it has been automated proves its numerical robustness.

G-FOLD algorithm provides a key new technology required for planetary pinpoint landing. The National Research Council report on National Space Technology Roadmaps and Priorities identifies precision or pinpoint landing as a top priority for technology investment. Pinpoint landing capability is important to NASA because, as landing precision increases, robotic missions are able to access science targets, which are currently inaccessible or are very risky for a rover to reach from large distances. For crewed missions, the increased precision with minimal fuel requirements enables the landing of larger payloads in close proximity to predetermined targets.

Description of G-FOLD Algorithm: We developed an optimal large divert PDG algorithm [1, 2, 3] that autonomously computes the fuel optimal path that takes the lander to a given surface target without violating any mission constraints. This powered descent **G**uidance algorithm for **F**uel **O**ptimal **L**arge **D**iverts (**G-FOLD**) is needed for planetary pinpoint landing. It enables access to unreachable but scientifically valuable science targets for Mars sample return mission and to deliver large payloads necessary for human class planetary missions.

The main purpose of Guidance, Navigation, and Control (GN&C) during the landing phase of planetary missions is to reduce the lander's velocity from orbital or interplanetary velocities to a velocity near zero. In case of planets with atmospheres (such as Mars), this first involves an entry phase (see Fig. 1). This phase cancels most of the surface relative velocity. Once the lander slows down to supersonic speeds, a parachute is deployed. Then at a prescribed altitude and velocity, the parachute is released and the Powered Descent (PD) phase is initiated. Due to atmospheric uncertainties in winds and density and due to the passive deceleration during the parachute phase, the position and velocity relative to the target is dispersed significantly and they cannot be predetermined. In the example of Mars landing, the distance error can be in the order of 8-10 km with the velocity trigger (used in MSL) and 5-6 km with a range trigger for the start of parachute phase [4]. To achieve pinpoint landing (position error $<$ 100 m at touchdown), an autonomous PDG algorithm is used to redirect the vehicle to the surface target in real-time to correct for these errors.

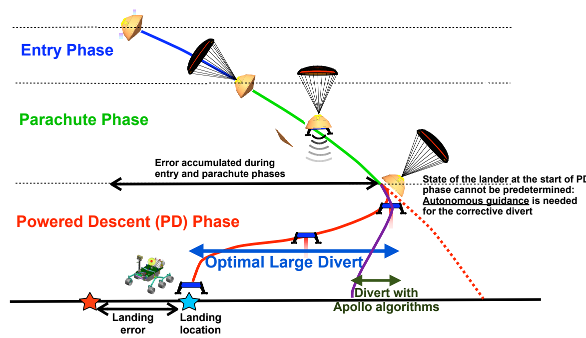

Fig.1: G-FOLD enables planetary pinpoint landing. It searches all possible diverts and dramatically increases the divert capability over the current state-of-the-art onboard algorithms.

The main benefit of increasing landing precision is the access to more scientifically valuable sites. For example the current landing accuracy for Mars landing is about 10 km. If the science target is in terrain that is too rough for landing then the rover may need to traverse more than 10 km to reach a desired target site, which implies months of surface operations that involve significant risk and cost. It also implies that a very capable rover must be used, which increases cost and the payload mass. In some cases, due to non-traversable terrain around the target site, reaching the target may not be possible. Indeed many scientifically valuable targets are in locations with geographically difficult terrains to traverse. G-FOLD is an enabling technology for accessing to these target sites and does it with minimum possible fuel use. This means that many of these scientifically valuable targets that are extremely risky to reach without G-FOLD. In human class planetary missions, the benefit of G-FOLD is the minimal fuel use in addition to increased precision. For example a human mission to Mars potentially includes multiple missions to establish a base at a prescribed location. Multiple robotic missions may deliver the necessary equipment, i.e. large payloads, to the surface. This implies high landing precision and achieving this with the minimal fuel use translates to more payload delivered to the surface.

With few exceptions (such as MER), planetary EDL finishes with a powered descent (PD) phase where the vehicle thrusters are used to slow the spacecraft to a desired velocity at touchdown. The vehicle position dispersions can be up to 8-10 km with respect to a prescribed target at the start of the PD phase [5, 4]. With improvements on the entry and parachute phases, these dispersions can potentially be reduced to 5-6 km [4]. At the start of the PD phase the target relative state of the vehicle is determined via measurements obtained by the Terrain Relative Navigation (TRN) sensor [6]. G-FOLD provides the algorithmic capability so that the lander vehicle can divert to fly out the dispersions at the start of PD. For MSL-like entry system, the divert needed can be up to 8-10 km. For a future lander with improved entry and parachute systems, the diverts needed are 4-6 km. As a point of comparison, the current PDG method implemented in MSL [7] is built on the Apollo era algorithms [8] and is not designed to achieve the large diverts required for pinpoint landing. It allows diverts less than 50 m. Table 1 clarifies key differences between G-FOLD and Apollo class PDG algorithms. This comparison was independently carried out by researchers in Georgia Institute of Technology and Charles Stark Draper Laboratory [9]. Their conclusion was that, among other available choices, our optimal PDG algorithm was the only one that had both adequate robustness and numerical stability required for onboard flight use.

Table 1: G-FOLD is more robust than Apollo class algorithms.

G-FOLD Algorithm	Apollo Class PDG Algorithms
Robust: Retargeting (divert) range is only limited by the spacecraft capabilities	**Not robust**: Retargeting range is severely limited by the algorithm
Guidance trajectories use the minimal possible fuel	Guidance trajectories use more fuel than necessary
Uses a moderate predetermined number of arithmetic operations	Uses a minimal predetermined number of arithmetic operations
Numerically stable	Numerically stable

G-FOLD solves an optimal control problem by explicitly accounting for the constraints imposed by the mission and the lander. As shown in Table 1, it guarantees generating the fuel optimal trajectory that guides the lander to the closest surface location relative to the target that is physically possible under mission constraints. In contrast, Apollo heritage algorithms do not optimize fuel use or account for the mission or lander constraints explicitly. After a trajectory is generated, the satisfaction of these constraints must be checked. Therefore they may fail to generate a trajectory even if one exists. This limits their effectiveness significantly. Fig. 2 demonstrates a comparison of divert capability provided by Apollo PDG algorithm and G-FOLD as a function of fuel in the MSL lander example. In collaboration with JPL EDL GN&C team (for Pathfinder, MER, MSL), we determined the following mission constraints to be necessary, and they are currently incorporated in G-FOLD: (i) Maximum and minimum thrust magnitude; (ii) Thrust pointing direction; (iii) Glide slope to avoid surface contact during flight; (iv) Maximum velocity to avoid supersonic flight.

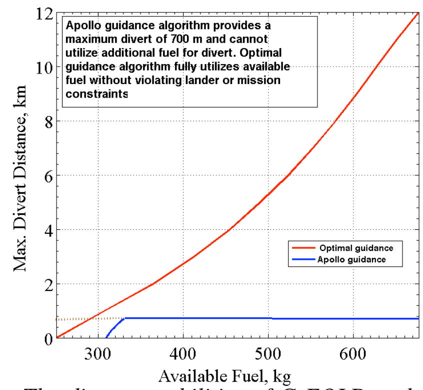

Fig.2: The divert capabilities of G-FOLD and Apollo guidance algorithms are compared for MSL vehicle as a function of increased fuel. G-FOLD can use any additional fuel to improve the divert. Apollo algorithm cannot utilize additional fuel beyond a certain value (330 kg in this example).This is because it does not account for the available fuel or other constraints as it generates the solution. For the same initial position and velocity, it computes the same solution regardless of the available fuel or thrust-to-weight ratio. Hence increasing lander capabilities does not change the trajectory that Apollo class guidance algorithms provide, which severely limits the diverts achievable.

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