Precision Mars terminal descent with autonomous thrust-augmented hang-glider

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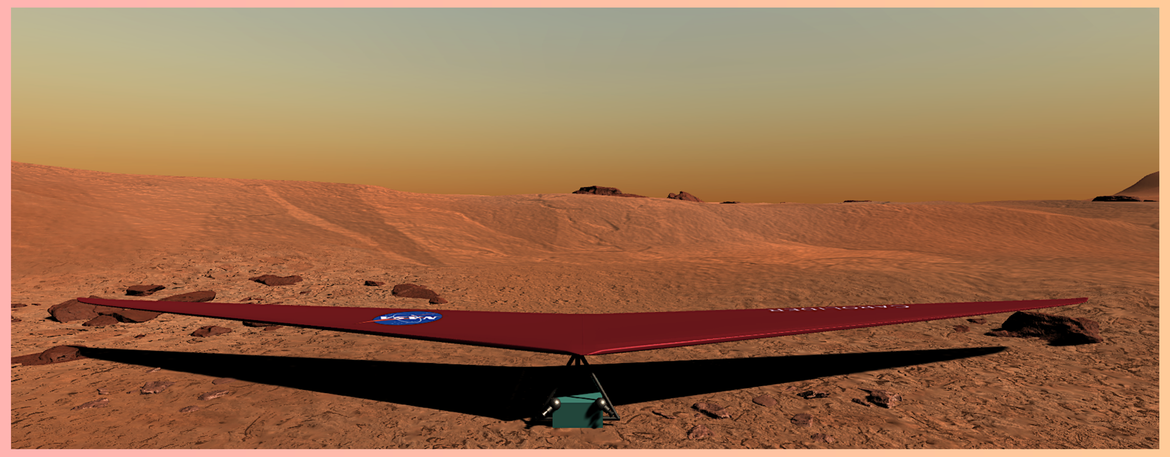
Introduction

This work describes a convex programming approach integrated with multi-body system flight-mechanics simulation to solve the minimum-time terminal descent problem of a powered 6-DoF hang glider with free final time, on Mars. Specifically, this work focuses on the final part of the landing trajectory, in which the payload position is fixed relative to the hang-glider body frame, and a propulsive braking thrust is turned on.

Motivation

Novel concepts for small payloads attached to gliding surfaces would allow small robots to approach unexplored territories on Mars. The combination of the small size and the precise landing would allow them to reach hard to reach places such as glaciers, craters, canyons, and volcanic regions. An appealing aspect of this new approach is the possibility of studying new geologically active sites, like polar geysers. The hang glider described by [1] and [2] has been employed for landing on Mars due to its cost effectiveness, high lift-to-drag ratio, and relatively low mass compared to the cost of the payload.



Hang glider concept on Martian surface, top view.

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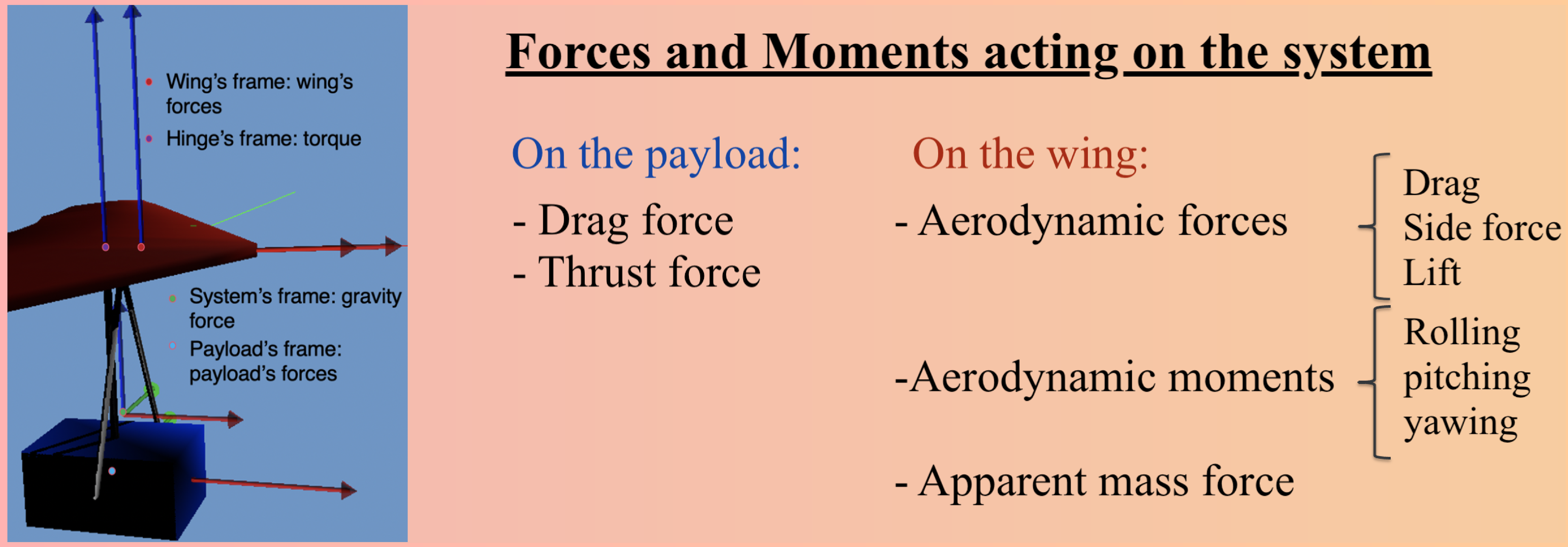
Hang-glider Model

The hang-glider consists of a flying wing and a scientific payload suspended below by a hang strap, and achieves its higher maneuverability by shifting the payload's center of gravity.
All the forces and moments are applied to the system's center of gravity, which lies on the line connecting the wing and the payload center of masses.
The terminal descent of the hang glider is actuated by a single gimbaled engine, located in the payload, which generates a thrust vector expressed in the body frame, within a feasible range of gimbal angles and magnitudes, to land at the desired location with high precision.



Successive Convexification with free final-time

The terminal descent algorithm implementation follows the one proposed by [3,4], but the aerodynamics has not been neglected.
The objective is to find the optimal thrust commands that minimize the time of flight while satisfying all the constraints in order to have optimal trajectory profiles that are both dynamically feasible and controllable.
Solving this kind of problem is challenging since the problem is non-convex and non-linear, the trajectory is subjected to both convex and non-convex state and control constraints, and it can be difficult to choose a suitable initial trajectory for the iterative solution process. Moreover, the efficacy of the solution depends on the accuracy of the time discretization.
In order to overcome these difficulties, the algorithm proposed by [3] uses a successive convexification to eliminate model non-convexities.
The algorithm can be initialized with any simple and even unfeasible trajectory, and it achieves its goal also with an inconsistent guess on the time-of-flight.
It has been implemented in Python using CVXpy, configured with the embedded conic solver (ECOS), [5], i.e. an interior-point method solver for second-order cone problems, designed for embedded applications.

Results

Figure 1 shows the descending trajectories starting from 1 Km of altitude. A *Proportional-Derivative* control law on the payload displacement was used to compensate for random wind gusts, while the thrust was turned off for the whole descent. To reduce the touchdown velocities to zero an additional thrust force was needed for the final landing stage. Figure 2 shows descent trajectories starting from different initial positions for the last 50 m of altitude, using the successive convexification to compute the optimal thrust commands. It can be seen that, whatever the initial conditions, the hang glider optimal trajectory ends in exactly the same landing point.

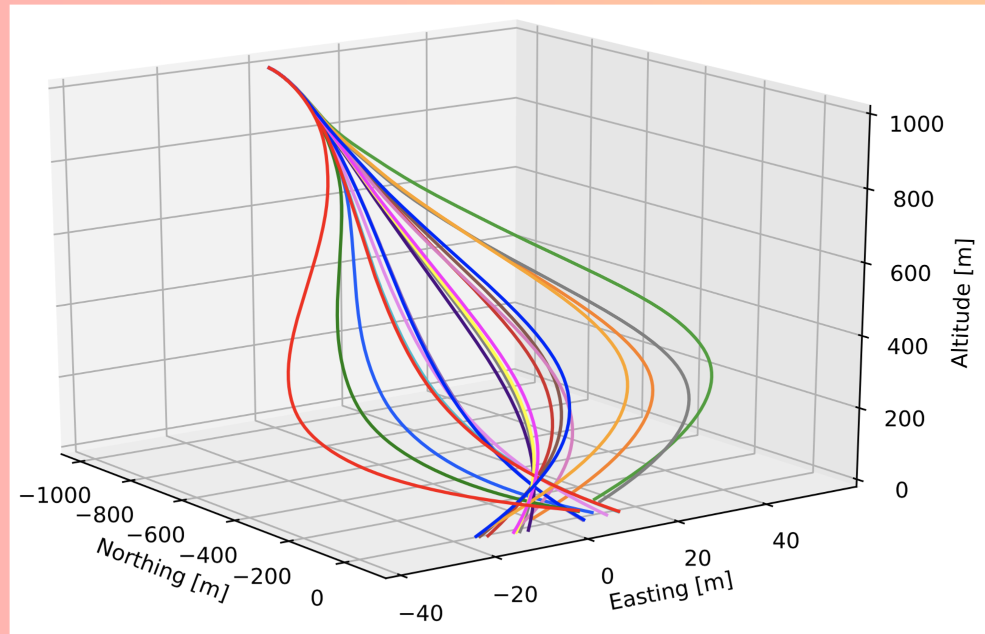


Fig. 1

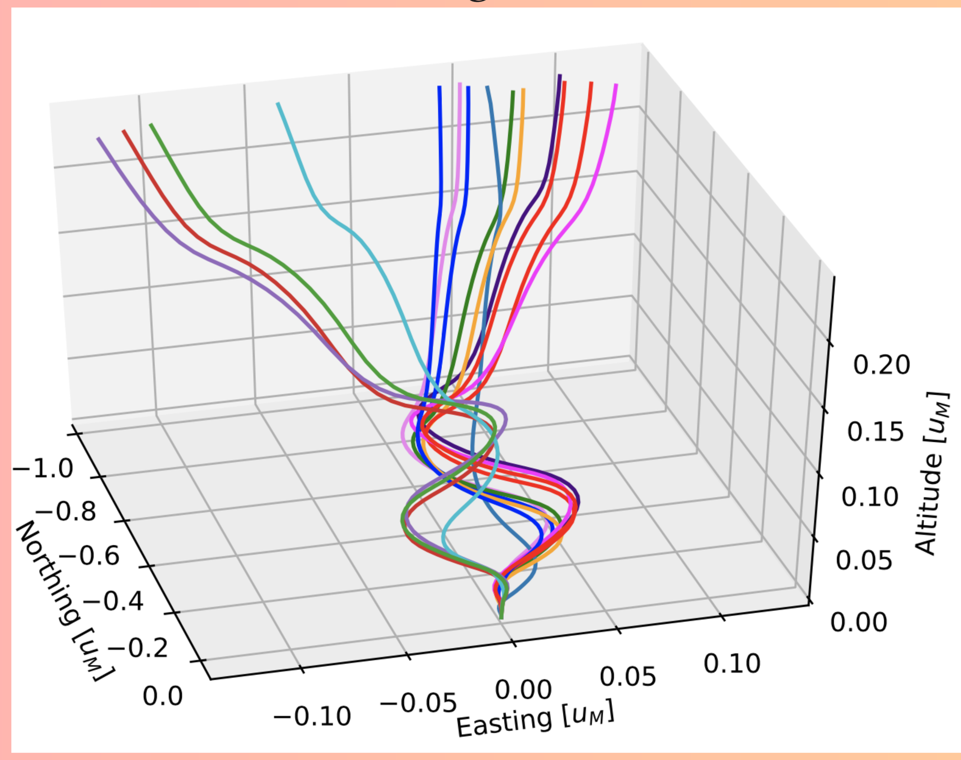


Fig. 2

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