Steering thrust: gimbals, actuators, and thrust vector control

Version PDF de travail - contenu du cours HTML canonique

Course compass

Guiding question : How can a vehicle redirect enormous thrust without using the whole rocket as a rudder?

Evidence tags : MEASURED · CONVENTION · CALCULATED · LEARNING ASSUMPTION · MISSION DATA · MANUFACTURER DATA · APPROXIMATION

Objectives :

• define TVC and gimbal

• connect thrust angle to torque

• understand actuator roles

• compare hydraulic and electromechanical actuation

• identify gimbal structural loads

Essential answer

Steering thrust: gimbals, actuators, and thrust vector control. The question to solve is: How can a vehicle redirect enormous thrust without using the whole rocket as a rudder? Evidence tags : MEASURED · CONVENTION · CALCULATED · LEARNING ASSUMPTION · MISSION DATA · MANUFACTURER DATA · APPROXIMATION Objectives : define TVC and gimbal connect thrust angle to torque understand actuator roles compare hydraulic and electromechanical actuation identify gimbal structural loads? When the thrust line no longer passes through the center of mass, it creates torque that rotates the vehicle. The rest of the course turns that idea into an auditable line of reasoning: explicit units, stated assumptions, reproducible calculations, order-of-magnitude checks and interpretation limits. A result is useful only when the reader can explain what it measures, where every input came from and which engineering decision it can support.

Starting synthesis: derivations, examples, limitations and sources are developed in the course body.

Key terms before you start

thrust · gimbal · unit · assumption · approximation

1 — TVC: control the thrust vector direction

TVC means Thrust Vector Control. Instead of changing only force magnitude, the system changes its direction slightly.

When the thrust line no longer passes through the center of mass, it creates torque that rotates the vehicle.

2 — Why a few degrees can be enough

Engine force is enormous and the lever arm to the center of mass can be several meters. A small lateral component can therefore create a large moment.

In a simple model the lateral component is about $F \cdot \sin(\delta)$, where δ is gimbal angle. For small angles $\sin(\delta)$ is small, but F can be huge.

3 — Learning torque example

LEARNING ASSUMPTION: $F = 1{,}000$ kN, $\delta = 2°$, effective lever arm $r = 15$ m. $\sin(2°)$ 0.0349. Lateral force 1,000,000 × 0.0349 = 34,900 N.

Simplified moment τ $r \times F_{lat}$ = 15 × 34,900 523,500 N·m. This demonstrates sensitivity; it is not a real launcher load model.

4 — What physically moves the engine?

An actuator converts command into mechanical motion. Energy may be hydraulic or electromechanical. ESA describes Vulcain hardware where small torque motors control hydraulic valves, then fluid moves the much larger engine.

The system must both move and hold the engine against thrust loads, acceleration, structural bending, and gimbal friction.

5 — Two axes: pitch and yaw

Two actuators in different directions allow rotation about two axes. NASA documents SLS architectures using actuators and a gimbal block/bearing.

Control must also coordinate multiple engines; moving every engine identically is not always optimal on multi-engine vehicles.

6 — Why the real problem requires a 3D model

Actuator load depends on real geometry, angle, pivot position, friction, and dynamic forces. NASA publishes modern 3D TVC load-prediction methods.

The course equation shows the principle; certification requires complete mechanical models and loaded testing.

7 — Turning a small engine angle into vehicle rotation

Gimbaling an engine does not instantly rotate the whole rocket. Thrust creates a moment about the center of mass; that moment creates angular acceleration; attitude begins to change; sensors measure that change; then command changes again. There is a time chain from command to mechanical action to vehicle response.

This is why a simple arrow diagram is useful for intuition but not enough for control. Mass, moment of inertia, engine location, structural flexibility and actuator speed all change the response. Thrust-vector control is a dynamics problem, not merely a geometry problem.

8 — Actuator saturation matters as much as the control law

Software can ask for a correction that mechanics cannot provide: too much angle, too much rate or too much load. This is saturation. A sound control design must know those limits instead of assuming an ideal actuator.

Mechanics, electronics and software must therefore be designed together. A brilliant guidance equation is useless if it requires impossible motion. Oversizing the actuator also adds mass, power and complexity. The compromise has to be closed at system level.

Exercises and answers

Component

$F = 500$ kN and $\sin \delta = 0.02$. Simplified lateral component?

Torque

10,000 N with an 8 m lever arm.

Limit

Why does torque not directly give vehicle rotation angle?

Primary and technical sources

• NASA Glenn — Rocket Control

• NASA NTRS — Considerations for TVC in-flight load predictions

• NASA NTRS — SLS core-stage thrust vector control performance

• ESA — Ariane 5 Vulcain engine

• ESA — Low Liquid Thrust Vector Actuation System for Ariane 6