almatech

SPACE & NAVAL ENGINEERING

THRUST VECTOR CONTROL SYSTEM

FOR SOLID PROPELLANT DE-ORBIT MOTORS

ESA Contract No. 4000112746/14/NL/KML

MECHANISMS WORKSHOP & FINAL PRESENTATION DAYS

15 FEBRUARY 2019

almatech

SPACE & NAVAL ENGINEERING

Almatech is a Swiss space engineering company with established expertise in four main fields

Integrated Systems | Ultra-stable structures | High precision mechanisms | Thermal hardware

PRESENTATION OUTLINE

1. Project Objectives

2. Summary of work package main outcomes
- Requirements and selection criteria definition (WP 2)
- Mechanism Trade-off and Concept definition (WP 3)
- Flex-Gimbal Mechanism architecture trade-off and study (WP N10)
- Consolidation of preliminary design of the Flex-Gimbal concept (WP N11)
- Sizing, motorization and structural analysis of consolidated Flex-Gimbal concept (WP N12)
- Design and development plan (WP N13)

3. Conclusion

PROJECT OBJECTIVES

- Almatech was selected for the ESA Clean Space initiative to investigate and design a Thrust Vector Control (TVC) mechanism as part of the Solid Propellant Autonomous Deorbit System (SPADES).
- almatech is Prime with 2 Italian partners:

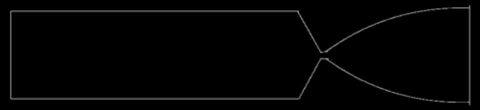
D-ORBIT SITAEL

- **The objective of the activity** was to
  - identify vectoring solutions;
  - trade-off vectoring concepts;
  - carry out detailed design on the chosen concept.

TRP UNDER CLEAN SPACE INITIATIVE

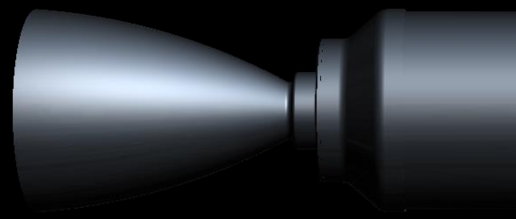
WP 2: BASELINE SCENARIO AND VECTORING REQUIREMENTS

- **Large spacecraft** ~ 1500 kg
- **LEO** ~ 800 km altitude
- **Rocket motor clustering**
- **Rocket motor thrust level** – 3 classes, nominal 250 N
- **Long burn-time** ~ 4.75 min, cigarette burning
- **Bell shaped nozzle**
- **High expansion ratio** ~ 450



$$Expansion\ ratio = \frac{Area_{exit}}{Area_{throat}}$$

Nominal SRM thrust level	250 N ± 20%.
Thrust deflection target performance (pitch, yaw)	±5°
Thrust deflection rate target performance	±10°/s
In-orbit non-operational lifetime	15 years



WP 2: MAIN DESIGN DRIVERS

Compactness

- low mass, volume
- low encumbrance for clustering

Performance

- thrust deflection angle > +/-5 deg
- thrust deflection rate > 10 deg/s

Cost-effectiveness

- minimized complexity
- standardized components and processes, commonality of components
- manufacturing and assembly reproducibility

Reliability

- non-operational lifetime of 15 years in-orbit
- long SRM burn time

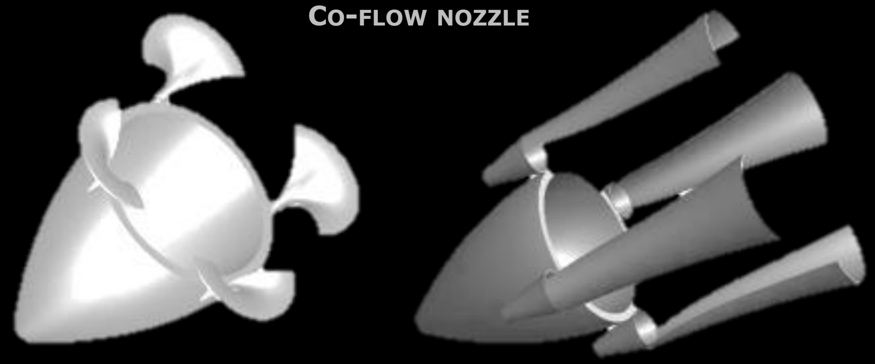
Integration

- interfaces
- ease of access and installation
- safety/late access for SRM
- AIT activities
- cleanliness

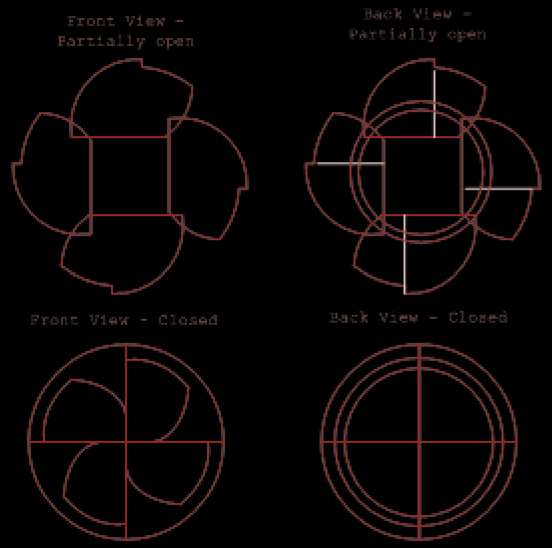
WP 3: DESIGN EVOLUTION – CONCEPT GENERATION

- TVC system
  - Moveable platform
  - Moveable SRM
    - **Gimbal**
    - Hinges
    - **Wedge mechanism**
    - **Other**
  - Moveable nozzle
    - Flexible seal
    - Ball and socket joint
  - Fixed platform and nozzle
    - Secondary injection (liquid gas)
      - **Co-flow**
      - Shock vector control
      - Throat shifting
      - Dual throat nozzle
    - Mechanical deflection
      - **Vanes**
      - **Tabs/paddles**
      - Jetevator
      - Variable geometry nozzle (segmented nozzle/petal/iris)
      - **Flaps**
    - Other
      - **Flow spill**
      - Hybrid methods

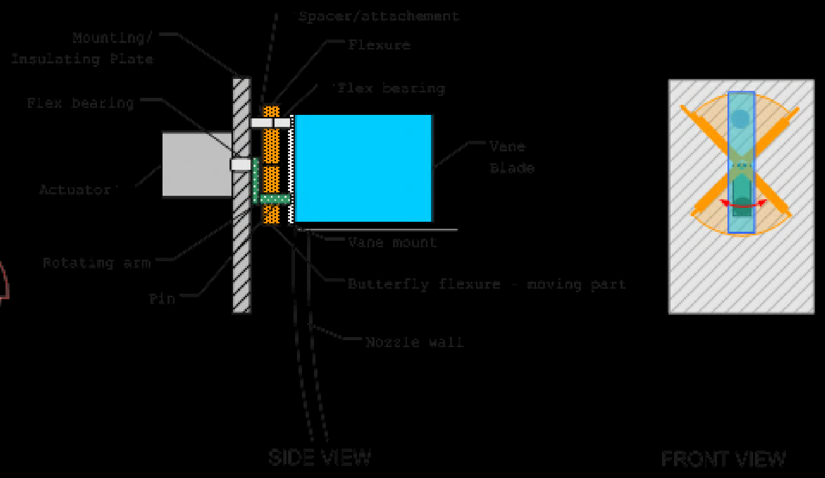
CO-FLOW NOZZLE



JET TAB IRIS MECHANISM



JET VANE MECHANISM

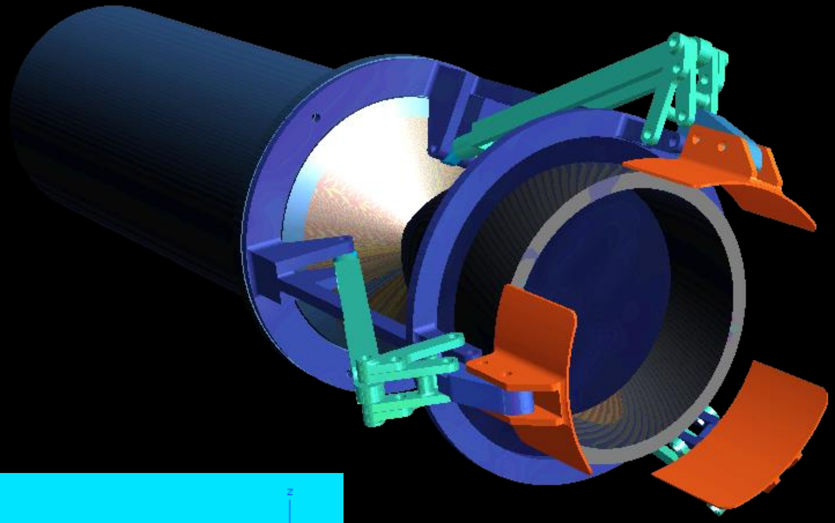


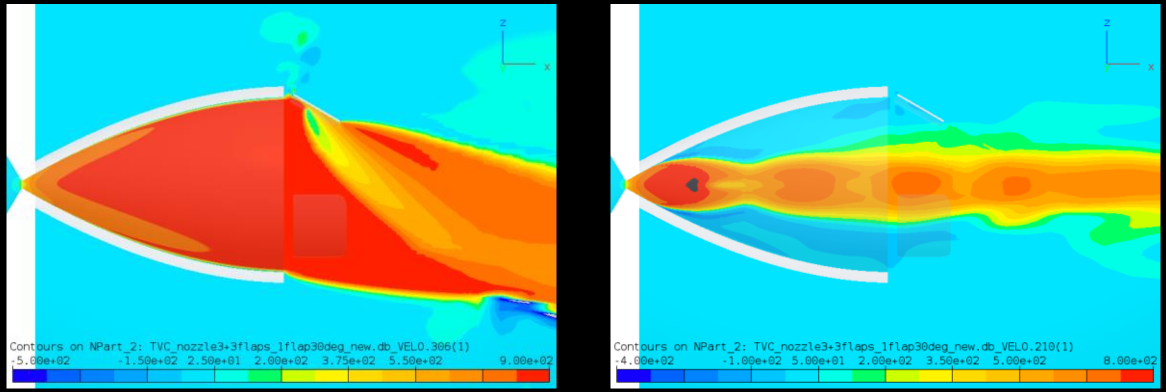
almatech

WP 3: DESIGN EVOLUTION – INITIAL TRADEOFF CHOSEN CONCEPT

- Compliant linkage mechanism
- Good performance characteristics
- Protected from environment
- No need for high temperature sealing
- Mechanism jamming risks greatly reduced
- Challenging testing and development

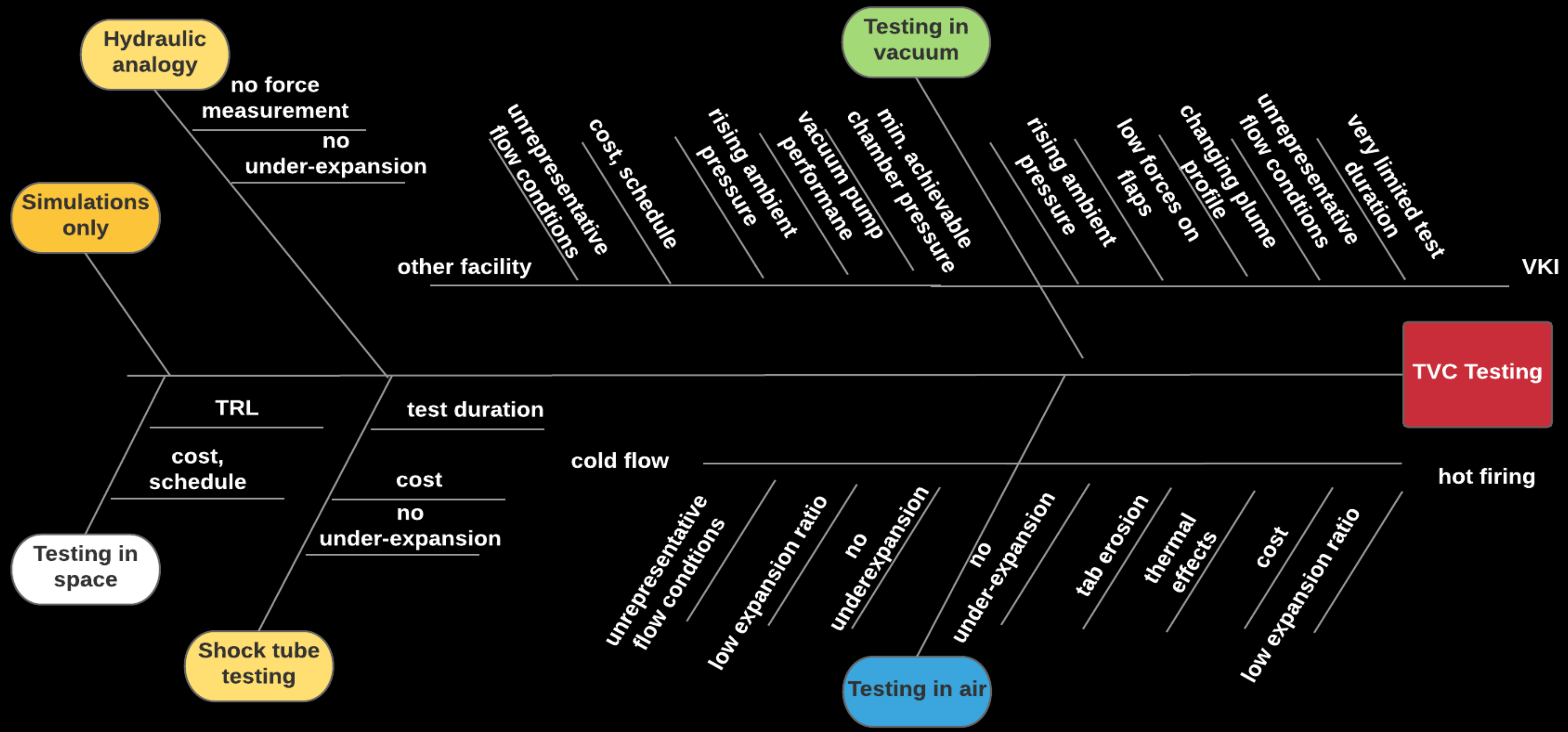
JET FLAP MECHANISM





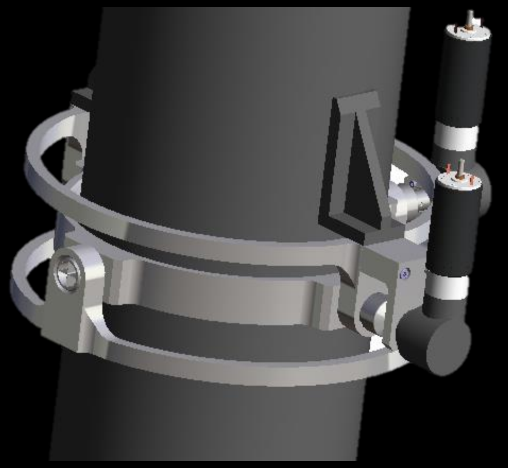
FLOW VELOCITY PROFILE AT 30 DEG FLAP DEFLECTION
MODEL WITH 65 PA AND 6500 PA AMBIENT PRESSURE

WP 3: DESIGN EVOLUTION – CHALLENGES OF TESTING



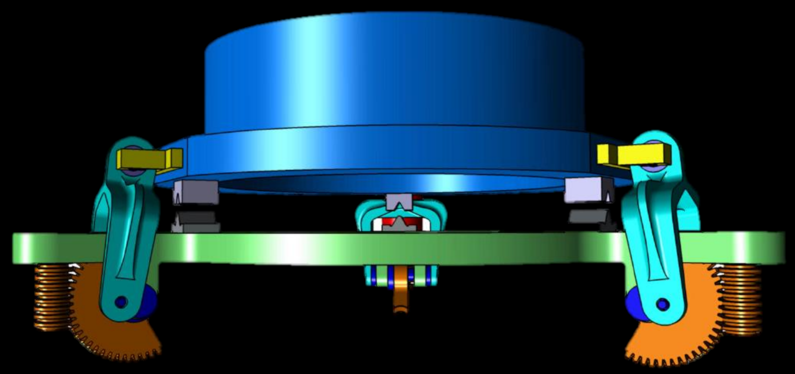
almatech

WP 3: DESIGN EVOLUTION – MECHANICAL SYSTEM CONCEPT GENERATION



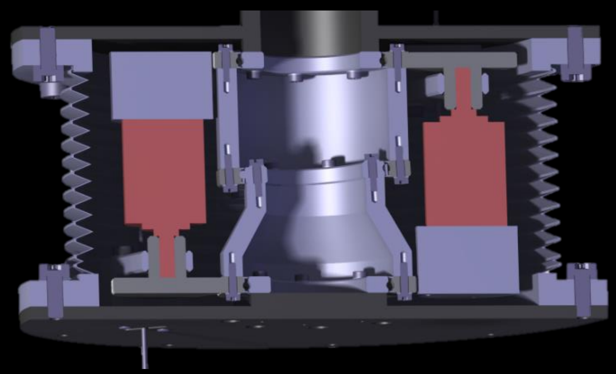
Flex-Gimbal Mechanism

with conventional geared stepper motors.



A-frame mechanism

a novel solution that encompasses redundancy and launch lock function.



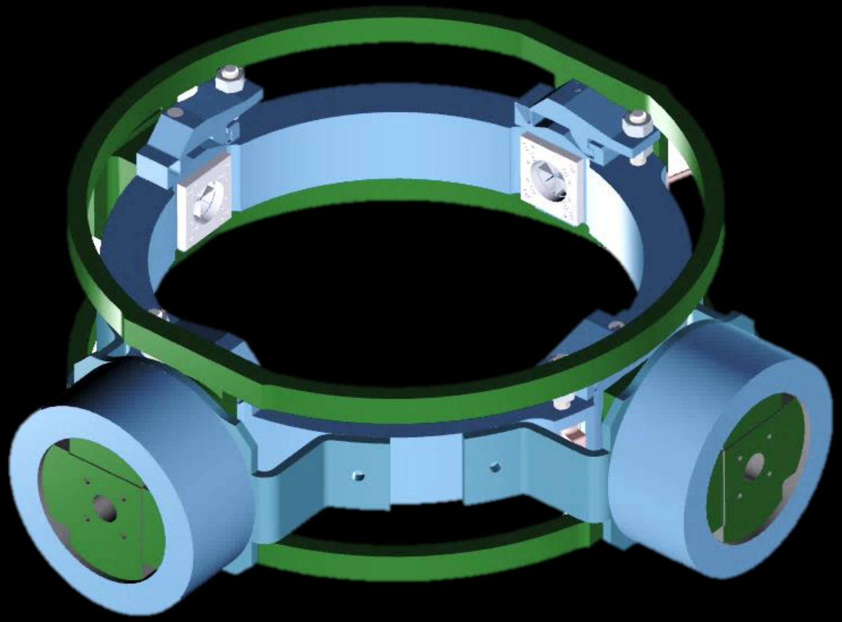
Wedge mechanism

with protected actuators; sized for vectoring loads only.

WP 3: DESIGN EVOLUTION – CHOSEN MECHANICAL CONCEPT

- Gimbaling is achieved with the help of **flexure pivots**.
- Pivots are **directly driven** by two limited angle torque motors.
- The SRM is mounted within an **annular interface ring**.
- This ring is actuated by motor and connected to the **middle stage mobile ring** by two flexure pivots 180° apart.
- The middle stage ring is connected to an **identical interface ring** at the spacecraft side through another set of pivots.

FRICTIONLESS FLEX-GIMBAL MECHANISM



WP 3: FRICTIONLESS FLEX-GIMBAL MECHANISM ADVANTAGES

Performance

- Expandable performance without major redesign.

Design and Development

- Representative accelerated life testing possible.
- Straight-forward analysis of motorization behavior
- Possibility to test with dummy SRM (safety, parallel TVC-SRM development)

Cost

- Low mechanical complexity
- Commonality of components
- No need of expensive /exotic materials or processes

Assembly complexity

- Low assembly complexity
- Simple interface provisions

Life / Reliability

- Number of active components is low
- Fully frictionless mechanism with maximized reliability
- Integrated launch lock solution

Reliability and low-cost driven

WP 3: FRICTIONLESS FLEX-GIMBAL MECHANISM PIVOTS (1)

Custom flexure pivots (patent pending) allow for sizing the mechanism for minimal rotational stiffness, lower actuation torque and larger rotational angle capability than commercial options.

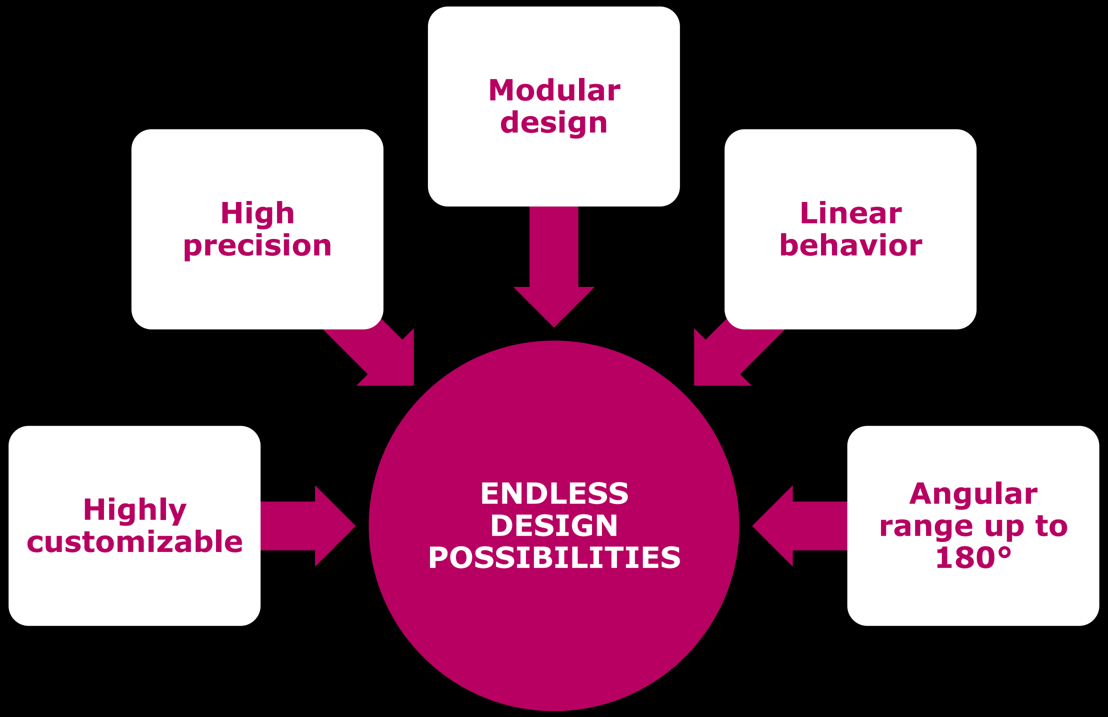
Custom flexure pivot advantages and benefits

- Robustness to environmental conditions
- No wear, and lubricant-free
- Reliable and predictable performance
- Integrated movement limiters to ensure flexure protection during assembly and integration.

WP 3: FRICTIONLESS FLEX-GIMBAL MECHANISM PIVOTS (2)

In-house optimization for

- Angular range
- Stiffness' (independently tunable axial and radial stiffness)
- Encumbrance
- Interface (inside/outside/through-hole)
- Material
- Configuration (no. of stages, blades)



Global optimizer implementation with analytical models and integrated FE modeling and verification

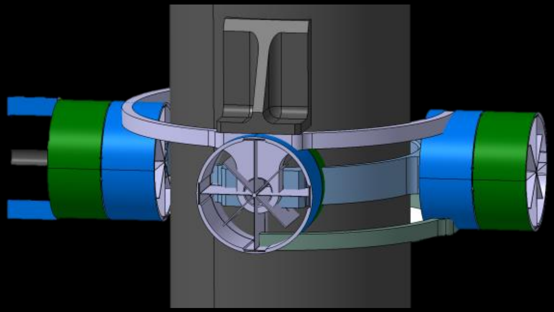
WP 3: FRICTIONLESS FLEX-GIMBAL MECHANISM IN LAUNCH ENVIRONMENT

Two possible scenarios

Flexures designed to withstand launch loads

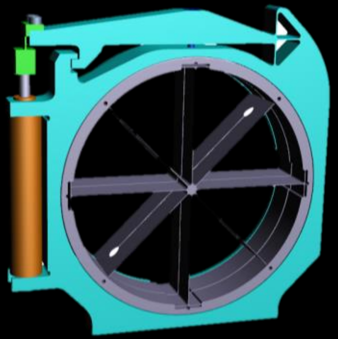
- Pivots sized for launch loads
- Performance significantly better than COTS with similar radial stiffness
- Encumbrance limitation

PIVOTS SIZED TO WITHSTAND LAUNCH LOADS

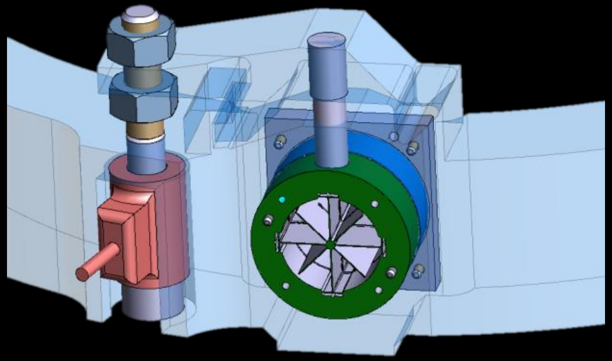


Integrated launch lock solution

- Pivots sized for operational and handling loads
- Integrated launch lock principle
- COTS actuators



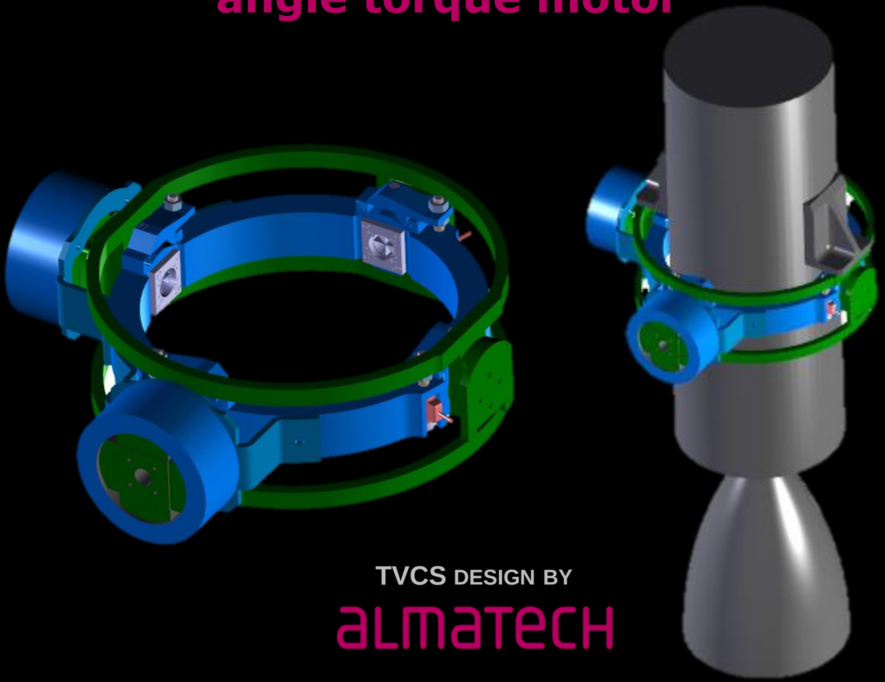
PIVOTS WITH INTEGRATED LAUNCH LOCK



WP N10-N12: DETAILED DESIGN - FRICTIONLESS FLEX-GIMBAL MECHANISM

Almatech Mechanism concept underwent critical review and detailed design by SITAEL.

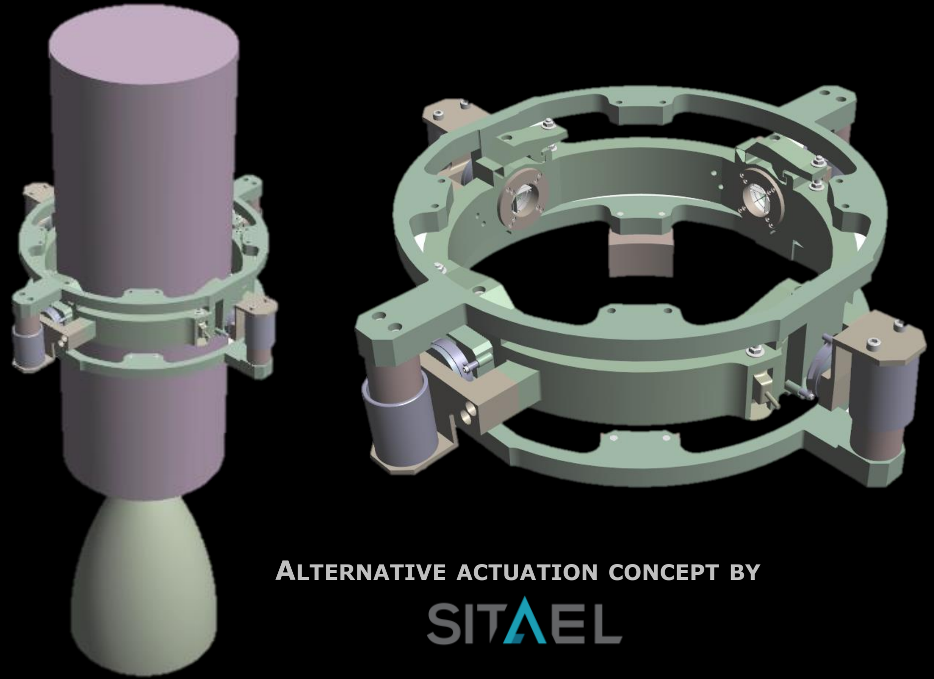
Frictionless flex-gimbal mechanism with limited angle torque motor



TVCS DESIGN BY almatech

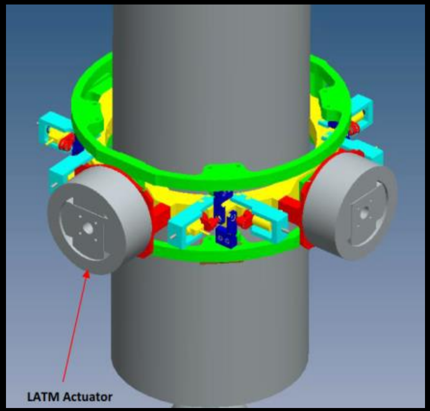
- ✓ **Direct drive**
- ✓ **Frictionless**
- ✓ **Simple control logic**

Frictionless flex-gimbal mechanism with custom voicecoil actuators



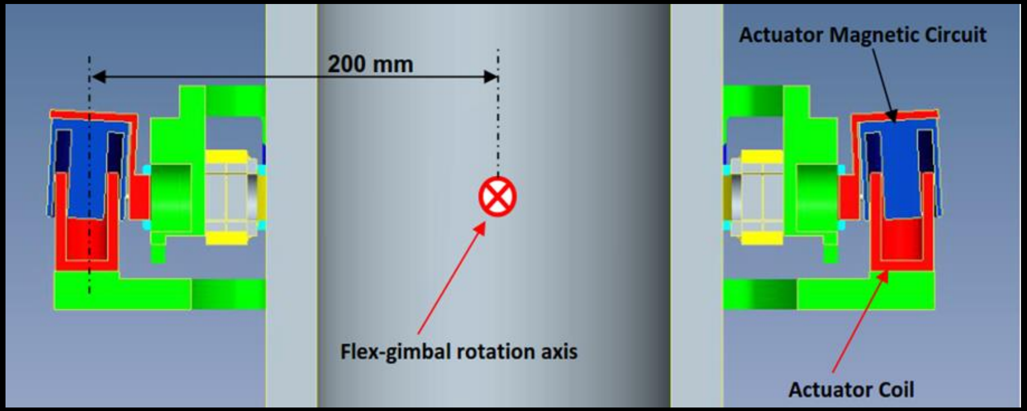
ALTERNATIVE ACTUATION CONCEPT BY SITAEL

WP N10: ARCHITECTURE TRADE-OFF – ACTUATOR CONFIGURATION



Single limited angle torque motor per axis

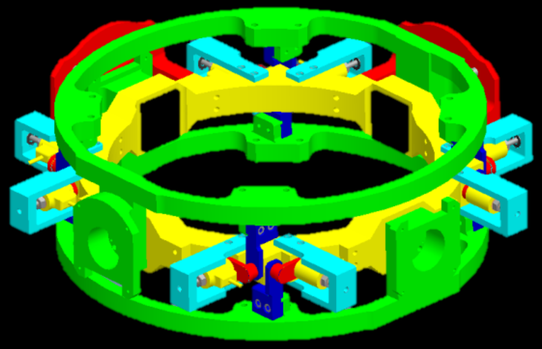
- Simplicity
- High mass
- Redundancy has to be implemented with dual wiring
- Limited actuator availability



Dual voice coil per axis

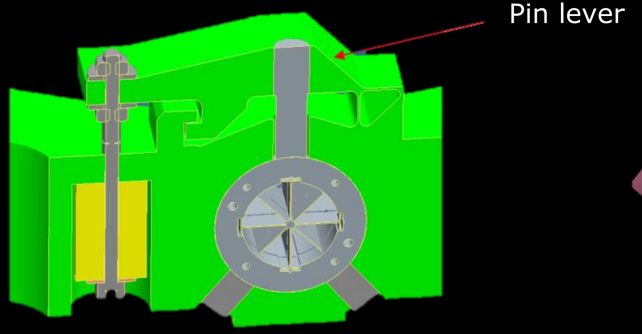
- Low mass
- Low power
- Redundancy
- Relatively high overall encumbrance

WP N10: ARCHITECTURE TRADE-OFF - LAUNCH LOCK



Ring locking

- Can generate more locking torque than the other solution
- Doubles the number of actuators required
- Higher mass
- Higher encumbrance
- More harnessing



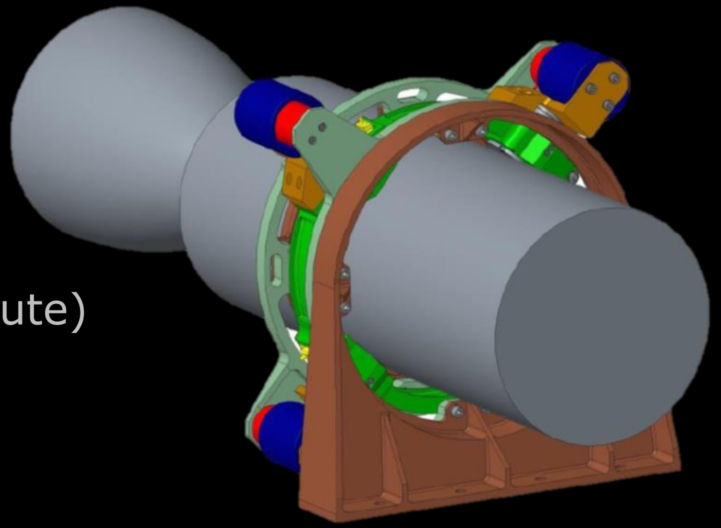
Pivot locking

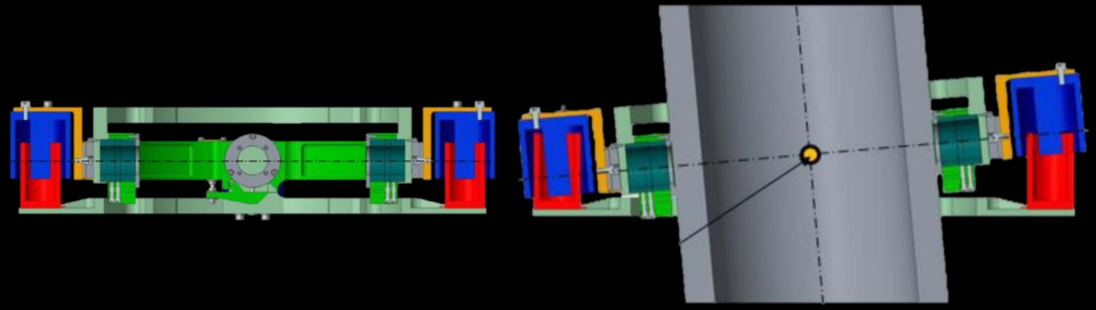
- Compact, integrated locking feature
- Internal design flexibility is low

WP N11: PRELIMINARY DESIGN CONSOLIDATION

Selected mechanism architecture

- Driven by 4 linear voice-coil actuators
- 4 custom flexure pivots
- Integrated launch lock feature (pivot locking)
- Contactless rotary encoders (1 per axis; induction-based, absolute)
- Mass: 8kg (non-optimized; without spacecraft interface)

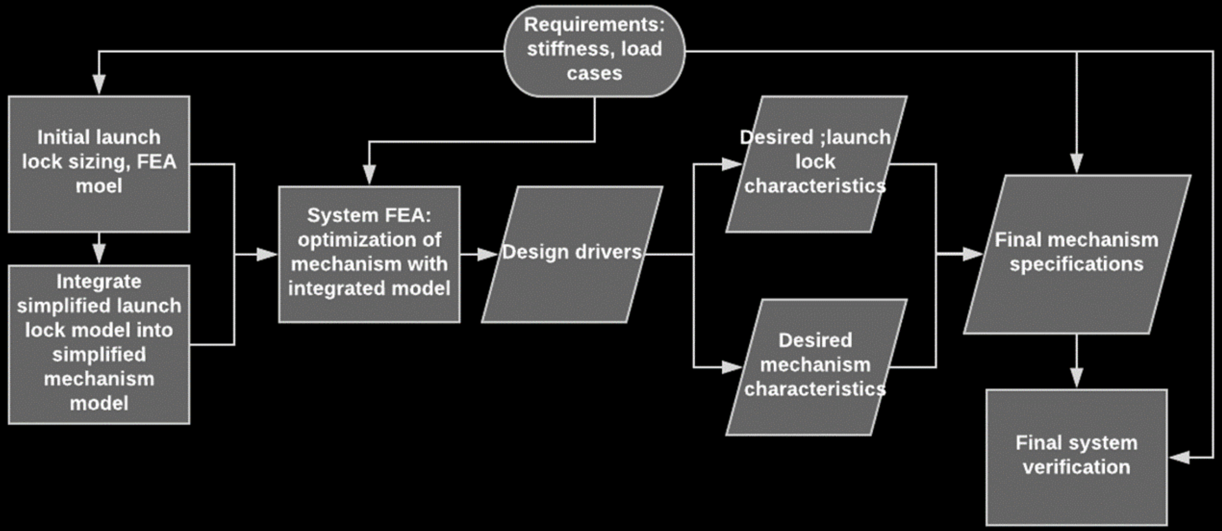




WP N11: PRELIMINARY ANALYSIS – STRUCTURAL (1)

Launch configuration stiffness

- Requirements
  - First eigenfrequency with SRM > 50Hz
  - First eigenfrequency without SRM > 140Hz
- Design iterations were carried out to assess feasibility of compliance by
  - Stiffening of the gimbal rings
  - Material updates
  - Updated launch lock design



PROPOSED OPTIMIZATION APPROACH FOR NEXT DESIGN PHASE

WP N11: PRELIMINARY ANALYSIS – STRUCTURAL (2)

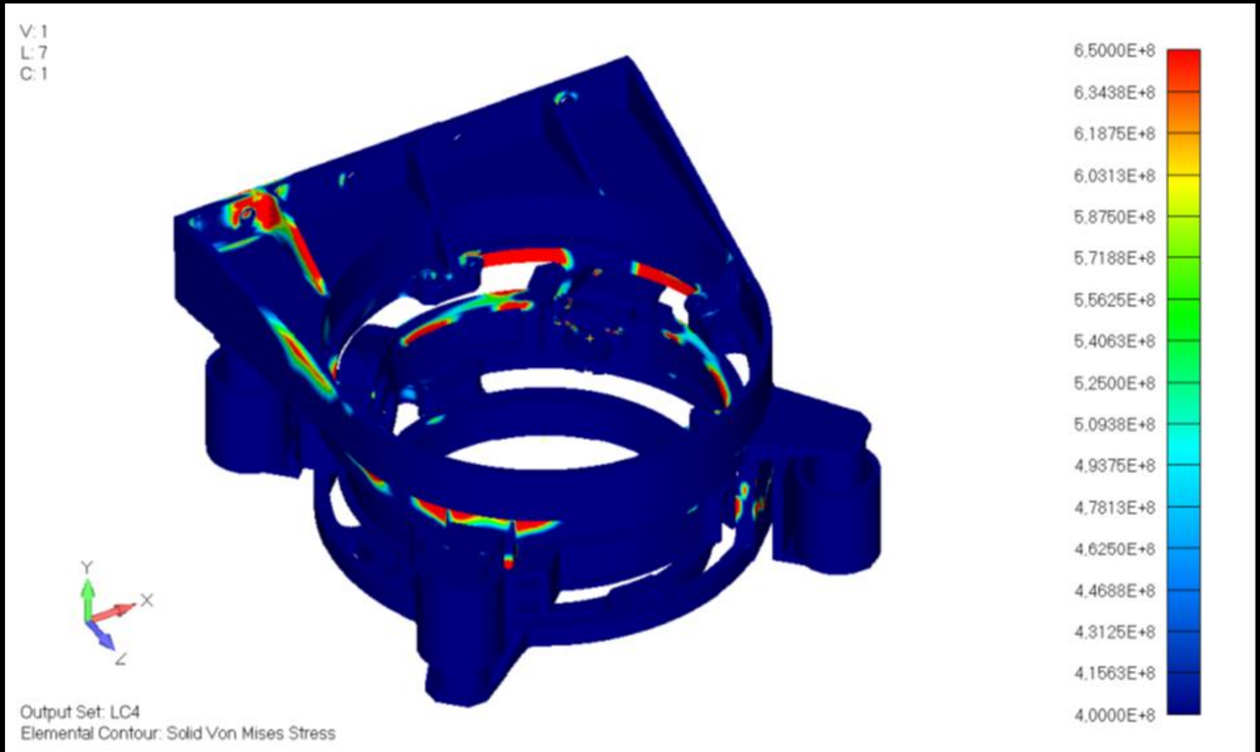
In-orbit stiffness

- Requirement:
  - In-orbit non-operational stiffness >2Hz
- Operational considerations:
  - Launch locks are to be disabled during early spacecraft operations
  - Low mechanism first eigen-frequency (~0.5Hz) due to low rotational stiffness of pivots
  - Immobilization of the mechanism during the in-orbit non-operational lifetime is needed
- Solutions using magnetic and electromagnetic fields have been explored.
- Three possible immobilizing solutions are have been considered:
  - Passive magnetic balance
  - Power-off electromagnetic brake
  - Electro-permanent magnets – baseline solution

WP N11: PRELIMINARY ANALYSIS – STRUCTURAL (3)

Load case

- Preliminary load case: 37g quasi-static
- Local stress concentrations observed, compliance deviations can be brought to compliance with reasonable design enhancements during the following phase.



THRUST VECTOR CONTROL SYSTEM FOR SOLID PROPELLANT DE-ORBIT MOTORS

WP N13: FUTURE DEVELOPMENT ACTIVITIES

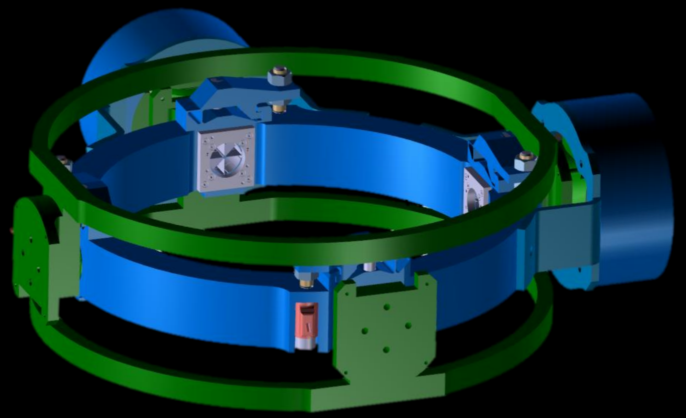
Breadboarding + Engineering model development < 2 years

- **TRL3** Mechanism detailed design and breadboard
- TVC Mechanism Engineering Model
- TVC Commanding Electronics
- TVC control system and related software
- TVC System Engineering and AIV activities **TRL6**

FRICTIONLESS FLEX-GIMBAL MECHANISM - SUMMARY

The **fully frictionless flex-gimbal vectoring mechanism with novel customized flexible pivots was selected** for its relative simplicity, good performance, high reliability, cost-effectiveness, ease of testing without safety concerns.

- Contactless solutions
- Direct drive
- Low number of active components
- Analysis of motorization behaviour is straight-forward
- Integrated launch lock



Nominal vectoring performance	
Deflection angle	± 5 degrees
Deflection rate	10 deg/s
Nominal thrust level	250 N ±20%
Thrust misalignment tolerance	±0.1 deg

We would like to thank

ESA and especially the project Technical Officer, Adam Tvaruzka, for his outstanding support and flexibility.

Anett Krammer
Aerospace Engineer
Tel: +41 21 555 3102
anett.krammer@almatech.ch

Dr Fabrice Rottmeier
Head of Business Development
Tel: +41 21 555 3002
fabrice.rottmeier@almatech.ch

Almatech
EPFL-Innovation Park
Bâtiment D
1015 Lausanne
Switzerland

www.almatech.ch