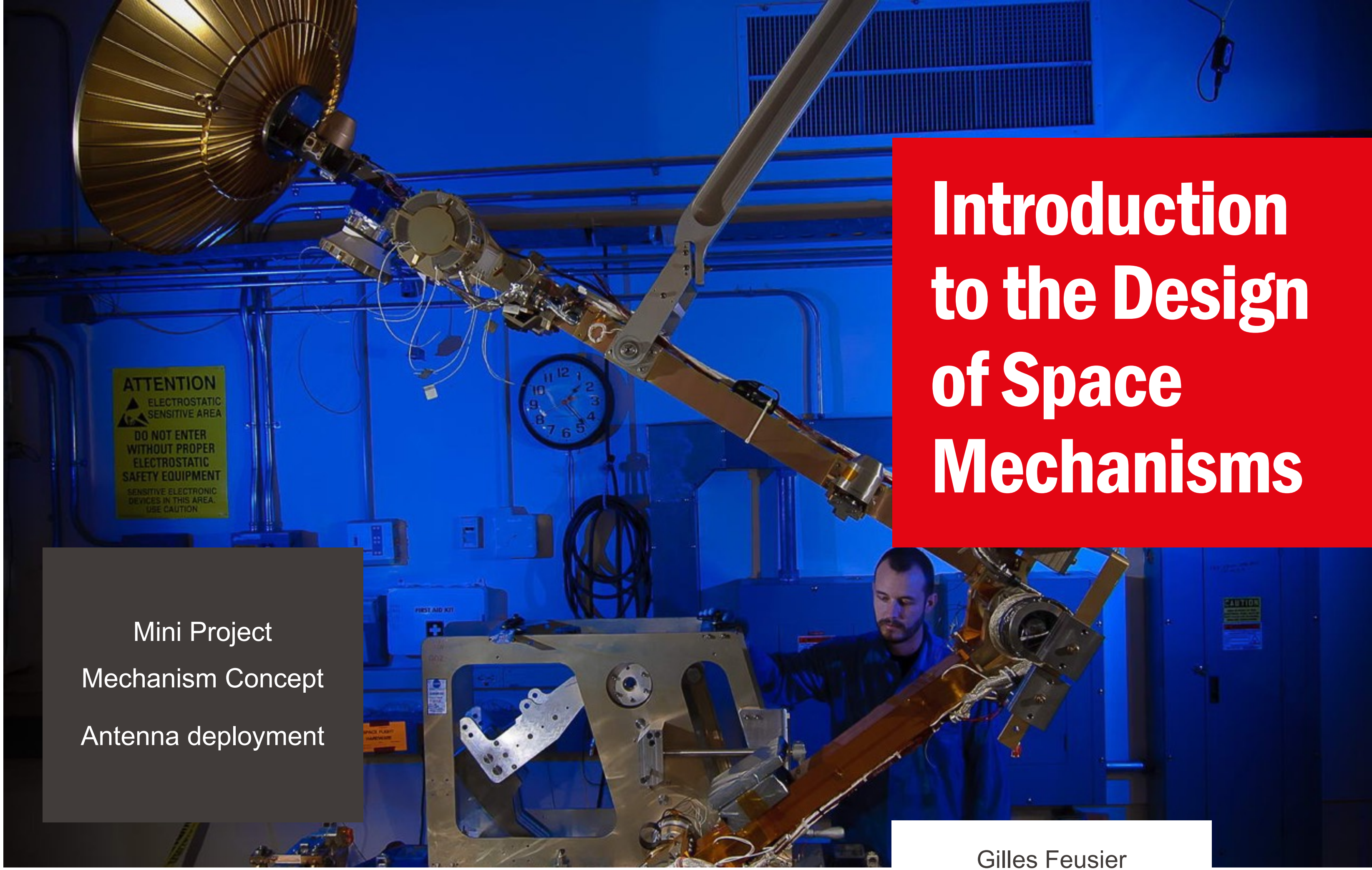
Introduction to the Design of Space Mechanisms

Mini Project

Mechanism Concept

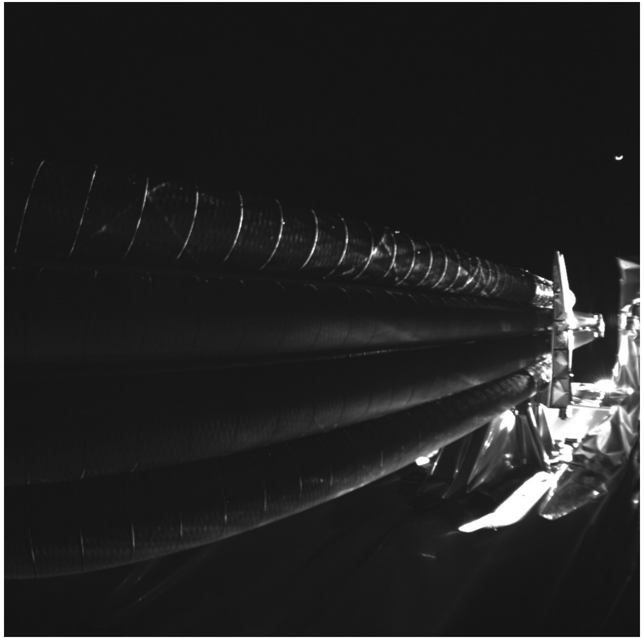
Antenna deployment



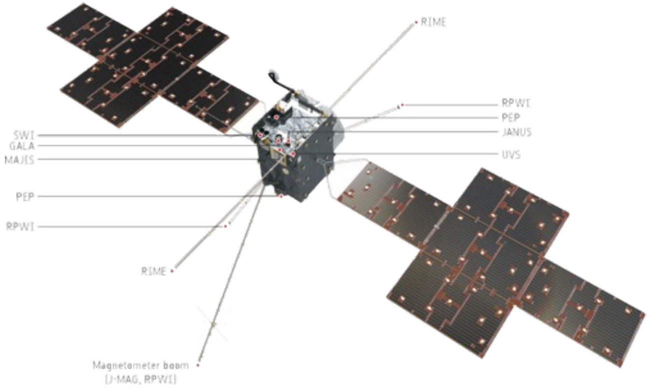
Gilles Feusier

ESA’s JUICE (Jupiter Icy Moons Explorer) - issue

Radar for Icy Moons Exploration (RIME)



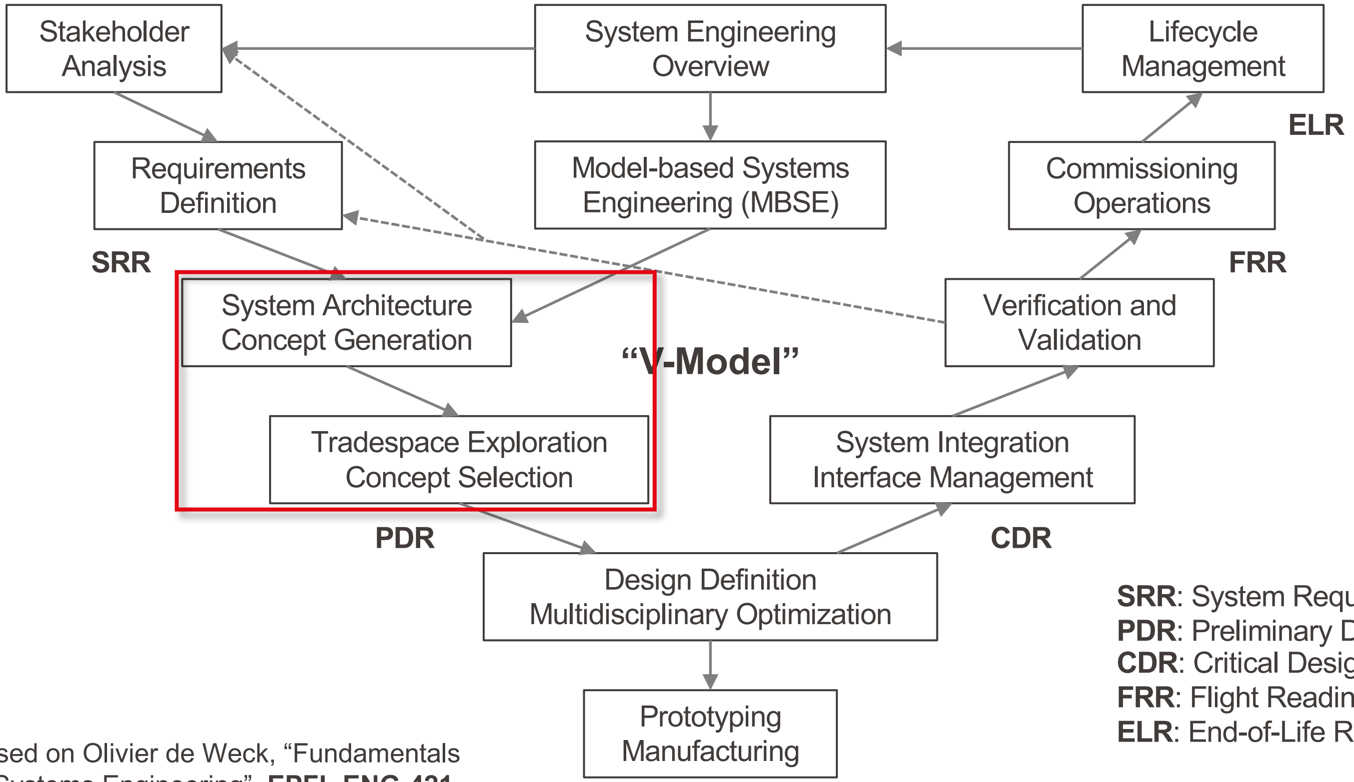
Source: ESA



Source: ESA/ATG medialab

- **17 April 2023** (three days after the launch): deployment begins
- **12 May 2023**: RIME antenna breaks free

The "V-Model" of Systems Engineering



SRR: System Requirements Review
PDR: Preliminary Design Review
CDR: Critical Design Review
FRR: Flight Readiness Review
ELR: End-of-Life Review

Based on Olivier de Weck, "Fundamentals of Systems Engineering", **EPFL ENG-421**

Note: reviews acc. to ECSS-M-ST-10C Rev. 1

Main Functions

[4.2.3] Mechanical Interfaces

Attach the payload (boom and antenna) to the S/C

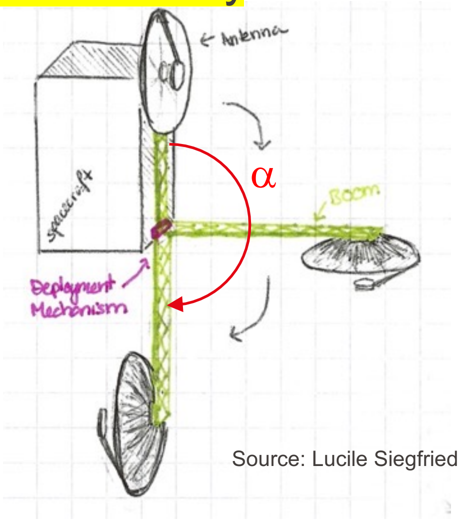
[4.1.1.1] Deployment function

The mechanism shall deploy an antenna (cf. Figure 1) from its stowed launch configuration to its deployed configuration

[4.1.1.2] The mechanism shall have one degree of freedom only.

[4.2.4.1] Angular Range of the Deployment

The angular range of the deployment performed by the mechanism shall be [0°;180°] (angle α on Figure 1)



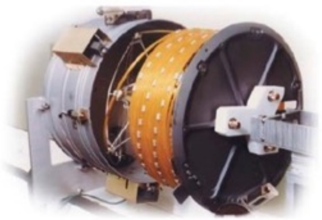
Source: Lucile Siegfried

- **Other functions**

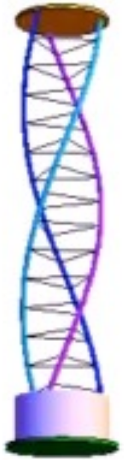
[4.1.1.3] Position measurement function

[4.1.1.4] Position holding function

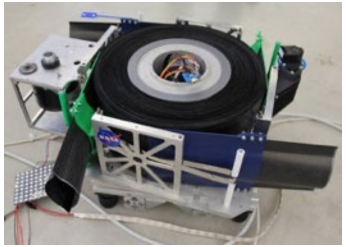
Other possible architecture (not compliant to req.)



Source: N. Grumman, AstroMast Data-Sheets DS307 and DS407, 2010



Source: Sándor Kabai & Szaniszló Bérczi/
Wolfram Demonstration Project



Source: NASA/DLR

Critical Requirements (acc. to G. Feusier)

- [4.2.3.7] Allowed Volume
- [4.2.3.11] Mass
- [4.2.4.5] Angular Position Holding (not powered)
- [4.2.4.7] Telemetry
- [4.2.7.1] Reliability
- [4.2.9.3] Passive Holding redundancy

Ambiguous/Missing

- [4.2.4.1], [4.2.4.5] Deployment angle: any angular position or fixed angle?
- Missing: accuracy of deployment angle (α). Only telemetry is specified.
- [4.1.2.3] Reversibility: in-orbit?
- Cable harness to antenna: missing

Environmental Requirements

Severe, but quite standard:

- [4.3.1.6] Shocks (… 100g/1300Hz, 700g/2000Hz, …)
- [4.3.1.4] Random vibrations (23.4g_{rms})
- [4.3.2.11] Space thermal environment (qualification: +90 to -30°C)

Other requirements are considered to be standard, including radiation and cleanliness requirements, …

Main Functions

- I/F
  - Fixed to S/C structure
  - Boom with antenna fixed to the mechanism
  - Electrical harness to antenna: TBD
- Environment
  - Withstand launch loads
  - …
- Operations
  - Non-operational: Stowed (**secured**) position during storage, launch…
  - Operational: deployment within defined constrains (speed, acceleration, range) => **rotation**
  - Passive: **maintain** the defined (pos. TBD) position during antenna operations
- Telemetry
  - Angular position

Selection of Components

- Rotation = 180°

- Position holding (passive, redundant)

- Telemetry

- Structure

Selection of Components

- Rotation = 180°
  - Ball-bearing
- Rotation
  - Actuator: TBD(*)
- Position holding
  - Latch and end stops?
  - Brake?
  - Nothing else?

Selected concept depends on deployment angle and reversibility

- Telemetry
  - Angular encoder
  - Micro-switches (TBC (*)): status monitoring
- Structure

(*) *TBD: To Be Defined, TBC: To Be confirmed*

Deployment performances

- Range: [0;180]° [4.2.4.1]
- Maximum rate: 6°/s [4.2.4.2]
- Maximum acceleration: 1 rad/s^2 [4.2.4.4]
- Maximum duration: 40s [4.2.4.3]

$$\alpha(t) = \alpha_0 + \omega t + \frac{1}{2} x\dot{\omega} t^2$$

  - *Acceleration phase*: $\dot{\omega}_{init} > 0$
  - *Constant speed phase (if any)*: $\dot{\omega} = 0$, $\omega = \omega_{constant}$
  - …
  - *Deceleration phase*: $\dot{\omega}_{fin} < 0$

- Required torque ?

$T = I\dot{\omega}$ with I = 3.8kg·m^2 [4.2.3.5]

Deployment performances (an example)

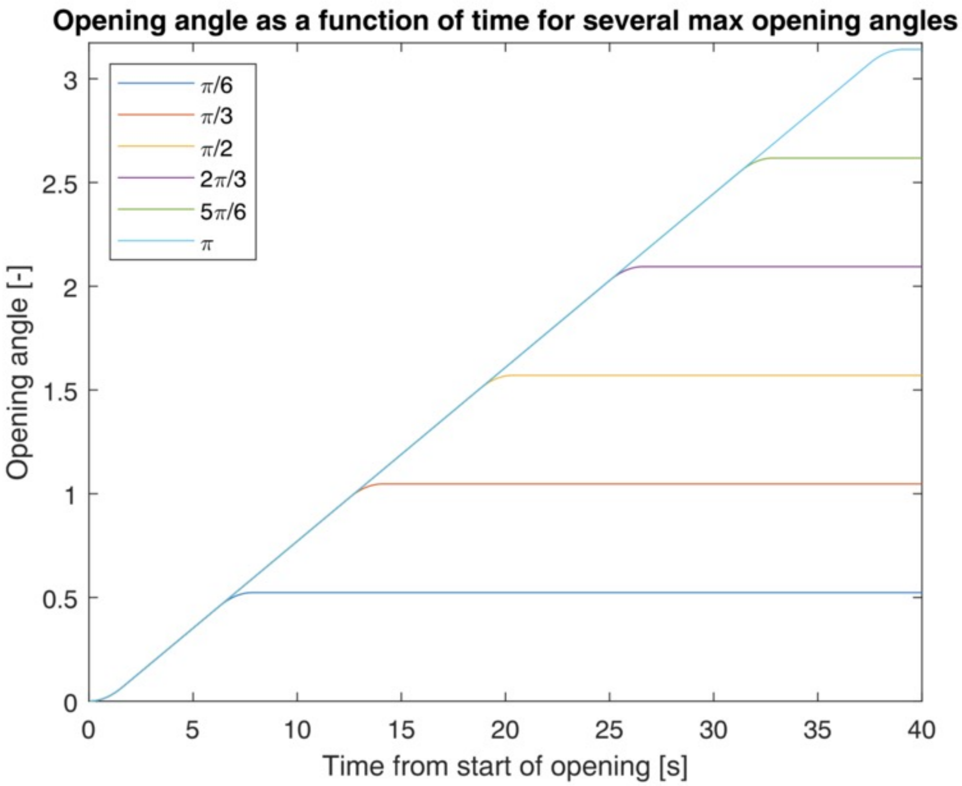


Figure 1: Antenna deployment as a function of time for various target angles.

Source: Arnaud Muller, Antoine Clout

With:

$\omega_{constant}$ = 80% x ω_{max}

T = 0.2 Nm

Duration ≤ 40s

Deployment performances

- Torque margin
  - ECSS-E-ST-33-01C Rev.2 - Mechanisms

Table 4-2: Minimum uncertainty factors for actuation function

Resistive torque or force contributors	Symbol	Theoretical Factor	Measured Factor
Inertia	I	1,1	1,1
Spring	S	1,2	1,1
Magnetic effects	H_M	1,5	1,1
Friction	F_R	3	1,5
Hysteresis	H_Y	3	1,5
Others (e.g. Harness)	H_A	3	1,5
Adhesion	H_D	3	3

T_D : inertial resistance torque

T_L : deliverable output torque (if specified by customer)

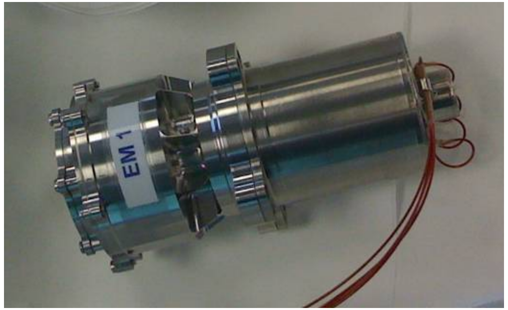
$$T_{min} = 2 \cdot [1.1 \cdot I + 1.2 \cdot S + 1.5 \cdot H_M + 3 \cdot F_R + 3 \cdot H_Y + 3 \cdot H_A + 3 \cdot H_D] + 1.25 \cdot T_D + T_L$$

- Example
  - Inertia (e.g.): T_D = 0.2 Nm => 1.25 x 0.2 = 0.25 Nm
  - Friction: 0.02 Nm per duplex bearing => 2 x 3 x (2 x 0.02) = 0.24 Nm
  - **Total: 0.49 Nm** (no harness, no spring, only bearing friction …)

EE580 Space Mechanisms – Quiz 4

http://tiny.cc/EE580Q04

Actuator

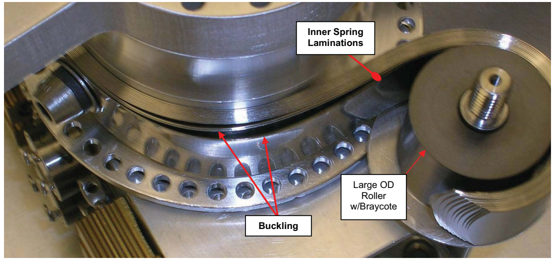


Source: C. Boesch et al., Proceedings of the 13th European Space Mechanisms and Tribology Symposium, 23-25 September 2009

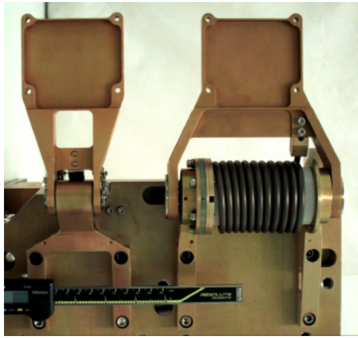
- Brushless DC motor
- Stepper motor
- Sealed brushed motor

❖ Gear box

❖ Complex control electronic (brushless motor, stepper motor)



Source: J.A. Johnson, Proceedings of the 39th Aerospace Mechanisms Symposium, NASA Marshall Space Flight Center, May 7-9, 2008.



Source: J.I. Bueno et al., Proceedings of the 9th European Space Mechanisms and Tribology Symposium, 19-21 September 2001

- Spring (passive)
  - Helical torsion spring
  - Constant torque spring
  - …

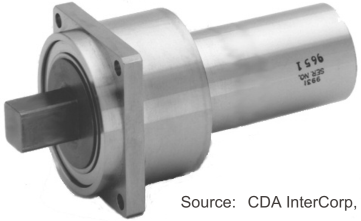
➢ Hold-down device (e.g. pin-puller, shall be resettable)

➢ Damper (deployment rate control)

➢ Resettable: on ground, not in-orbit

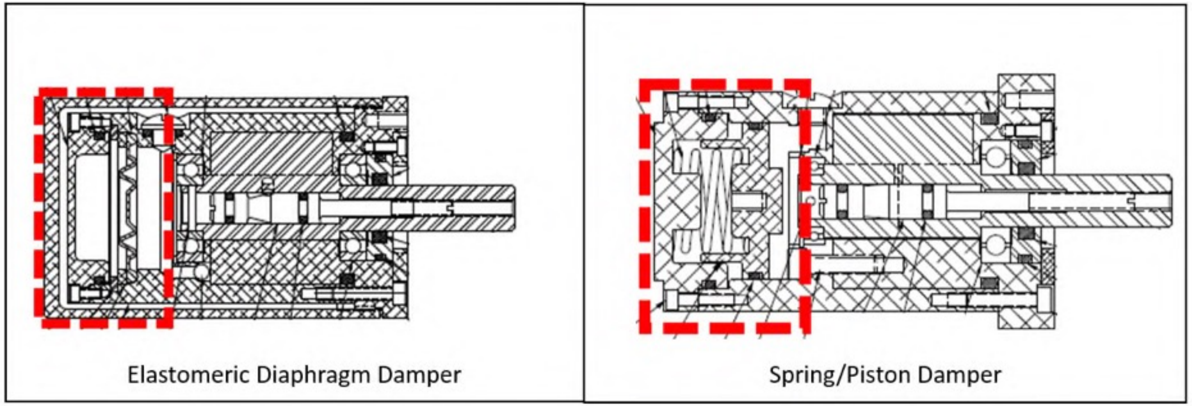
Spring Actuator: acceleration/speed control

- Damper:
  - Eddy current damper
  - Viscous damper



Source: CDA InterCorp, USA


Source: W. Mitter et al., Proceedings of the 13th European Space Mechanisms and Tribology Symposium, 23-25 September 2009



Source: P. Lytal et al., Proceedings of the 44th Aerospace Mechanisms Symposium, NASA Glenn Research Center, May 16-18, 2018

Viscous: Flight heritage, but for much larger torque. Not a commercial product. Depends also on full mechanism characteristics. Depends on temperature (thermal control required).

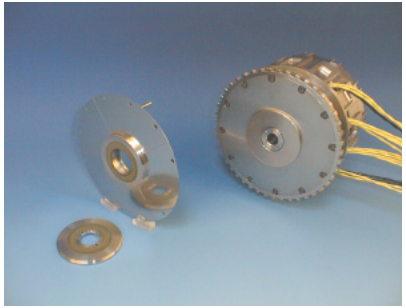
Eddy current: commercial products available

Very critical
Early stage analysis. BBM testing?

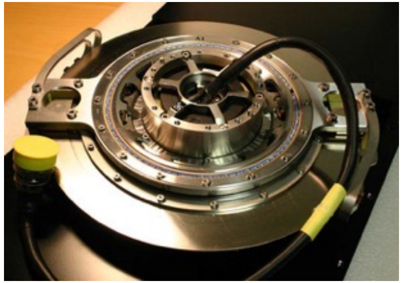
Performances to be assessed.
Includes gear box?

Brake?

Source: F.C. Baker et al., Proceedings of the 8th ESMATS, 29 Sept.-1 Oct. 1999

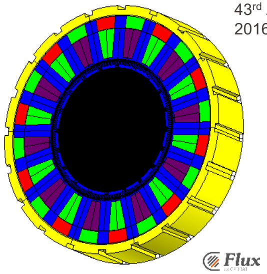


- Mechanical brake
  - Shall operate under vacuum and under air
    - Change of tribological characteristics, non-linear
    - Running-in when changing environment?
  - Requires an actuator (contact pressure, braking torque force, power)
  - Behavior under vibrations?
  - Size
  - Monitoring the status?
  - No (limited) commercial product available



Source: T. Hopper et al., Proceedings of the 43rd AMS, 4-6 May 2016, NASA/CP-2016-219090

- Other option: reluctance brake
  - Passive or Active

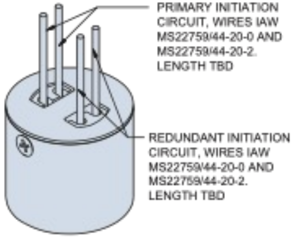


EPFL

Pin-puller

ELECTRICALLY REDUNDANT HOLD DOWN RELEASE MECHANISM, MEDIUM DUTY

How To Order		
Sample Part No.	061	-007
Basic Part No.	Light/Medium Duty HDRM	
Dash No.	Redundant Circuit	



Source: Glenair, Inc

Reset requires the replacement of the initiator

NOK
(reversibility?)

Source: Ensign-Bickford Aerospace & Defense Company

P5 Details

Mass:	1.06 oz [30 g]
Power:	1.25 W @ 0.4 A
Operational Current:	0.4 to 1.5 A
Resistance:	7.7 ± 0.5 Ω @ 23°C
Pull Force:	5 lbf [22.2 N] MIN
Pull Stroke:	0.250 in [6.3 mm] MIN
Axial Load (Actuation):	2 lbf [8.9 N] MAX
Side Load (Actuation):	10 lbf [44.5 N] MAX
Side Load (Non-Actuation):	100 lbf [444.8 N] MAX
Function Time:	130 msec. MAX @ 0.5 A (23°C)
Reusable:	By Manual Reset
Life:	100 Cycles MIN
Operational Temperature:	-65° C to +70° C
Size (max):	D31.75 x 41.275 mm

Can be reset
However T_{op} range not OK

Check if T_{op} can be increased

Angular encoder, switches

Potentiometer

Source: Betatronix

Source: Novotechnik

Resolution: better than 0.01°
(even better than 0.007°)
=> 0.17 mrad

Optical encoder

Source: Codechamp

Resolution: 15bits: ~0.011°
(can reach 23bits, i.e. $0.07 \cdot 10^{-3}$ mrad)
=> 0.19 mrad

Micro-switch

Source: Honeywell

Reed switch

Source: Standex Electronics, Inc.

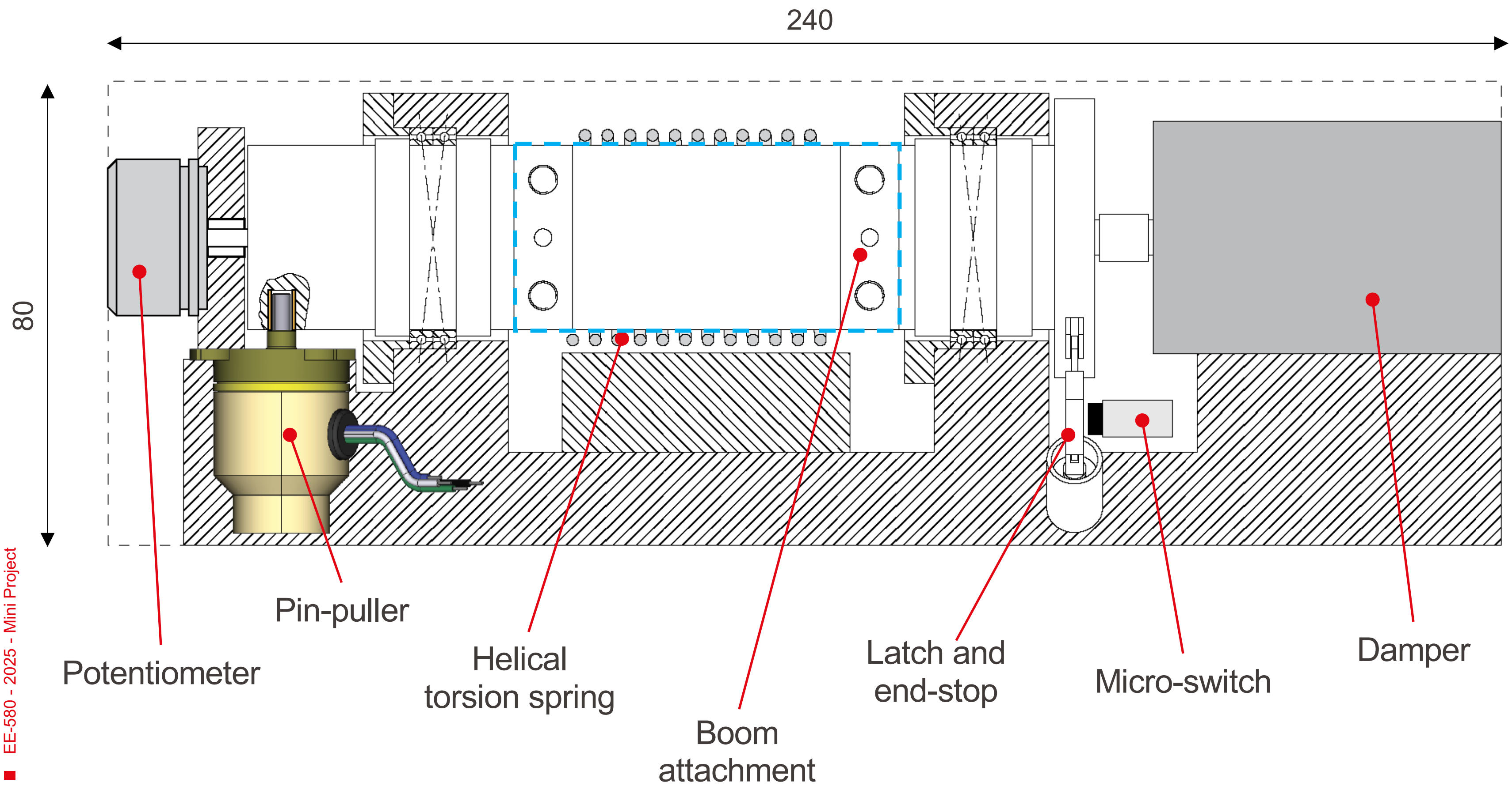
<u>Requirement [4.2.4.7]: < 0.2 mrad</u>

Trade-off

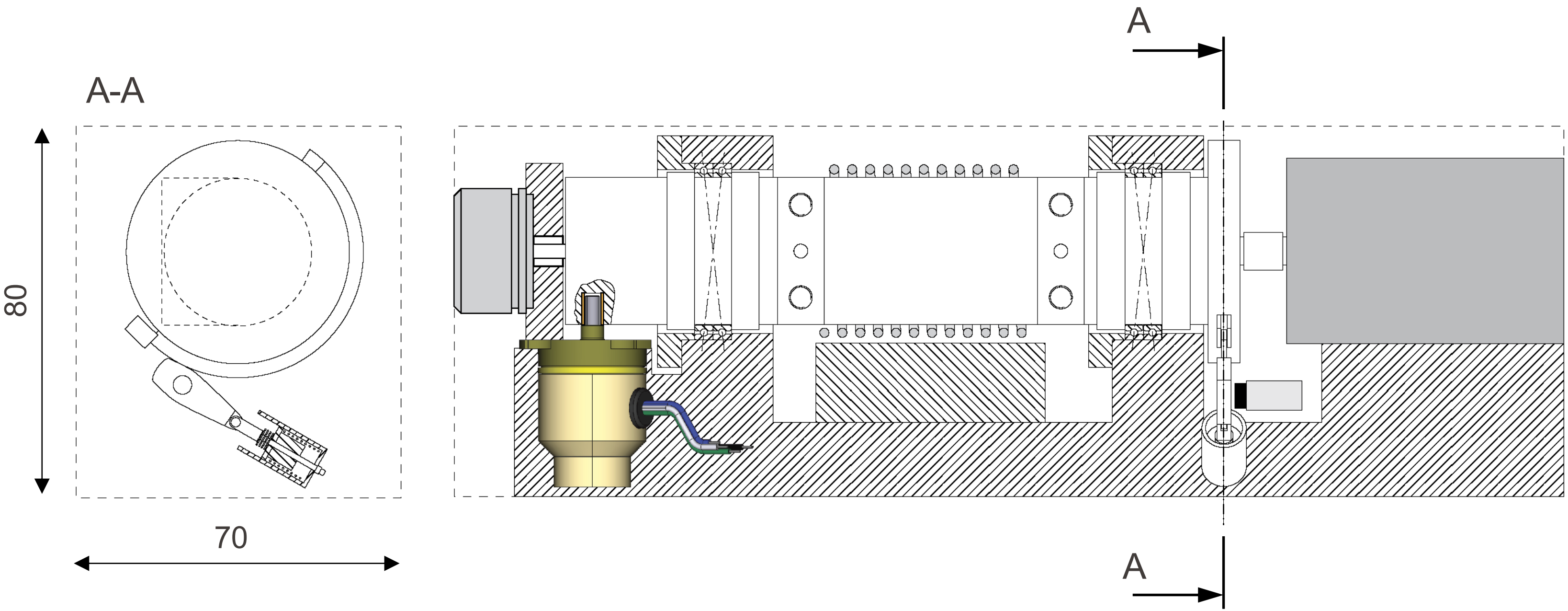
- Pugh matrix

		Concept 1	Concept 2	Concept 3	Concept 4
Criteria 1	Mass	+	Datum	-	+
Criteria 2	Size	-		+	-
Criteria 3	Control	S		+	-
Criteria 4	Power	S		+	S
…	…				
Σ+		1		3	1
Σ-		1		1	2
ΣS		2		0	1
Σ+ - Σ-		0		2	-1

Concept with spring actuator



Concept with spring actuator

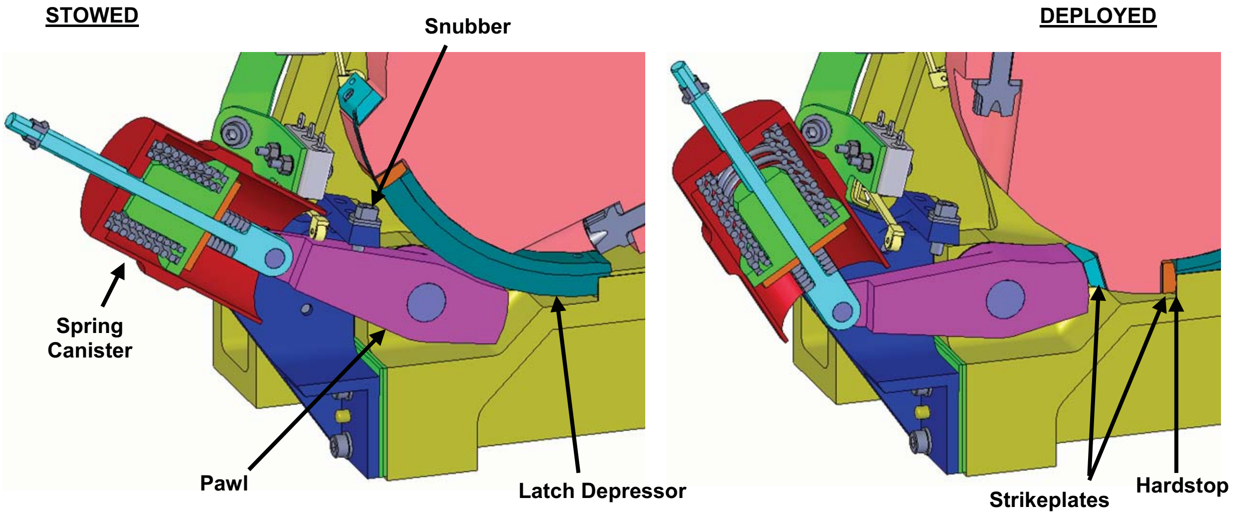


As low force is required, latch maybe simplified

Concept with spring actuator

- Latch concept (example)

  From Joel A. Johnson "*Development of the Aquarius Antenna Deployment Mechanisms and Spring/Damper Actuator*", Proceedings of the 39th Aerospace Mechanisms Symposium, NASA Marshall Space Flight Center, May 7-9, 2008.



Power budget: selection of cables

Components	Model	# wires	Max I_r [A]	AWG	Length [m]	Total mass [g]
Pin puller	EBAD P5	4	1.5	AWG26	0.2	1.6
End-switch	Honeywell HM	6	<0.001	AWG28	0.2	1.6
Potentiometer	Novotechnik P2500	3	$<1 \cdot 10^{-6}$	AWG28	0.2	0.8
Total	N_{nom} =	**13**				**4**

Single wires acc. to ESCC 3901 001

Cable derating: ECSS-Q-ST-30-11C Rev 1 Derating - EEE components

Maximum current for single wire

AWG26 2.5 A
AWG28 1.5 A

Bundle factor *K* for N wires (derated allowable current: $I_{derated} = K \cdot I_r$):

$N = \lceil 0.5 \times N_{nom} \rceil$ for cold redundancy wires or not in the same bundle $\Longrightarrow$ $\boldsymbol{N = 7}$

$3 < N \leq 7$ $K = 1.01 - (0{,}07 \times N)$ $\Longrightarrow$ $\boldsymbol{K = 0.52}$

Derated Current:

AWG26 1.3 A $\Longrightarrow$ pin puller **current shall be limited**: OK (I > 0.4 A, function time)
AWG28 0.78 A

Mass budget

Components	Model	Quantity	Unit mass [g]	Total mass [g]
Duplex bearing	ADR WAD420	2	15	30
Damper		1	150	90
Pin puller	EBAD P5	1	30	30
End-switch	Honeywell HM	2	10	20
Spring		1	50	50
Potentiometer		1	20	20
Screws	M3x8	50	0.3	15
D-SUB 25		2	12	24
Cables				4
		Total		283
		Contingency	10%	28.3
		Total		**311.3**

Available for structure and parts (incl. coupling, latch …): 700 g – 311.3 g = 388.7 g

→ Not much. Structure shall be optimized!

Gear-Motor concept: Mars Rover PMA

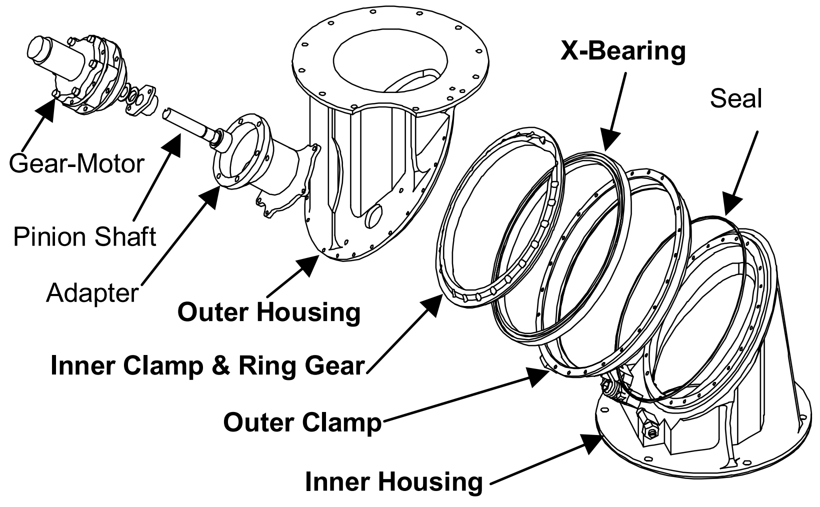


Figure 8: Exploded view of the Mast Deployment Drive

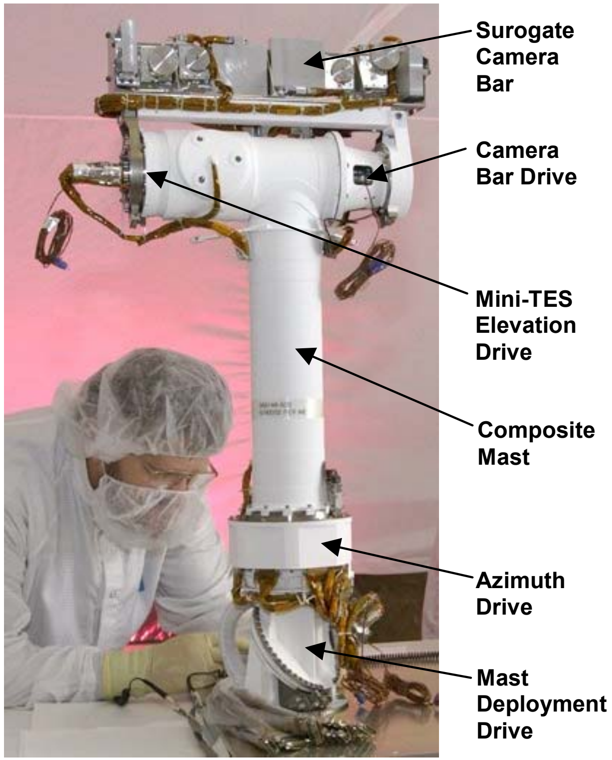
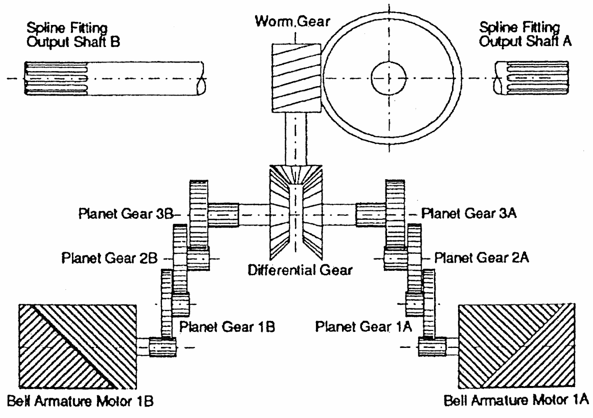
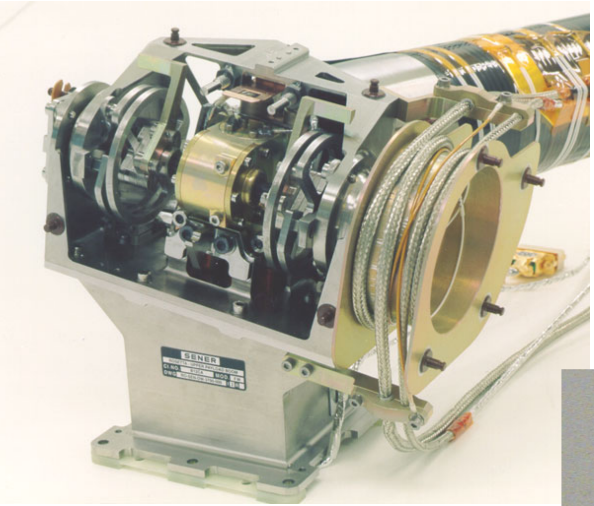


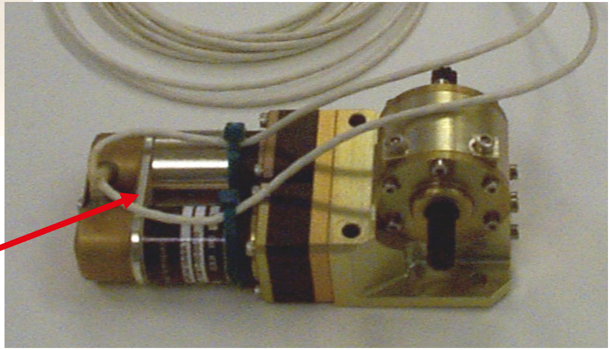
Figure 2. PMA in the Deployed Configuration

Source: R.M. Warden et al., Proceedings of the 37th Aerospace Mechanisms Symposium, Johnson Space Center, May 19-21, 2004.

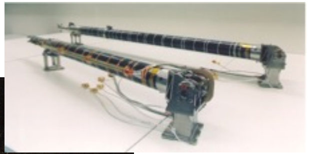
Worm Gear concept: Rosetta deployable boom

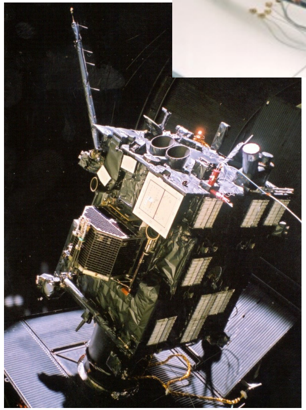






two redundant sealed brush motors

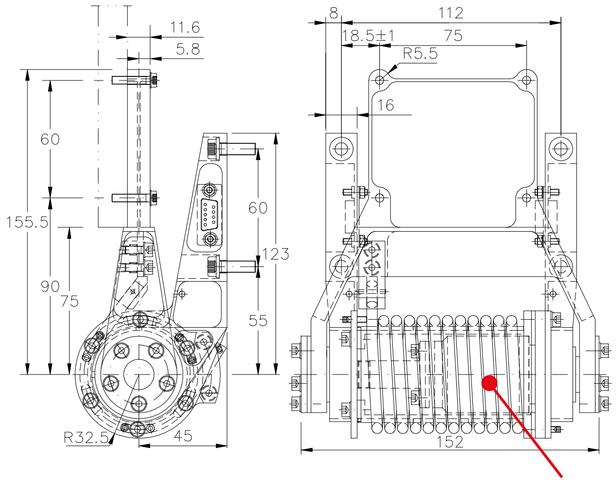




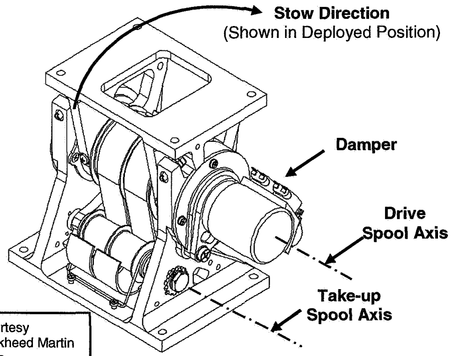
Source: J.A. Andión et al., Proceedings of the 10th European Space Mechanisms and Tribology Symposium, 24-26 September 2003

Spring concepts

Source: J.I. Bueno et al., Proceedings of the 9th European Space Mechanisms and Tribology Symposium, 19-21 September 2001

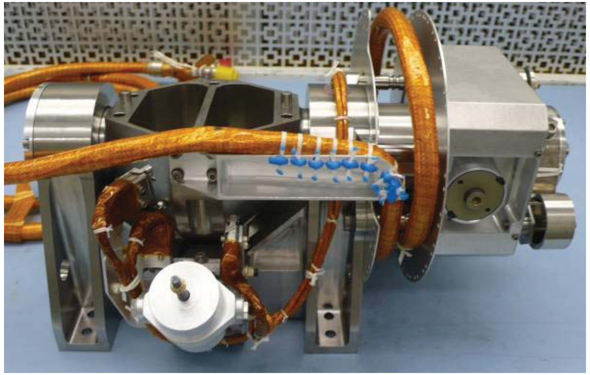


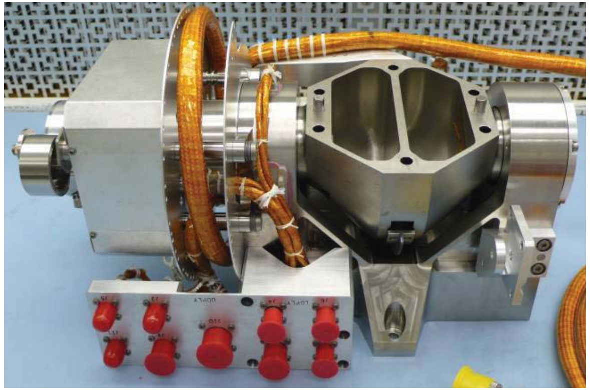
Deployment Regulator



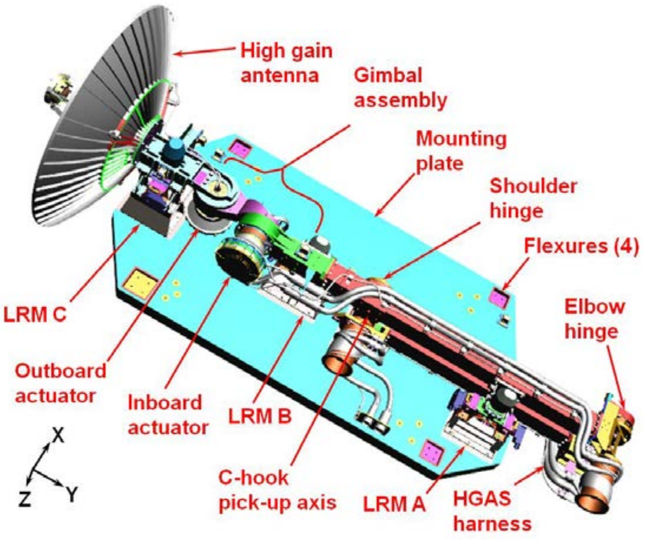
Courtesy Lockheed Martin Corp.

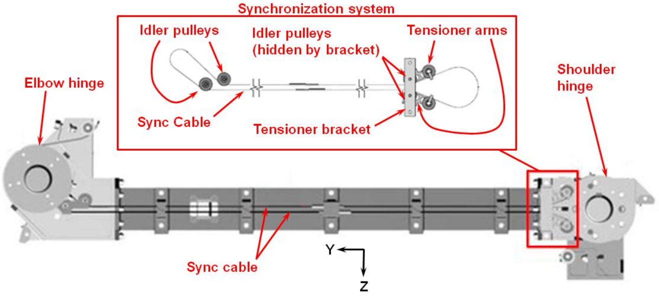
Source: J. A. Johnson, Proceedings of the 39th Aerospace Mechanisms Symposium, NASA Marshall Space Flight Center, May 7-9, 2008.



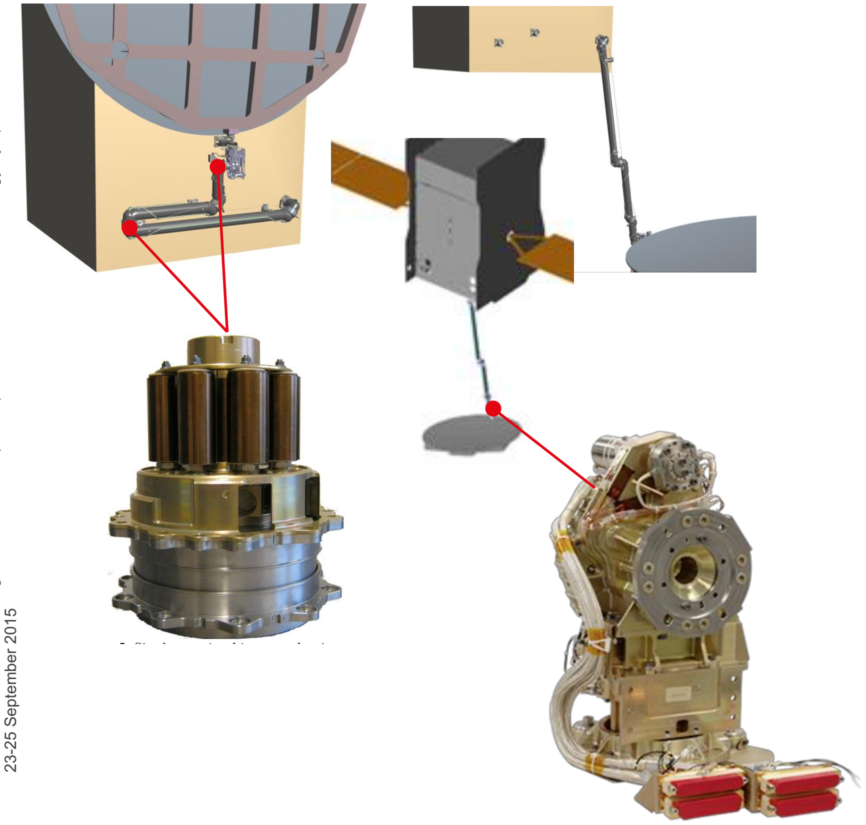


Antenna deployment



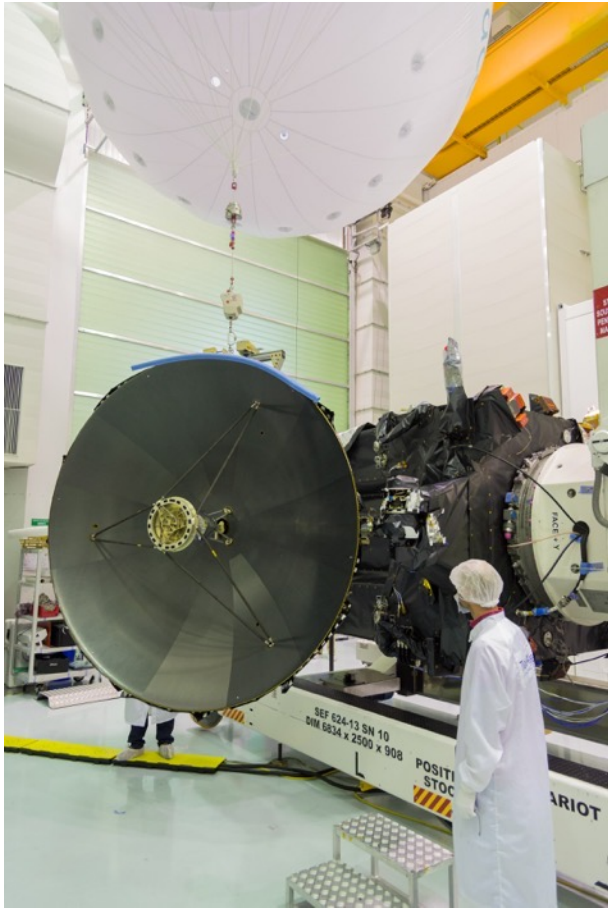


Source: F. Parong et al., Proceedings of the 42nd Aerospace Mechanisms Symposium, May 14-16, 2014

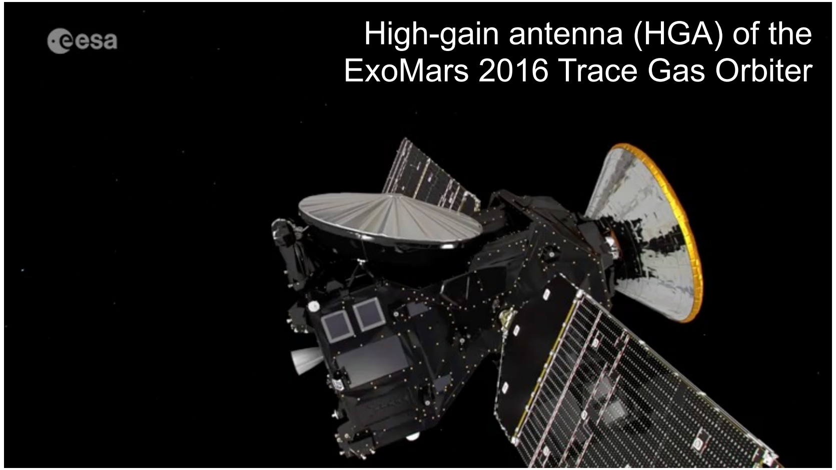


Source: M. Kroon et al., Proceedings of the 16th European Space Mechanisms and Tribology Symposium, 23-25 September 2015

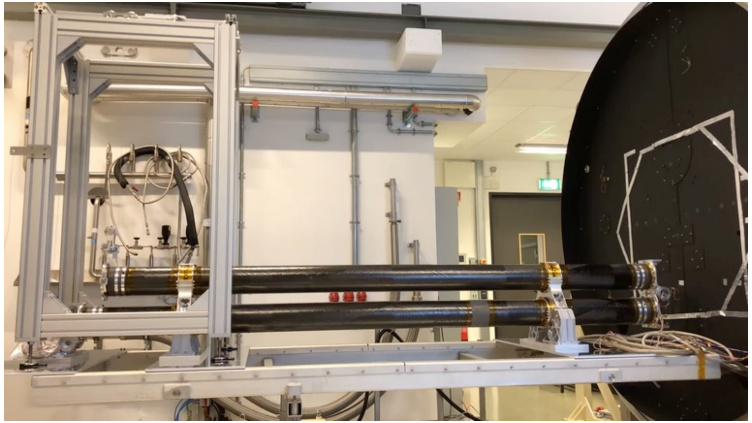
Antenna deployment



Source: ESA - B. Bethge



Source: ESA/ATG medialab

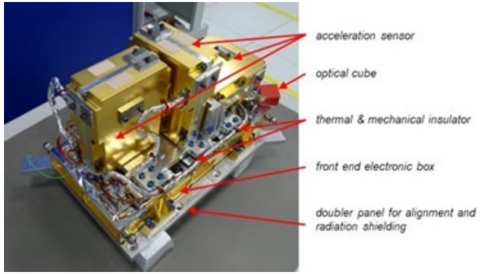


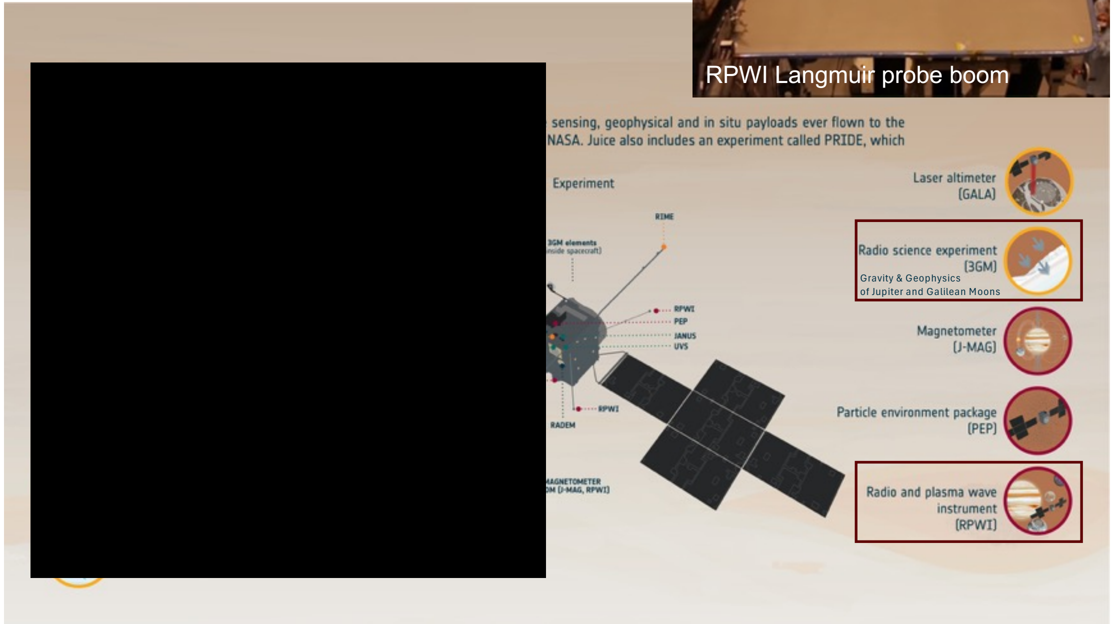
Source: ESA-A. Ihle

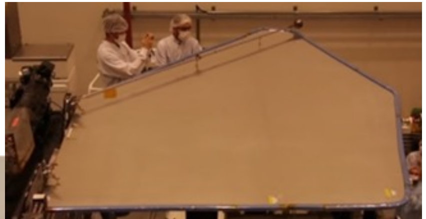
Deployment (booms and others)

- **Indirect ways to monitor**: e.g. use of an onboard accelerometer to monitor the deployment of a boom
  - Bandwidth of the accelerometers
  - Comparison between ground and in-orbit values maybe difficult

3GM High Accuracy Accelerometer (HAA)



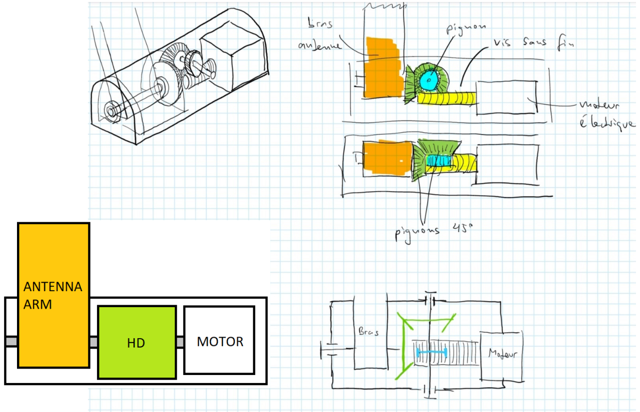



RPWI Langmuir probe boom

R. Le Letty et al., "*Listening into the JUICE Deployments with the On-Board High-Accuracy Accelerometer*", Proceedings of the 47th Aerospace Mechanisms Symposium, NASA Langley Research Center, May 15-17, 2024

Source: ESA

Student concepts



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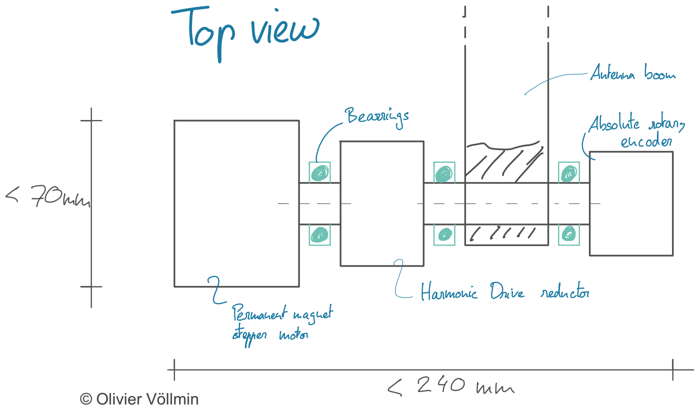

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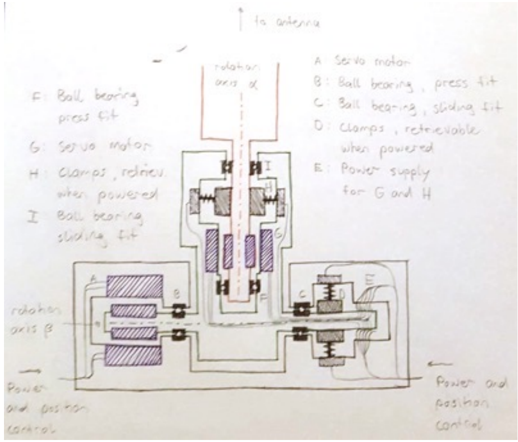

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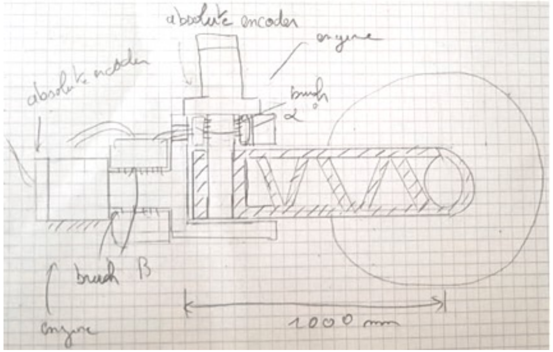

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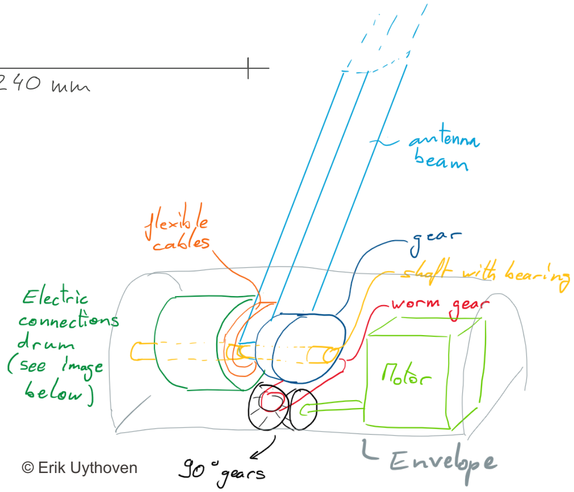

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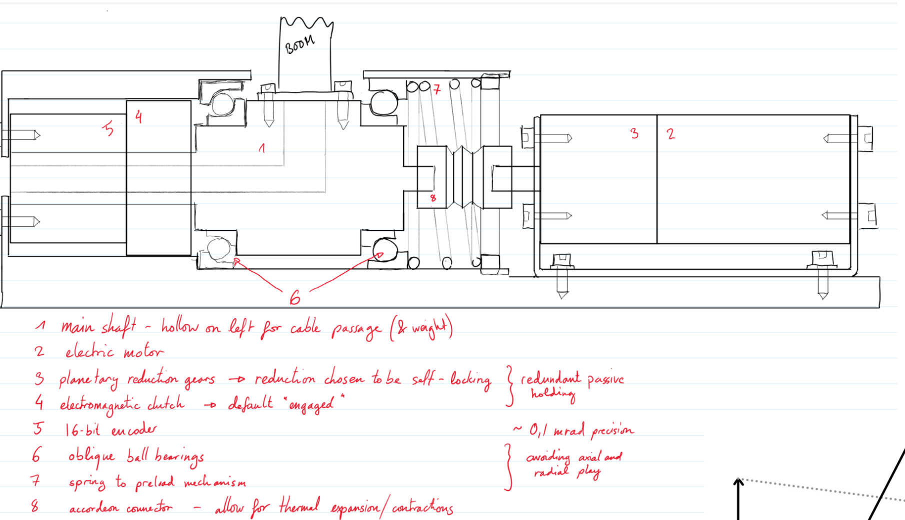
Student concepts



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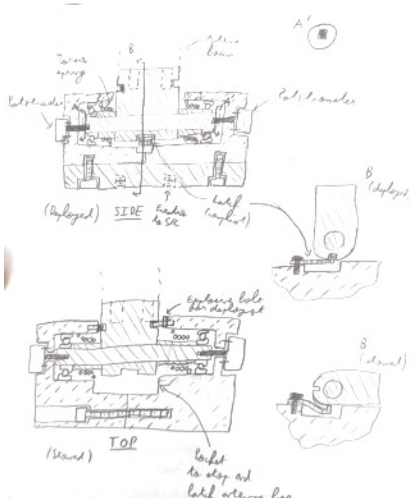

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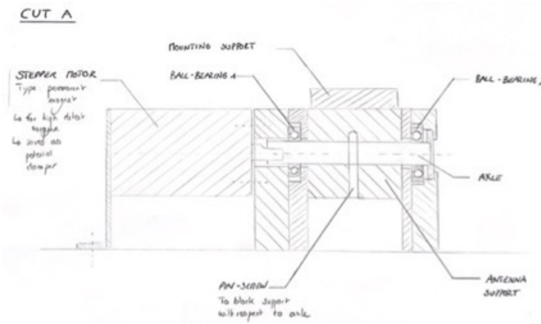

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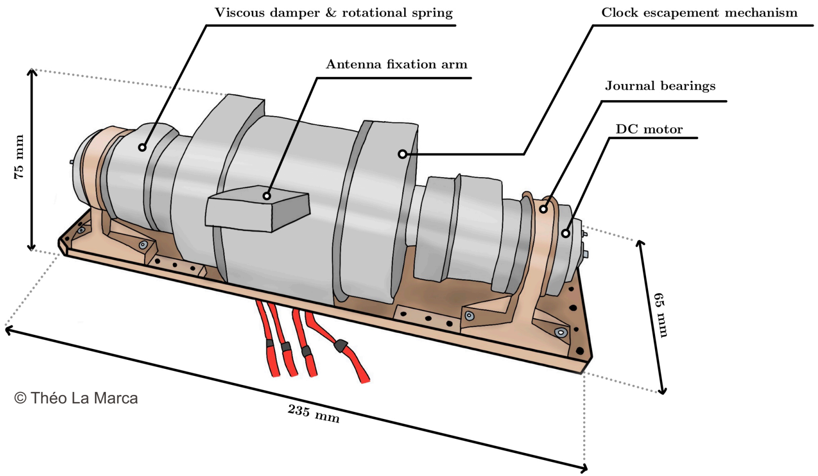

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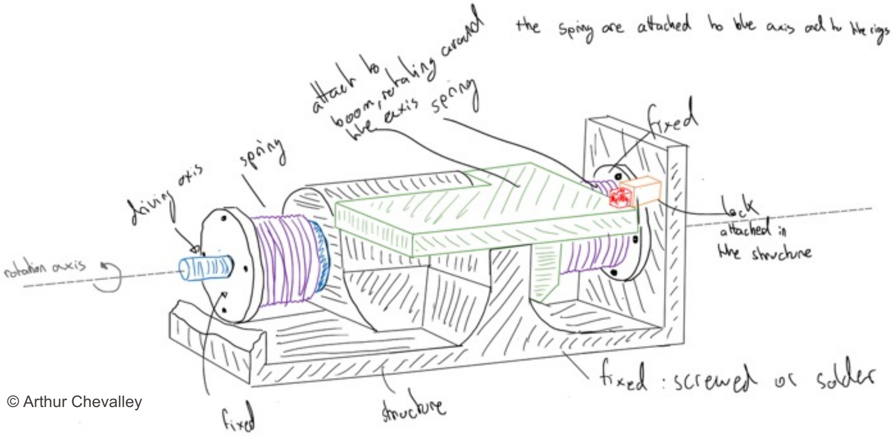
Student concepts



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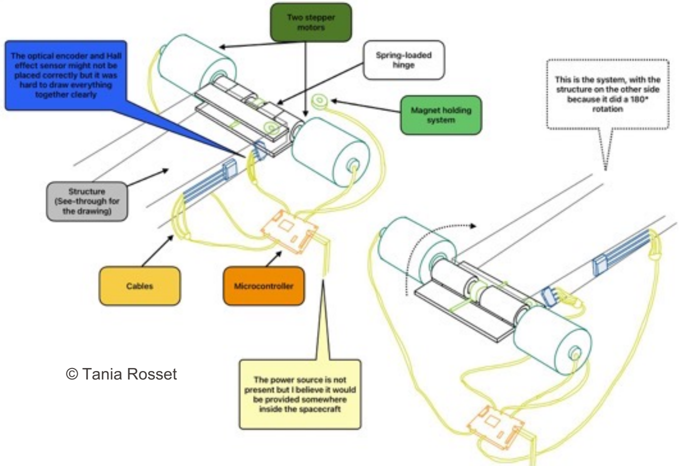

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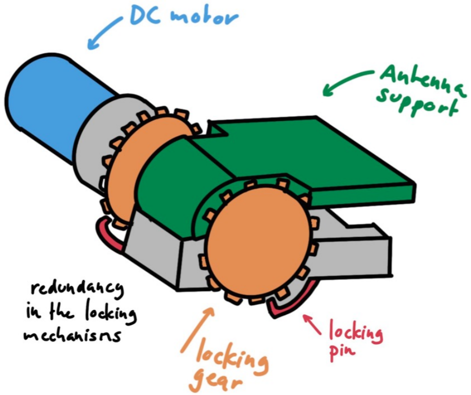

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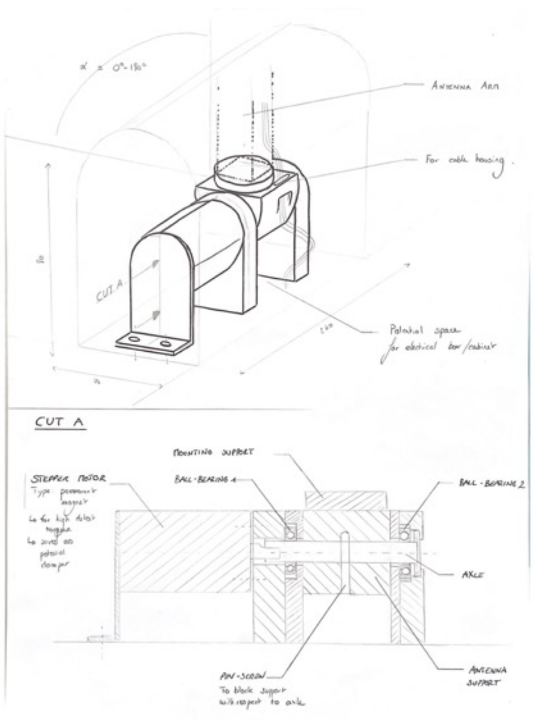

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Mini Project Summary

- Identify the critical and key requirements
- List the functions
- Map the functions to forms (architecture)
  - List of potential components, incl. specifications
- Make preliminary analysis
  - What are the required performances?
  - Pre-sizing of the components
- Selection of concept and components
  - E.g. Pugh matrix, …
- Sketch your concept(s)
- Make some preliminary budgets (size, mass, power, …)
- Convince customer, management, … that you will be able to achieve the requirements, within time and budget

Next week

- Theme 7 – Reliability

- Fill the exam schedule on MOODLE (Exams June 27 & 30, July 1)
  https://moodle.epfl.ch/mod/scheduler/view.php?id=1206907
  To be filled until June 6th, 17:00.