THE CURIOUS CRYOGENIC FISH (CCF)

DEVELOPMENT OF A DIAGNOSTIC ROBOT FOR LARGE CRYOSTATS

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Outline

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  - Aim & Potential Applications
  - Technical Requirements

- State-of-the-art
  - Underwater Robotics
  - Space Robotics
  - Breakthrough character of the project

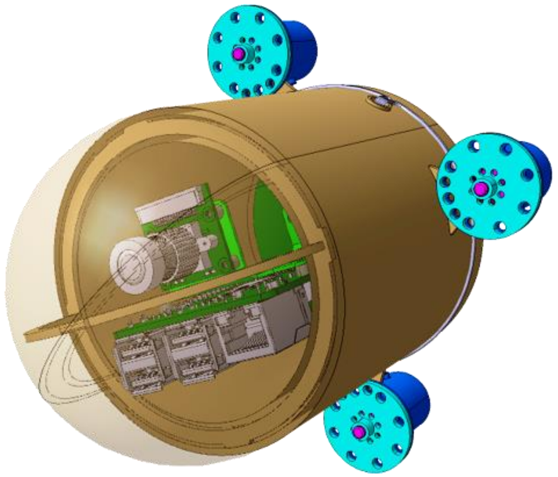
- Feasibility Studies
  - Visual Data Recording
  - Wireless Communication
  - Energy Storage
  - Propulsion

Project Overview

A robot for **operation inside large cryostats**, while filled and throughout their volume:

FUNCTIONALITIES

- Visual Inspections;
- Environmental Measurements;
- Repair Tasks;
- [in particle detectors] Support for Detector Calibration.



POTENTIAL APPLICATIONS

- Particle Physics Experiments (e.g., DUNE);
- Liquified Gas Transport;
- Cryogenic Plant Monitoring.

Technical Requirements

ENVIRONMENTAL

- Resistance to Thermal Stress & Pressure;
- Easy Mobility in confined volumes ⟶ - Compact Size (max 30cm-diameter);
  - Tetherless Operation.

PERFORMANCE

- *Operational Life*: several months (in DUNE-like experiments);
- *Rate of Operation*: 2-3 few-day missions per year (in DUNE-like experiments);
- *Level of Automation*: Semi-Autonomous.

CONSTRAINTS

- No Damage/Interference to the working environment

  ⟶ No contamination of cryogen, Autonomous "parking", etc.;
- [in particle detectors] No Maintenance when the detector is running.

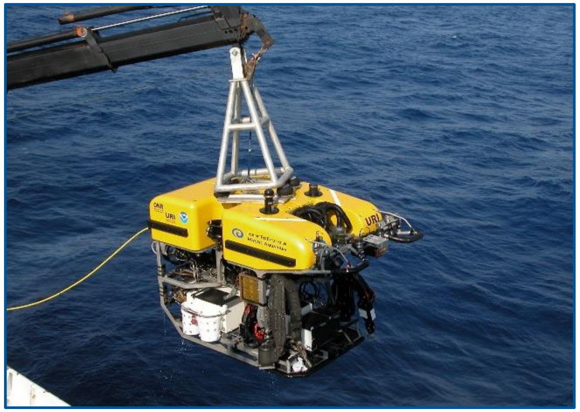
State-of-the-art – Underwater Robotics

WHY The CCF is a *tetherless semi-autonomous underwater vehicle*

- Prominent and expanding role in commercial, scientific and military applications;
- Powerful operation in harsh environments;
- *Propulsion*: Thrusters + Control Surfaces;
- Use in liquids other than water is quite a novelty;
- Autonomous Manipulation still a challenge.

ROVs (Remotely-Operated Vehicles)

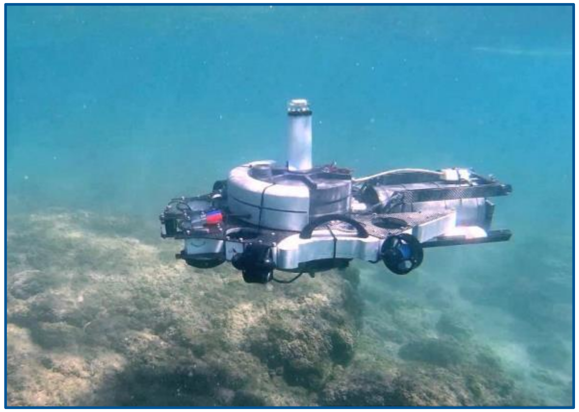
Tethered to operator and power source



Courtesy of *Ocean Exploration Trust, Inc. (OET)*

AUVs (Autonomous Underwater Vehicles)

Untethered, Self-Powered, often Fully Autonomous



Courtesy of *MDM Team, University of Florence (IT)*

State-of-the-art – Space Robotics

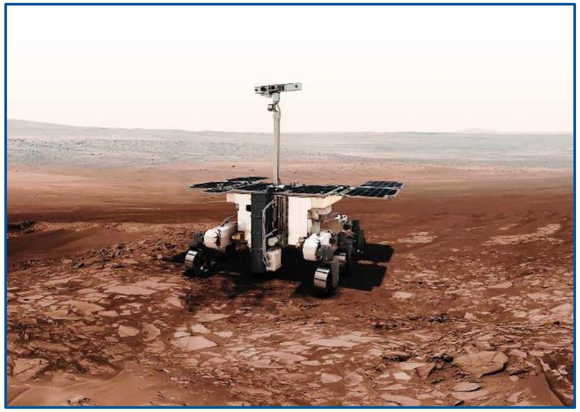
WHY The *highest reliability in extreme environments* is required

- Fundamental for both planetary and orbital missions;
- *Control*: Teleoperation;
- Much is still to be done: Diversified Locomotion & Increased Autonomy.

POTENTIAL CONTRIBUTIONS

- **Power and Thermal System**

  RTG (Radioisotope Thermoelectric Generator): decades of operation with no maintenance.
- **Actuators**: Reliability in operation and control.



Courtesy of *ESA*

Courtesy of *NASA*

Breakthrough Character of the Project

- **First device** for thoroughly inspecting large cryostats while filled

  ⟶ - No Periodic Shutdown for maintenance;

  - No severe Contamination or Mechanical Failures;

  - No Distributed Sensors and Cameras.

- Integration of technologies in a single cryo-capable device;

- Enhancement of technologies to work in a cryo environment;

- **Innovative Propulsion**: Jet Propulsion based on Cryogen Heating

  - Exploitation of the environment:

    Cryogen close to boiling point ⟶ Rapid expansion with little heating;

  - Minimum use of Moving Parts ⟶ Prolonged Durability + Reduced Maintenance;

  - Less efficient than Thrusters.

Visual Data Recording

At cryo temperatures:

- Many COTS electronic parts still functional;
- Some imagers have guaranteed cold-capability;
- No Cameras able to operate: Performance Degradation or Failure.

Solution A: Development of custom electronics **REJECTED**

- Long R&D required

Solution B: Integration of COTS parts **REJECTED**

- Parts Selection + System Validation

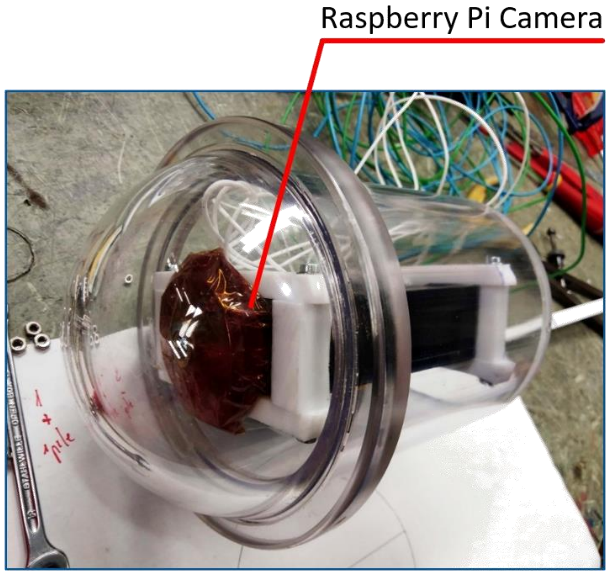
Solution C: Commercial cameras within heated cases **TESTED**

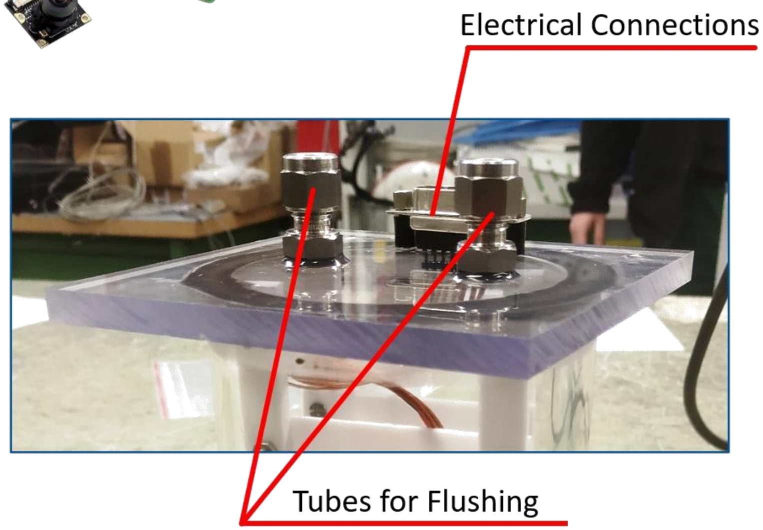
- **Successful reactivation** after long exposure to LAr (87K), by heating back to operating temperatures (above -40°C);
- Additional energy for heating.

Wireless Communication, I

- **AIM** Transmission of data produced onboard **+** Control of the robot;
- **Successful Wi-Fi Data Transmission in LAr** experimentally demonstrated.

- Wi-Fi Netcam (*Raspberry Camera v2*) in a transparent, protective case;
- Heating Pads on the camera;
- Case continuously flushed with nitrogen.





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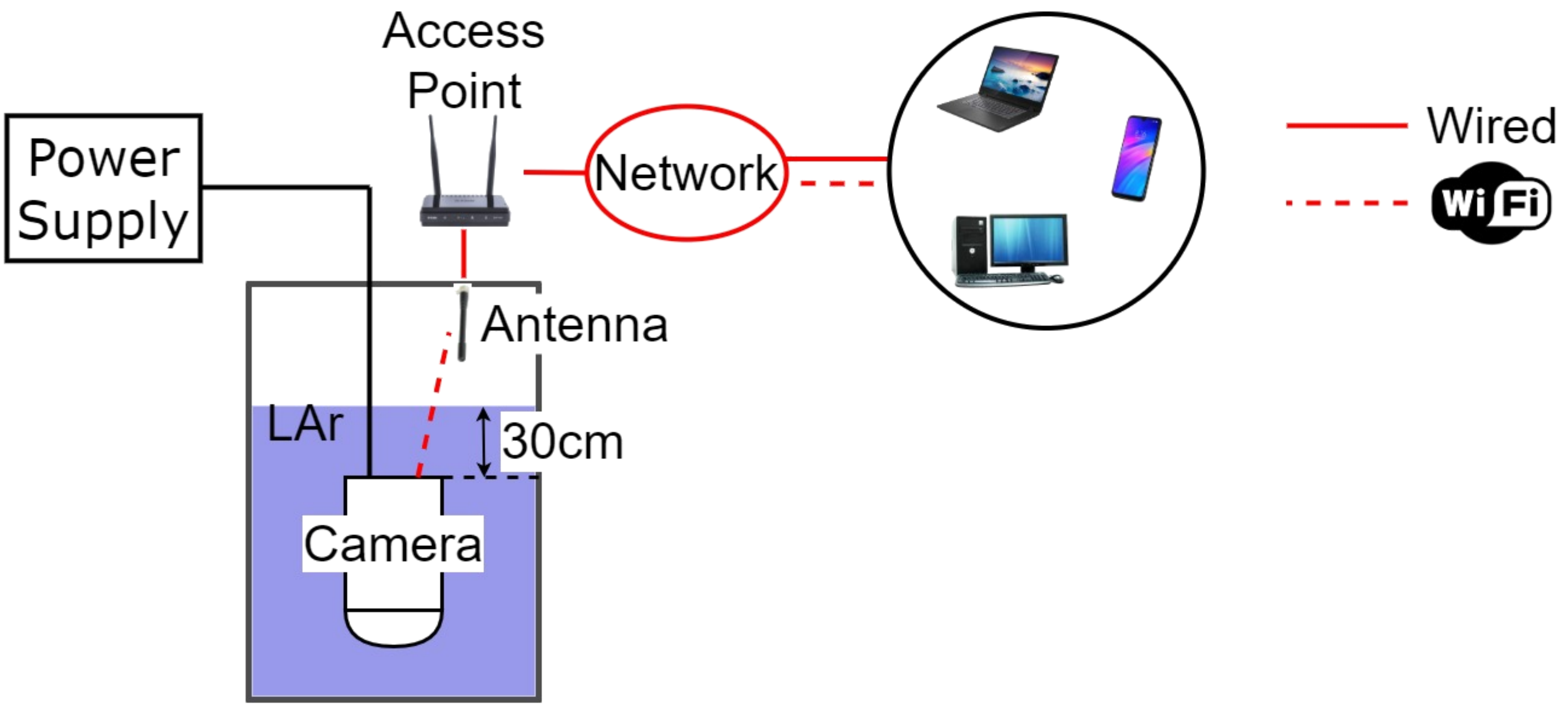


Wireless Communication, II

- Network connection established – Video stream transmitted;
- Any device on the network could access the video stream and drive the camera;
- Camera temperature always kept in its nominal range (-40° to 85°C).

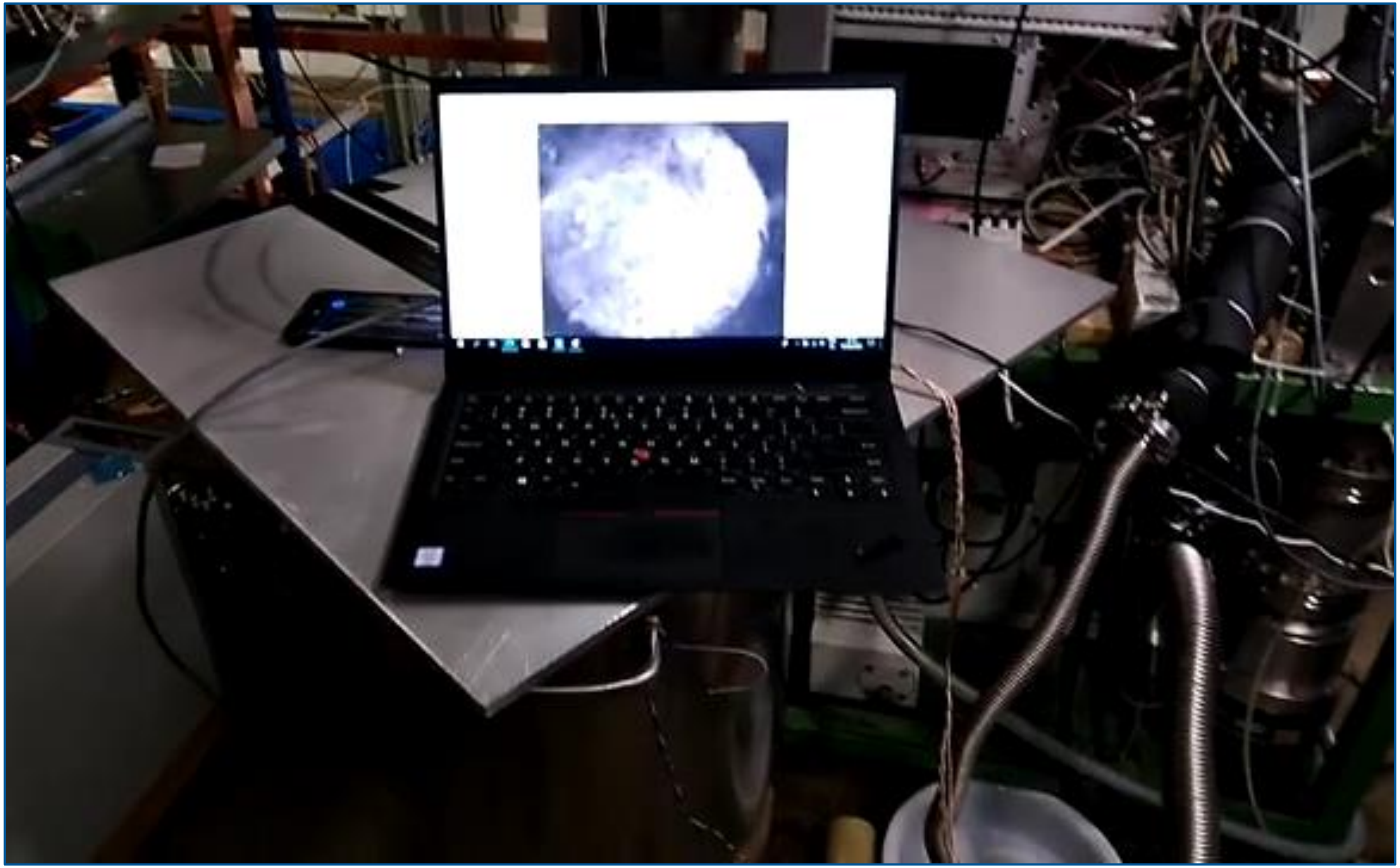
RESULTS (compared to RT operation)

- Connection established with no significant delay;

During the entire test run (more than 30min):

- Connection active with no major degradation;
- Responsiveness to remote commands not significantly delayed;
- Video stream simultaneously accessible to all connected devices;
- Video quality not appreciably degraded,
  regardless of the number of connected devices.

Wireless Communication, II



Energy Storage, I

- Low-Temperature operation of any battery is a serious issue;

- **Solution**: to identify batteries surviving storage at cryo temperatures,
  + to heat back to operating temperatures before use;

  CCF in "hibernation mode" until reactivated;
  Battery heated with an external power link.

- Use of Li-ion batteries experimentally explored:

- Battery (*standard* - 14.8V 5.2Ah) immersed in LAr (87K);
- Double protective case;
- Heating Pads on the battery;
- Innermost case continuously flushed with nitrogen;
- Possibility of Vacuum between the two cases.

Energy Storage, II

RESULTS

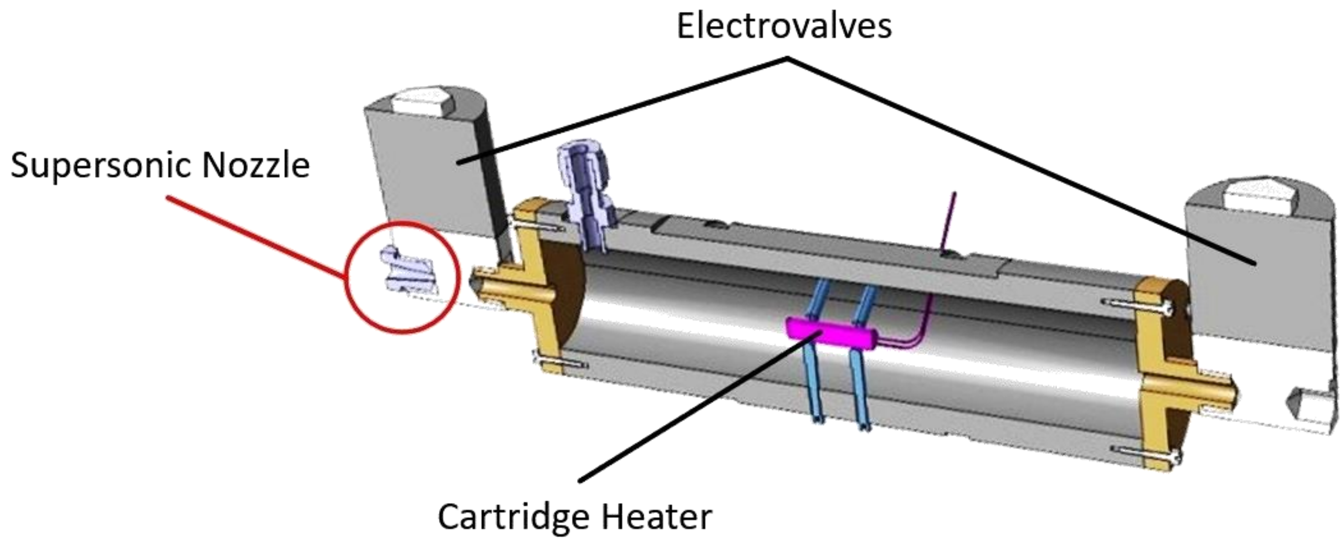
- Battery proved to:
  - Survive in storage mode at low temperatures;
  - Be operational again when heated to operating temperatures (above -30°C);

- *Long-Term Durability*: Promising results, but more studies are needed;

- *Insulation*:
  - Vacuum sufficient to keep temperature in the nominal range;
  - Heaters for redundancy;

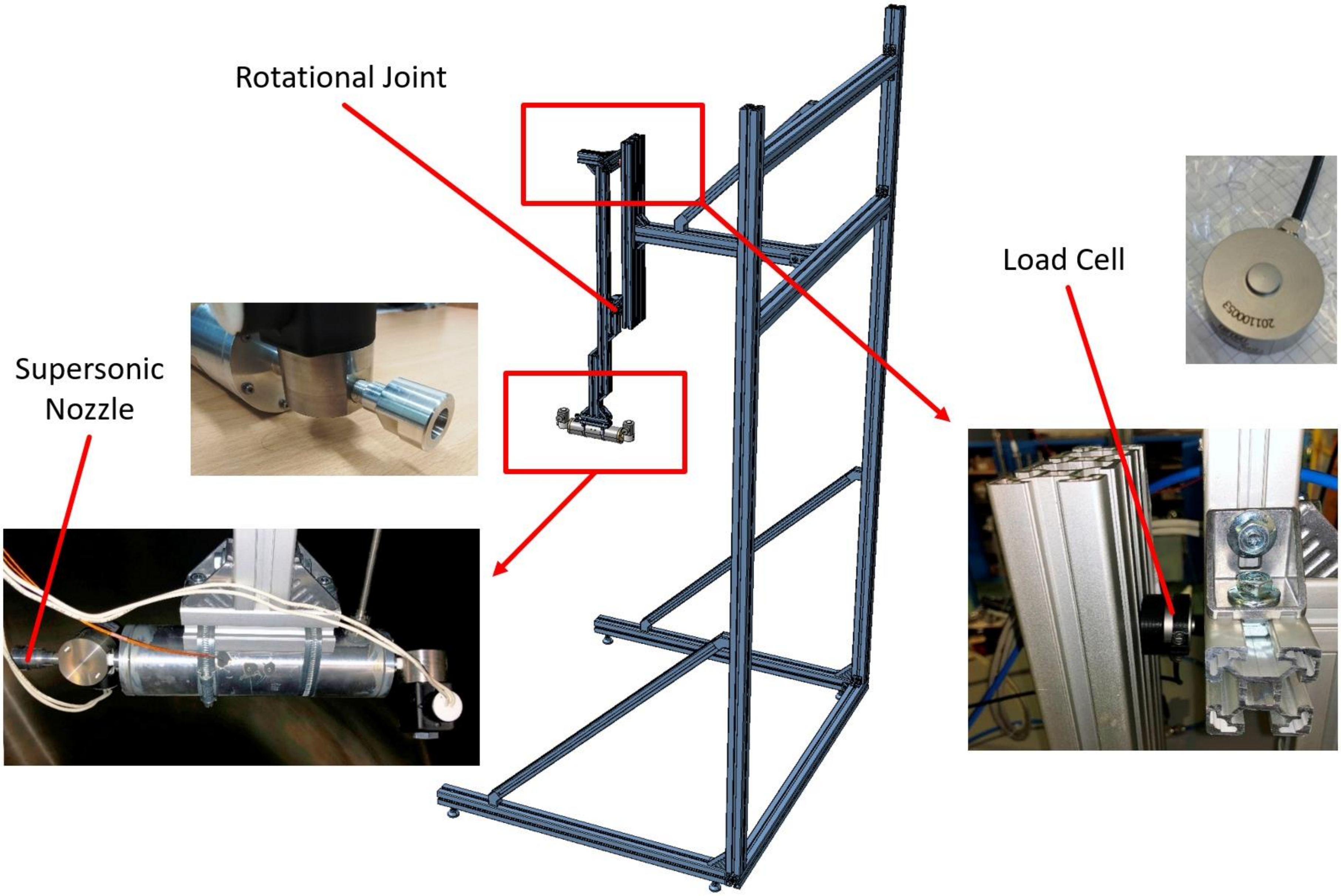
- Enhanced performance with specialised batteries.

Propulsion – Prototype A

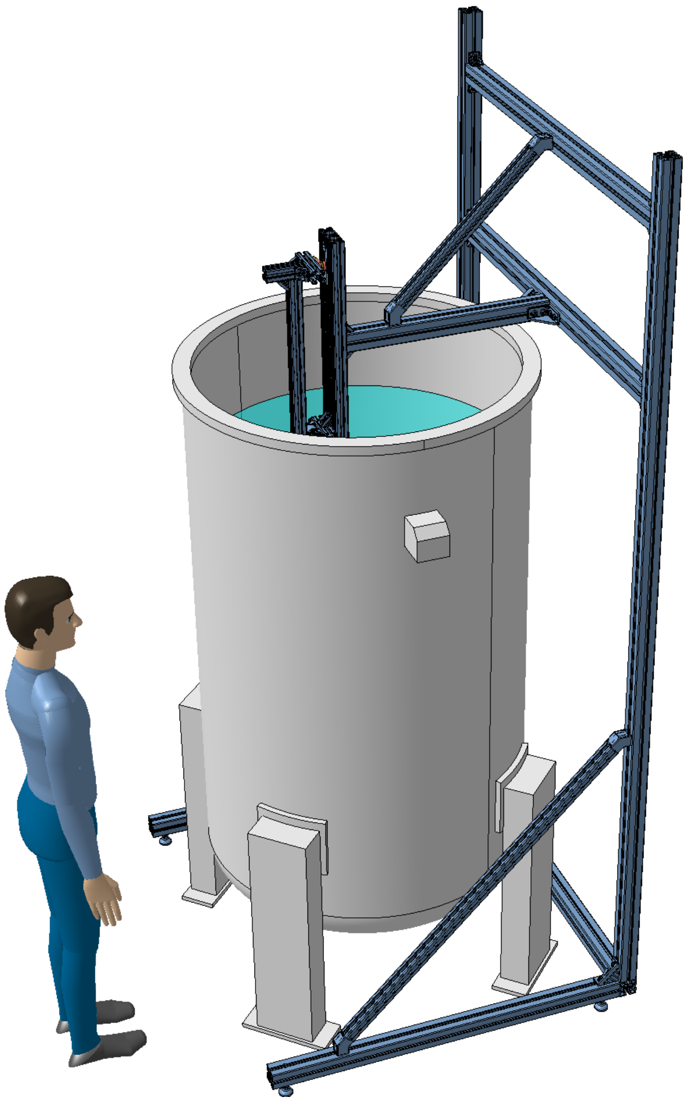


1. Compartment filled with cryogen;
2. Compartment closed + Cryogen heated;
3. One valve open ⟶ Thrust generated by high-pressure fluid emerging through the nozzle.

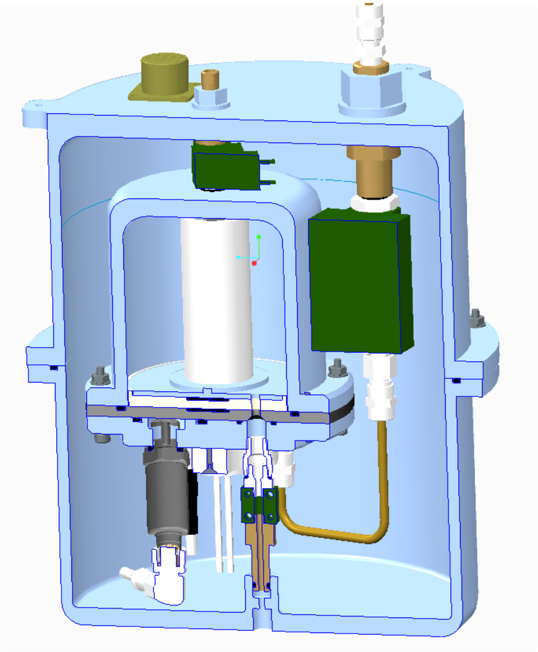
- Simulations to determine optimal nozzle size and shape;
- Tested directly in LAr.

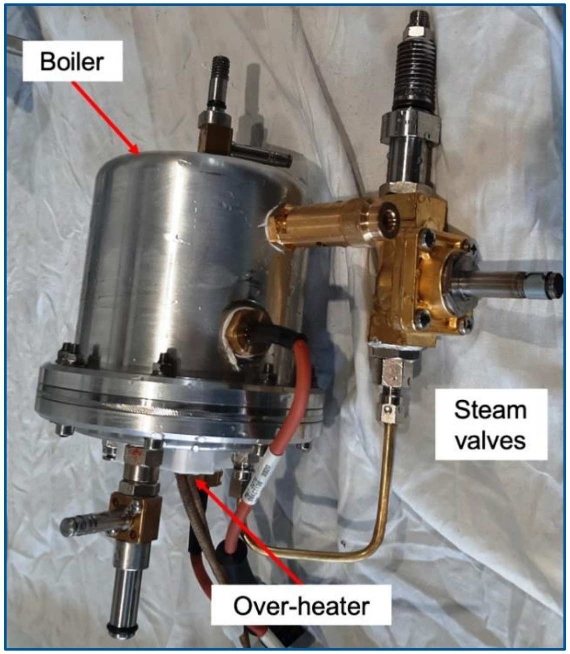

Rotational Joint
Load Cell
Supersonic
Nozzle

Propulsion – Prototype A



Propulsion – Prototype B





Centralized steam generator supplying a network of *supersonic nozzles*

1. Boiler (for liquid evaporation);
2. Over-Heater (for increasing steam temperature and pressure);
3. Pressurized steam selectively distributed over the nozzles for propulsion.

- Heat from the boiler also used to regulate robot temperature;
- Tested in *R245fa* (LAr simulant).

Thanks

for

your attention!

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