Descent and Landing Simulation of SpaceX Starship on Mars

Gravity Guardians

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Objective and Motivation

In this project, we seek to simulate the entry and landing of the SpaceX Starship vehicle into the Martian atmosphere. This problem is of primary interest due to future Mars missions utilizing the Starship vehicle, in which the entry, flip maneuver, and vertical landing will be implemented. While proprietary simulations have likely been accomplished and controllers modeled, this project aims to provide applications of control fundamentals to a reduced complexity and low fidelity model of the Starship spacecraft to demonstrate understanding of PID controllers. The project team has also determined this endeavor to be of personal interest, providing intrinsic motivation to research, design, and implement control of the spacecraft.

Figure 1: Starship Spacecraft (Source: SpaceX)

Problem Identification

Within this simulation, we aim to implement aerodynamics using simplified models of flow over blunt bodies in 2D. Using these models, the equations of motion of a 2D object with blunt body aerodynamic features can be generated using simplified characteristics of the Martian atmosphere. These equations of motion would provide us with measurable outputs, such as the angle of attack of the blunt body, α, as well as the inputs resulting from the aerodynamic moments provided by the fins and canards (modeled as flat plates for the simulation) and propulsive force vectoring from the reentry burn of the engine. Following the analytical derivation of the equations of motion, we will implement a controller to maintain the attitude of the craft tracking to predetermined metrics. This controller will most likely take the form of a MIMO PID controller due to the complexity of the model as well as the likelihood of assumed conditions generating steady-state errors. To properly control the full reentry and landing process of the Starship vehicle, the project team has identified two key substages which will be the focus for the controller design prior to complete integration – Reorientation Phase and Landing Phase.

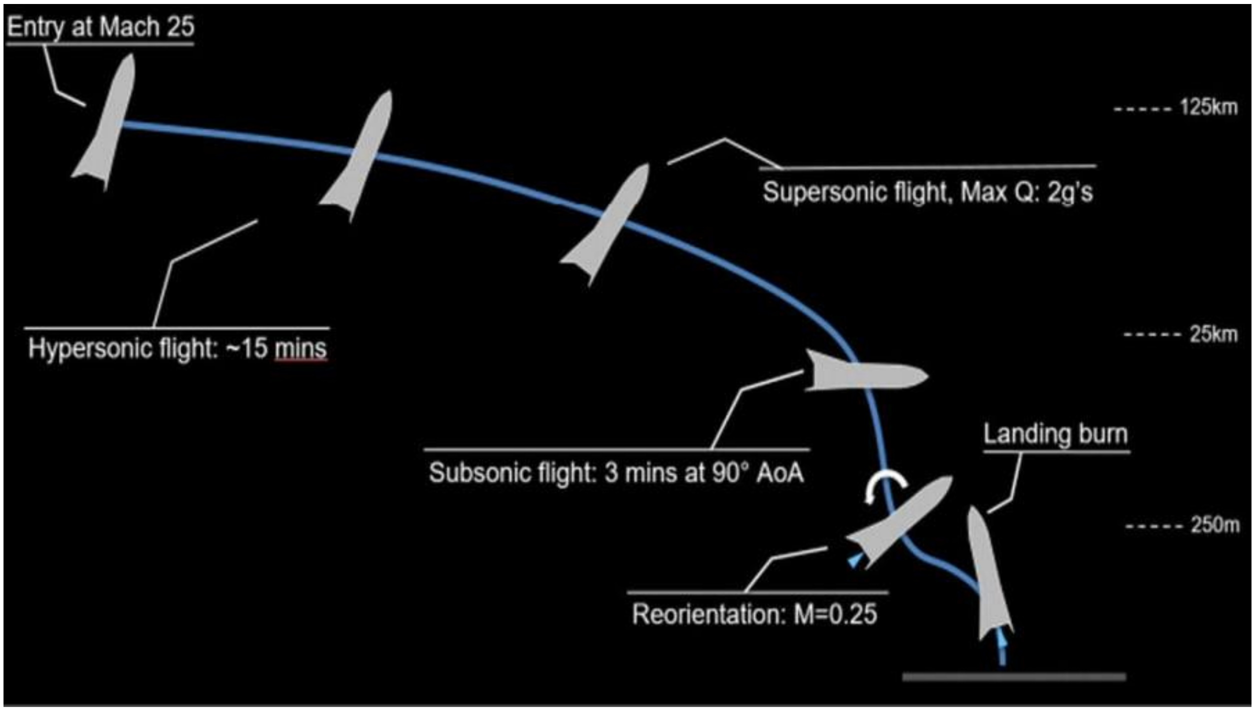

Figure 2: Diagram of Starship Reentry and Landing Stages (Source: clickorlando.com)

Entry Phase

The goal for the entry phase would be to trim the spacecraft at an angle of attack of 90° as seen above in the subsonic flight portion of the diagram with a decreasing descent velocity due to the aerodynamic drag of the spacecraft. Due to the complexities related to hypersonic flight, the focus of the project will begin once the spacecraft reaches a subsonic velocity. In this phase, the available control surface inputs to the controller will be both the forward mounted canards as well as the rear flaps, both hinged to provide variation in drag. Within the dynamics, the four control will be modelled using flat plate drag characteristics, dependent on the angle of attack, for the controlled descent, with the body aerodynamics derived from the drag on a cylindrical body dependent also on angle of attack. The end of this phase will be completed when Starship reaches a desired altitude at a desired distance down range where the reorientation phase will begin.

Reorientation Phase ("The Flip")

The goal of the controller for the reorientation phase is to orient the spacecraft from an angle of attack of 90° to 0° clockwise from the vertical plane. The altitude of the craft is not of primary control importance within this phase. The dynamics of Starship are different within this phase, as the control surface inputs to the controller reduce to only the forward mounted canards and thrust vectoring of a singular relit Raptor engine. The models that the project team will be using will thus be reduced and modified to account for the differences in inputs to control the craft. Once the craft is reoriented, the final landing phase can begin. Additionally, the flip maneuver would cause a singularity in Eulerian coordinates, therefore quaternions will be used for the project.

Landing Phase

The goal of the controller within the landing phase of Starship is like that of the inverted pendulum controller in maintaining the vertical orientation of the craft with the added complexity of tracking to and reducing the altitude to the ground state of h = 0 m. Due to the assumption of low velocity and thus negligible aerodynamic control from the canards and fins at the final phase at a starting altitude of ~25m, the only control input comes from the thrust vectoring of the single Raptor engine. This entails another set of equations of motion of the craft.

Further Considerations

Once the project team has successfully demonstrated the control on each of the phases, if time allows the integration of both phases of control will be attempted. Despite significant complexity reductions, this low fidelity 3D control problem is still challenging due to the potential differences in dynamics at the different flight phases, and therefore presents potential issues within integration. This is, however, dependent on the derivation of the equations of motion and a more robust set of equations could be derived that encompass all phases of flight simultaneously. This would reduce the need for rederivations of equations for both phases and allow for seamless control integration.

Future Development

The current scope of this project is the reduced 3D descent and landing control of the Starship spacecraft within a Martian atmosphere. Another key aspect of missions that involve the Starship spacecraft is the recycling of the Super Heavy first stage within the Earth atmosphere. A 3D control simulation of the booster descent and landing at the launch site is also a future development opportunity if time permits. Finally, it is natural that additional considerations, such as 3D behavior of control surfaces, higher-complexity body geometry, transonic flow phenomena, and multi-engine vectoring can be included to create a robust 3D control simulation.

References

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Milestones

1. Create animation of Starship in python.
    a. *Success:* Actuatable fins and the body's orientation can be changed.
2. Implement dynamics into the animation.
    a. *Success:* Body dynamics can be simulated, and the body responds as expected to initial conditions.
3. Implement forces and moments.
    a. *Success:* Body responds as expected to aerodynamic forces and moments. As well as gravitational forces.
4. Design controllers.
    a. This will likely take the form of full state feedback due to the number of control parameters in this simulation.
    b. *Success:* Distance down range and ending altitude are controlled effectively.
5. Run a full simulation:
    a. *Success:* The body starts at the initial condition and propagates down range under control until it reaches the desired end fight condition.
    b. For the Starship body, this means successfully making it through the previously stated stages of flight under control.

Deliverables

- Final Report detailing our derivations and assumptions.
- Final animation showing the body progress through the milestones under control.
- Complete Python code for the animation, dynamics, forces and moments, and controllers.
- Final presentation, detailing our process and the final result.