Automatic Control Laboratory
Department of Information Technology and Electrical Engineering, ETH Zurich
Master thesis project

Integration of robust control design and flexible optimal guidance for reusable launch vehicles

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1 Abstract

Autonomy is a key enabler for successful and reliable space missions carried out with reusable rockets, which are in the forefront of space endeavours. This project will investigate systematic procedures to integrate the design of optimal guidance strategies with robust controllers to improve safety and performance.

Keywords: Robust control, Optimization, Flight dynamics, Reentry vehicles.

2 Project description

Recent years have witnessed a revival of interest in space endeavours boosted by the successful missions carried out with reusable rockets by the commercial companies Blue Origin and SpaceX. Reusability is a key enabler for a sustainable and cost-effective access to space, but poses important engineering challenges and thus it is not fully developed yet. One of these challenges is ensuring autonomous precision landing of space rockets (or, more in general, space transportation systems). There are many factors making this a difficult problem: extreme environments (e.g. strong wind perturbations); the need to precisely control the spacecraft's trajectory to avoid catastrophic impacts; complicated touchdown manoeuvres with limited control authority. These technical challenges are exacerbated by modeling and environmental uncertainties, which make essential to work with robust methodologies.

The main objective of the project is to investigate the integration of optimal guidance strategies, used to plan the trajectory of the spacecraft, with the design of robust controllers, which allow the trajectory to be tracked in the face of exogenous perturbations and model mismatches. A typical mission for a reusable rocket booster consists of the following steps (Figure 1): powered ascent; stage separation; flip maneuver; boostback (only for return-to-launch-site); entry burn; aerodynamic reentry; and powered landing.

Within this project, it is envisaged a closer focus on the last two phases, which present interesting and challenging aspects. During the unpowered phase of reentry, as the vehicle descends towards the thicker part of the atmosphere, the aerodynamics control surfaces (fins) increase their control authority. Moreover, also the body of the booster can generate lift and drag. From the control viewpoint, it is necessary to leverage these effects to improve the trajectory tracking performance while keeping the aerodynamic loads within safe margins. As for the powered landing, here the controller has to precisely track the planned trajectory

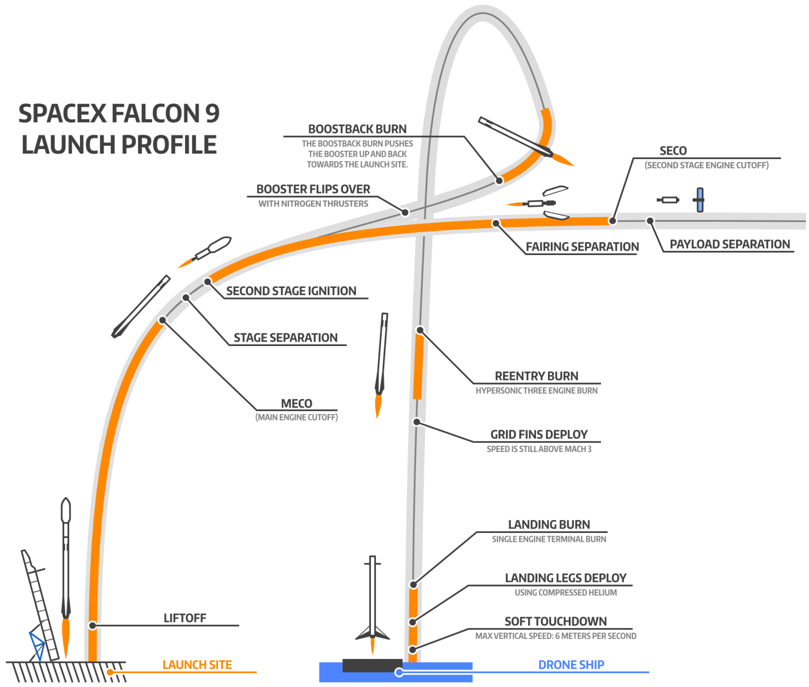

Figure 1: Pictorial representation of the separation and reentry trajectory of the Falcon 9 launch vehicle (from https://www.spacex.com/launches).

leveraging thrust vectoring while rejecting disturbances. It is paramount to reduce dispersion and follow the desired position/velocity profile to guarantee a successful landing.

The project is co-supervised by aerospace and optimization experts from Embotech (`www.embotech.com`), that will provide their expertise and share their optimal guidance algorithm. As for the robust control part, the starting point is represented by well-established techniques such as $\mathscr{H}_\infty$ and Linear Parameter-Varying (LPV) control, that have already been successfully tested in space applications. The main technical challenge that this project aims to address is a systematic integration between the optimal guidance and the controller employed to track the commanded trajectory. In order to cope with dispersion (i.e. variations in the trajectory caused by the aforementioned uncertainties), the guidance trajectory is not known at the design stage, instead it changes throughout the mission. This flexible guidance gives rise to a family of possible paths that the robust controller should be able to cope with. Besides having to cope with exogenous and endogenous disturbances, i.e. the standard objective of robust controllers, this application thus also requires robustness with respect to the tracking reference.

3 Goals

The project will investigate different approaches to this problem by breaking it down into smaller parts and looking for novel solutions from different perspectives. One concerns the investigation of more flexible robust control solutions, such as those offering more means of adaptation of the feedback law. Another considers the possibility to define, within the guidance problem, a *controller-feasible* constraint. Namely, can one appropriately modify the guidance optimization problem so that the robust controller will be able to track all the possible resulting trajectories? This tight coupling between guidance and control is rarely explored and could represent an important new contribution to Guidance Navigation and Control for space transportation systems.

Preliminary control design models are available, and will be used by the students in the beginning to familiarize with the problem and try the first designs. The fidelity of the control design models will be improved in order to capture relevant features of the problem, such as aerodynamic actions and environment. A simulator (implemented in Simulink) is also available, and will be used as ground truth to validate the results. Concretely, the expected outcome of the project is an integrated guidance-control design pipeline, whereby (parts of) a standard mission of a reusable rocket can be successfully achieved in the face of dynamic perturbations.

Below there is a summary of the main tasks defining the project.

- Literature review on guidance and control of re-entry vehicles
- Development of a guidance and control design pipeline for nominal trajectory
- Critical assessment of the fidelity of the control design models and update
- Definition of meaningful environmental and model perturbations, and investigation of their effect on the nominal solution proposed initially
- Investigation of strategies to match the guidance's flexibility in the controller
- Numerical tests to validate the approach in different scenarios

Application: The candidate should apply with a CV, transcripts with grades, and possibly a short motivation letter.

Relevant subjects: Robust control, Optimization, Flight Dynamics. Experience on these topics is not a pre-requisite, but it is a plus. Knowledge of the fundamental concepts of state-space and frequency domain control design methods (e.g. loop-shaping) is expected.