

2 - 3 June 2026, Leganés, Madrid

Digital Twinning and Control for Cryogenic Fluid Storage

From Sloshing Dynamics to Active Pressure Management

Francisco Monteiro^{1,2}

supervised by

Miguel Alfonso Mendez^{1,2}

¹von Karman Institute for Fluid Dynamics, Bruxelles, Belgium,

²Aerospace Engineering Research Group, Universidad Carlos III de Madrid, Leganés, Madrid, Spain.



uc3m

Universidad
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de Madrid

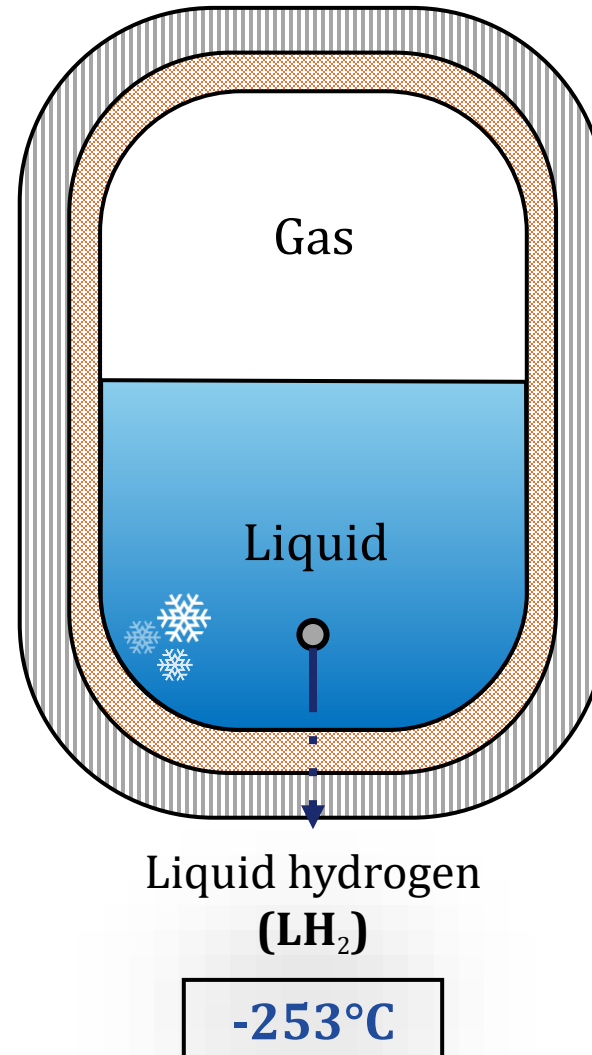


VLAIO



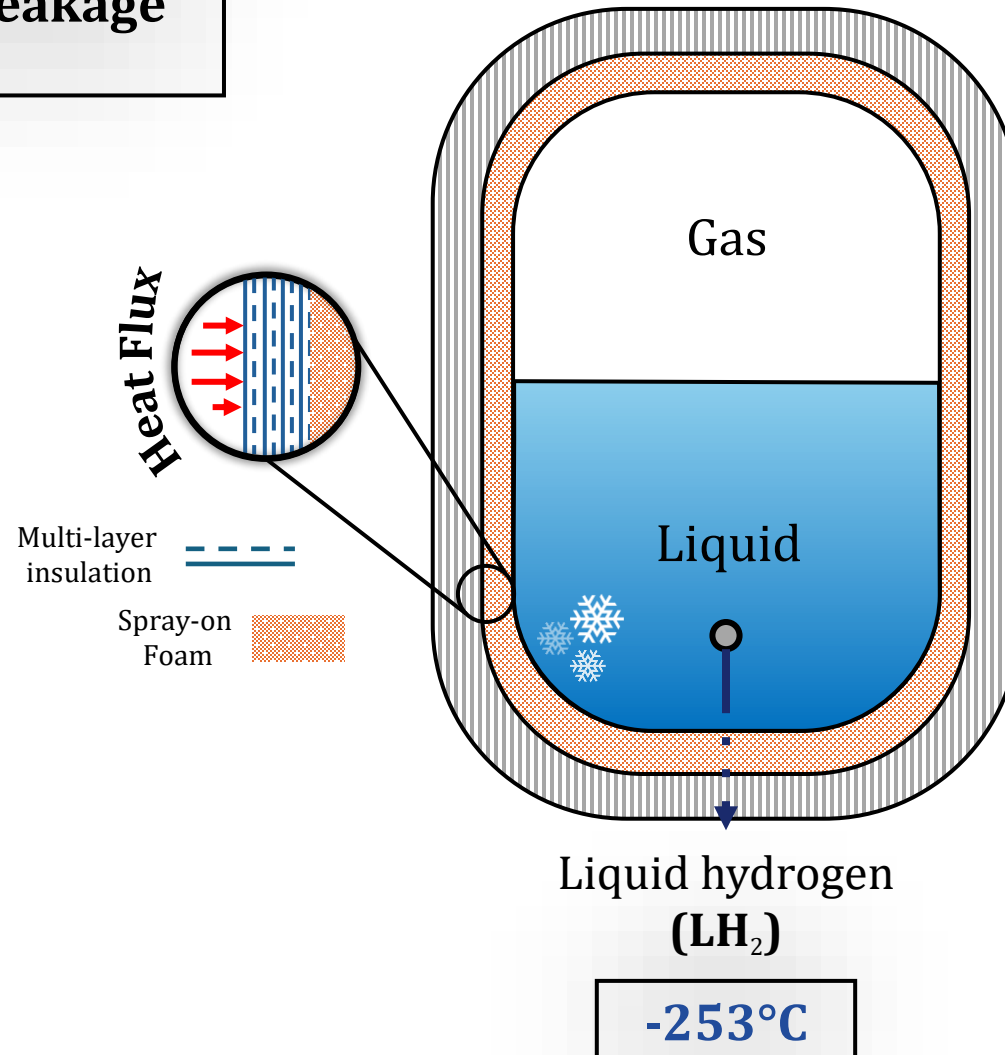
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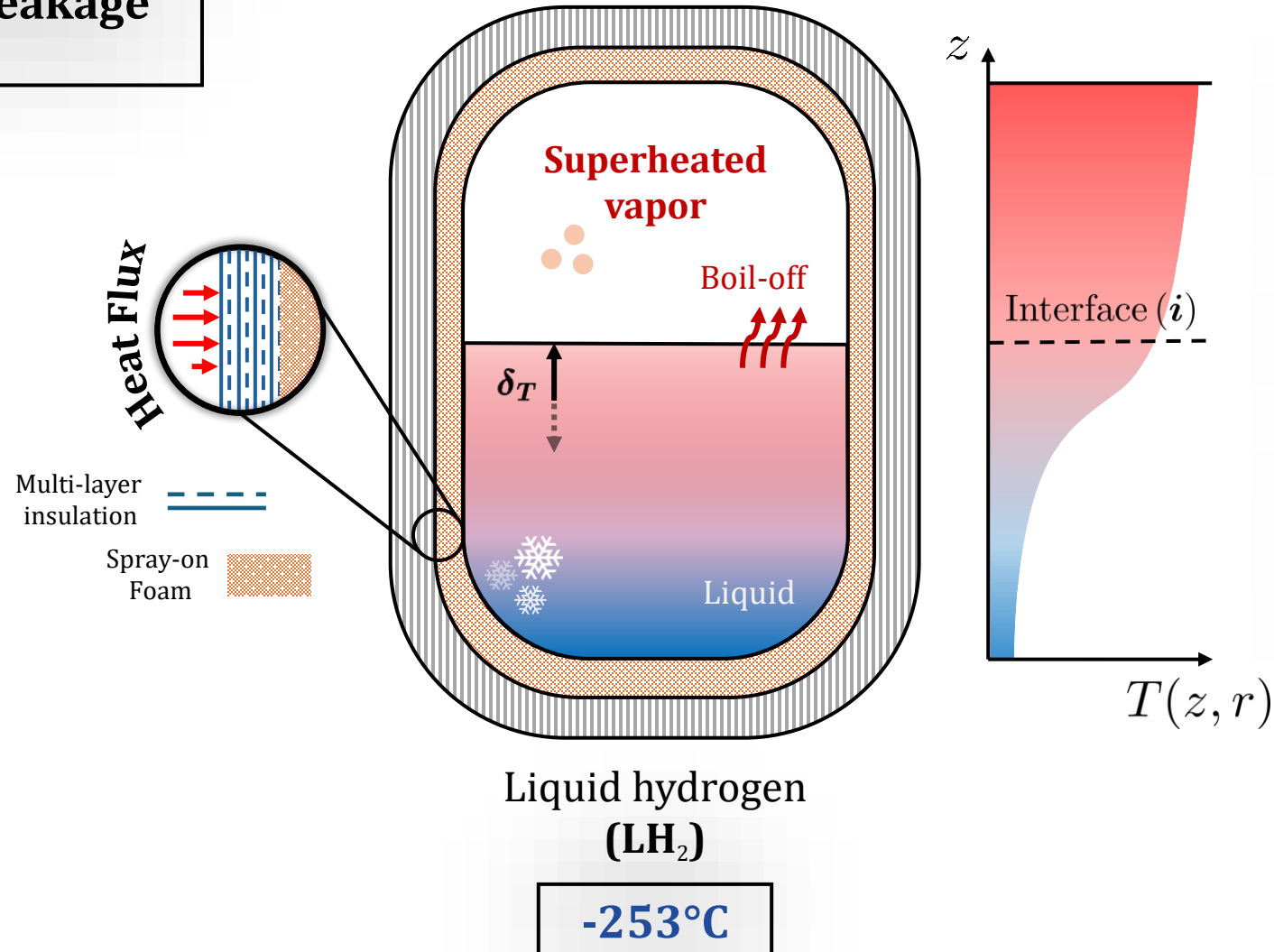
Thermal Management of Cryogenic Tanks

Heat leakage



Thermal Management of Cryogenic Tanks

Heat leakage



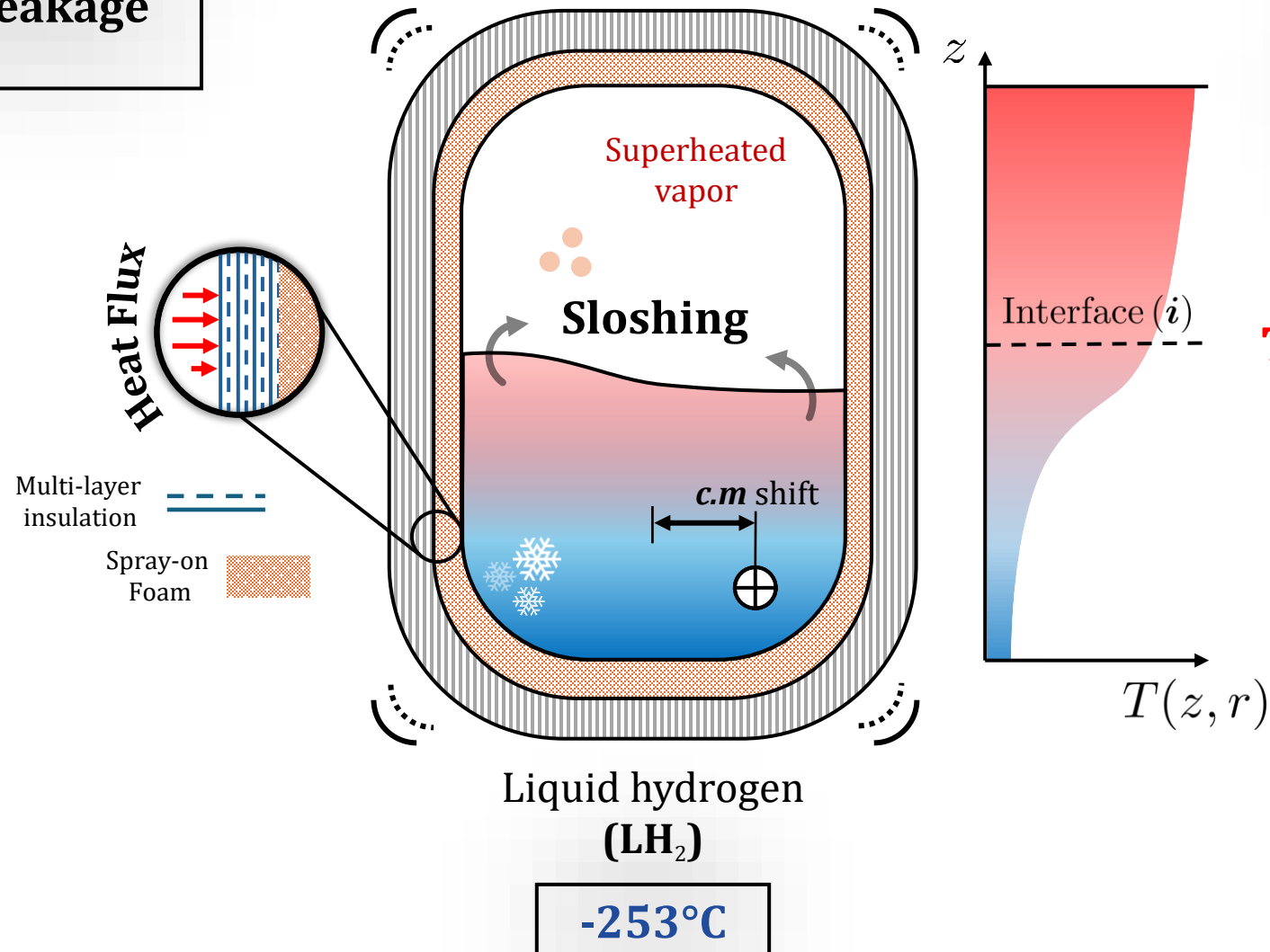
Thermal non-equilibrium

Pressure build-up

Boil-off losses

Thermal Management of Cryogenic Tanks

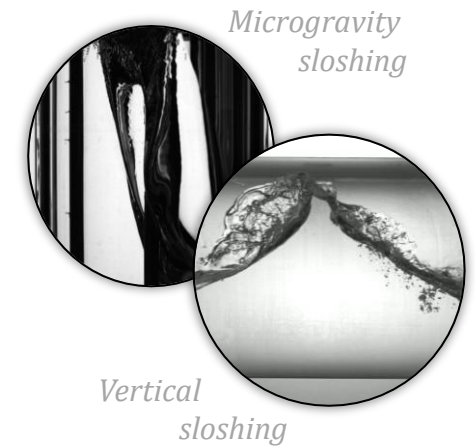
Heat leakage



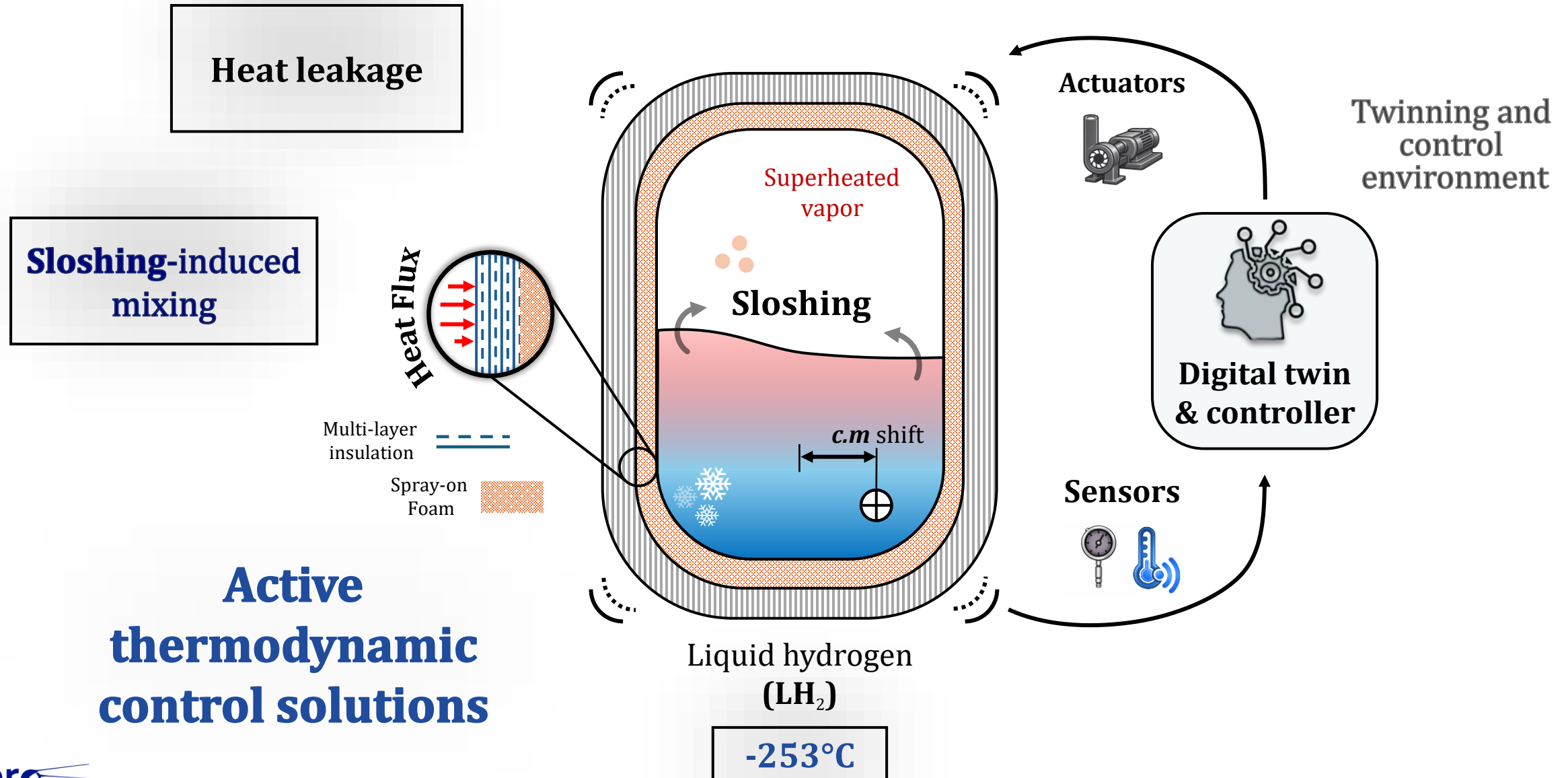
Sloshing-induced mixing

Dynamic impact

Thermodynamic impact



Thermal Management of Cryogenic Tanks



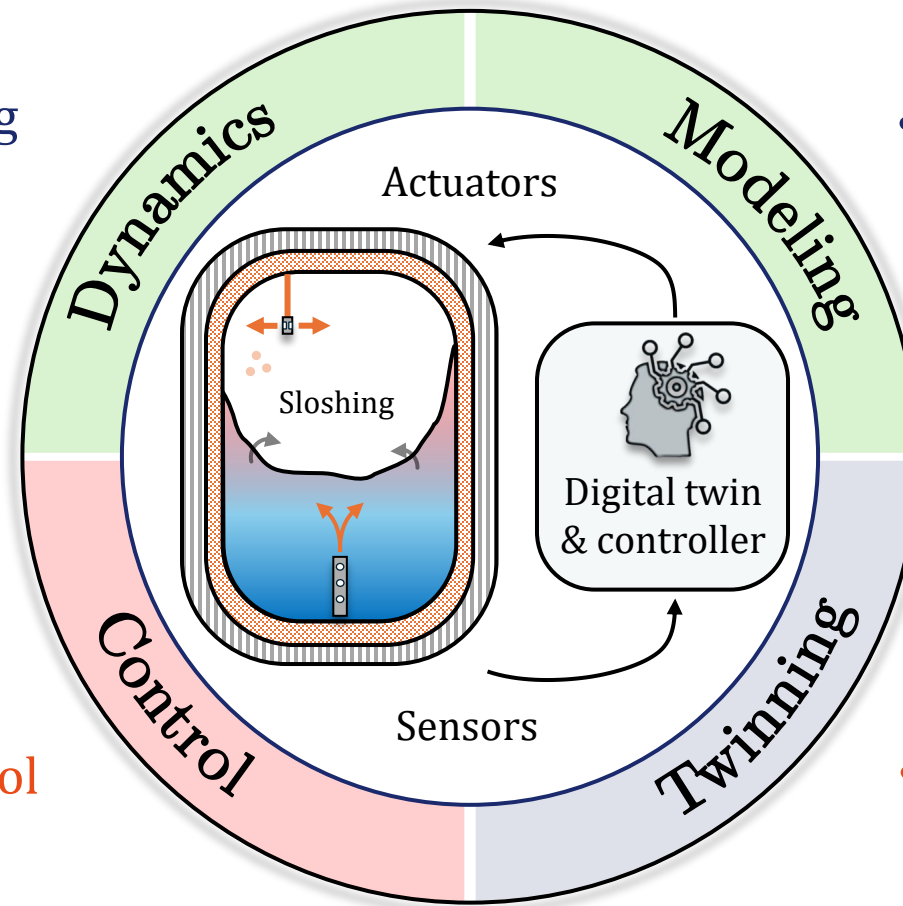
Research Framework

Space applications

- Lateral sloshing
- Microgravity sloshing

Aviation applications

- Vertical sloshing
- Non-isothermal sloshing
- Thermodynamic modeling
- “Online” learning



Control & Actuation

Research Framework

Space applications

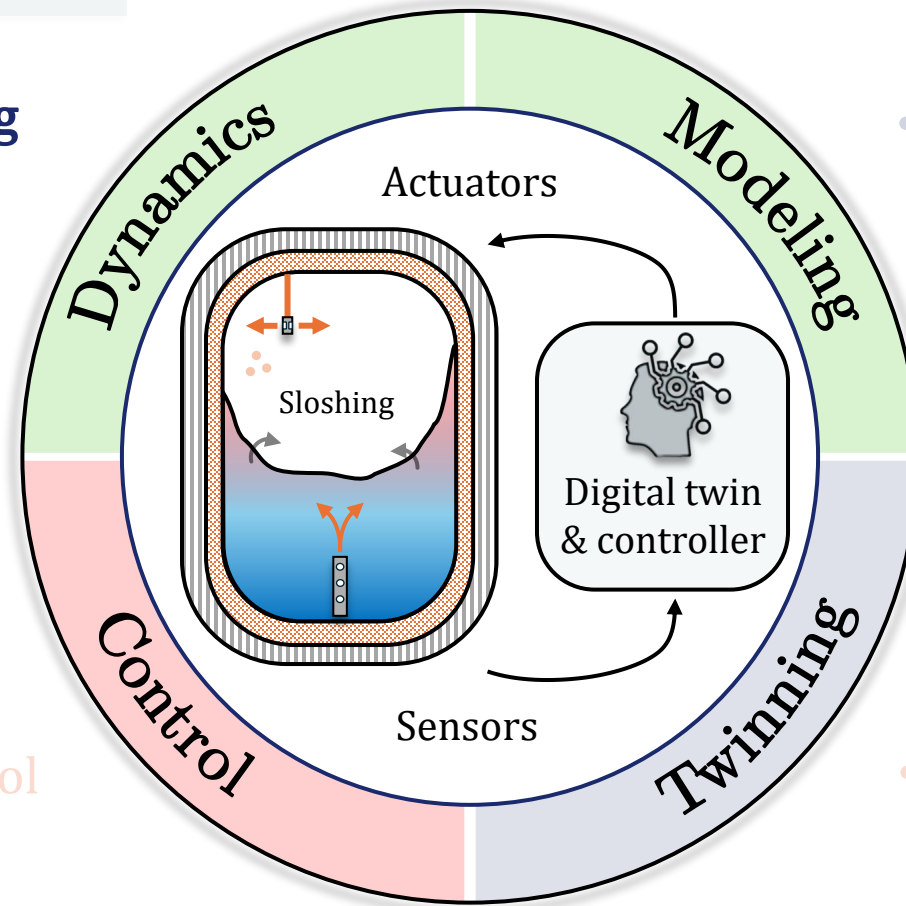
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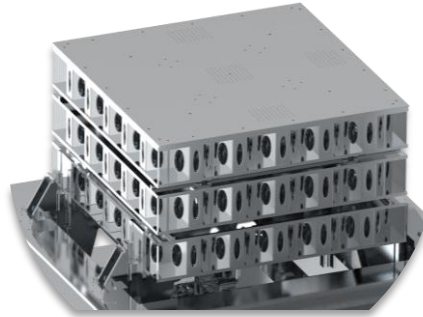


Control & Actuation

Sloshing in space applications

Objective: Characterize sloshing-induced heat and mass transfer across gravity regimes

von Karman Institute sloshing
table **Shakespeare**



$\downarrow g_0$



**Experimental
characterization**



~~$\downarrow g_0$~~

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parabolic flight



Calibration & closure
correlations



**Engineering models
(0D/1D) and Scaling
laws**



Sloshing in space applications

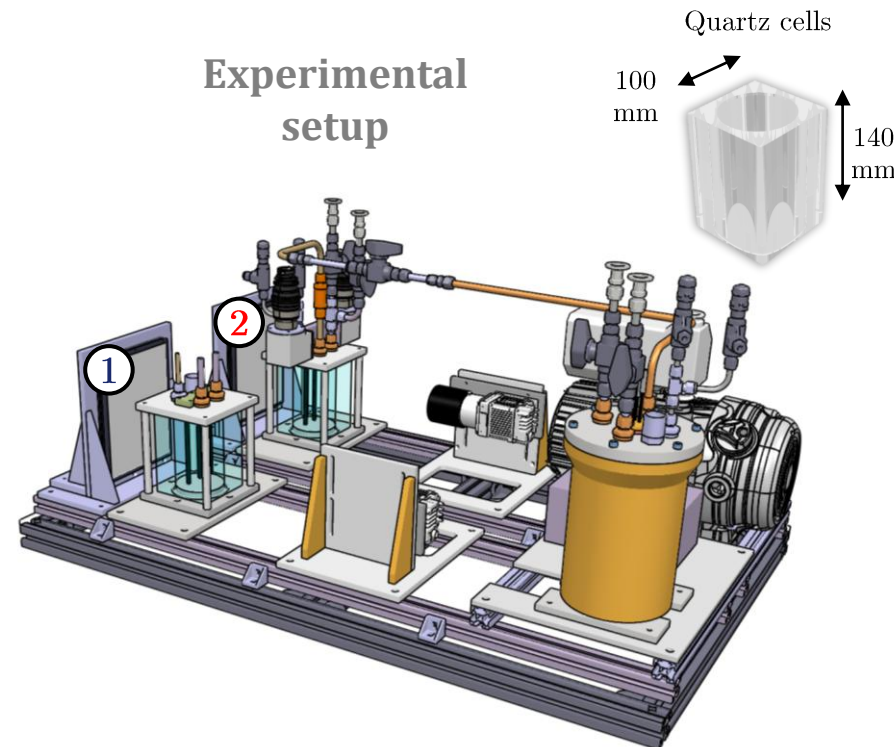
Objective: Characterize sloshing-induced heat and mass transfer across gravity regimes

RQ. 1

Do thermal conditions modify sloshing **dynamics**?

RQ. 2

How do thermal conditions affect tank **thermodynamics**?



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AirZero G
weightless with Novespace

Sloshing in space applications

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RQ. 1

Do thermal conditions modify sloshing dynamics?

$$T_{I,w} \approx 300 \text{ [K]}$$

Isothermal tank

Characterize sloshing dynamics



-0.01 s

2

$$T_{N,w} \approx 330 \text{ [K]}$$

Non-isothermal tank

Characterize dynamics with diabatic boundary conditions



~~$1g_0$~~

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AirZero G
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[1] F. Monteiro, P. A. Marques, A. Simonini, L. Carbonnelle, and M. A. Méndez, Experimental characterization of non-isothermal sloshing in microgravity, ETFS, 2025.

[2] P. A. Marques, S. Ahizi, F. Monteiro, B. Scheid, and M. A. Méndez, Scaling of heat and mass transfer in cryogenic propellant tanks, ATE, 2026.

Research Framework

Space applications

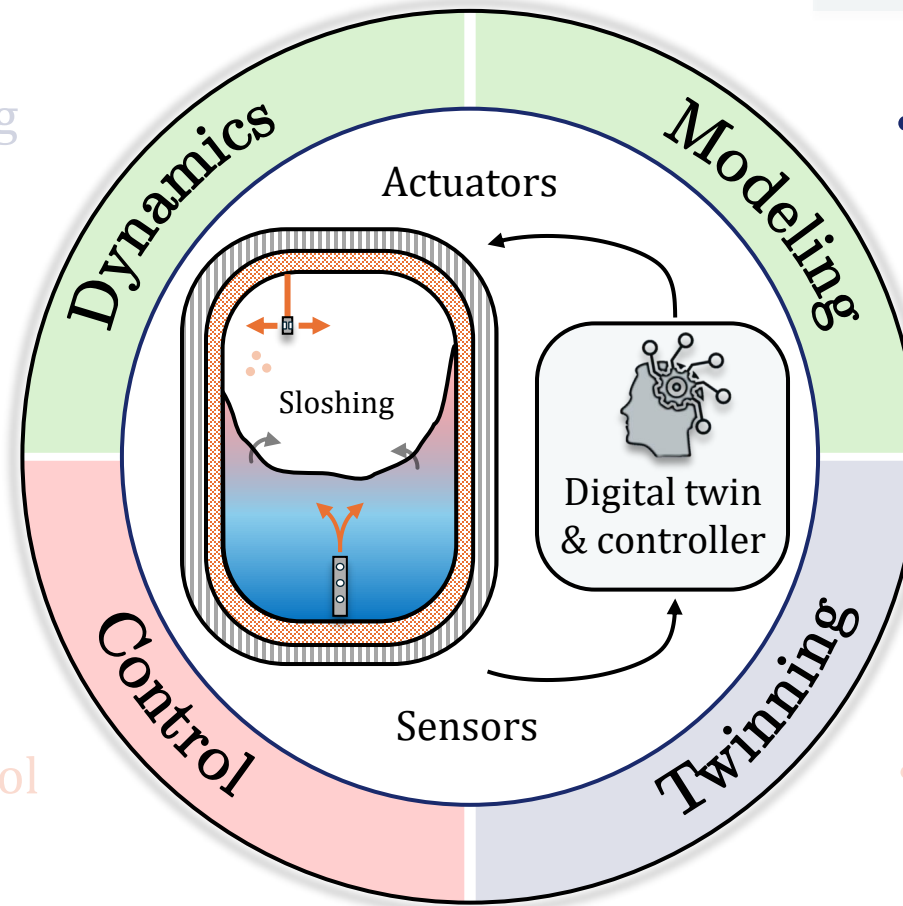
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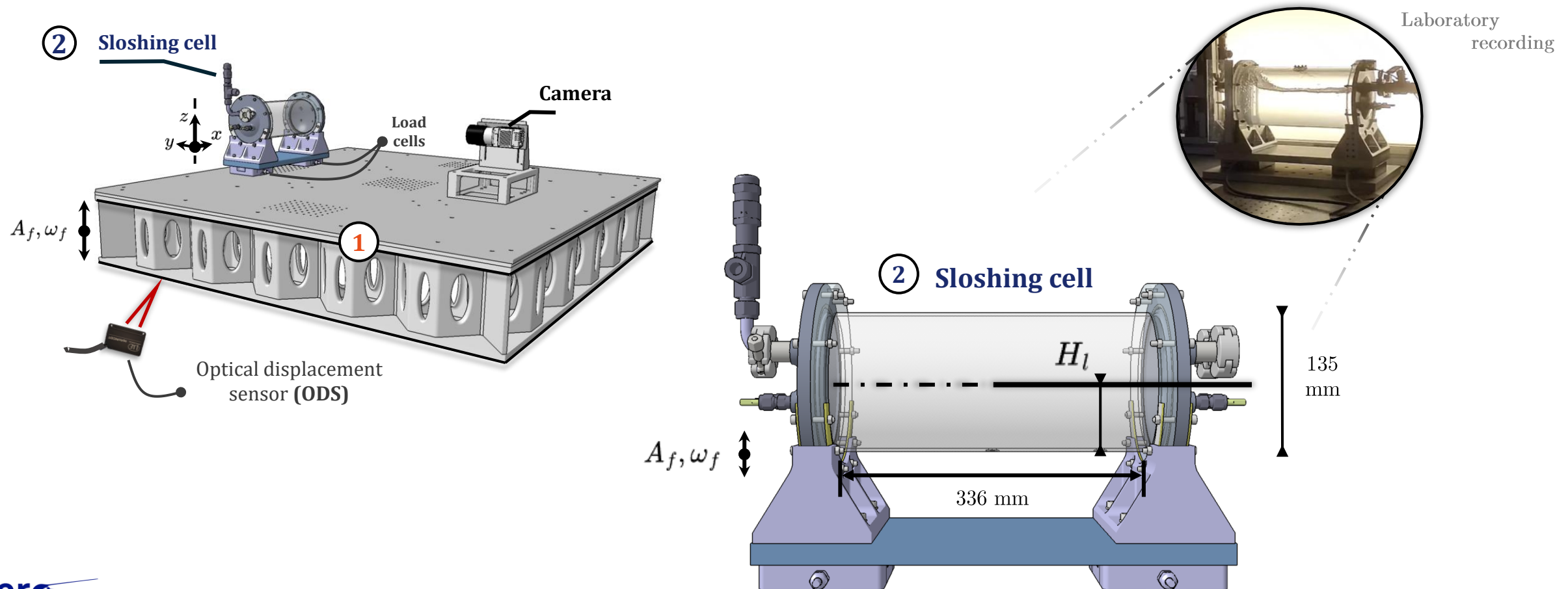
- Thermodynamic modeling
- “Online” learning



Control & Actuation

Sloshing in aviation applications

Objective: Characterization of liquid sloshing under conditions representative of **aviation flight environments**.

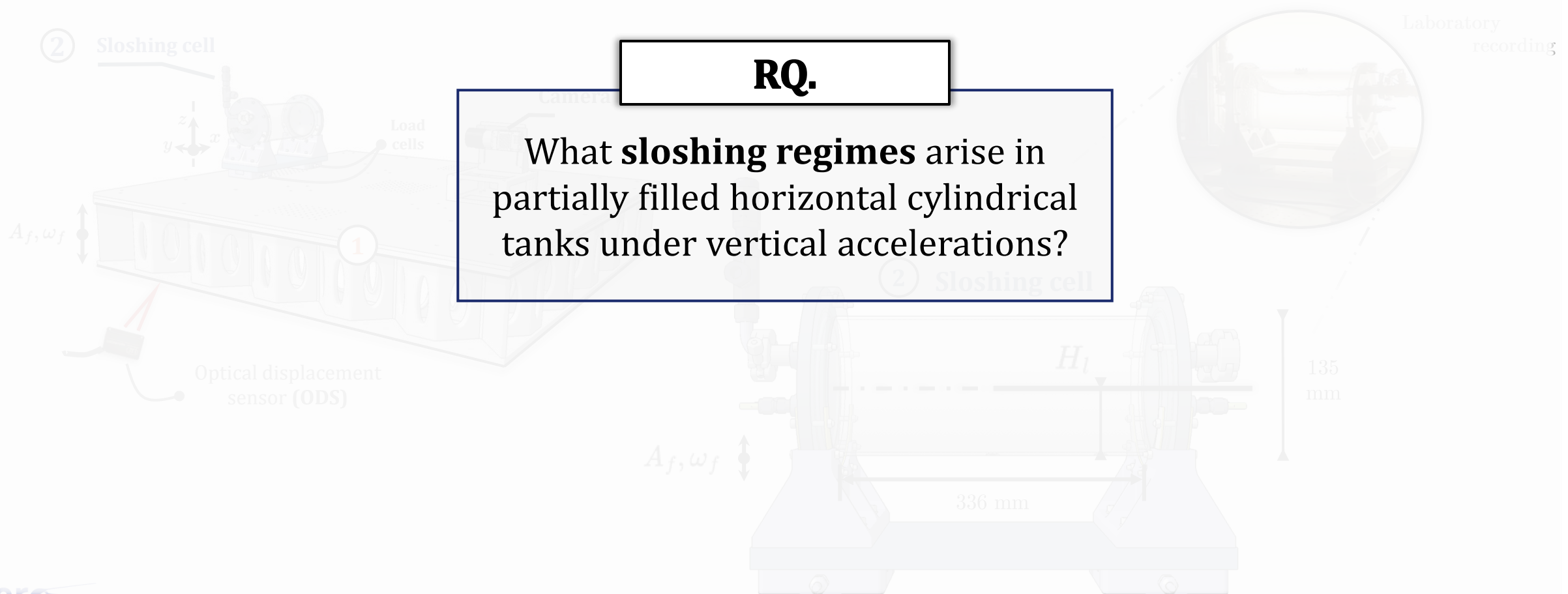


Sloshing in aviation applications

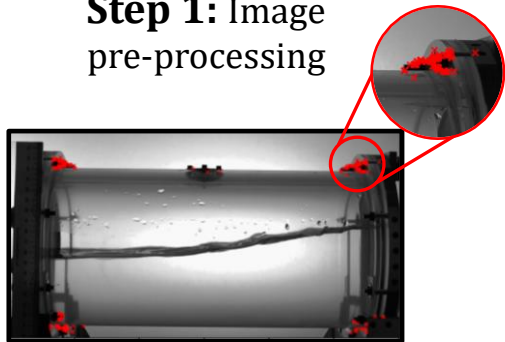
Objective: Characterization of liquid sloshing under conditions representative of **aviation flight environments**.

RQ.

What **sloshing regimes** arise in partially filled horizontal cylindrical tanks under vertical accelerations?



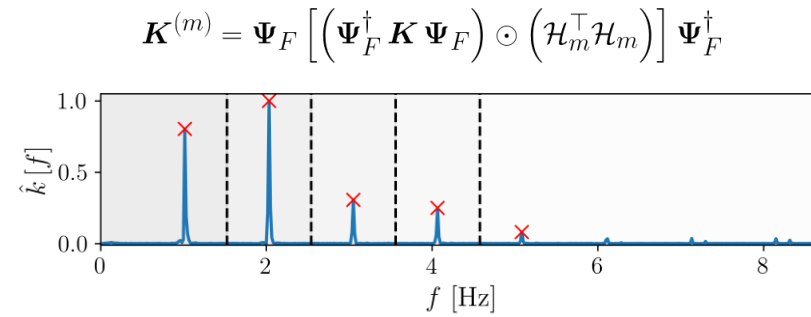
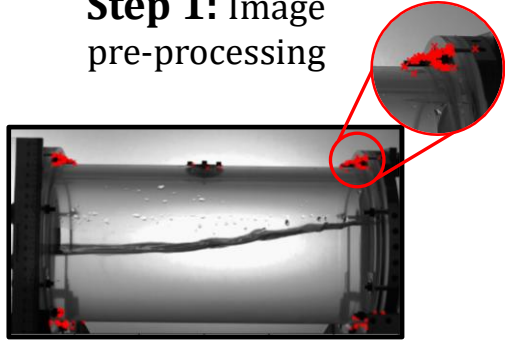
Step 1: Image
pre-processing



Sloshing in aviation applications

Step 2: multiscale Proper Orthogonal Decomposition (mPOD)

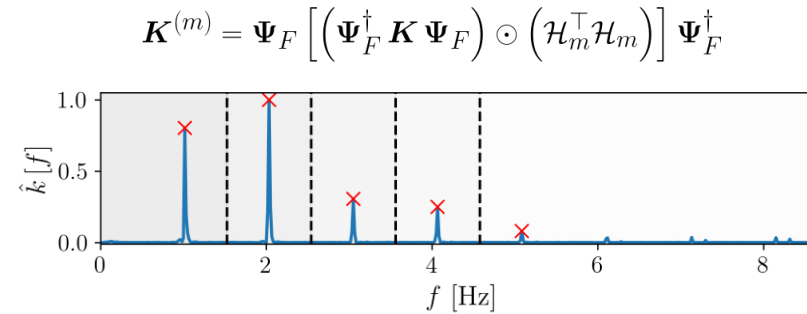
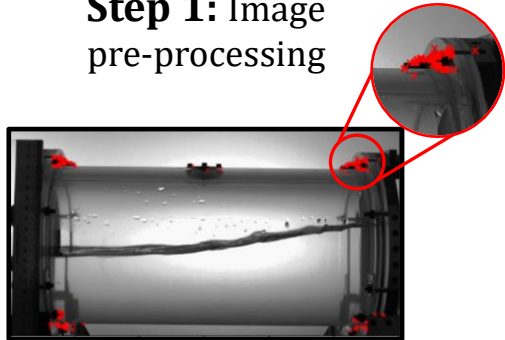
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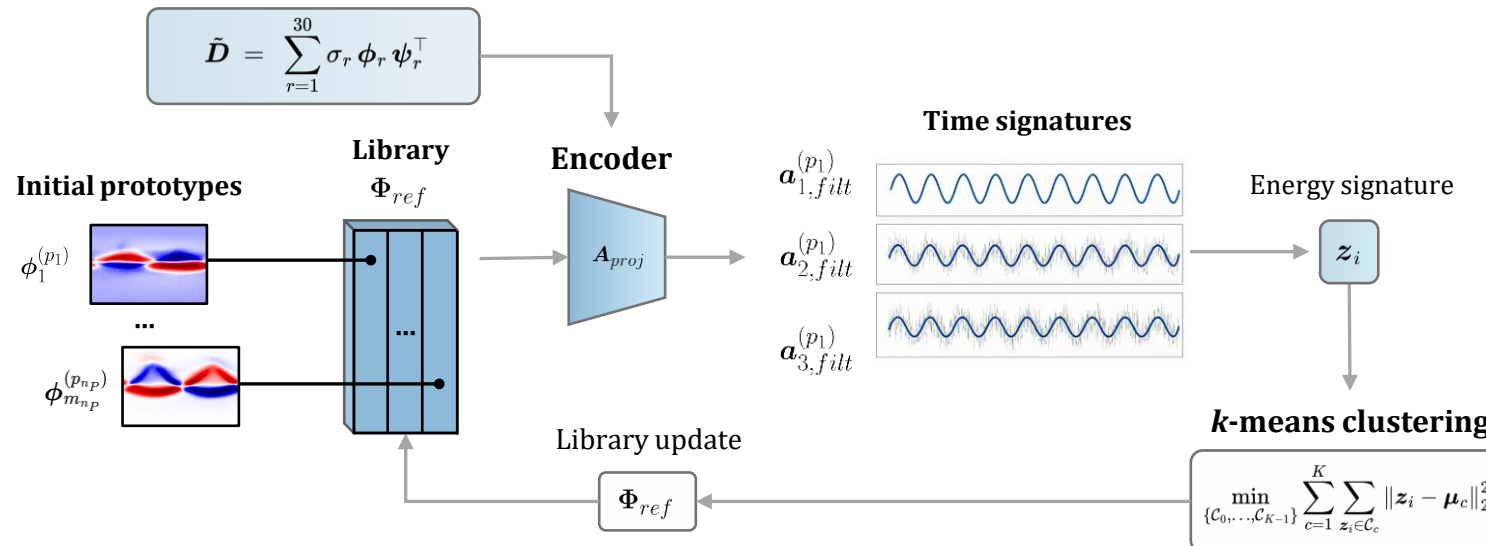
Sloshing in aviation applications

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Step 1: Image pre-processing



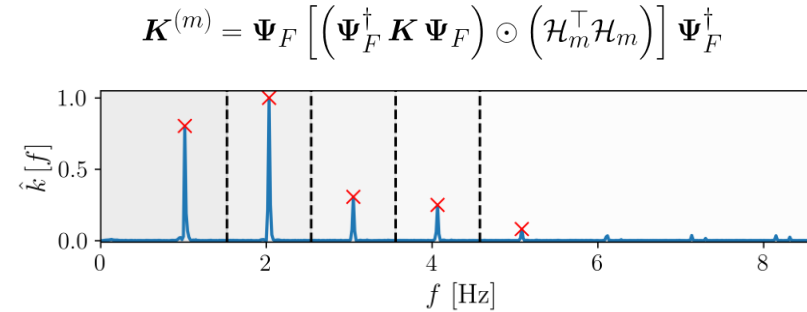
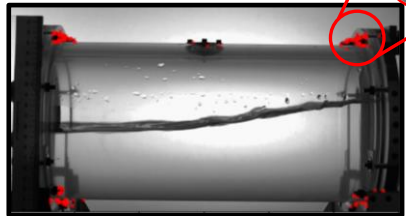
Step 3: Prototype-based data clustering



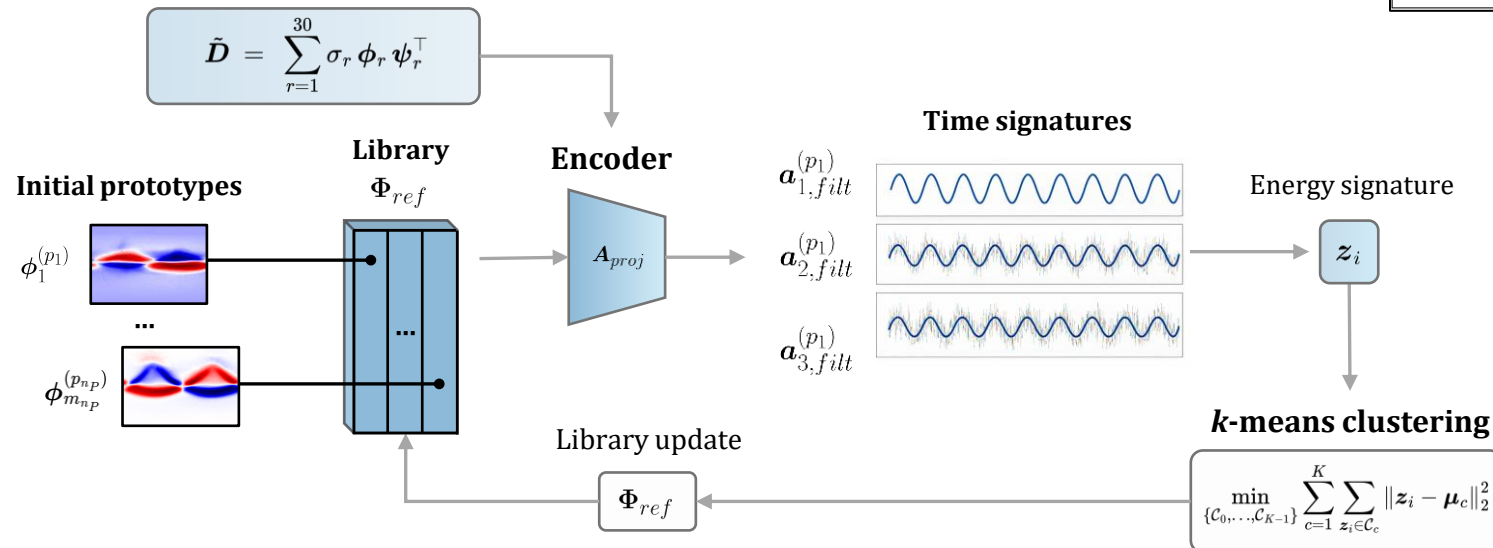
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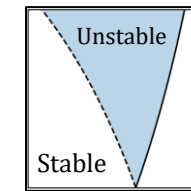


Step 3: Prototype-based data clustering



Step 4: Data classification and regime mapping

Mathieu equation

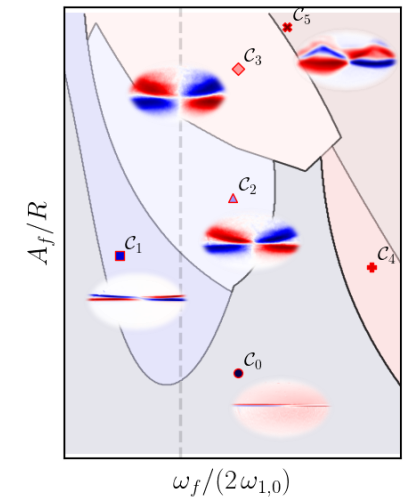


Physics informed

Parameter space

$$\mathbf{x}_i = \begin{bmatrix} A_f/R \\ \omega_f/(2\omega_{1,0}) \end{bmatrix}$$

Sloshing maps



Support vector machine (SVM)

[3] F. Monteiro, T. De Maria, S. Ahizi, R. Abarca, G. C. A. Caridi, and M. A. Méndez, Regime maps for sloshing in horizontal cylindrical tanks under vertical acceleration, arXiv, 2025.

Research Framework

Space applications

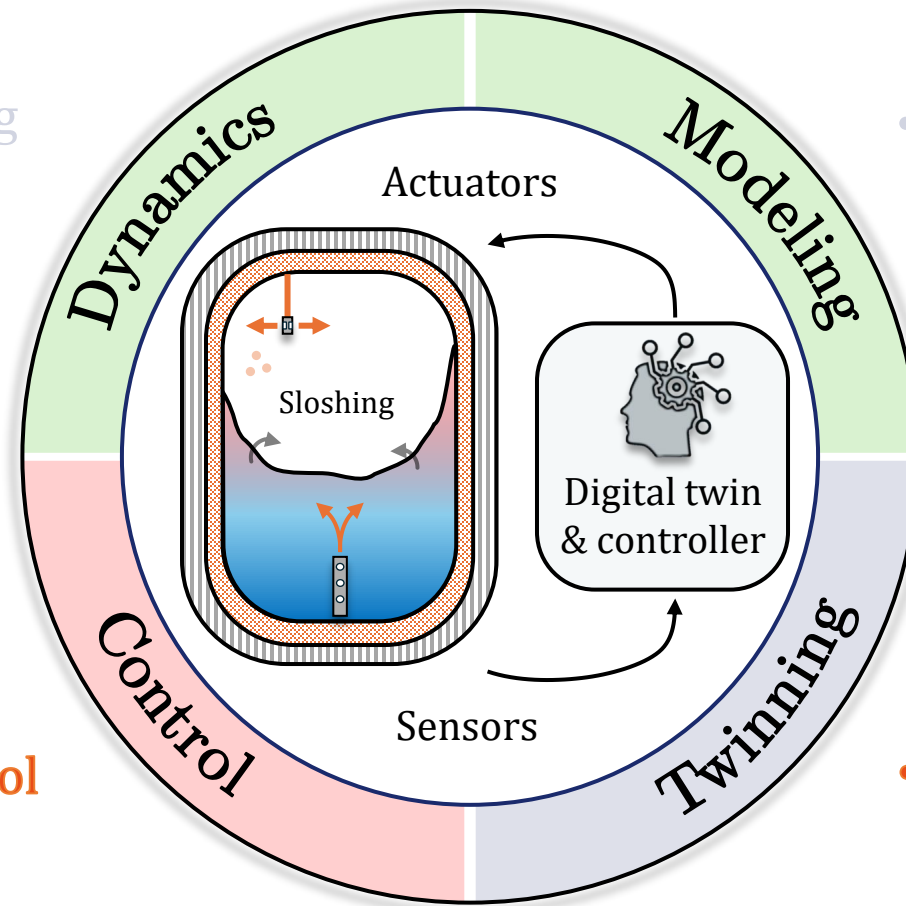
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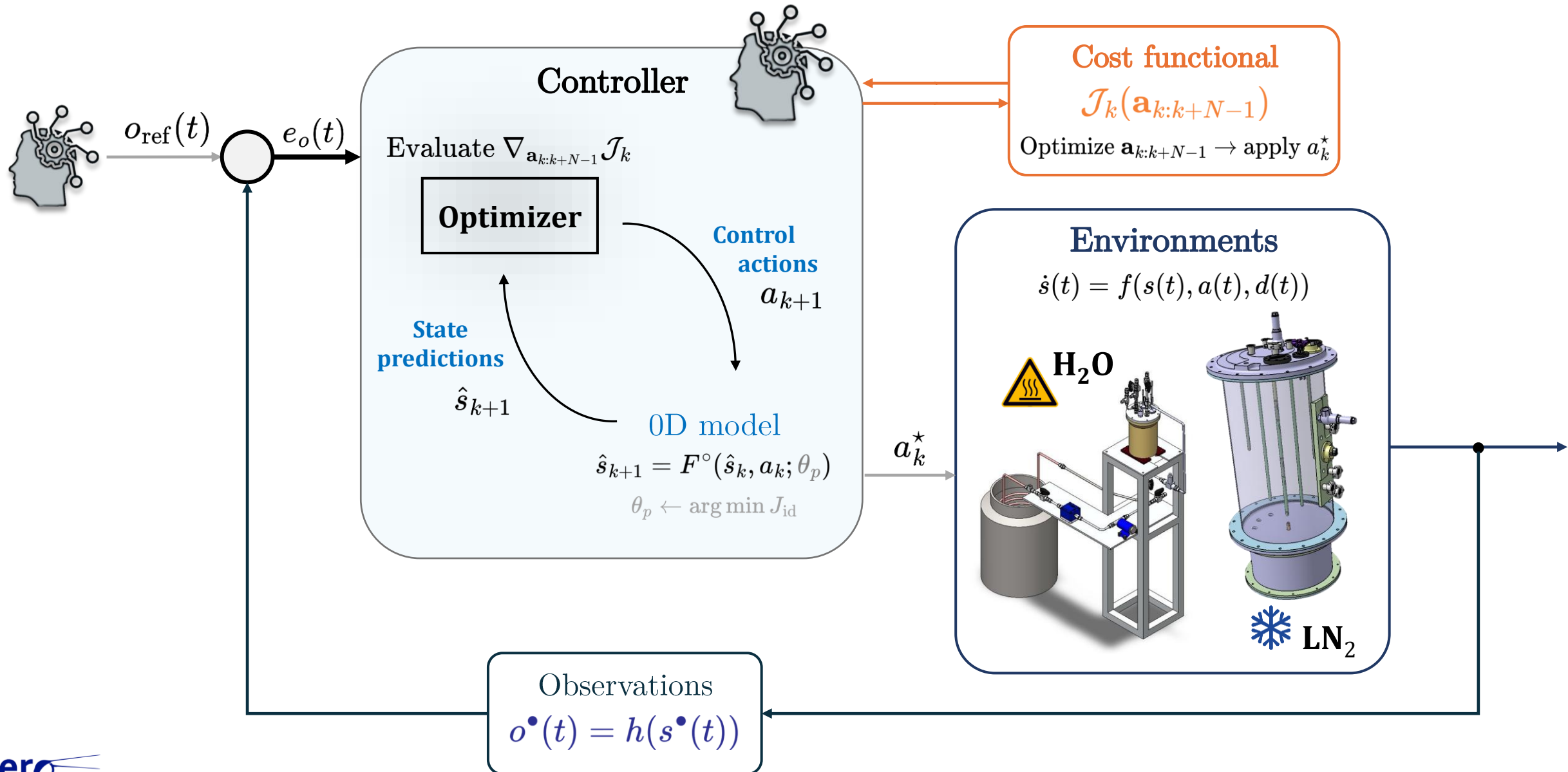
- **Actuators design**
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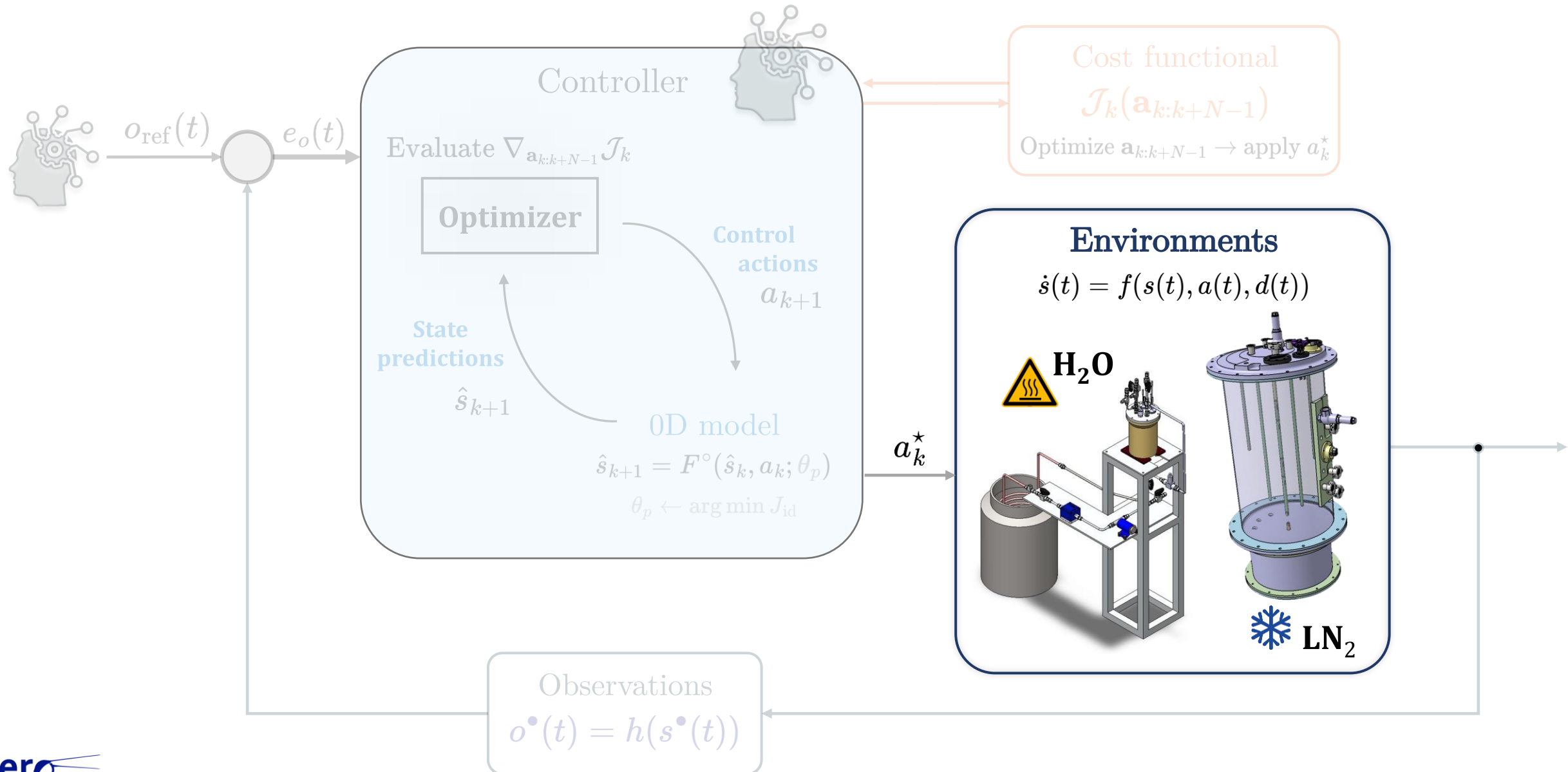


Control & Actuation

Twinning and control

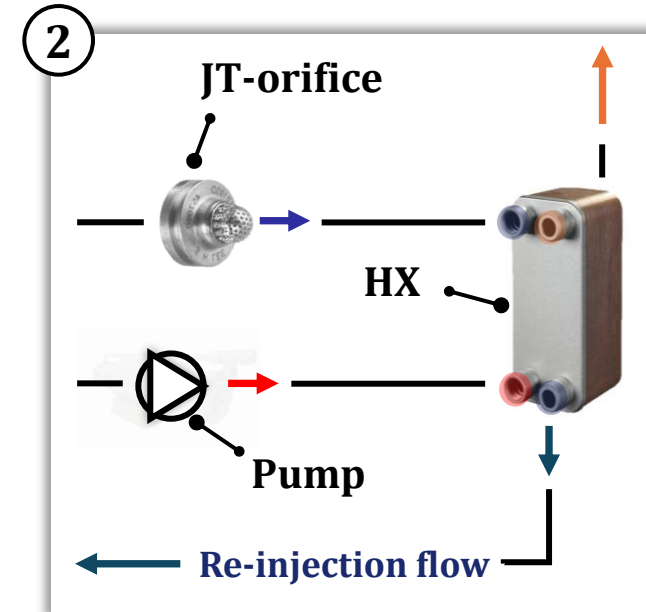
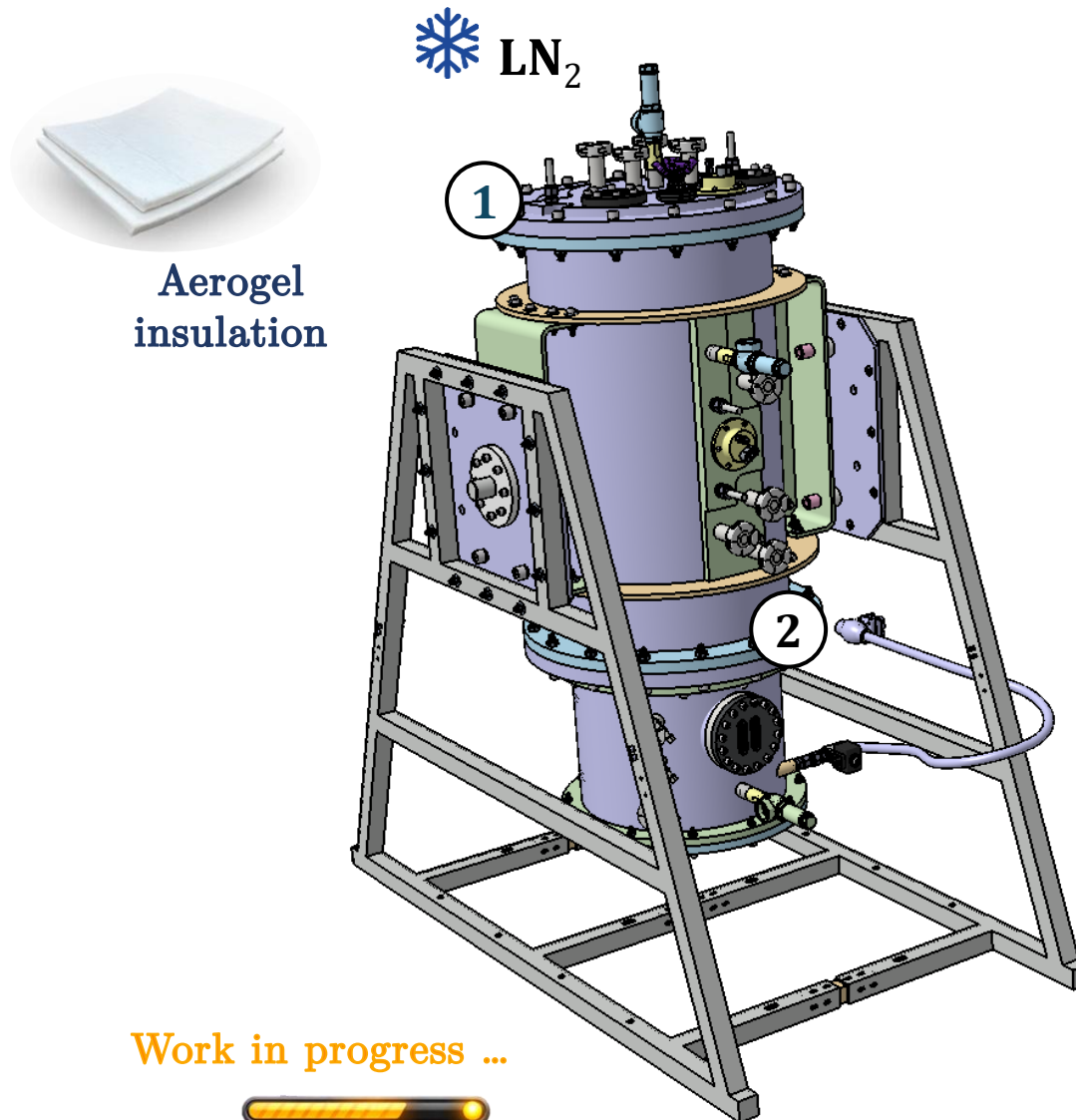


Twinning and control



Environments: Cryogenic facility

Vacuum chamber TVS



Work in progress ...



Environments: Cryogenic facility

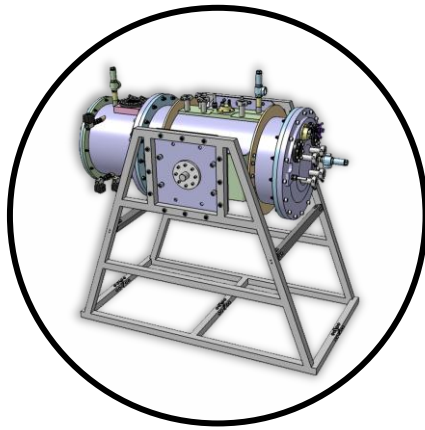
Vacuum chamber TVS

❄️ LN₂

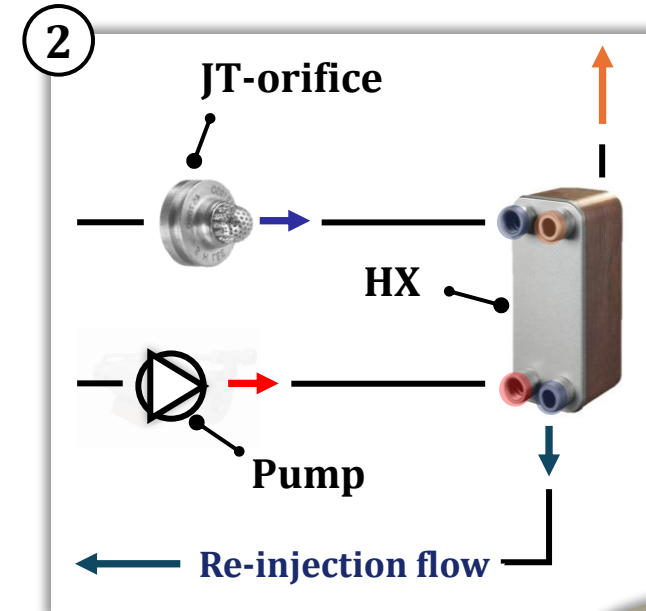
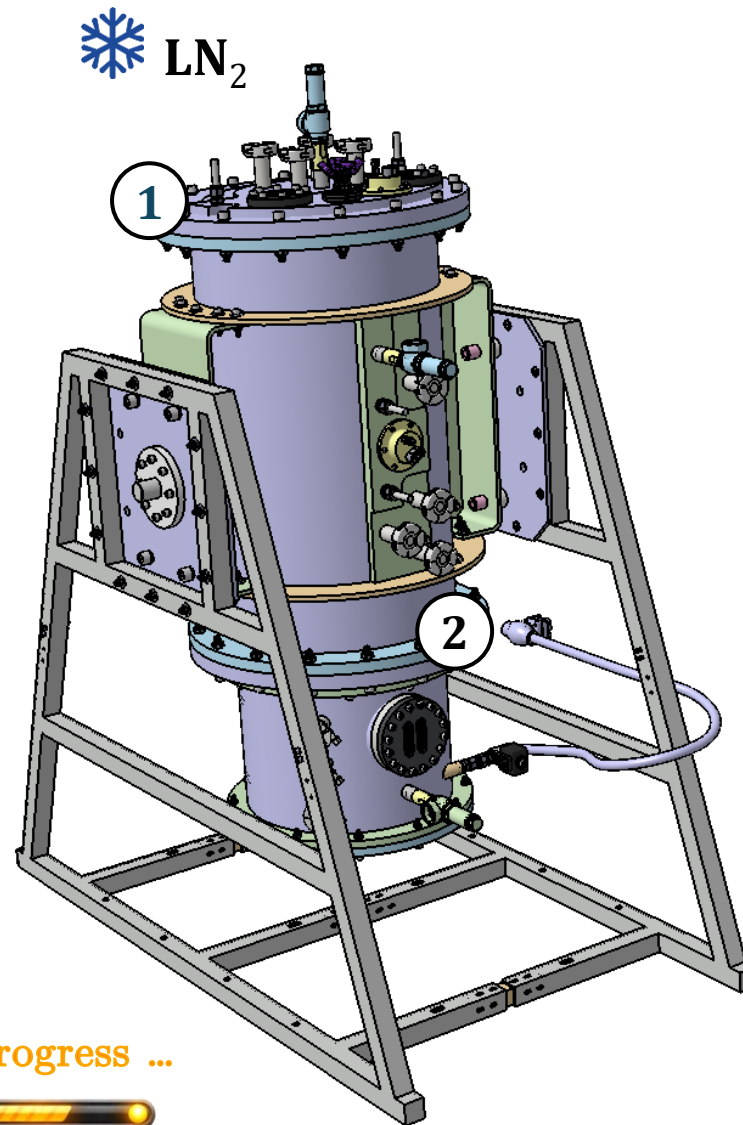


Aerogel insulation

Horizontal configuration



Work in progress ...



Valorization perspective

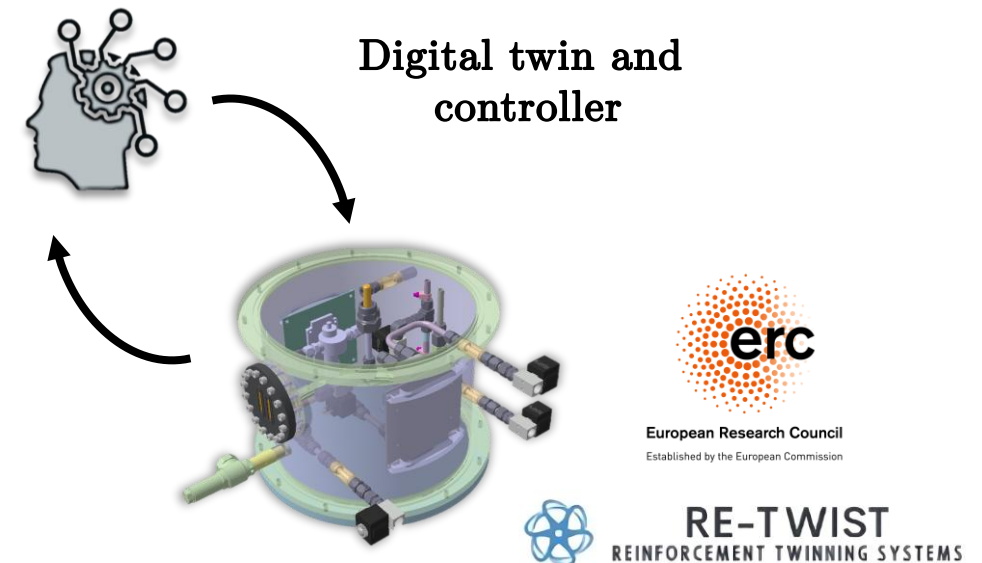
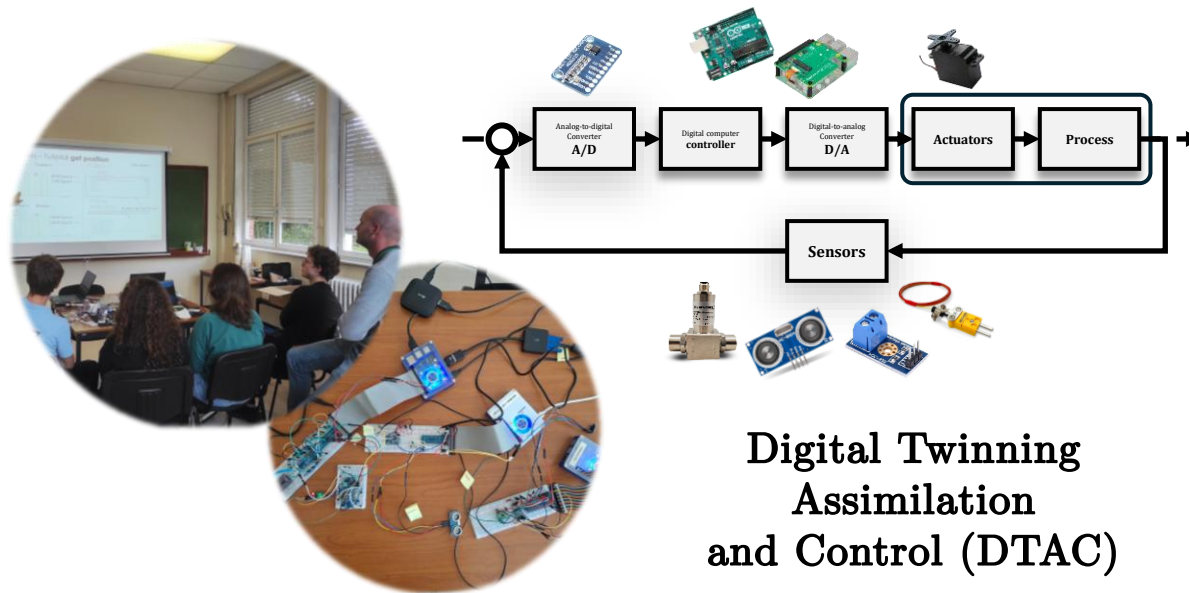
• Publications

- [1] Experimental characterization of non-isothermal sloshing in microgravity, ETFS, 2025
- [2] Regime maps for sloshing in horizontal cylindrical tanks under vertical acceleration, arXiv, 2025

• Teaching activities

• Conferences

- [1] Data-Driven Modal Decomposition and Automatic Classification of Parametric Sloshing Regimes in Horizontal Cylindrical Tanks, EUCASS, 2025
- [2] Experimental analysis of sloshing-induced thermal mixing in horizontally oriented cylindrical tanks subjected to vertical acceleration, EUCASS, 2025



Thank you for your attention!
Questions?



Francisco Monteiro^{1,2}

supervised by

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