A Trajectory Generation and Tracking System for Reusable Launch Vehicles during TAEM

Luca De Filippis

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Outlook

1. Terminal Area Energy Management (TAEM)
2. Trajectory Generation and Tracking in TAEM phase
3. Simulations and Results
Gliding flight and Terminal Area Energy Management (TAEM)
The re-entry mission of a RLV is made of three main phases, derived from Shuttle missions:

• **Entry**

• **Terminal Area Energy Management (TAEM) phase**

• **Approach and Landing (A&L)**
When the Shuttle has dissipated almost the 95% of its total energy, a gliding phase called Terminal Area Energy Management (TAEM) starts. This phase is required to steer the aircraft toward the point where approach and landing begins.
Energy Corridor

During TAEM a re-entry corridor is defined that represents the total energy of the vehicle as a function of the ground track:

\[
\frac{E}{W} = h + \frac{q}{g \cdot \rho}; \quad q = \frac{1}{2} \rho V^2
\]
High Mach gliding

- Even if the most part of the energy had been dissipated when TAEM phase starts, vehicle speed is still approximately two times the speed of sound.

- Aerodynamics and flight performance in supersonic flight are completely different with respect to subsonic ones.

\[
Mach = \frac{V}{a} \approx 2
\]
The Lift to Drag Ratio

• Maximum lift to drag ratio is a function of the vehicle aerodynamic characteristics.
• Competition gliders have very high ratios due to their optimized aerodynamics (L/D ~ 50/1).
• A general aviation aircraft is designed to have sufficiently high L/D ~ 15/1.
• RLVs have better aerodynamic performance with respect to blunt bodies, but they still have very low lift to drag ratios.

\[
\begin{align*}
&\text{L/D (Mach = 2) } \sim 2/1 \\
&\text{L/D (Mach = 0.7) } \sim 5/1
\end{align*}
\]
Autonomous Flight

The Space Shuttle guidance technique relied on preloaded trajectories defined several months before the launch and requiring the evaluation of every possible mission scenario.

The task of GNC engineers working on RLVs is to improve the level of autonomy of these vehicles, during each phase of their mission.
Trajectory generation and tracking in TAEM phase
• The classic guidance system steers the vehicle as it travels through space and atmosphere along the desired path. If re-planning of the optimal trajectory is required during flight, the guidance system is devoted also to this task.

• Navigation is the process of extracting the vehicle current “condition” using sensors. The data coming from navigation are used to determine the error with respect to the desired “condition”.

• The control system acts on the actuators of the vehicle in order to change its attitude, according with the desired references coming from the guidance system.
GNC-system architecture
Trajectory Generator and Trajectory Tracker

Concept

Designing the Guidance System to:
• Generate the desired trajectory of the TAEM phase during flight.
• Generate the reference variables for the Control System to track the desired trajectory.

Objective

• Adapt the TAEM trajectory to the flight conditions encountered during re-entry.
• Compensate for disturbances acting on the vehicle and pulling it far from the desired trajectory.
Terminal Area Energy Management

1. Acquisition subphase
2. Heading alignment subphase
3. Prefinal approach subphase

Runway
Final approach plane

S-turn energy dissipation

$\vec{V}$
Approach & Landing

Dynamic pressure error:
\[ \Delta q < 24 \text{ PSF} \]
\[ \Delta Y < 4 \text{ deg} \]

Glide slope error:
\[ \pm 1000 \text{ ft} \]
error about steep glide slope

TAEM/AV switching point
\[ \Delta q = 24 \text{ PSF} \]
\[ \Delta H = \pm 50 \text{ ft} \]
\[ \Delta Y = \pm 0.5 \text{ DEG} \]

Final switching point
Altitude 5000 ft

Steep glide slope
\( (Y = 19 \text{ deg}) \)

Flare through rollout

Approach and landing

Trajectory capture

Altitude above 10,000 ft

Heading alignment circle

TAEM prefinal approach
Horizontal Plane

- **TEP**: TAEM Entry Point
- **ALI**: Approach and Landing Interface

- **Down-track**: distance between TEP and ALI, along the runway axis.
- **Cross-track**: distance between TEP and ALI, normal to the runway axis.
- **Relative Heading**: orientation of the vehicle with respect to the runway axis.
- **Sideslip**: angle between the wing plane and the horizontal plane
Vertical Plane

• **TEP**: TAEM Entry Point
• **ALI**: Approach and Landing Interface

• **Altitude**: altitude of the vehicle with respect to the ground.
• **Flight path angle** (\(\gamma\)): angle between the vehicle trajectory and the horizontal plane.
• **Speed**: vehicle speed with respect to the ground.
The energy corridor concept is used to provide a reference dynamic pressure profile for a given initial altitude, speed and an estimated range.

The maximum bank angle is evaluated assuming constant turn at maximum load factor.
• **Dynamic Pressure Profile:** it is extracted from the energy corridor according with the initial conditions.

• **Maximum Bank:** it is estimated with respect to the dynamic pressure profile.

• **Ground Track Generator:** it calculates the ground track to connect TEP and ALI.

• **Trajectory Propagator:** it propagates the trajectory to meet the dynamic constraints.
Trajectory Tracker Architecture

- **Desired Dynamics**: it is a model of the vehicle dynamics.
- **Dynamic Inversion**: it is needed to extract from the desired dynamics the commands that allow to follow that dynamics.
- **Aerodynamic Model**: it is a model of the aerodynamic forces acting on the vehicle.

**References**: they are the reference variables provided to the control system to control vehicle attitude.
Simulations and Results
Simulations

• A wide range of simulations during the design, implementation and integration of the guidance system was performed.

• The guidance block has been tested in a complex 3DoF simulator that includes an accurate model of the vehicle dynamics and of the atmosphere.

• The integration of the trajectory generator with the trajectory tracker and the simulation of the closed-loop guidance, allowed to improve significantly the two systems.
Simulations from different TEPs

![Graph showing simulations from different TEPs]
Simulations from different TEPs
Simulations from different TEPs
Introduction of constant speed-break deflection in the trajectory generator
Introduction of constant speed-break
Introduction of constant speed-break
Multiple runs of the trajectory generator during flight
Multiple runs of the trajectory generator
Multiple runs of the trajectory generator
Multiple runs of the trajectory generator
Thank you