FLOAT – Flexible Levitation on a Track

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Mission Overview

Build the **first lunar railway**, to provide reliable, autonomous, efficient payload transport on the Moon.

Deploy 100-1000s of **unpowered, individually-controllable, meter-scale levitating magnet robots** over a **flexible track** to perform the repetitive transportation tasks between a lunar base, ISRU mining / refining sites, lunar landers, and other outposts.

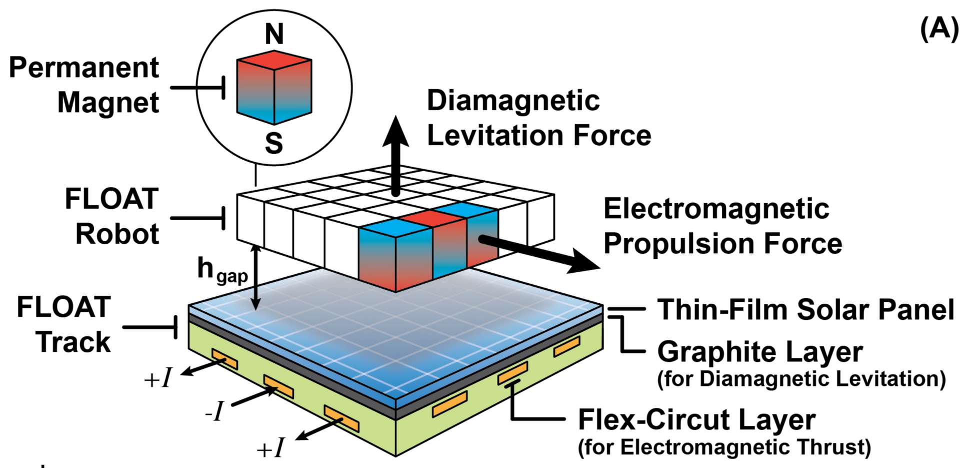
Challenge – Provide autonomous, reliable payload transport across the inhospitable lunar environment to facilitate ISRU and long-term base operations. Existing concepts require significant site preparation and substantial infrastructure, or consume operational life of sophisticated robots.

Innovation – FLOAT consists of **unpowered magnet robots** that levitate over a **3-layer flexible film track:**

- Thin-film solar panel generates power
- Graphite layer enables robots to **passively float** over tracks using diamagnetic levitation
- Flex-circuit layer generates electromagnetic fields to **controllably propel** robots along tracks

Robots have **no moving parts** and support **30+ kg/m² payloads** on the Moon, and tracks unroll directly onto lunar regolith (with limited preparation) to avoid major on-site construction.

Builds on the Diamagnetic Micro-Manipulator system invented at SRI International.



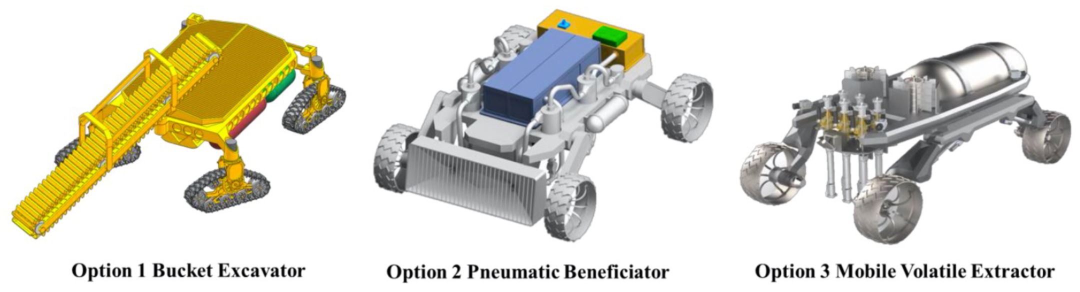
Robotic Lunar Surface Operations 2 (RLSO2)

The Robotic Lunar Surface Operations 2 (**RLSO2**) [1] mission concept envisions:

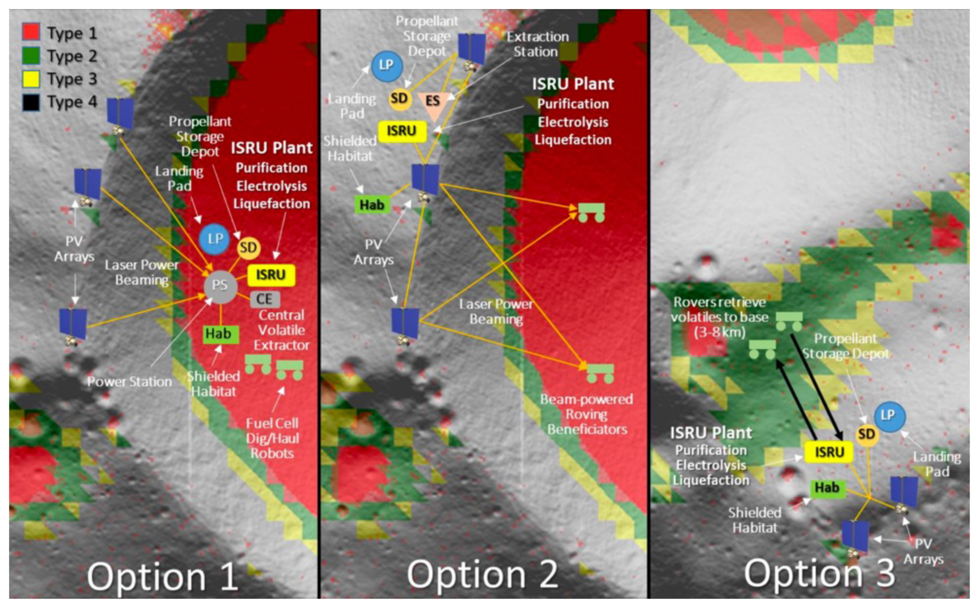
- Human-tended base at the lunar south pole, near the Shackleton Crater
- ISRU of water ice deposits used to support base operations and refuel spacecraft (multiple visits planned per year)

3 site layouts are explored (see figure to right), including establishing a complete lunar base within Shackleton Crater near resource-rich regolith, or establishing the lunar base on the Shackleton Crater rim and transporting beneficiated regolith or refined water ice from more remote mining sites.

Various **resource extraction robots** are proposed for each mission option:

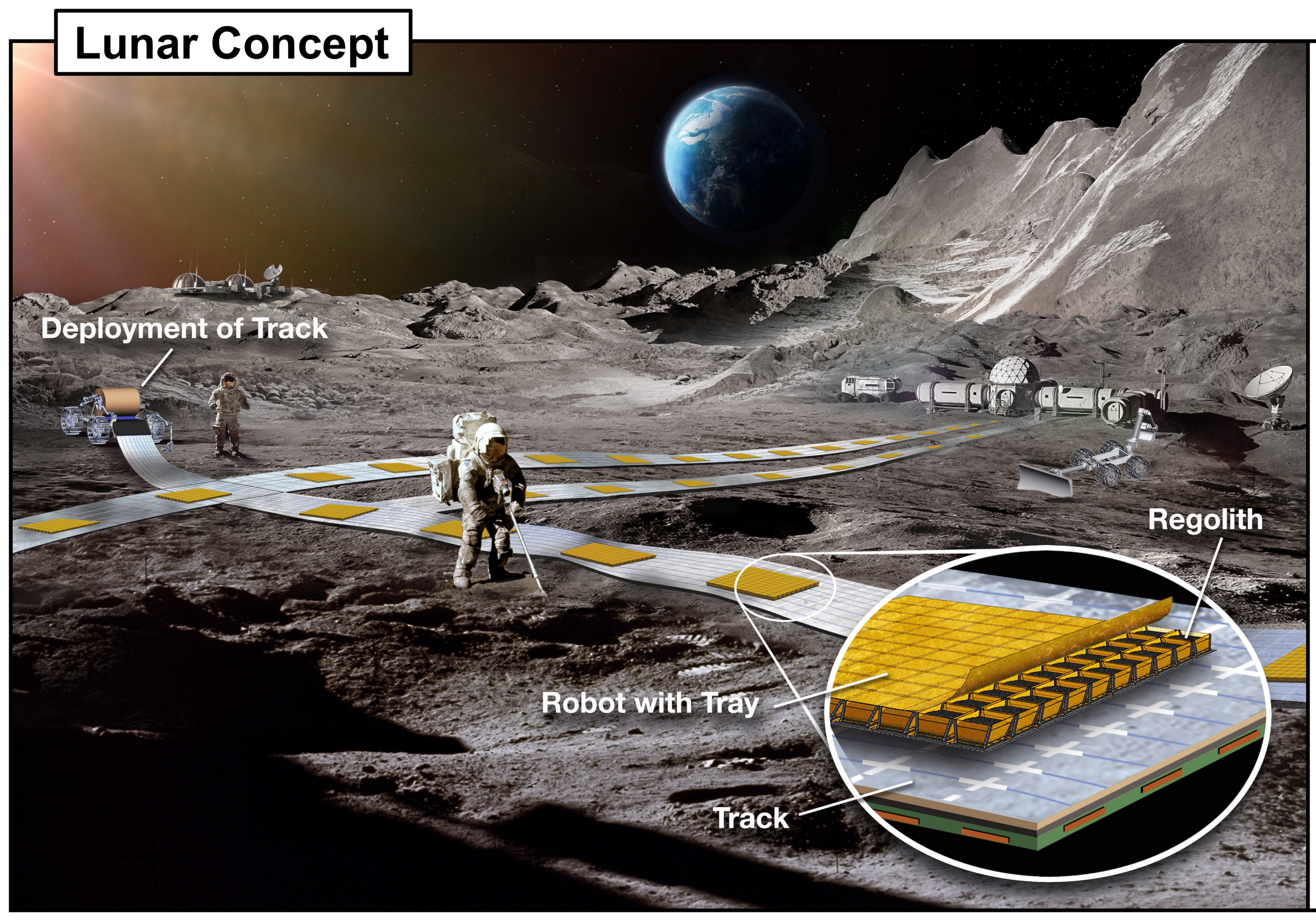


[1] Austin, A., *et al.* "Robotic Lunar Surface Operations 2", Acta Astronautica, vol. 176, 2020



Mission Description		Volume [kg/day] (Material)	Distance [km]	Terrain	Sunlight
Option 1	Base / mining in Shackleton crater	236,000 (raw regolith)	<1	Flat	None
Option 2	Base on Shackleton rim / mining in crater	80,000 (beneficiated regolith)	~10	Sloped	Partial
Option 3	Base / mining on Shackleton West Ridge	1,130 (water)	3-8	Moderate	Majority

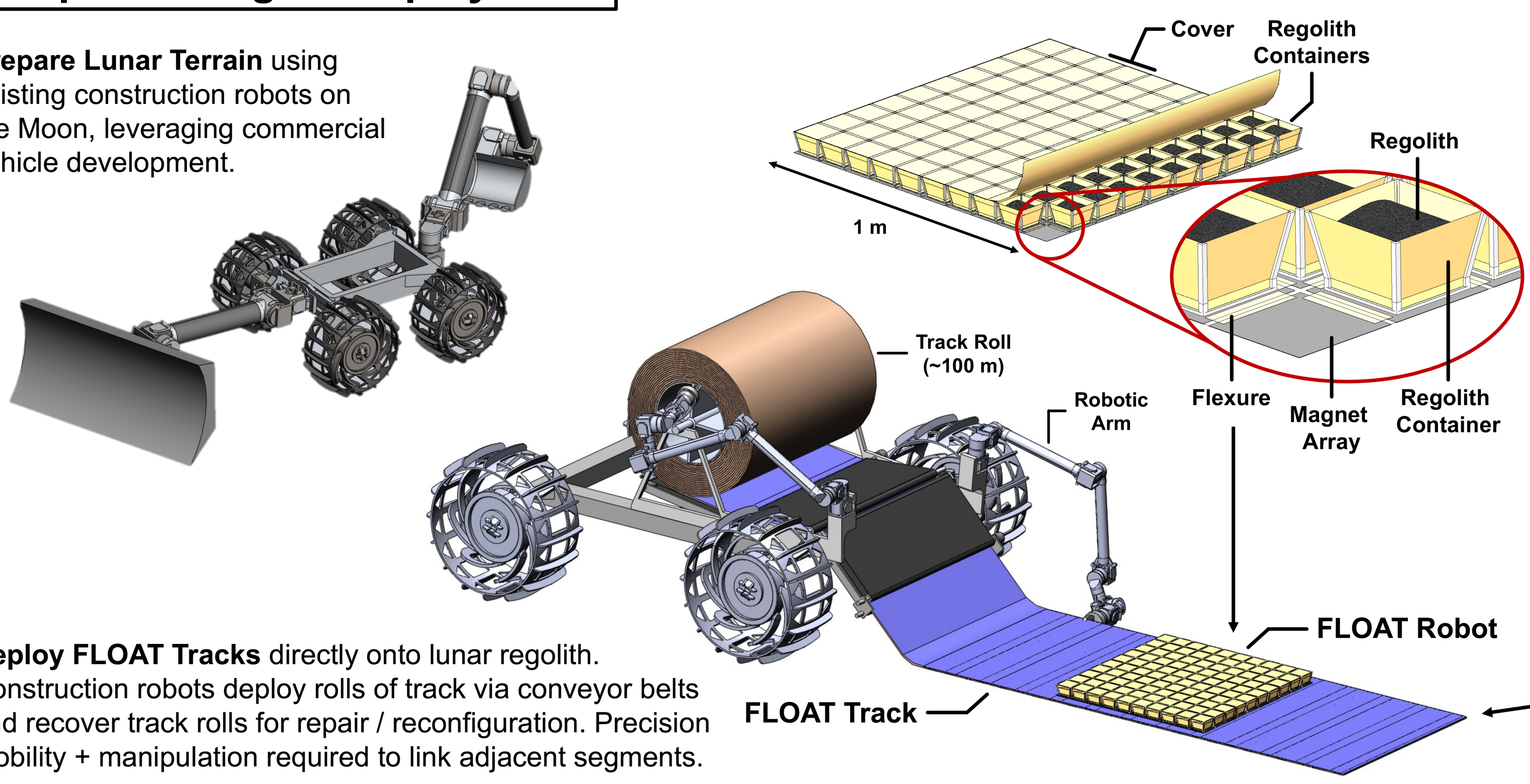
Lunar Concept



Concept of Design + Deployment

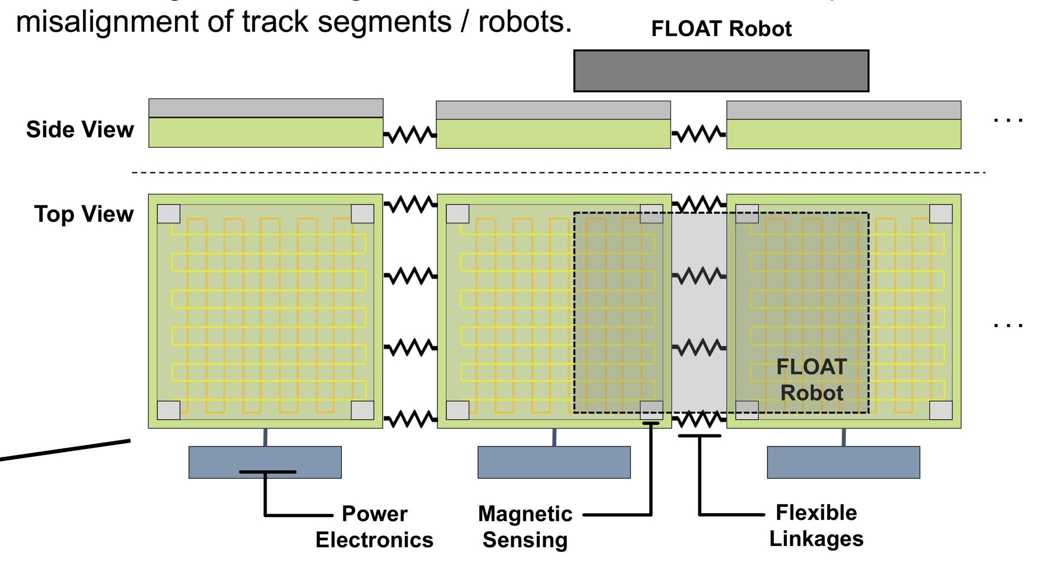
① **Prepare Lunar Terrain** using existing construction robots on the Moon, leveraging commercial vehicle development.

② **Deploy FLOAT Tracks** directly onto lunar regolith. Construction robots deploy rolls of track via conveyor belts and recover track rolls for repair / reconfiguration. Precision mobility + manipulation required to link adjacent segments.



③ **FLOAT Robots** consist of magnet arrays linked by flexures, and support **Regolith Containers** that passively align and secure to magnet arrays while maintaining robot compliance. Magnet + film construction is lightweight, low-cost, and uses flight-qualified materials.

FLOAT Track Segments are composed of self-contained meter-scale panels, connected by flexible linkages to minimize thermal expansion effects. Magnetic sensing + feedback used to correct for in-plane misalignment of track segments / robots.



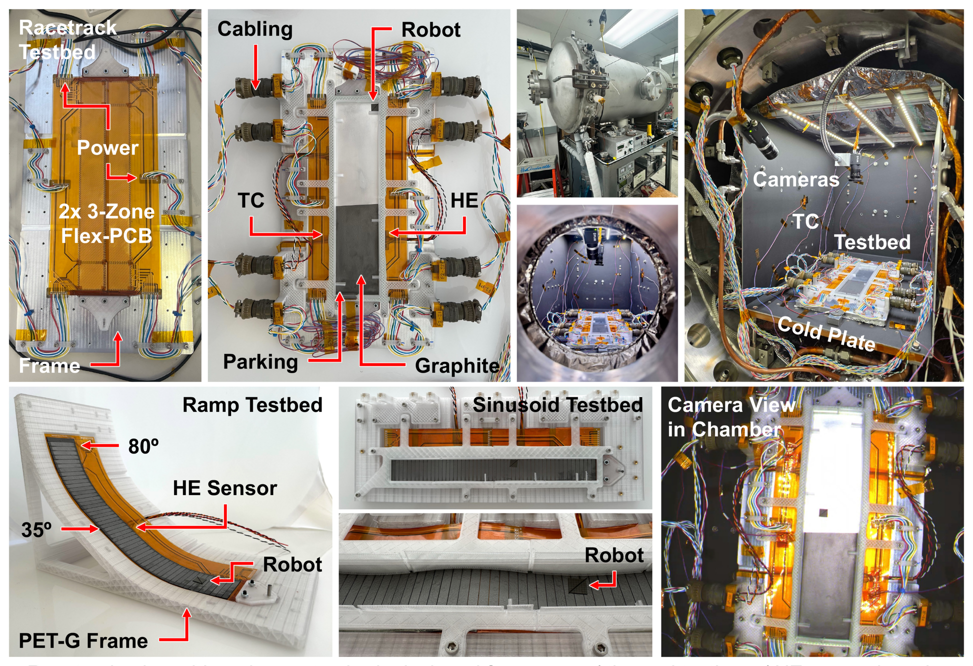
Environmental Considerations

Goal: study / mitigate challenges to operating FLOAT in a lunar env. (on regolith, at vacuum / cold, with radiation / electrostatic charging)

Approach:
- Define the expected lunar south pole environment in / around permanently shadowed craters and identify relevant hazards
- Test sub-scale FLOAT prototypes to characterize performance in relevant environments and identify / mitigate failure modes

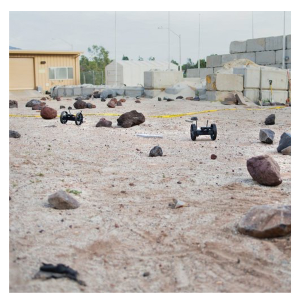
Lunar Environment Hazards Definition: (based on NASA DSNE)
- **Temperatures –** coldest PSR at 18 K and <-85 deg Lat. at 61 K mean (41 K, 1-sigma) to 182 K (224 K)
- **Radiation –** Total Ionizing Dose (TID), Displacement Damage Dose (DDD), and Single Event Effects (SEE) quantified
  - Controller boxes to be buried under 10+ cm regolith
  - In-track sensors must be radiation tolerant + redundant
- **Micrometeroids + Orbital Debris (MMOD) –** >1 particle/m²/ yr able to penetrate graphite, need circuit redundancy in tracks
- **Surface Charging –** 0 to -50V (sun), -100 to -1000V (shadows)
  - Need electrical bleed path between load / track (graphite?)
  - Currents + dust transport at sunlit-shadow terminator

Environmental Testing: developed 3 testbeds for robot mobility experiments; **actively testing** in a thermal-vacuum chamber
- In-chamber instrumentation + cameras to measure operating power, hardware temp., and robot levitation height / motion



Racetrack, sinusoid, and ramp testbeds designed for vacuum / thermal testing w/ HE sensor boards. Initial testing with 1 cm² Robots (7 x 7 array, rigid, levitated, 2.5×10^{-5} Torr).

Next Steps:
- Continued **thermal / vacuum testing**, to expand operational limits of system speed, payload, size, and temperature
- Testing in **Lunar regolith analogues**
- Testing **track misalignment** + mitigations
- Pursue **reduced-gravity** flight opportunity

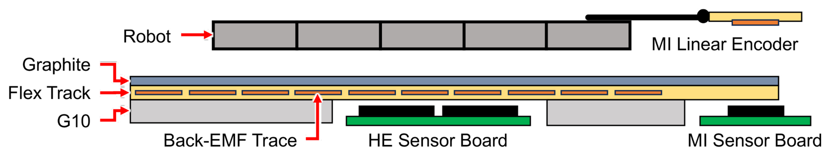


Robot Control

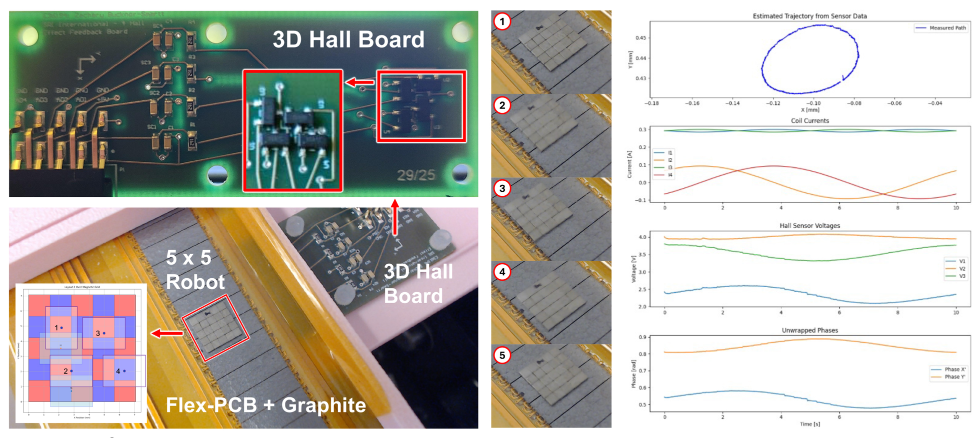
Goal: develop reliable closed-loop control of robot state (position + velocity) via low-power sensing hardware **integrated in the track**

Approach:
- 3 Sensor Strategies: Back-EMF, Hall-Effect, Magneto-Inductive
  - Use sensor arrays to constrain robot's 3D position
  - Minimize (unpowered) hardware on robots
- Prototype / calibrate sensors with open-loop robot control
- Implement closed-loop control with 1+ sensor types

Sensor Strategy		Measured States	Robot Hardware	Track Hardware
Back-EMF	Measure back-EMF voltage in the track traces, induced by magnet motion	Voltage prop. to robot position, speed, size, and mag. strength over traces	N/A	PCB Traces
Hall Effect	Measure magnetic field strength over sensor array	Signal prop. to robot position and local mag. strength over sensors	N/A	SMT Chips
Magneto-Inductive	Measure electromagnetic induction through encoder positioned over sensor array	Signal prop. to encoder shape and position over sensors	Flex-PCB Encoder	SMT Chips

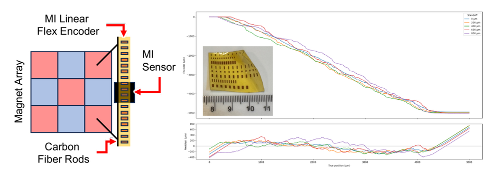


Hall-Effect Sensor:
- Demonstrations of **2D robot position / velocity control**, including **suppression of under-damped oscillations**

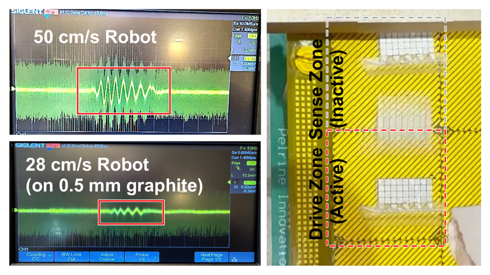


0.5 cm² Robot (5 x 5 array, levitated) driven in a circle via HE sensor board + closed-loop control.

Magneto-Inductive Sensor:
- Demonstration of 1D encoder position measurement
- Stable across Z-offsets



Back-EMF (V_b) Sensor:
- Observation of V_b from robot driven over control zones in a rigid-PCB track



Next Steps:
- Finalize sensor selection and configuration
- Fabricate sensor arrays directly into future track iterations
- Continued testing at greater robot speeds / sizes

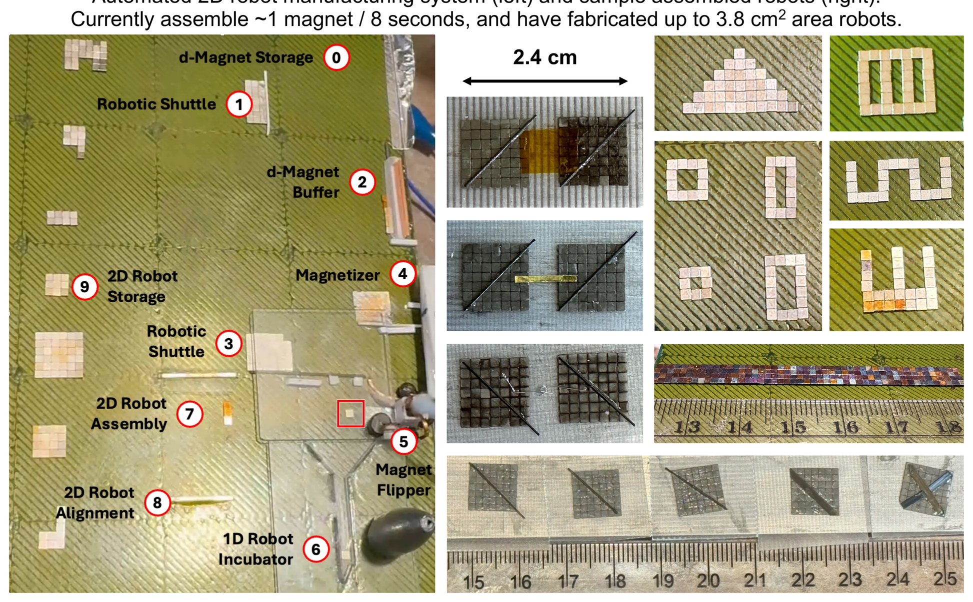
Robot + Track Scaling

Goal: manufacture and operate FLOAT robots / tracks at increasingly large sizes (targeting 1/10-scale)

Approach:
- Employ **flight-qualified materials** for robots + tracks
- **Scaling up tracks** via increased area flex-PCB, precision-machined graphite plates, and testing new strategies for bonding layers, connecting wiring, and linking track segments
- **Scaling up robots** via automated assembly, and testing new strategies for intra-robot flexible linkages
- Document costs, challenges, and vendor constraints

Robot Scaling:
- **Automated assembly** of individual magnets into robots
- **Automated re-magnetization** for **in-situ robot fab. + repair**
- Testing linkages with different materials / degrees of compliance

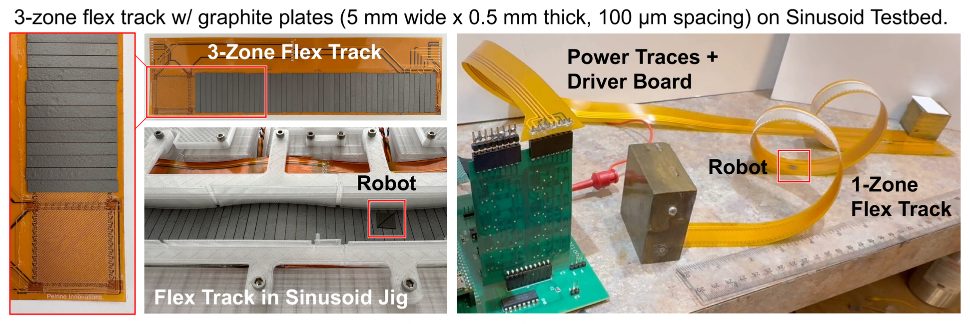
Automated 2D robot manufacturing system (left) and sample assembled robots (right). Currently assemble ~1 magnet / 8 seconds, and have fabricated up to 3.8 cm² area robots.



1 cm² Robots (w/ carbon fiber reinforcing) and 2 x 1 cm² Robots (w/ Kapton, brass, and wire flexures).

Track Scaling: robots successfully maneuver on larger flex-PCBs
- Fabricated 1- and 3-zone flex-PCB tracks for ≤10 cm² robots
- New methods to machine / bond graphite to PCBs at >10x area

3-zone flex track w/ graphite plates (5 mm wide x 0.5 mm thick, 100 µm spacing) on Sinusoid Testbed.



1-zone flex track (3 x 60 cm) with robot in sliding-mode can overcome Earth gravity.

Next Steps:
- Finalize intra-robot flexible linkage design
- Fabricate robots at increasing sizes via **automated assembly**
  - Targeting 10 cm², 40 cm², and 100 cm² robots
- Fabricate tracks at increasing sizes using commercial vendors
  - Targeting 10 x 100 cm tracks, plus junctions

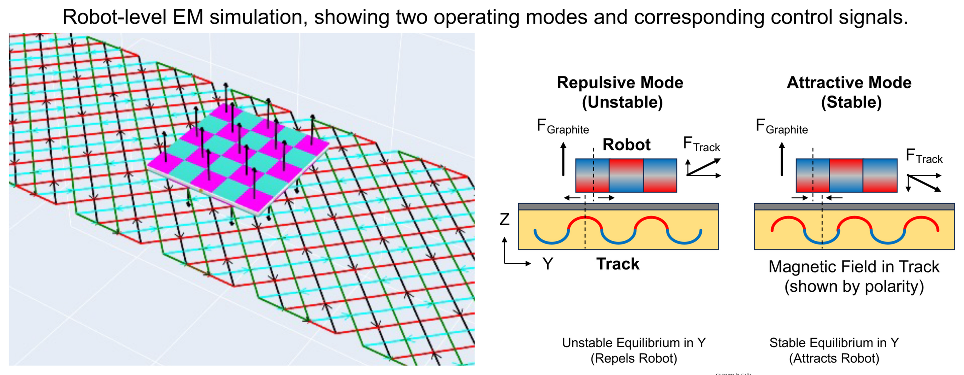
Simulation

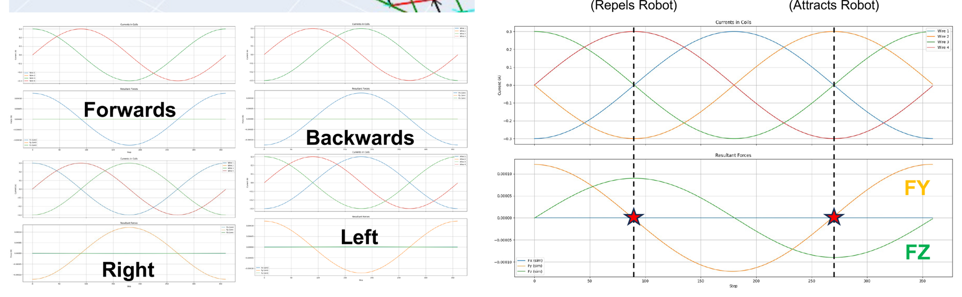
Goal: study FLOAT **robot-level** and **system-level performance** via analytical, finite-element, and path-planning / scheduling models

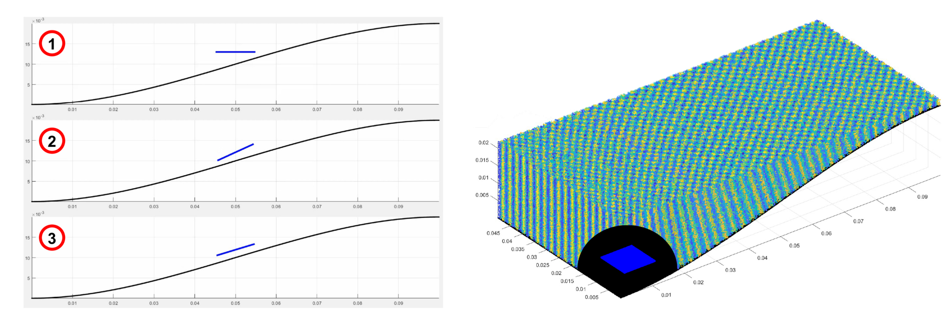
Approach:
- Robot-level simulations to test new control strategies and balance robot performance (speed, payload, levitation height) with terrain curvature and track power
- System-level simulations to plan track routes on Lunar DEMs and optimize robot scheduling (via extrapolated performance)
  - Combine with RLSO2 / Artemis mission parameters to size potential lunar FLOAT systems
  - Calculate system mass, volumetric flow rate, power consumption, power generation, etc.

Robot-Level Simulations:
- Implemented electro-magnetic simulation for dynamic control
  - New, unstable operating point accessible w/ closed-loop control for greater payload capacity or levitation height
- Implemented 3D rigid-body dynamics model with force-functions (from EM simulation) mapped to non-flat tracks

Robot-level EM simulation, showing two operating modes and corresponding control signals.







Robot-level rigid-body dynamics simulation, showing robot and mag-field over curved track.

Next Steps:
- Continued study of robot-level dynamics modeling
  - Identify tradeoffs in robot speed / payload vs. track curvature / slope and operating power
- Develop system-level simulations of optimized track pathing and robot scheduling on lunar DEMs