THE OHIO STATE UNIVERSITY
COLLEGE OF ENGINEERING

AMCC-AAC
OSU 2025

HuLC
HUMAN LANDER CHALLENGE

NASA

AMCC-AAC

Autonomous Magnetized Cryo-Couplers with Active Alignment Control
for Propellant Transfer

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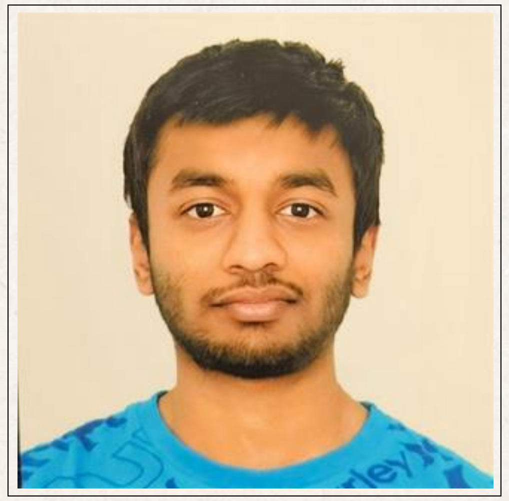

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Thermal

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Not pictured: Rahul Ravishankar (Manufacturing), Artur Leonel Machado Ulsenheimer (AI/CV)

Agenda

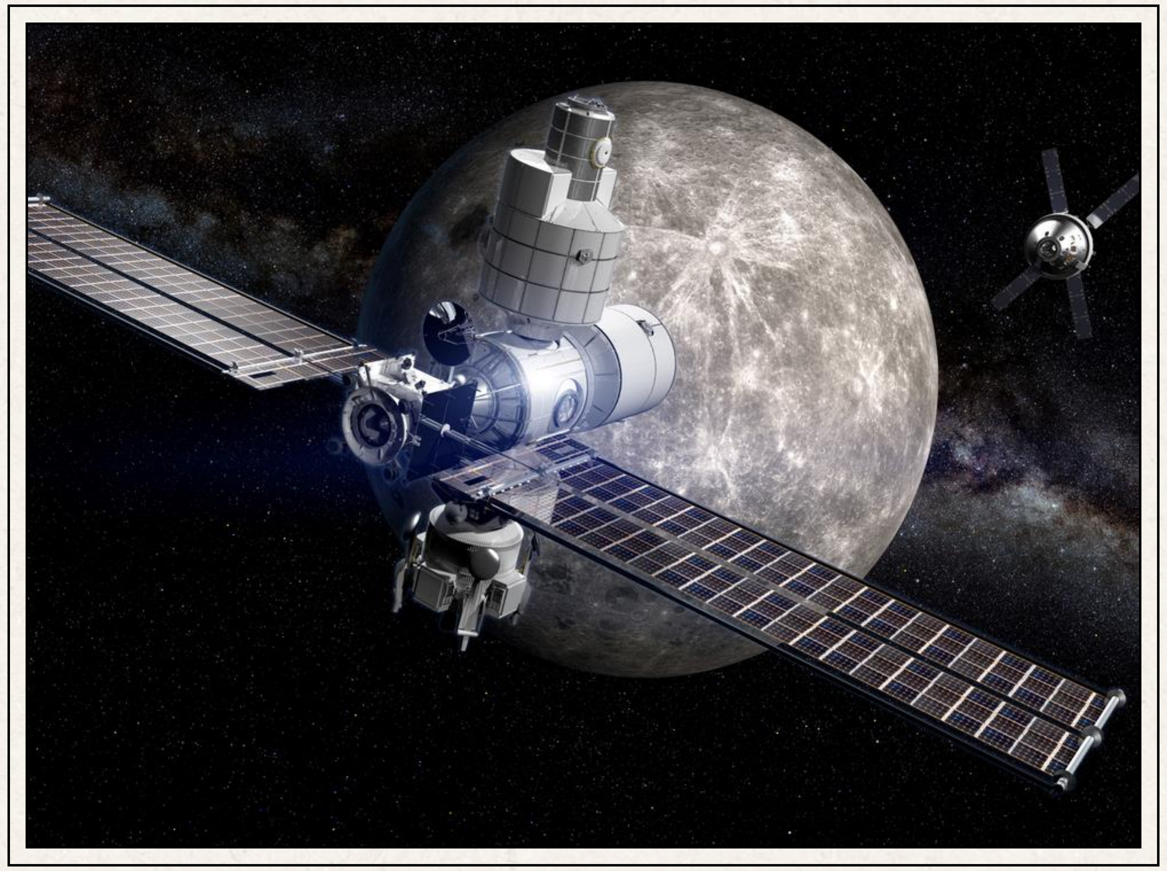
Problem Overview

Current cryogenic systems lack the autonomy, durability, and precision required for long-duration propellant storage and transfer in space

01 Why is this a problem?
Ground-based cryogenic systems are not designed for autonomous operations in space

02 What makes it challenging?
Cryogenic fluids like LOX and LCH4 are difficult to store and transfer in microgravity

03 What needs to change?
The creation of next-generation cryo-couplers that are reusable, low-leakage, and capable of autonomous alignment



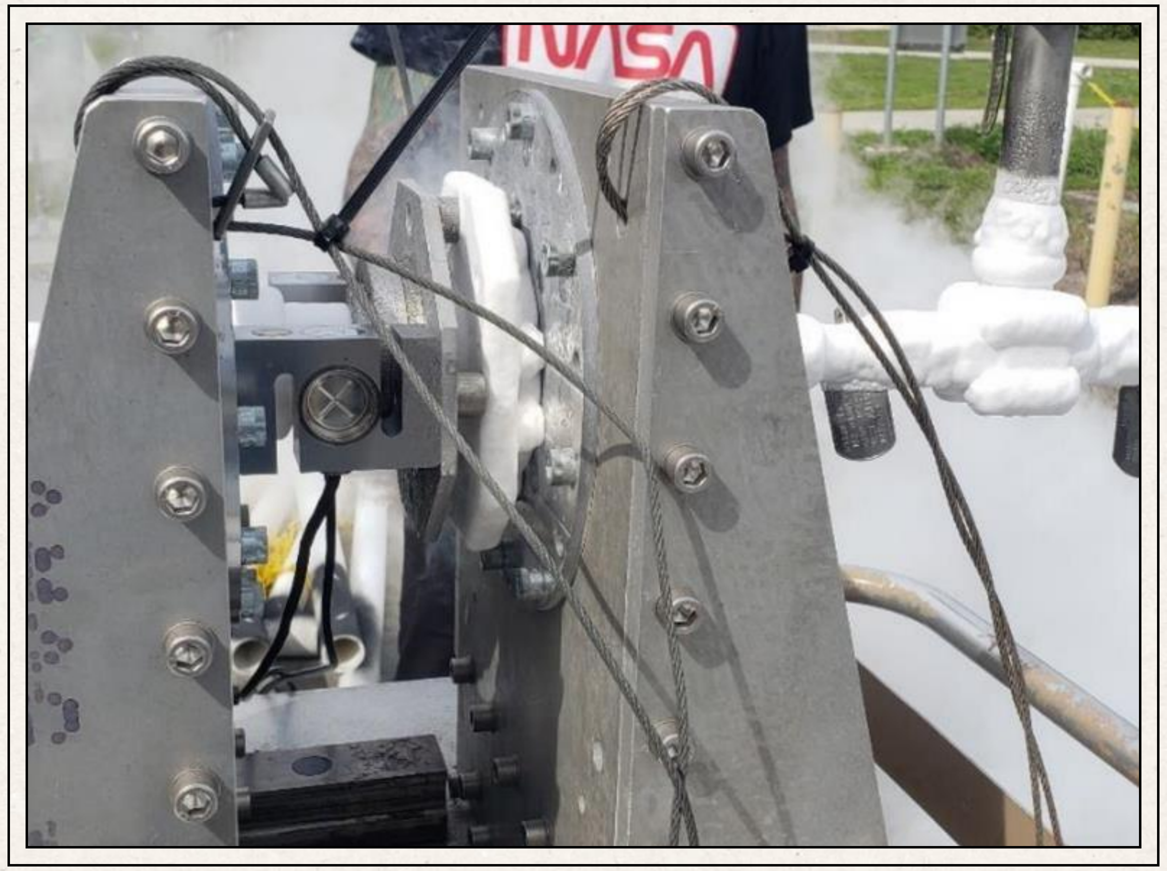


Image Credit: NASA (2024)

Impacts and Urgency

Why it matters:

Without autonomous cryogenic refueling systems, future missions to the Moon and Mars will require frequent resupply and *manual intervention*. This poses *high cost, complexity, and risk* in lunar missions.

Operational Limitations:

NASA's desire to support extended habitation or long-range human exploration is nearly impossible.

Mission-Critical Capabilities:

Artemis and future Mars missions depend on *scalable propellant transfer solutions*

Agenda

Objectives and Goals of AMCC-AAC

Three main goals for the project

Repeatable Autonomous Docking

Achieve repeatable autonomous docking using both active and passive alignment

Minimize Propellant Losses

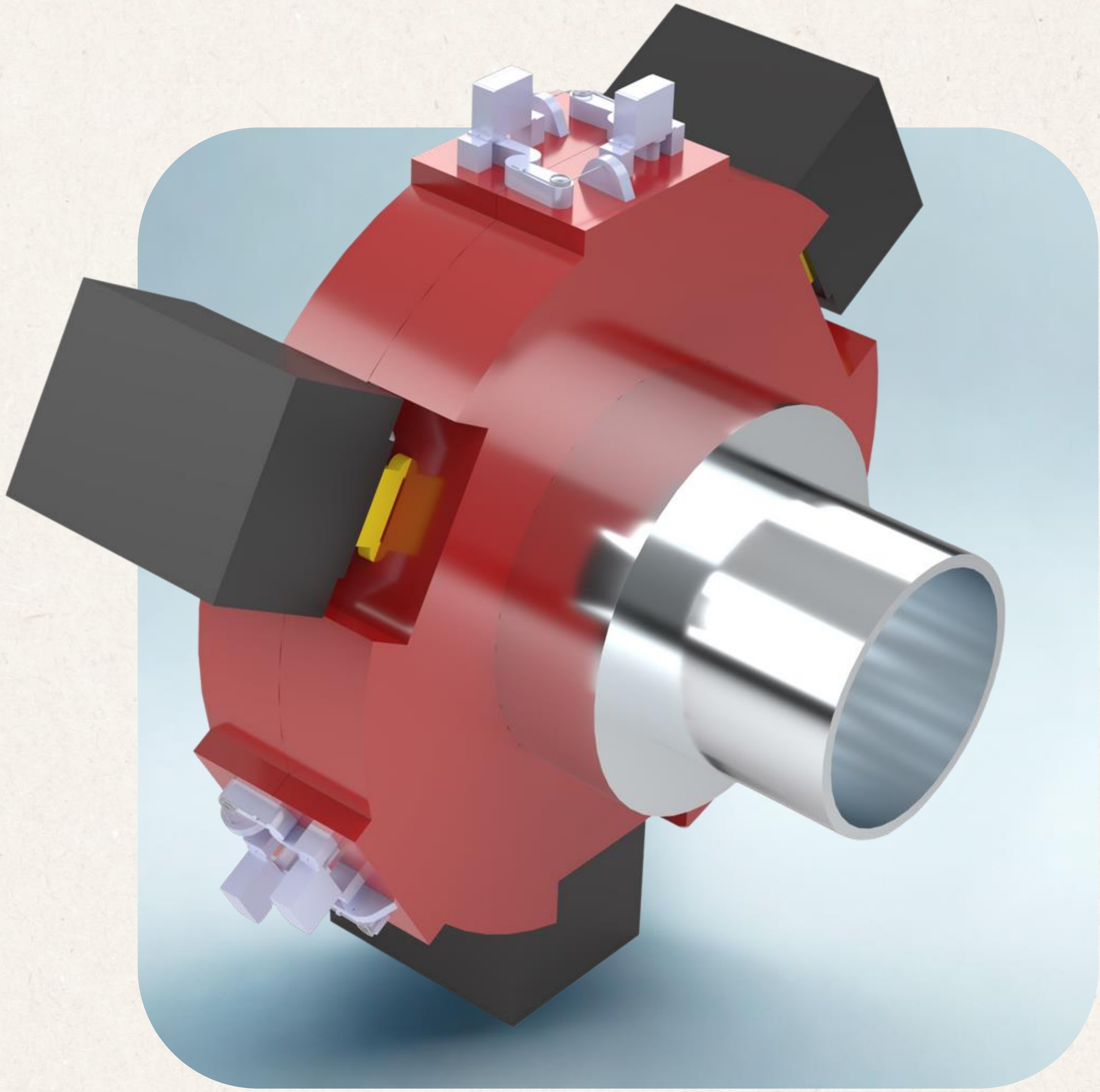
Reduce leakage and boil-off during cryogenic transfer through use of MLI and robotic grippers

Emergency Disconnect

Rapid magnetic disconnect in the event of an emergency to prevent further failure

AMCC-AAC

Enables autonomous coupling through a dynamic movement system and high force clamping mechanisms



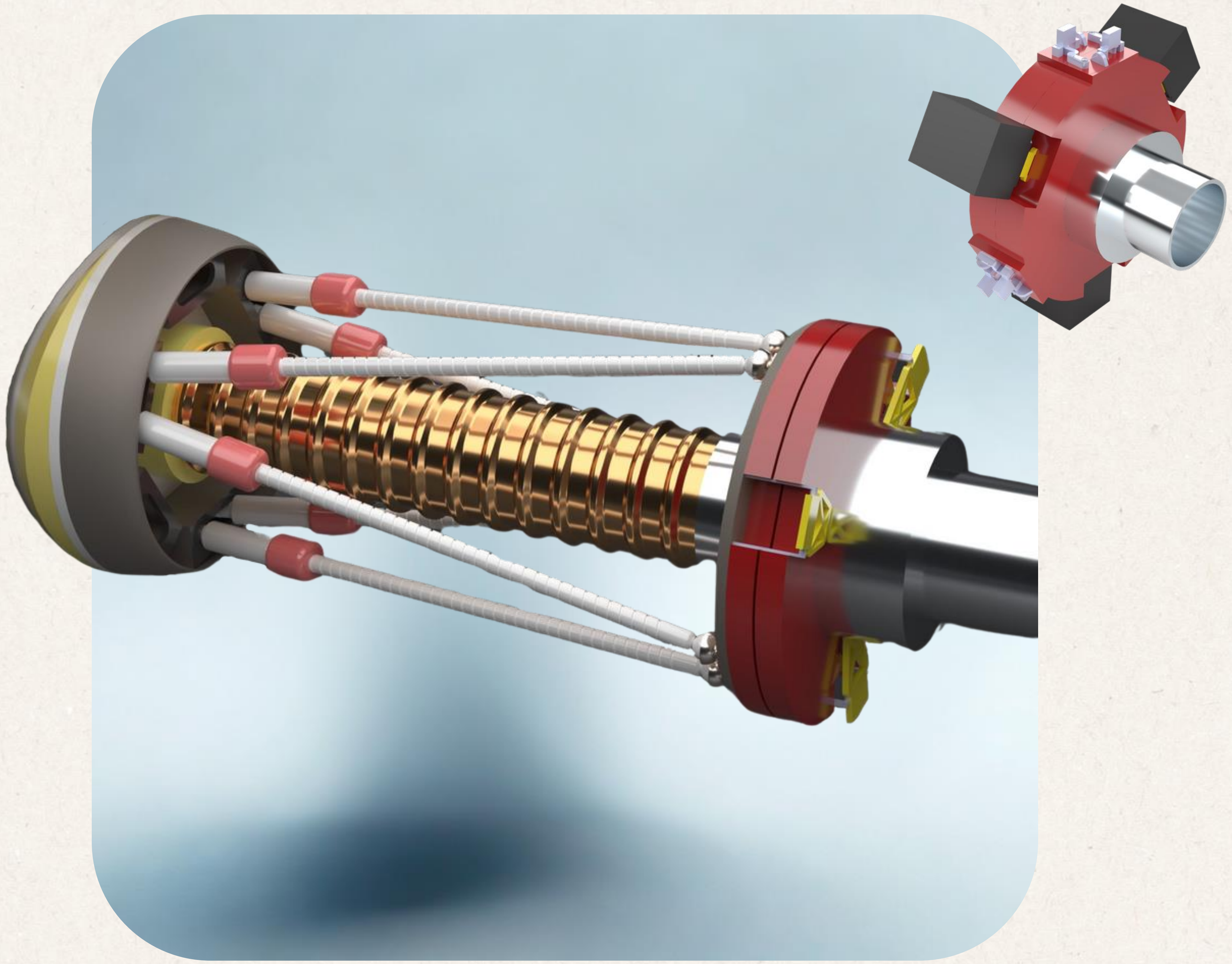
Soft Engagement & Secure Seal

A gentle capture mechanism transitions into a firm, *leak-tight seal*, ensuring dependable propellant transfer.

Designed for *repeatability and resilience*, the system maintains a secure connection through both nominal operations and off-nominal conditions.

AMCC-AAC

Enables autonomous coupling through a dynamic movement system and high force clamping mechanisms



Autonomous Alignment & Capture

Six actuated struts dynamically guide the coupler into position with high precision using *LiDAR and AI computer-vision.*

A *passive magnetic assist system* provides soft capture before full locking and sealing occur.

AMCC-AAC

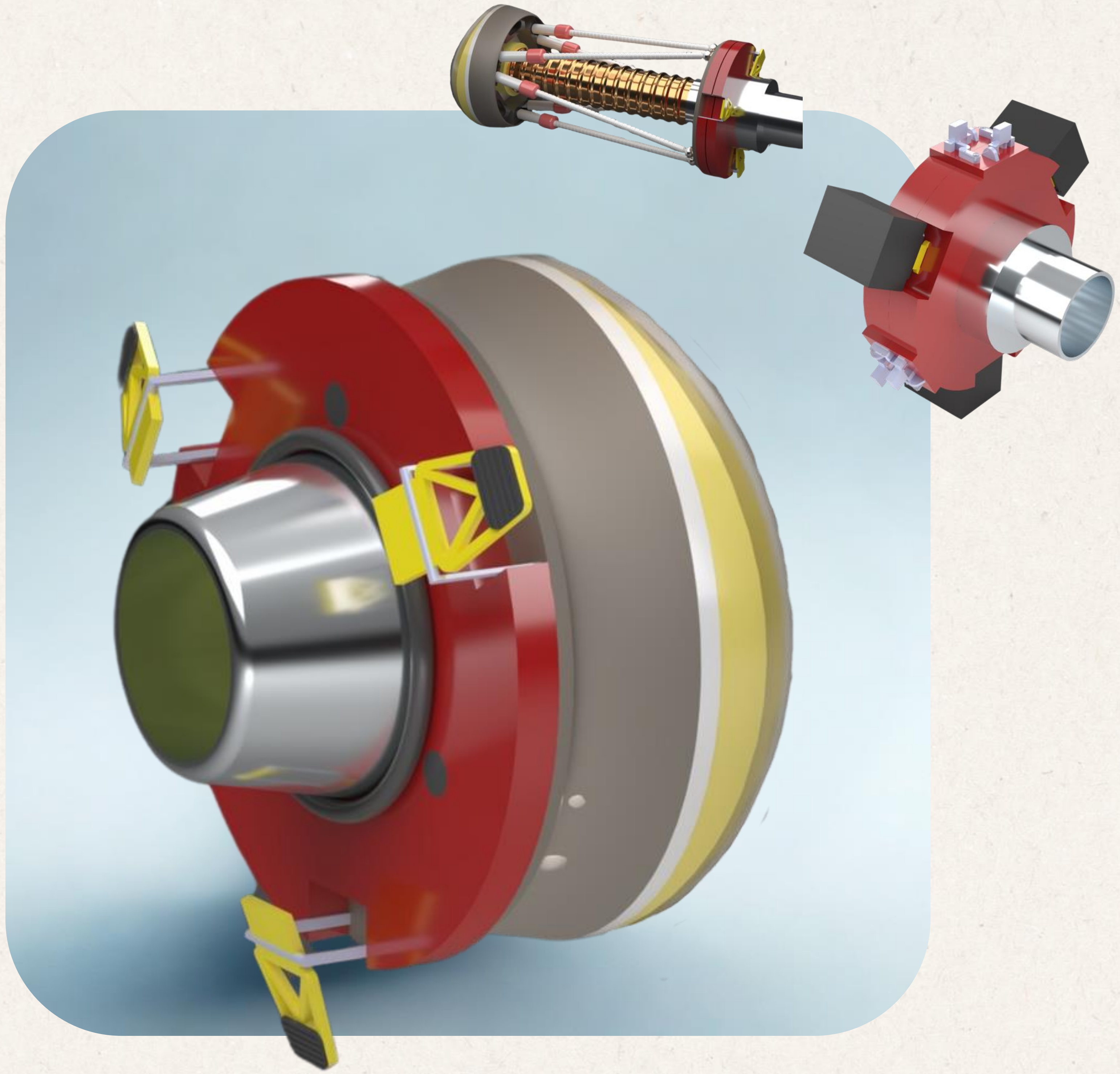
Enables autonomous coupling through a dynamic movement system and high force clamping mechanisms

Locking & Disconnect

The coupler uses a triple-hook locking mechanism adapted from the ISS docking standard.

A magnetic sealing arrangement creates a clamping force that can also be reversed in the event of an emergency

Multi-hook configuration is redundant and prioritizes safety over fluid transfer



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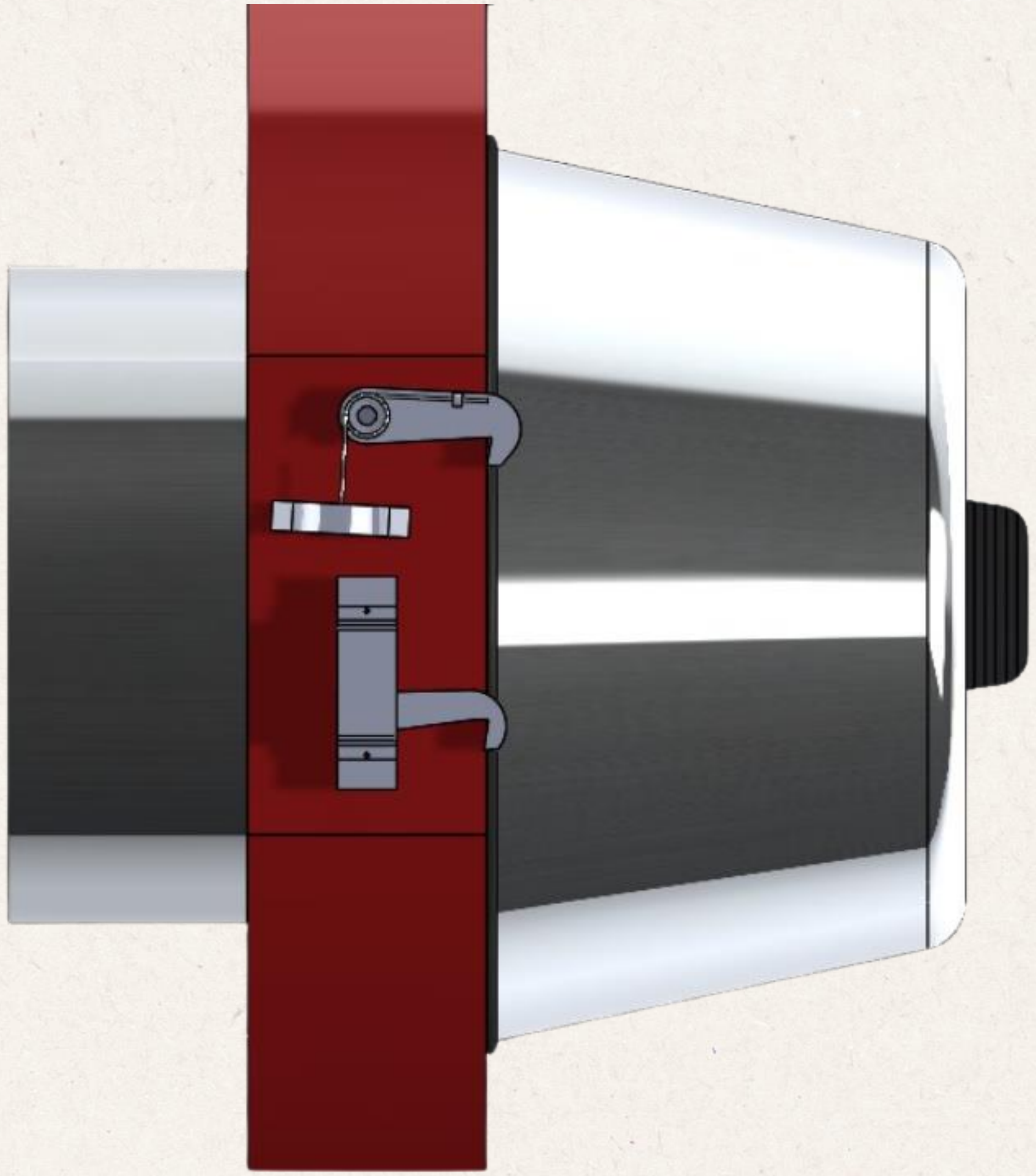
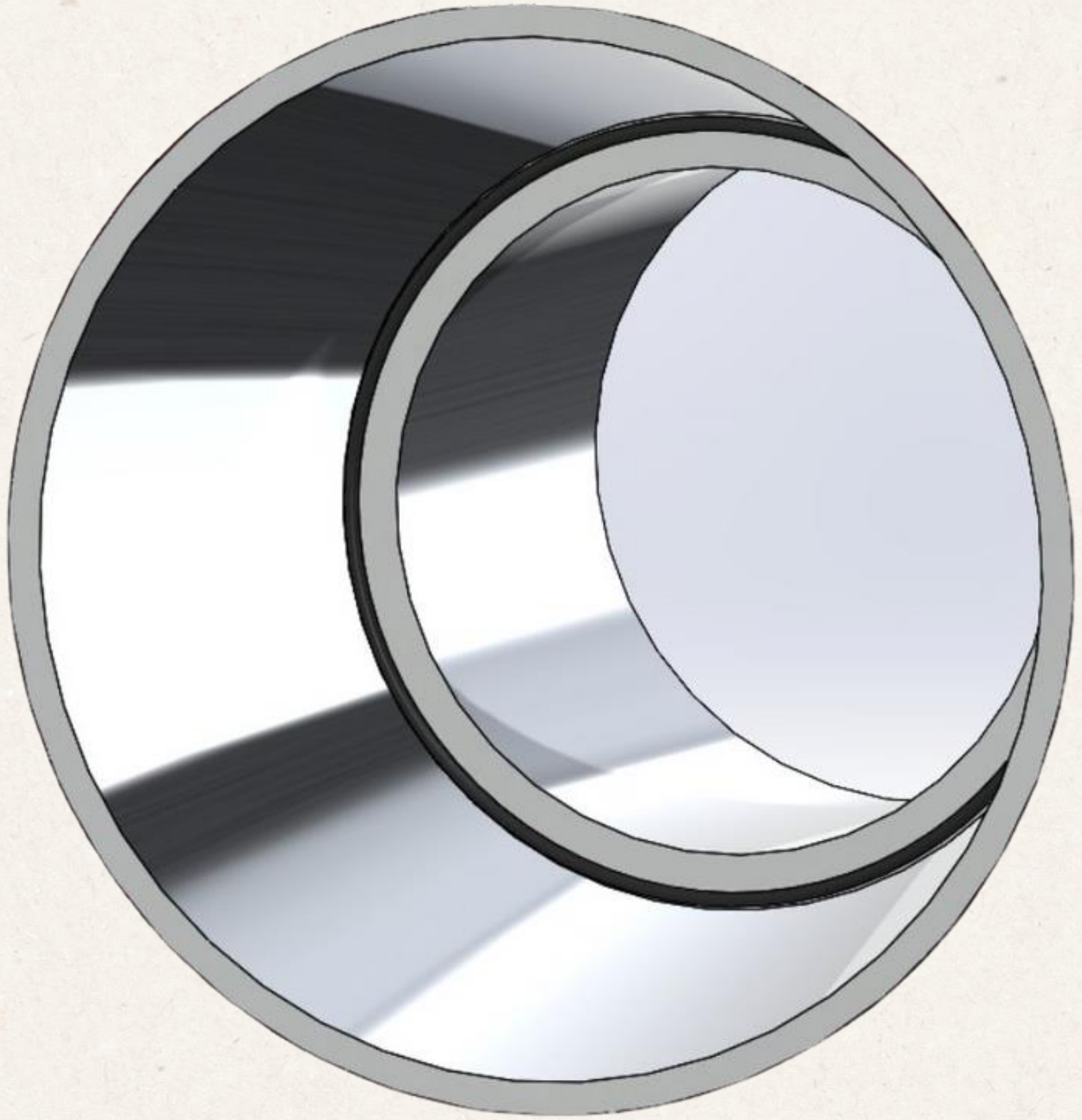
Coupler Design: Sealing Surface

Tapered mating surfaces guide, center, and seal the two halves



Male End



Female End

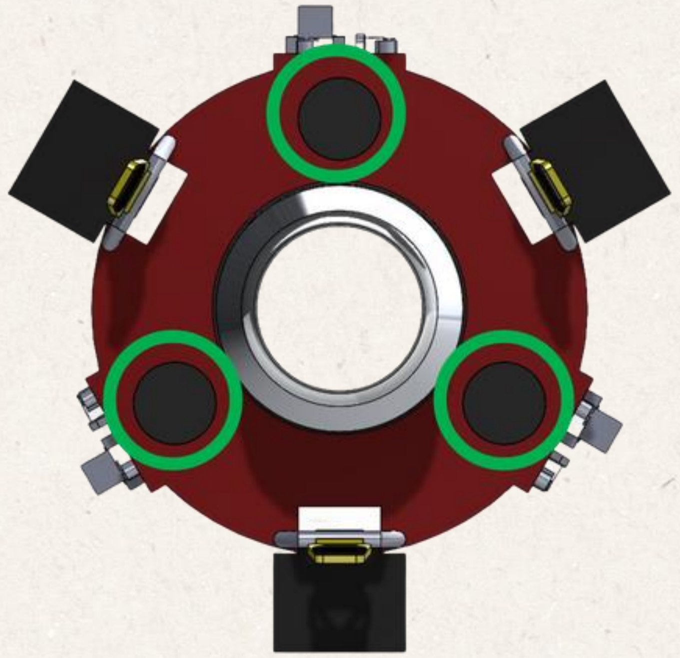
- Male 5° vs. Female 3° taper self-aligns and tightens as clamp load rises
- Geometry absorbs small lateral/angular errors, protecting the O-ring and giving a leak-tight seal

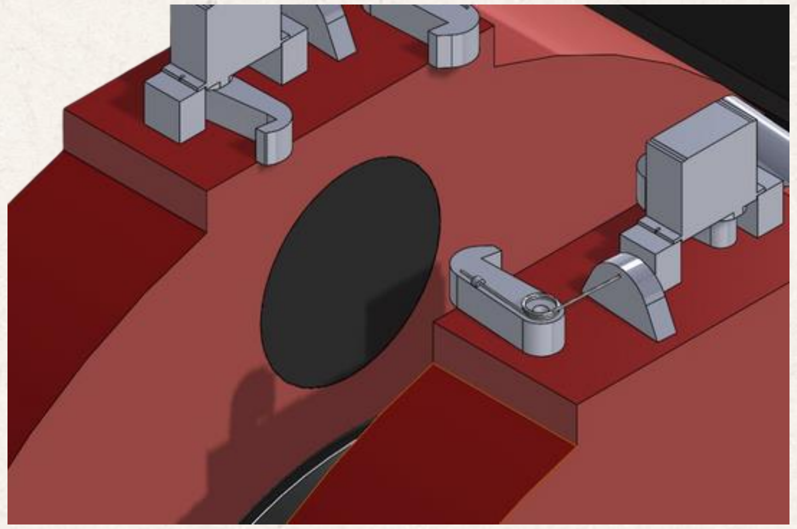
Coupler Design: Redundancy

Couple features triple redundant sealing system

Magnets

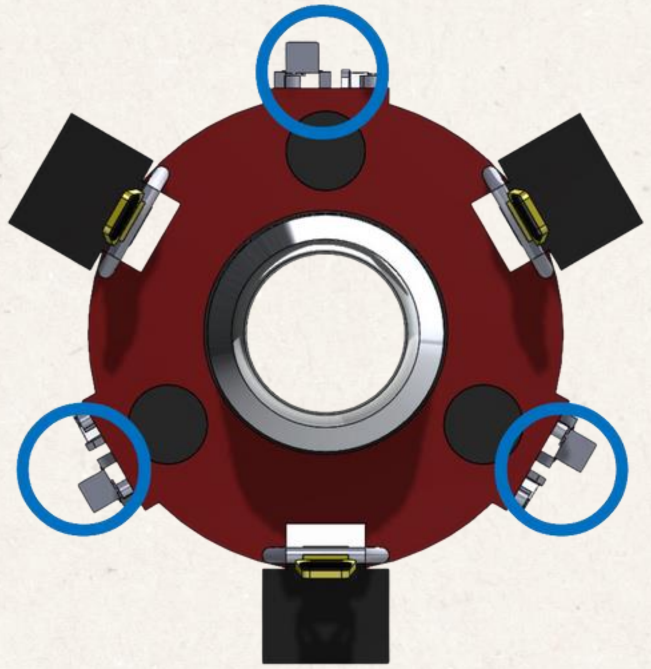
Passive auto-align & preload

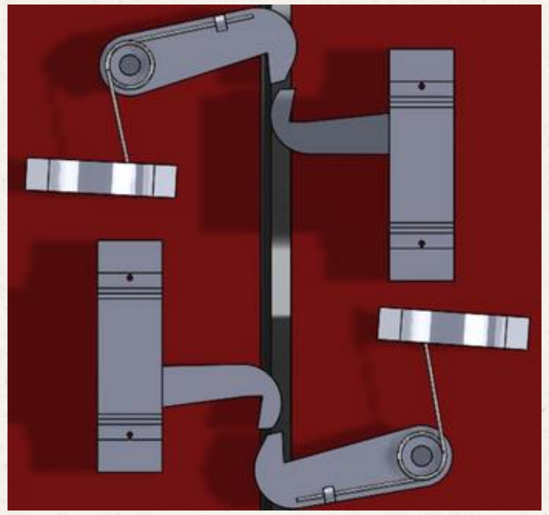


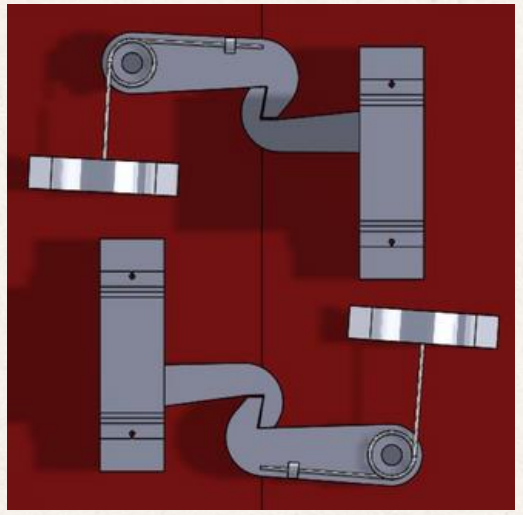


Hooks

Fail-safe mechanical lock (high TRL)

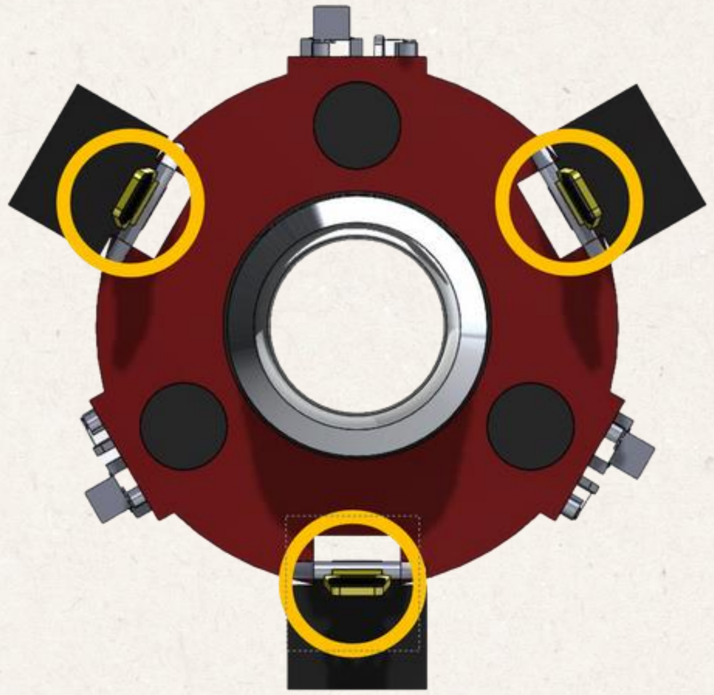


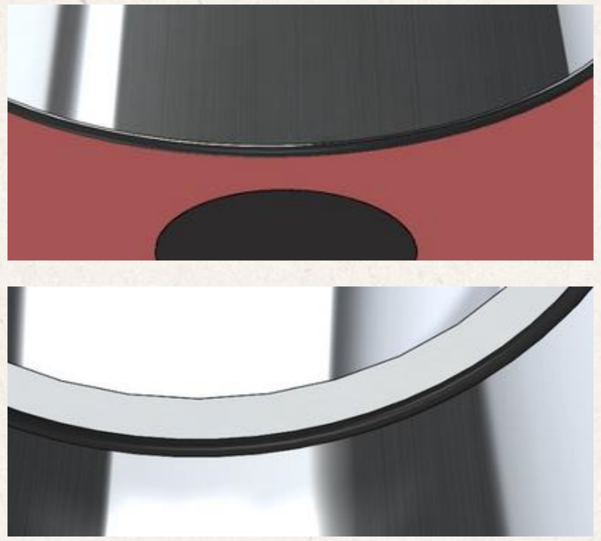




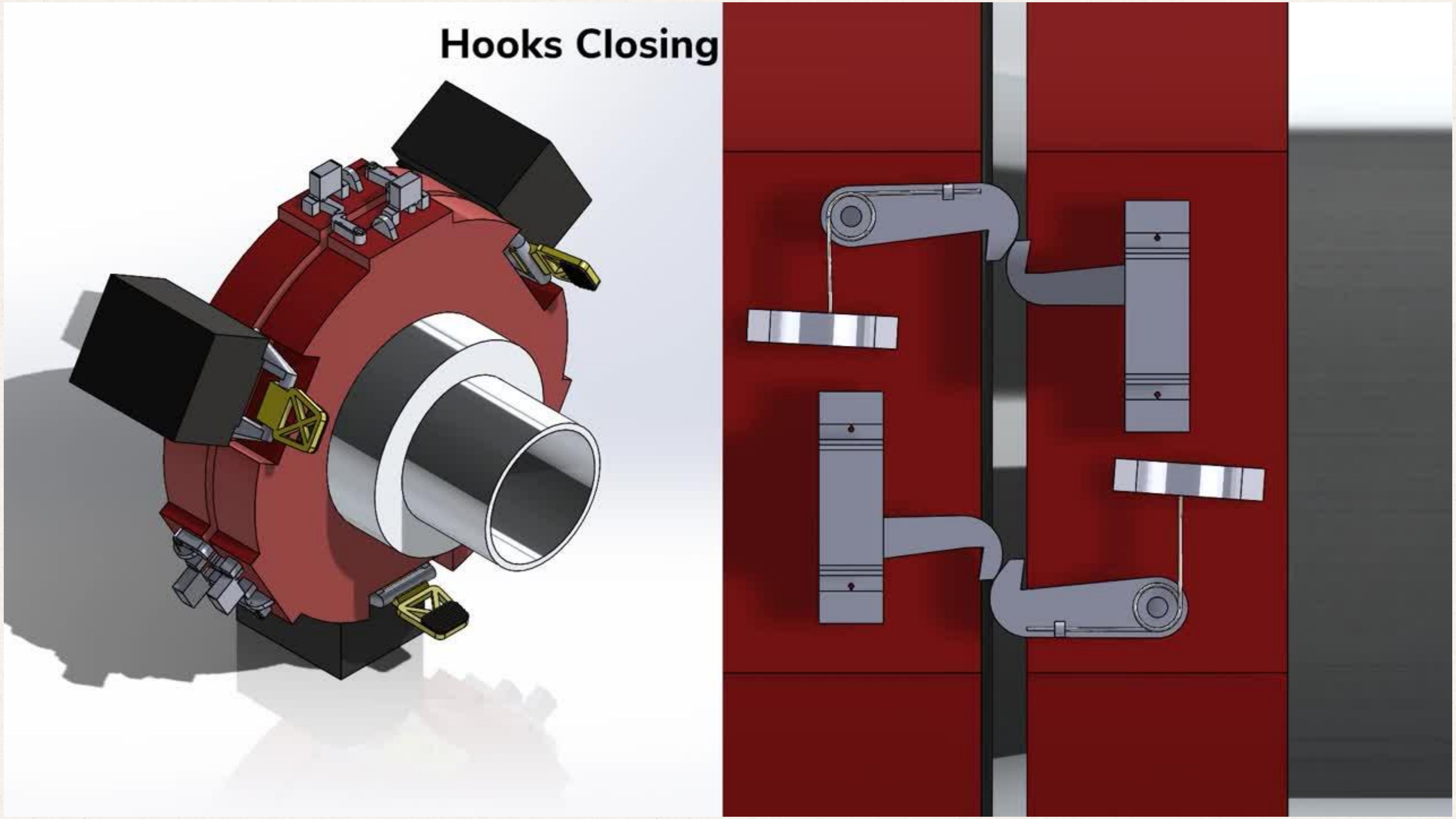
Clamps

High-force seal compression





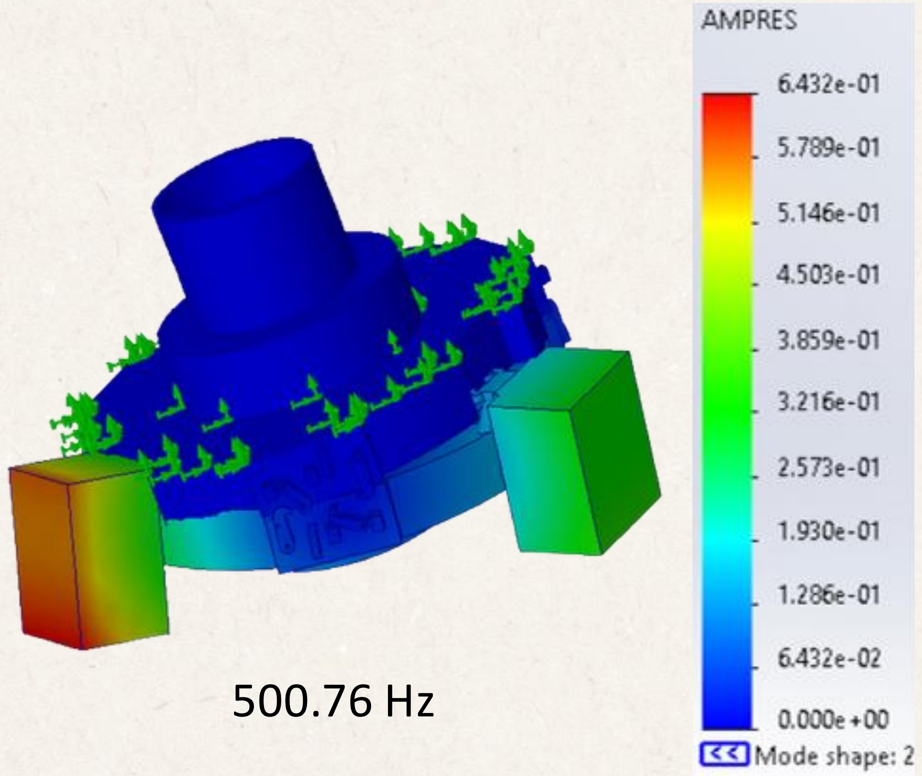
Coupler Design



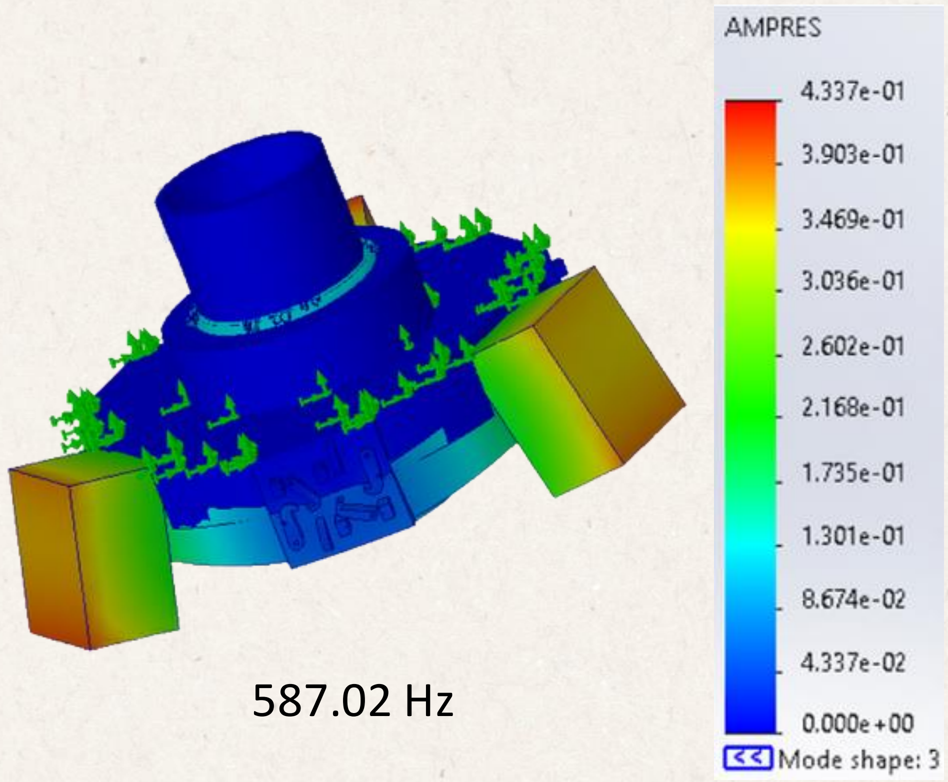
Structures and Mechanisms

Modal Analysis

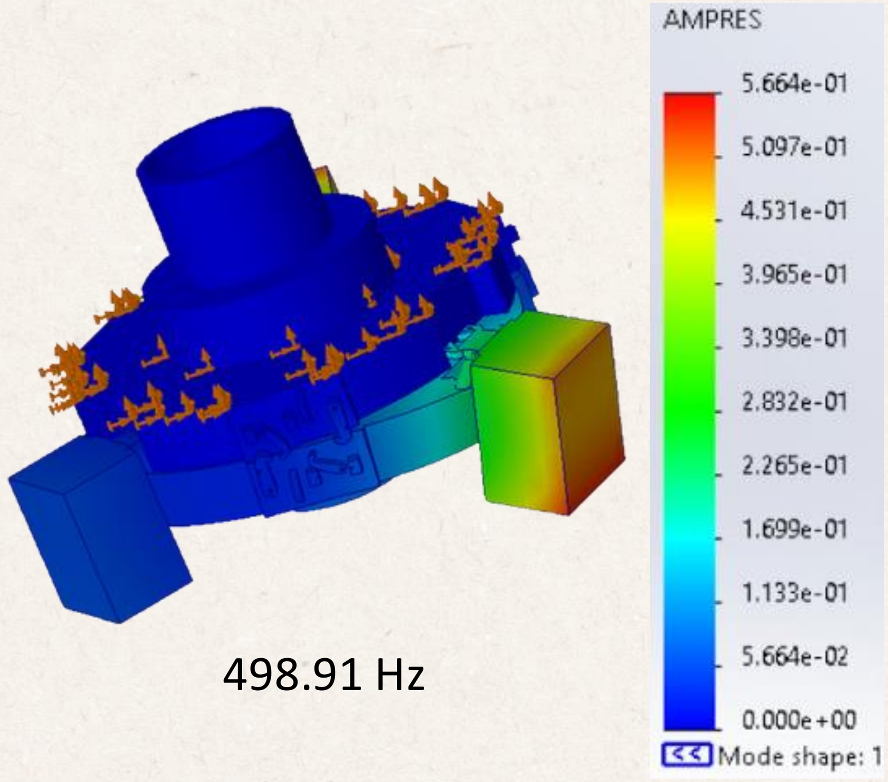
- Five dominant natural frequencies identified
  - ~499 Hz, 501 Hz, 587 Hz, 900 Hz
- Modes < 550 Hz show whole-body motion but remain within allowable deflection, confirming base stiffness against launch random vibe.
- Above ~600 Hz, deformation localizes at support blocks & outer lip
- Results set first-pass keep-out band for avionics & sensors as well as flags areas for mass-balancing



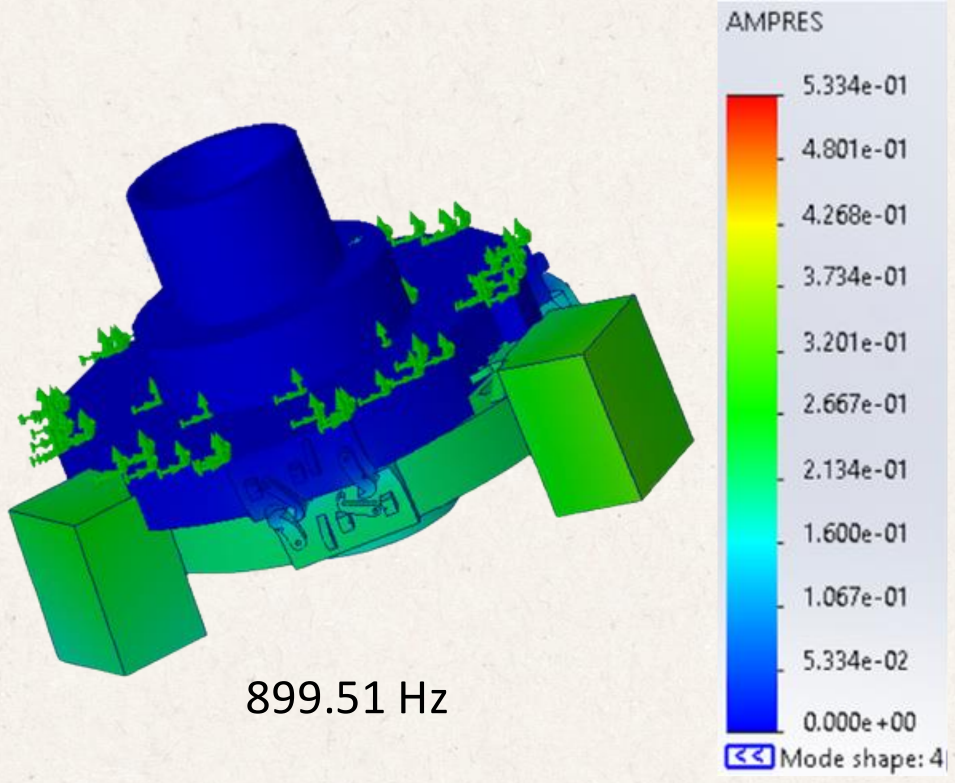
500.76 Hz



587.02 Hz



498.91 Hz



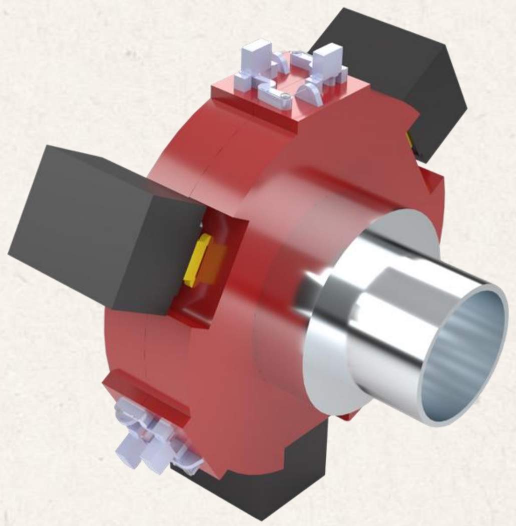
899.51 Hz

Fluid Flow/CFD Setup

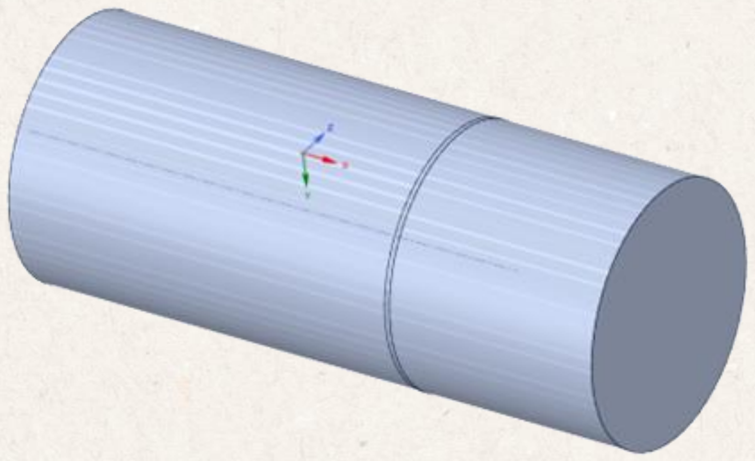
Ansys Fluent Setup

- Simplified full coupler CAD to a straight-bore flow domain, then generated high-res. poly-hex core mesh with boundary layers for viscous accuracy.
- Laminar, incompressible liquid-methane model; SST k-ω for fidelity at low Re.
- Micro-g body force (0.001 m/s2) and cryogenic wall temperature applied; inlet mass-flow/pressure pair chosen to match 25 kg/s design point.
- 100-iteration steady run - residuals < 10-5 and stable monitor history

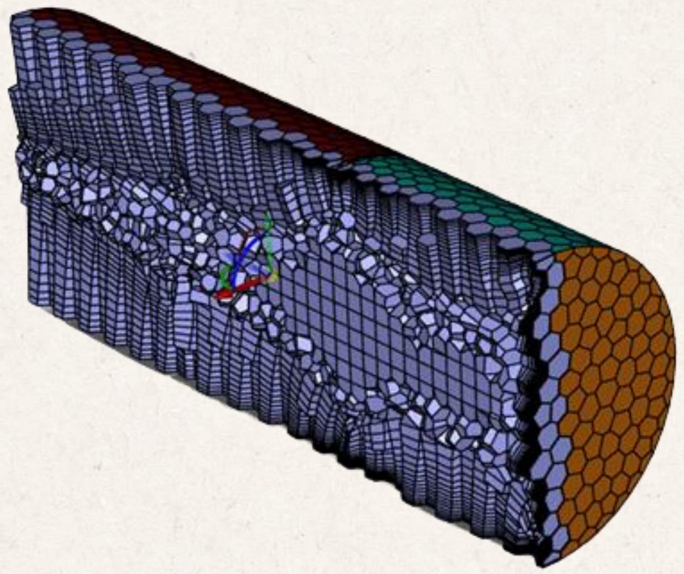
CAD



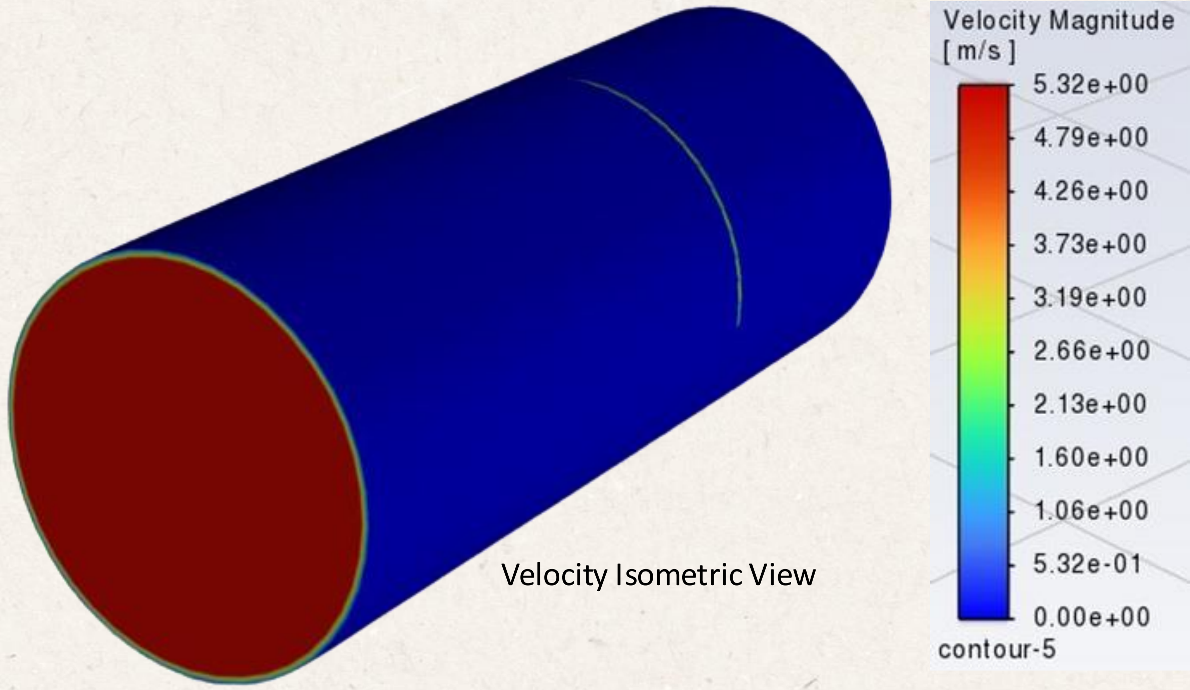
Reduced CAD



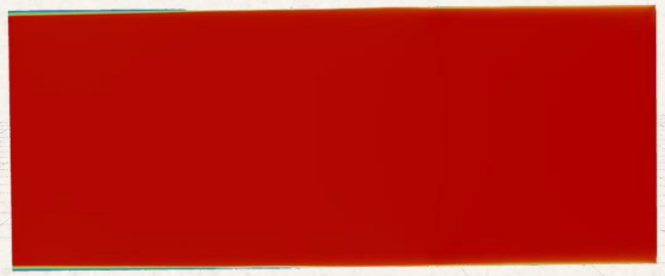
Final Mesh



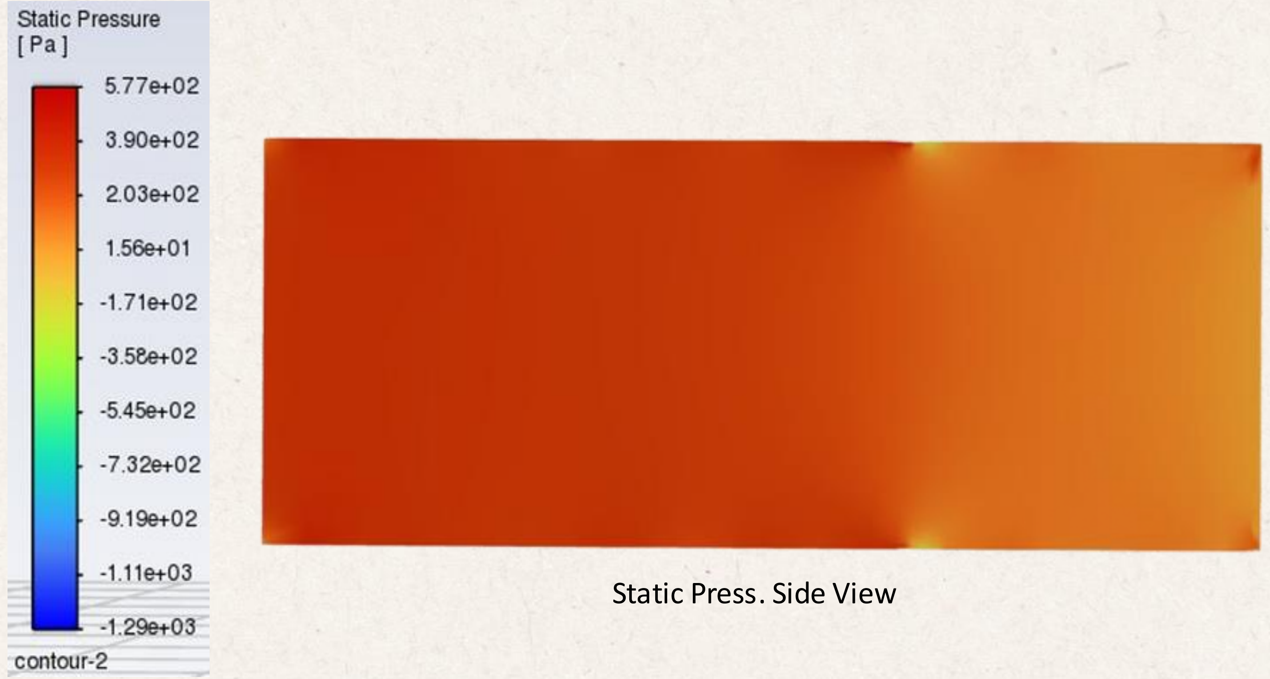
Fluid Flow/CFD Results



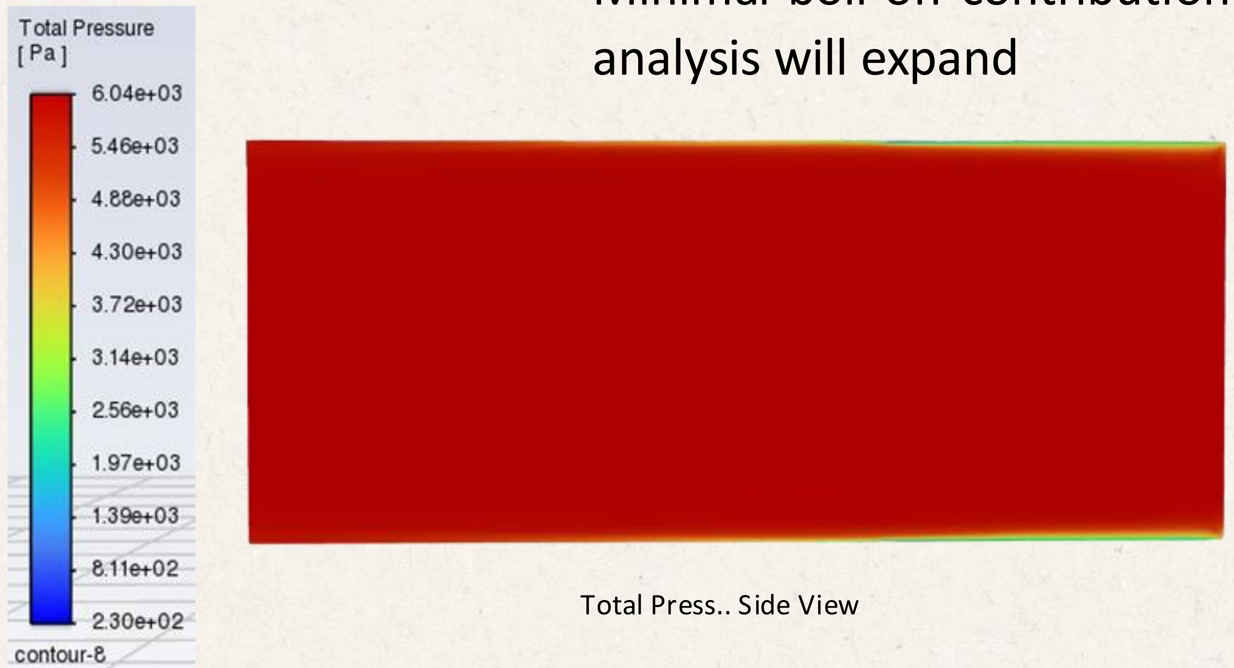
Velocity Isometric View



Velocity Side View



Static Press. Side View



Total Press.. Side View

CFD Analysis

- Velocity field near plug-flow (~5 m/s) w/o recirc.
  - Confirms smooth internal passage
- Static ΔP < 0.6 kPa over full length
  - Meets low-loss req. for 12 hr transfer window
- Total pressure contours uniform
- Boundary layer growth well resolved
- Negligible thermal rise along wall
  - Minimal boil-off contribution from the coupler itself. Thermal analysis will expand

Thermal Analysis: MLI

Multi-Layer Insulation (MLI)

For prototype (functional):

- Metalized Mylar film with reflective bubble-wrap
  - Mylar has low outer emissivity (ε = 0.03) while bubble-wrap provides volume and flexibility
- Reflectix foil-poly sheet (mid-layer)
  - Low cost (<$20/7.5 m) stiffener; easy "wrap-n-tape" install for lab demos
- Aluminized Kapton seam tape
  - -200 °C to +400 °C durability, locks fibers/flakes, adds local puncture resistance

For full-scale production:

- Aluminized Kapton exterior skin
  - -269 °C to +400 °C rating, ultra low outgassing characteristics & UV tolerance
  - Proven on JWST and ISS (TRL 9+)
- 10 - 30 alternating plies of Mylar/Spacer/Mylar
  - Aluminized Mylar mirrors > 99% of IR; Dracon or Nomex mesh breaks conduction bridges
  - Target ε eff < 0.005 in high vacuum
- Close out edges with Kapton Tape
- Beta-cloth micrometeoroid cover
  - Teflon-coated fiberglass improves cut/abrasion resistance
- Designed for < 2 W/m2 total heat flux out at 300 K with 25-ply wrap around coupler

Thermal Analysis: Simulation

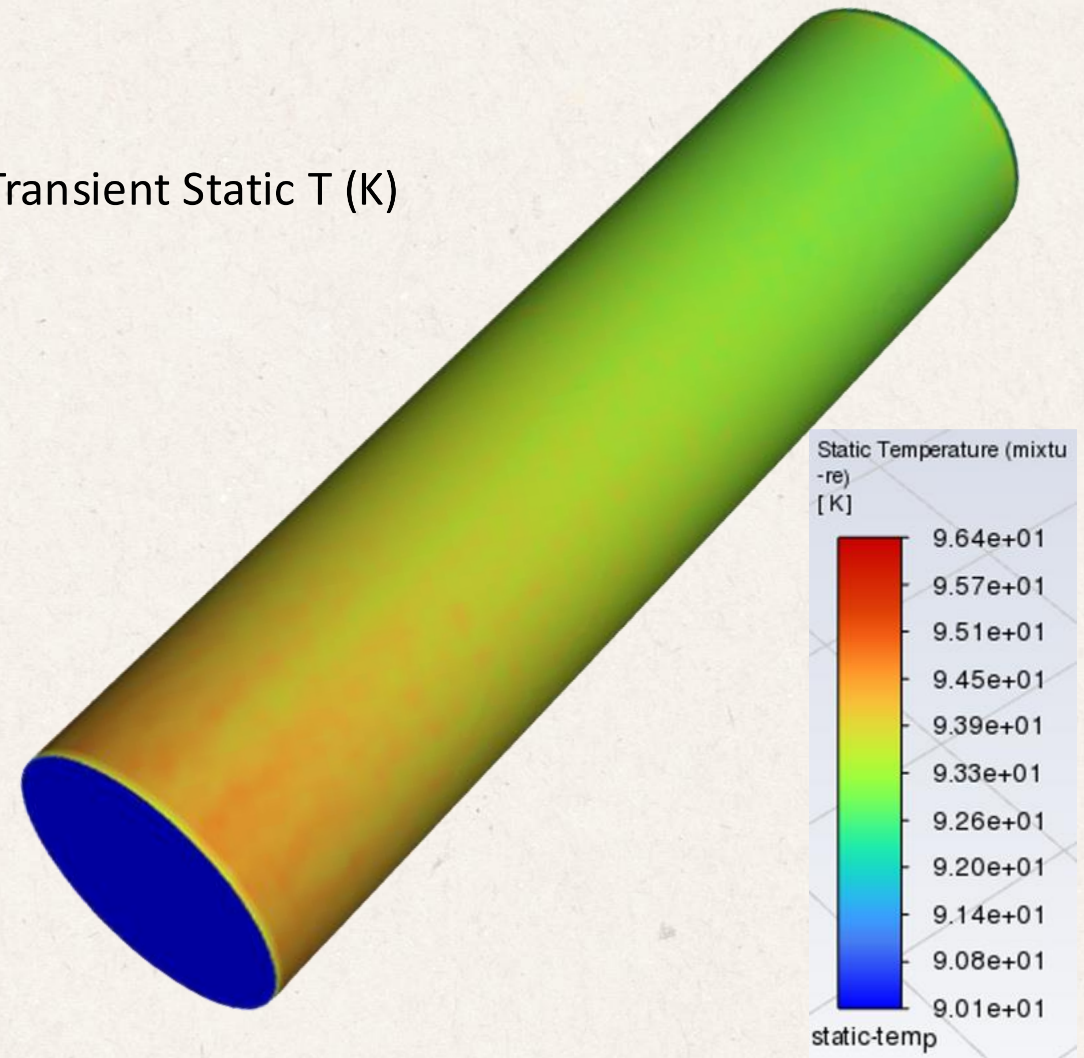
Thermal Desktop

Predict wall temp. gradients & LOX boil-off in cislunar orbit to size insulation and venting req.

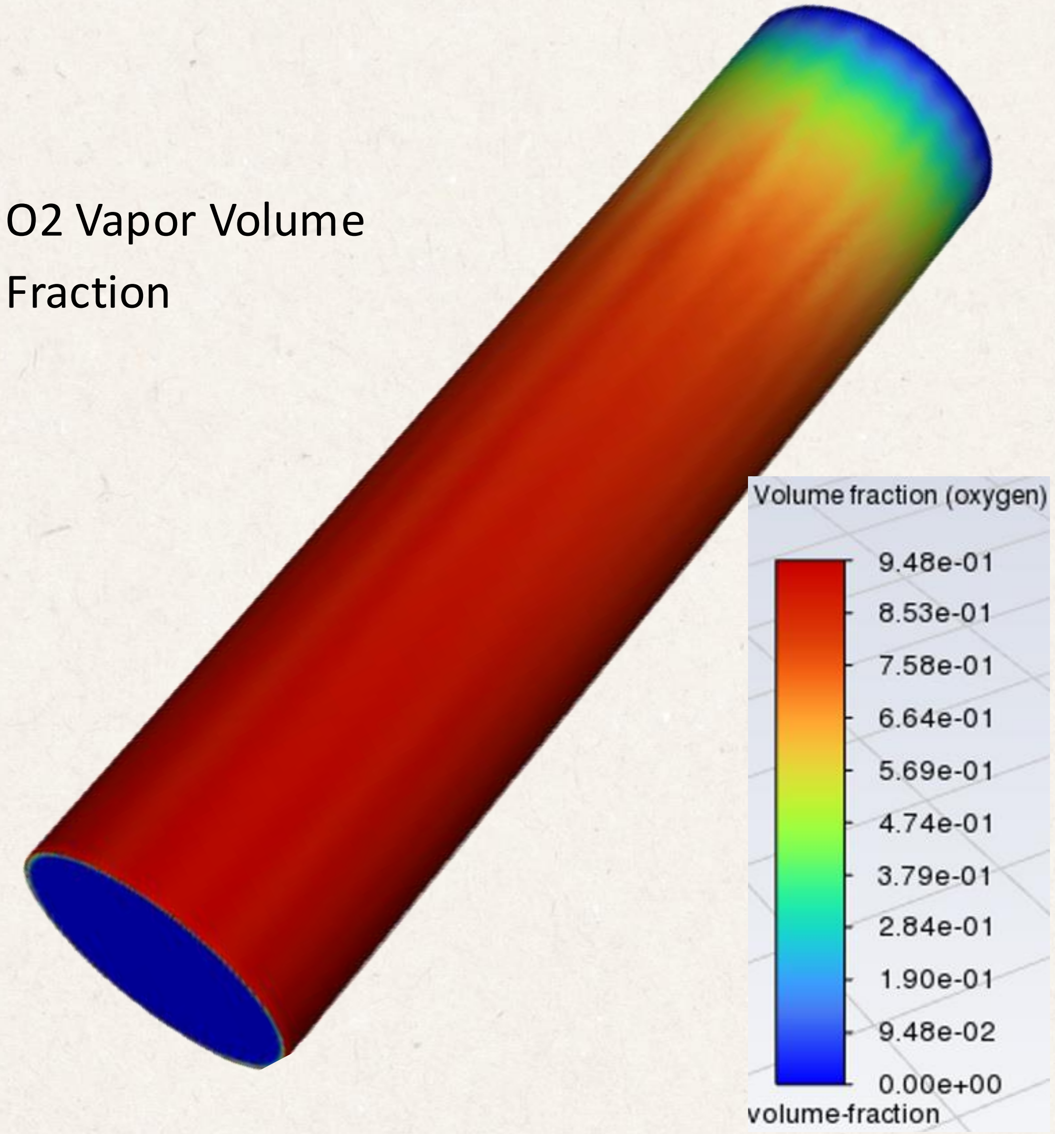
Setup

- Solar load = 1,368 W/m2 (worst case noon NRHO)
- Ti-6AL-2Sn-2Zr-2Mo tube (6mm wall)
- Lee model for two-phase O2
- Laminar inlet @ 100 m/s and 90.15 K
- Pressure-based solver, coupled energy, Δt = 20 x 25 iter. and SS

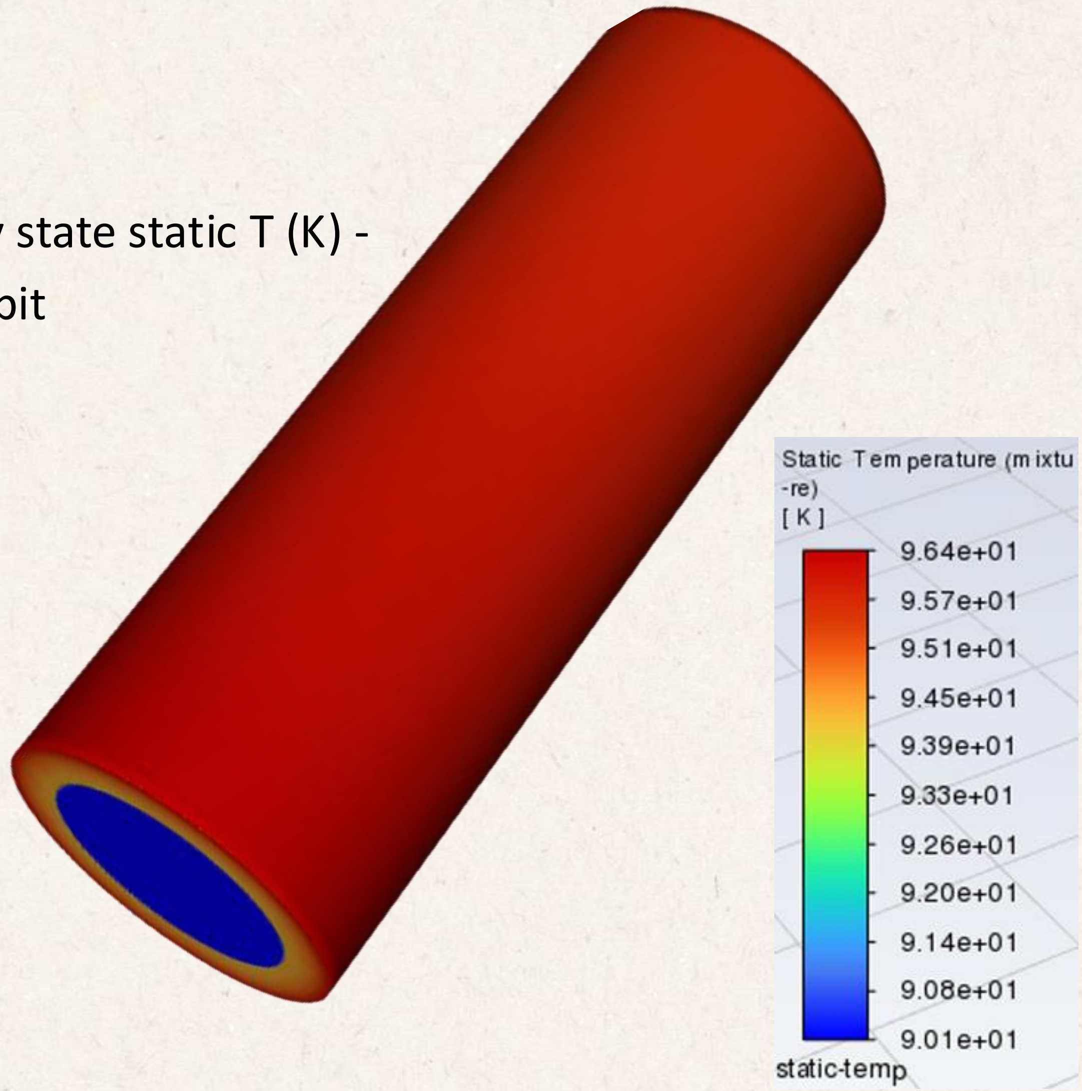
Transient Static T (K)



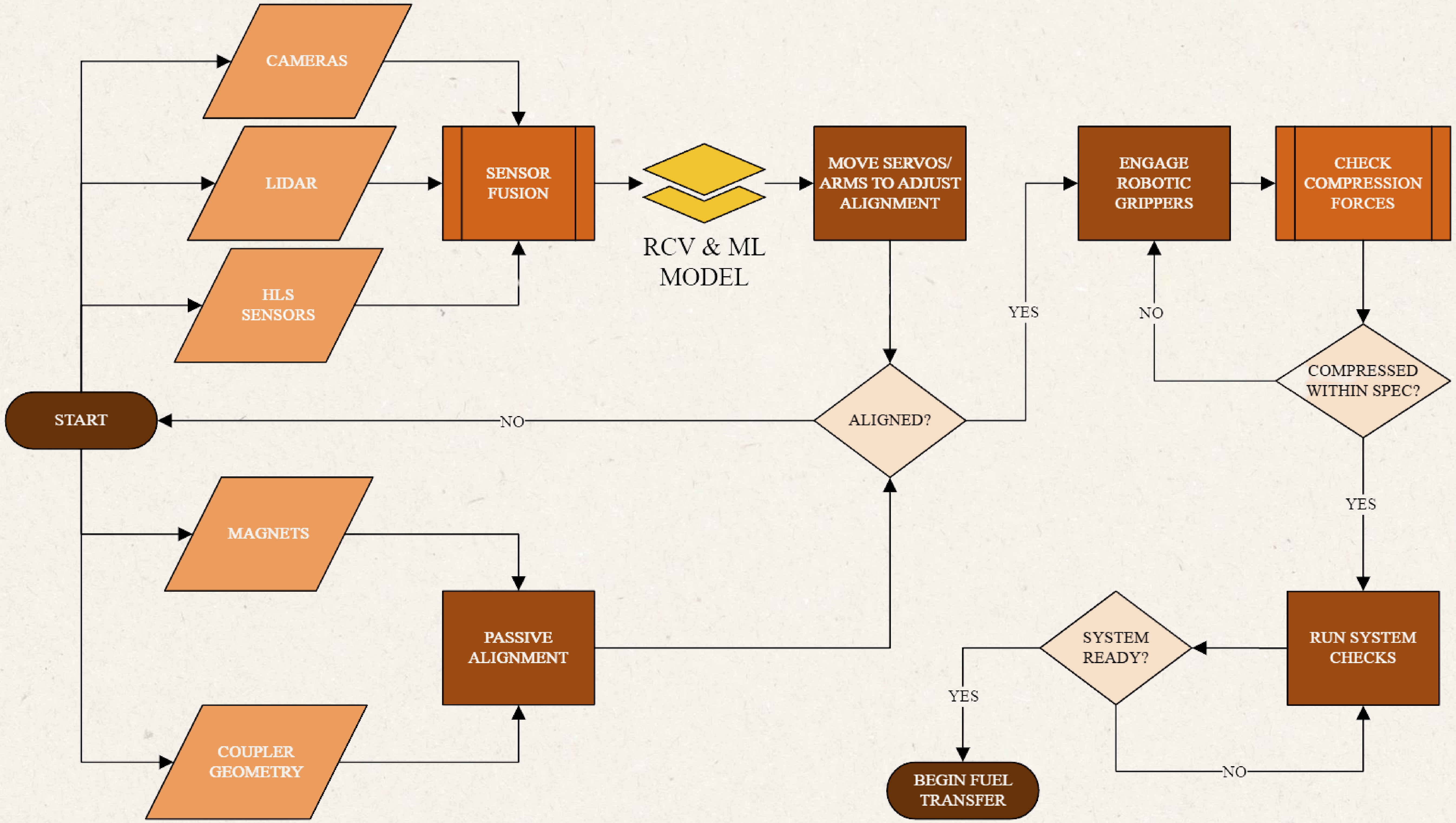
O2 Vapor Volume Fraction



Steady state static T (K) - 2hr orbit



Coupling Algorithm CONOPS Overview



Active Alignment: Computer Vision

Autonomous coupling powered by a blend of AI and traditional Methods

01

April Tags

Compact, low-data markers ideal for our *50 mm tag area*. We place three uniquely IDed tags based on the coupler's geometry. Knowing their 3D positions allows us to estimate the coupler's center from just one tag, with more tags *improving accuracy*.

02

Method

Detection involves converting the *image to grayscale* and matching binary patterns. A red-to-white mask *enhances tag visibility* against the background.

03

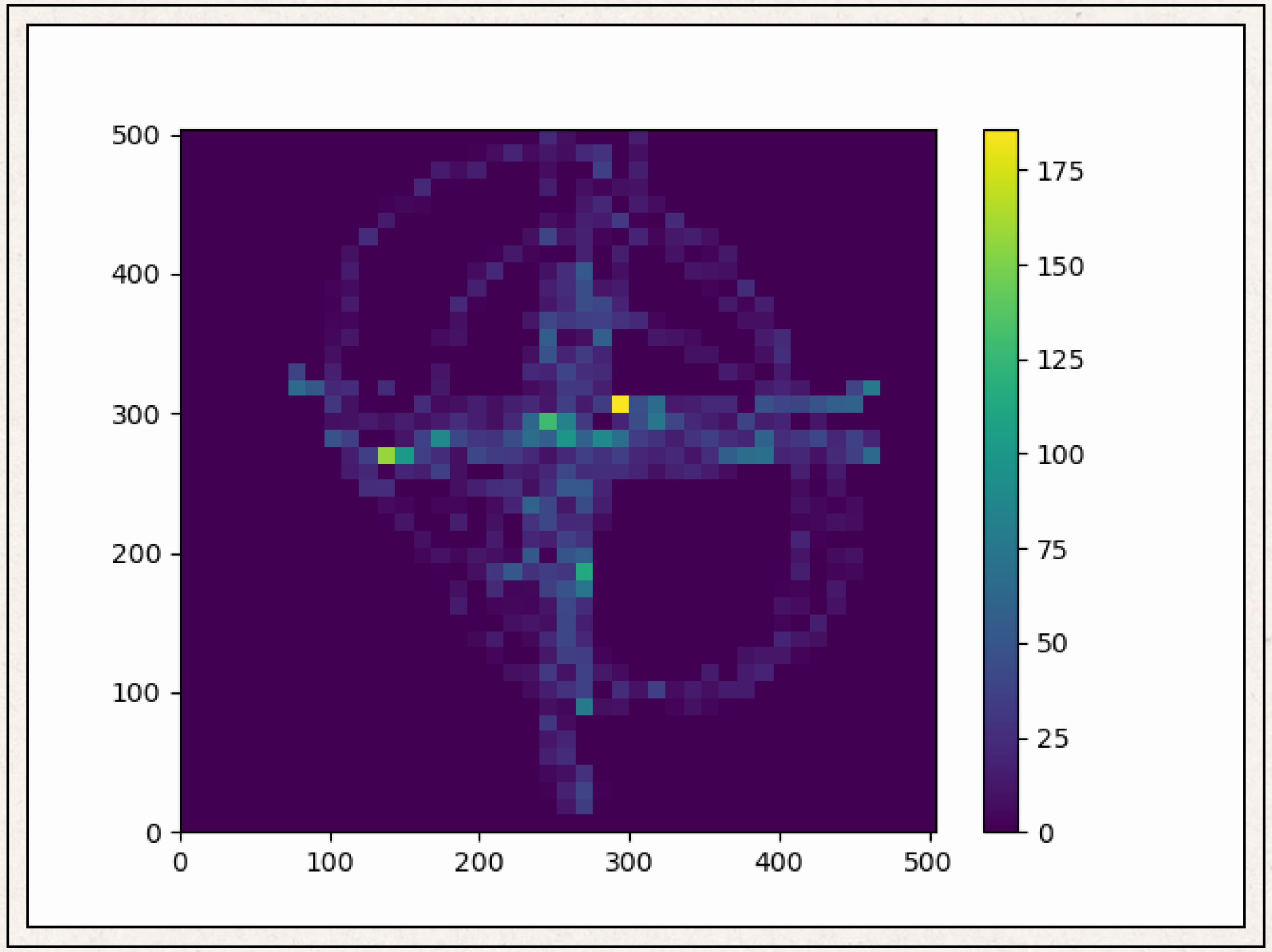
Sensor Fusion

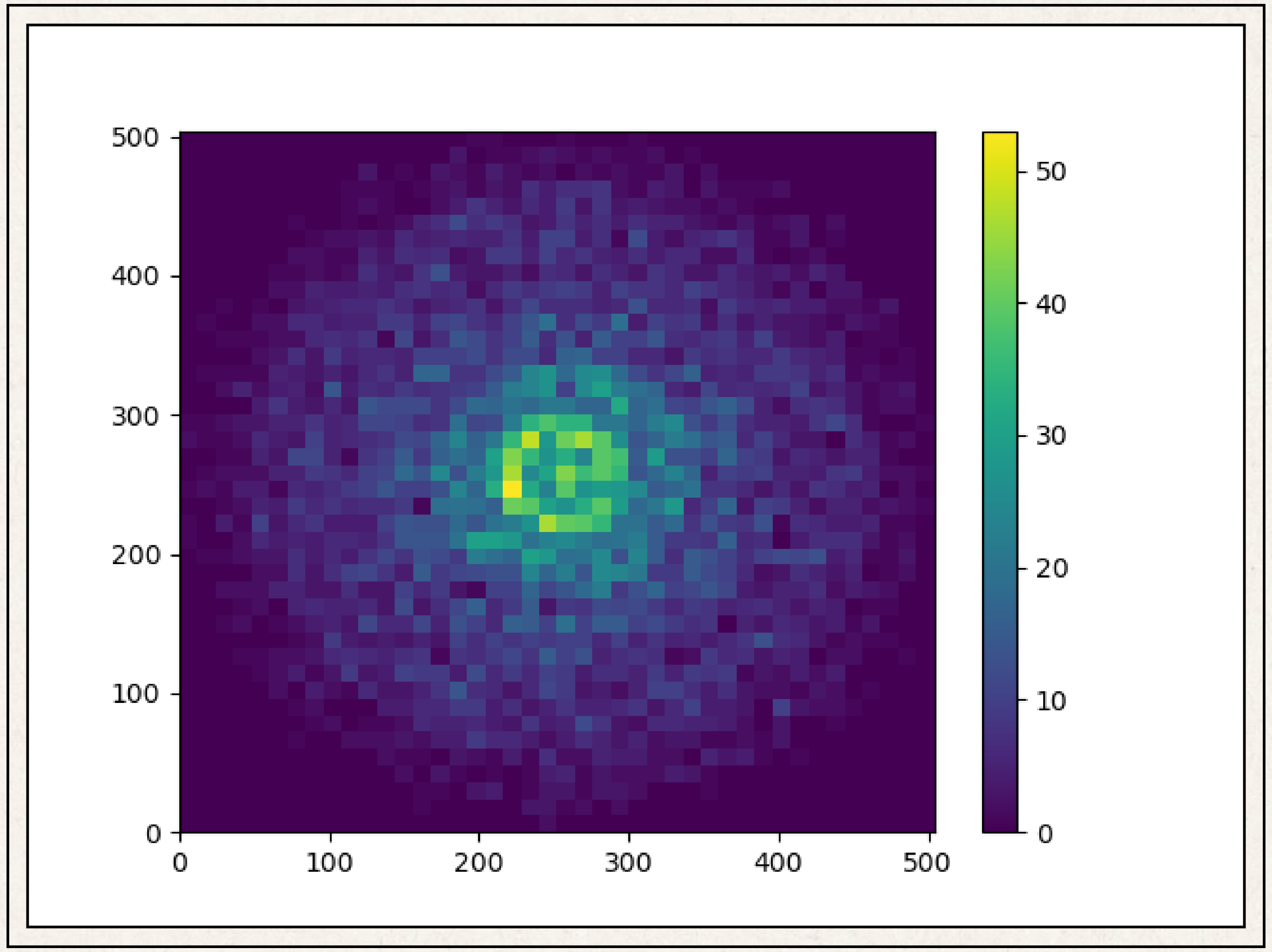
AI heat-maps, AprilTag poses, and LiDAR ranges are blended into a two-stage Kalman filter, authorizing *docking only when error < 5 cm*.

Computer Vision: Data Collection

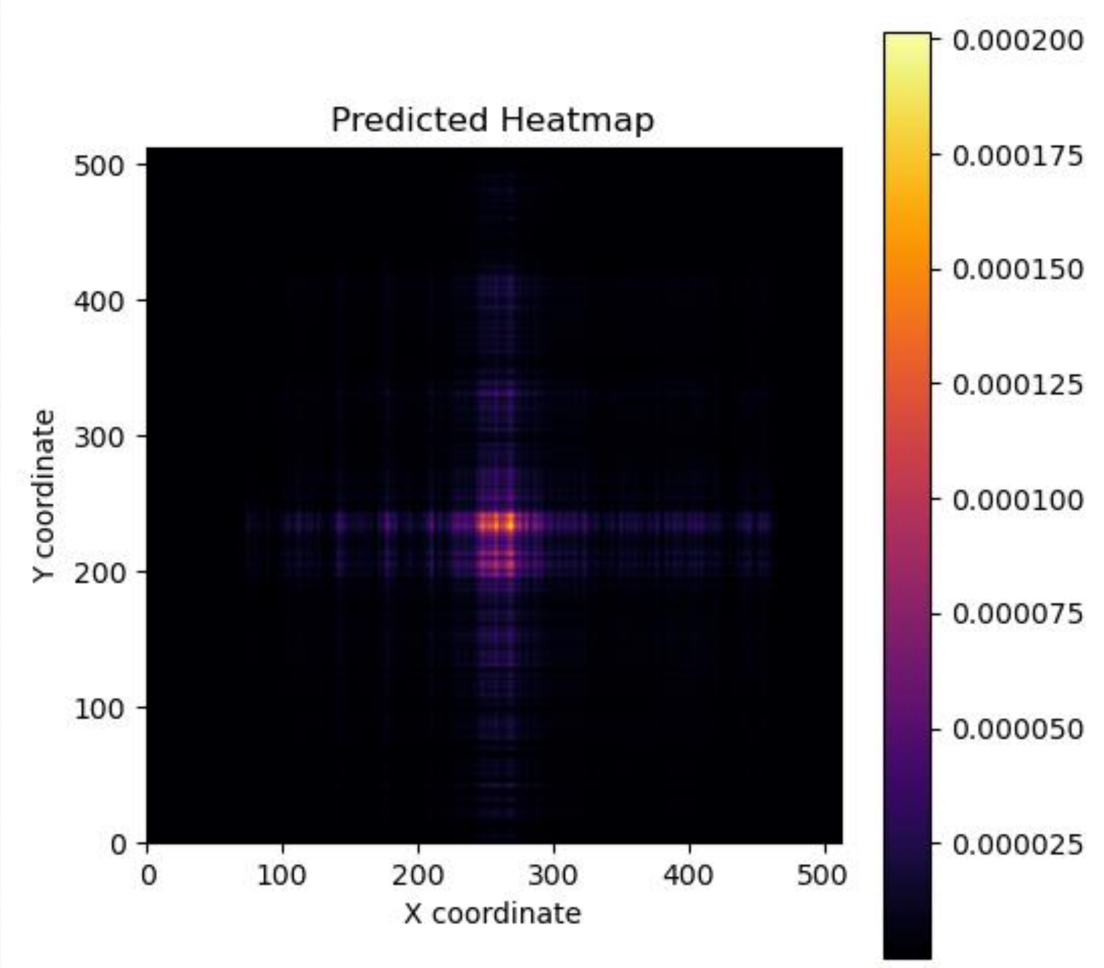
Training data collected by videoing the coupler from various angles, then converting each frame into an image.

Potential for bias in the training data. Application of image rotations to the data, can be used to even out the center point distribution, improving coverage of different coupler positions and orientations.





Computer Vision: Training and Prediction

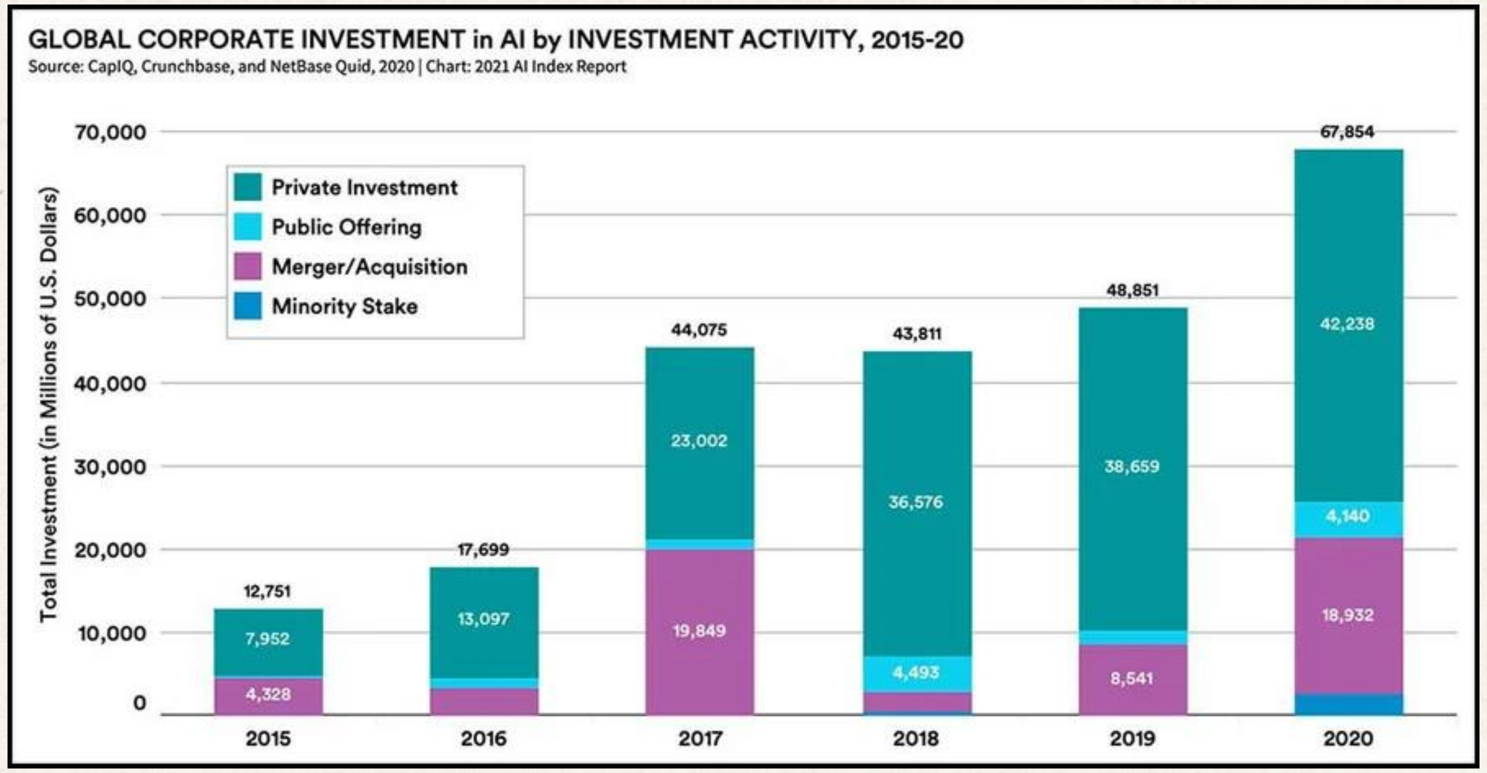


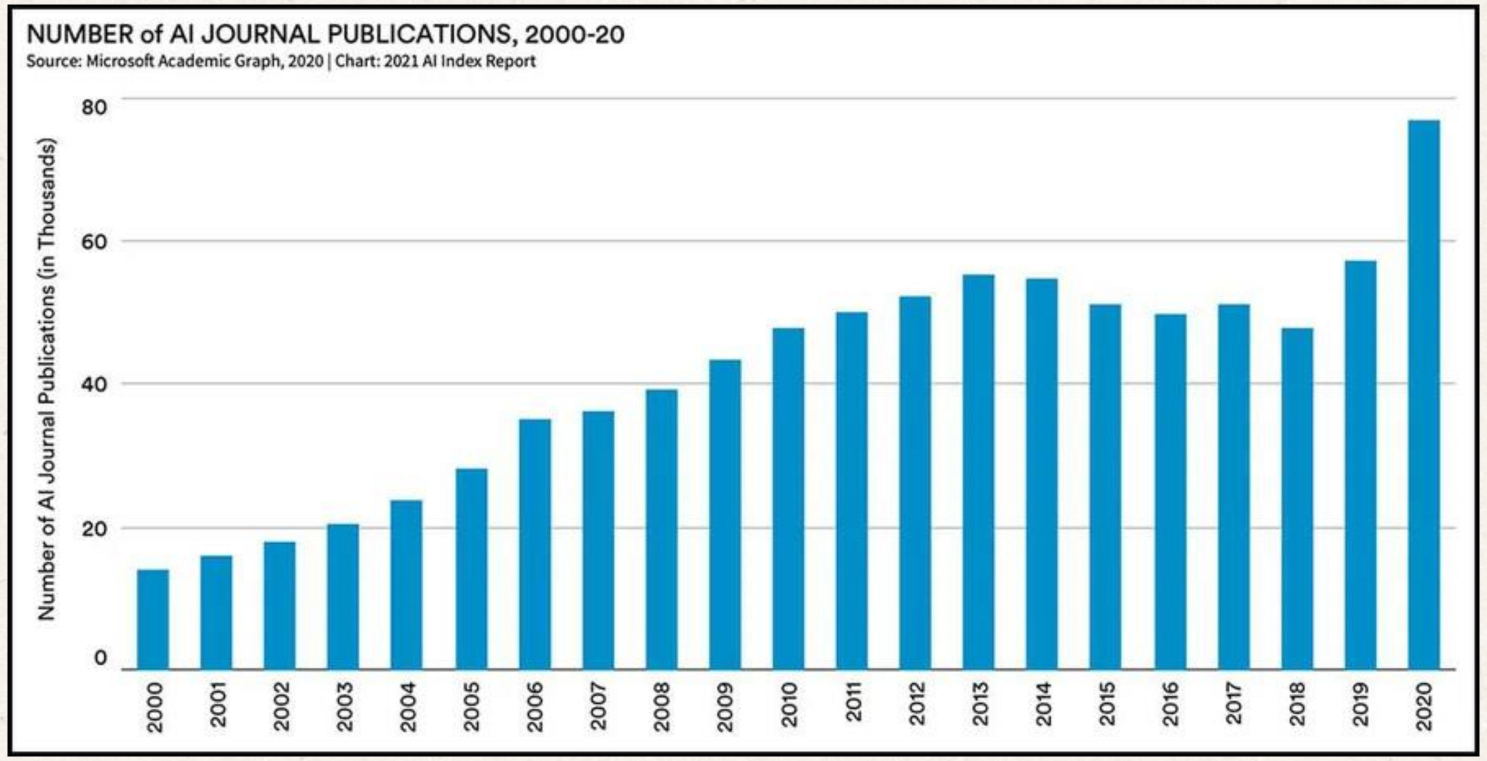
AI Model

To improve training, Gaussian heatmaps centered on the coupler's true location should be implemented to reward nearby guesses.

Instead of predicting a single point, the model will output a probability distribution across the image.

Selecting the top 10 highest-confidence pixels and averaging their coordinates yields more accurate and stable predictions.





Computer Vision: Integration & Validation

Integration

Weight based predictions used in order to manually control how much each subsystem contributes to the end prediction.

Physical restrictions are hard coded in so the Computer Vision System can't move the coupler in such a way that might cause failures to occur

---

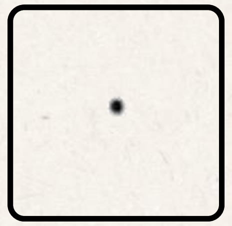
Why AI?

AI isn't something we should rely on blindly. It's a rapidly evolving tool that makes autonomous systems more robust, adaptable, and accurate.

With the rapid advancement of AI in recent years, sooner rather than later, AI will catch up to modern methods of computer vision.

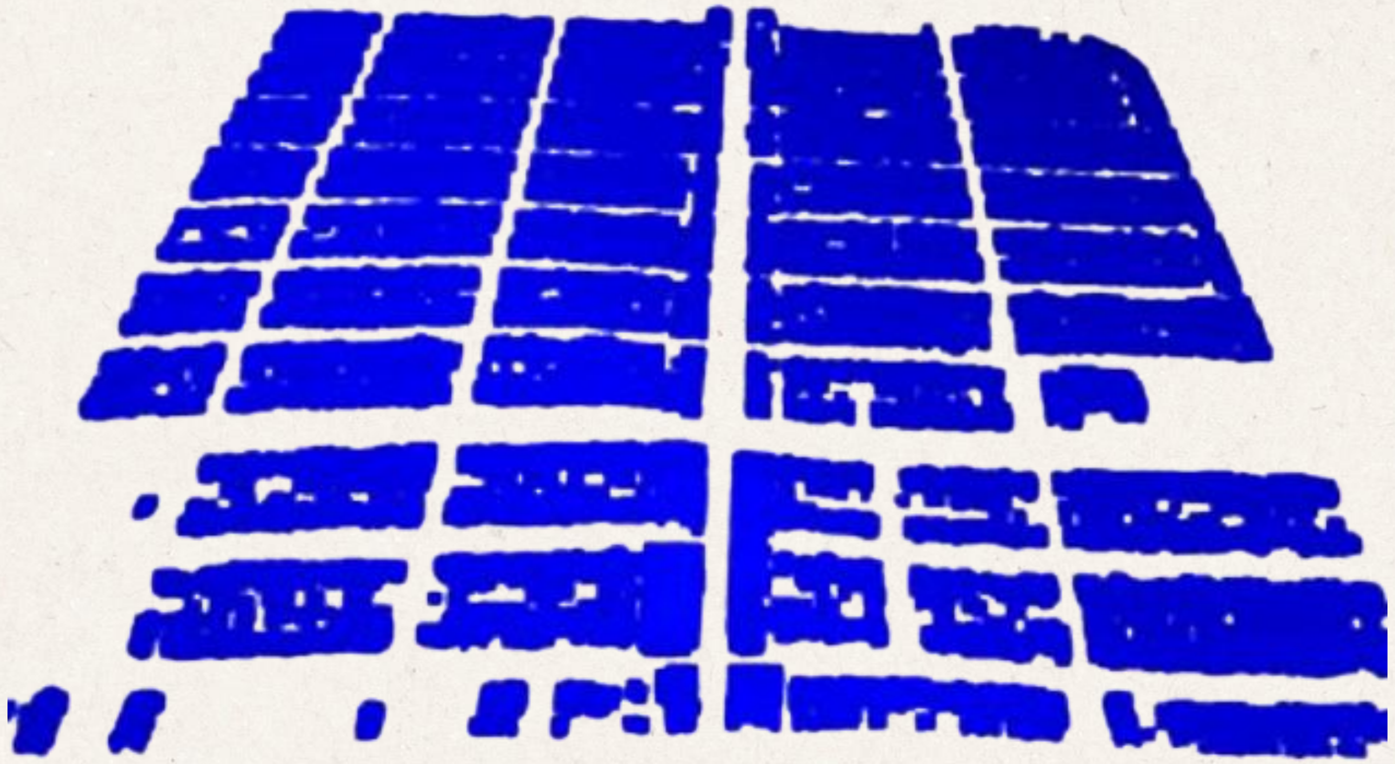
LiDAR Sensor Fusion

Potential implementation of LiDAR in the CV system



01 **Synthetic Point-Cloud Testbed**
Open-source LiDAR map is imported into ROS to reflect similar data as achieved during a docking sequence

02 **Closing-Rate Emulation**
Sphere representing measuring marches toward the point cloud; after each step, script recomputes point-to-sphere ranges



03 **Early Stage Value**
Allows for sampling rate tuning and noise handling before purchasing hardware and supplies synthetic range data to augment AI-training images for a 3D CV stack.

Magnetic Quick Disconnect & Alignment

Low-force capture that finishes alignment & holds seal until emergency

Magnets

Fpair = (B2A)/(2µ0) $\longrightarrow$ Fpair = 31 N, Ftotal = 185 N

for 6 pairs of N52-grade neodymium ring magnets (diam. 20 mm x 5 mm and B = 0.55 T)

Enough preload to keep the O-ring compressed after actuators settle, yet small enough for 50 N quick-disconnect per actuator

Cryo-Robust Performance

NdFeB retains > 90% magnetization at 90 K and remanence increases as temperature drops

Provides 6-DOF slef-centering for residual misalignments < 5cm/15° during docking

Safety & Reusability

Balanced seal loads means near-zero separation force once magnets are disengaged

150 ms emegency release prevents side-loads on the fluid line and vents propellant safely

Manufacturing

Material Selection

- Ti-6Al-4V (Grade 5)
  - High strength-to-weight-ratio
  - Cryogenic thermal stability (low CTE)
  - Corrosion resistance & sealing compatibility

Prototype

- PLA/ABS for main body
- Latching PLA only
- Flexible interfaces TPU
- Evaluate fit, form, and latch ergonomics
- Demonstrate requirements are met to customer

Workflow

1. CAD optimization for Laser Powder Bed Fusion (LPBF)
2. LPBF under argon atmosphere
3. Heat treatment + HIP
4. CNC machining (Ra < 0.8 µm)
5. Surface finish validation
6. Non distructive testing (NDT) via X-ray/CT
7. AI&T using helium leak tests

Component	Material	Quantity	Estimated Unit Cost
Main Housing	Ti-6Al-4V Powder	1	$450/kg
Quick Disconnect Latch Assembly	Ti-6Al-4V	1	
Seal Interface Surface Inserts	Ti-6Al-4V	1 set	$150
Cryogenic Metal Seal	Inconel/X-750	1	$90
Assembly Fasteners (Hex socket)	Ti Grade 2	6 pcs	$4/pcs
Heat Treatment & HIP Processing	Service Cost	—	$200
CNC Machining (Surface Finish)	Service Cost	—	$250
NDT (X-ray or CT Scan)	Service Cost	—	$300

Preliminary Mission CONOPS

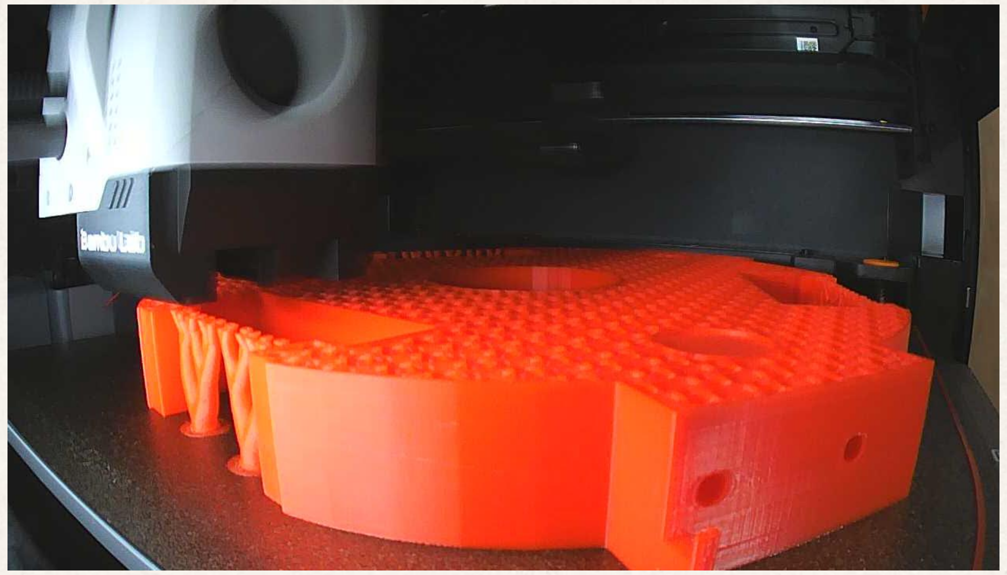
Agenda

01	Problem Overview
02	Technology Concept
03	Subsystem Overviews
04	**Prototype Demonstration**
05	Timeline to Completion
06	Budget
07	Acknowledgements and Conclusion

Prototype Demo

Active Alignment System Actuator Model

3D Print of Both Coupler Ends



Agenda

Timeline to Completion

Delopment and validation of AMCC-AAC to TRL 6+ will span approximately 3.5 - 4 years

Year 1:

- Team assembly
- Workspace setup
- System requirements & customer agreements
- Initial design iterations
- Low-level CFD and preliminary design review (PDR)

Year 2:

- High-level system design
- Advanced simulations
- Prototyping & AI&T setup
- Microgravity flow testing
- Critical design review
- Customer requirements revisions

Year 3:

- Software integration
- AI model training
- System validation (HITL)
- Pre-integration review
- AI&T finalized setup
- Full-scale prototype demonstration

Year 4:

- Final system validation
- Launch preparations
- “Flat sat” software demonstration to customer
- Conclude with a comprehensive report and recommendations for future development

Agenda

Budget: Salaries

Salaries absorb ~90% of the $6.7 M total program budget

20 engineers and 3 support staff

~3,718 salary FTE-weeks across the 3.5 year schedule

Spend rate of ~$1.6k per FTE-week, totaling about $6.1 M

Category	Cost				Notes
	Amount	Unit	Unit Cost	Total Cost	
A. Salaries			**FTE (Weeks)**	**FTE (Weeks)**	
Project Director	1	employee	182.0	182.00	Will be required throughout project duration
CAD Engineers	3	employee	182.0	546.00	Will be required throughout project duration
CFD Engineers	2	employee	182.0	364.00	Will be required throughout project duration
Manufacturing Engineers	4	employee	182.0	728.00	Will be required throughout project duration
Space Environment/HF Specialist	1	employee	104.0	104.00	Will only be required for the 1st phase of design
Thermodynamics Engineers	2	employee	182.0	364.00	Will be required throughout project duration
AI/Robotics Engineers	3	employee	182.0	546.00	Will be required throughout project duration
Test Engineers (System Validation)	3	employee	104.0	312.00	Only needed for last 2 years of testing/validation
Software Engineers (Controls/UI)	2	employee	104.0	208.00	Needed for UI dev. For around 2 years
Administrative/Technicians	2	employee	182.0	364.00	Will be required throughout project duration
Salaries Total:	**23**	, employees		**3718.000**	, total salary FTE weeks over 3.5 years

Budget: Hardware

Hardware represents ~6.5% of the $6.7 M total program budget

Robotics (actuators) and camera/LiDAR suite consume the most

$438k spead over prototyping, brassboard, and flight-unit builds

Spending peaks in Year 2 (brassboard) and Year 3 (full-scale flight article)

B. Hardware			**USD ($)**	**USD ($)**	
Thermal Insulation (MLI)	165	sqft	800.00	132000.00	MLI including custom fab. (20+ layers)
Coupler Materials (AISi10Mg)	200	$/kg	60.00	12000.00	Materials for prototyping, testing, and extra
Coupler Casing (Titanium)	70	$/kg	400.00	28000.00	Materials for prototyping, testing, and extra
Laser Powder Bed Fusion (LPBF)	20	$/hr	175.00	3500.00	LPBF machine and facility usage for all phases
Manufacturing Post-Processing	1	$	1000.00	1000.00	Additional costs incured during post-processing
LiDAR Sensors	3	$	2000.00	6000.00	1 for prototyping, 1 for final design tests, and 1 backup
Cameras	3	$	350.00	1050.00	1 for prototyping, 1 for final design tests, and 1 backup
Liquid Methane	100	$/ton	400.00	40000.00	33 cycles of 2.5 min at <20kg/s (if not reused)
Liquid Oxygen	100	$/ton	271.06	27106.00	34 cycles of 2.5 min at <20kg/s (if not reused)
Movement System (servos, robotics)	1	$	150000.00	150000.00	Entire movement system (minus sensors & cameras)
Electronics	1	$	35000.00	35000.00	Addtional on-board chips, wiring, batteries, etc.
Miscellaneous	1	$	2500.00	2500.00	Additional expenses like repairs/tools/etc.
Hardware Total				**$ 438,156.00**	, total hardware cost over 3.5 years

Budget: Software

Hardware represents ~4% of the $6.7 M total program budget

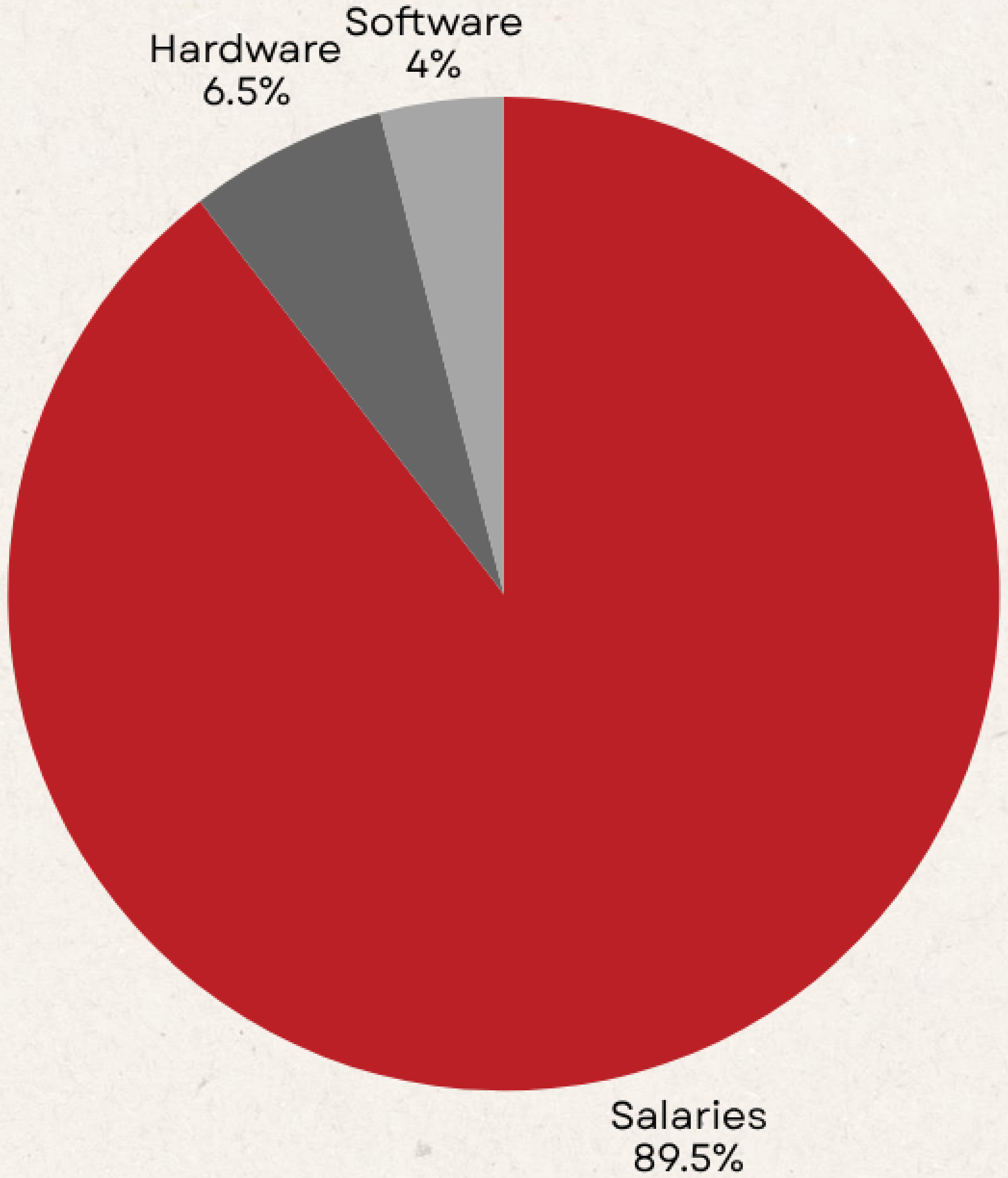
Core licenses: ANSYS Fluent, SolidWorks, MATLAB/Simulink, GPU cloud time, DevOps tools

$273k covering multi-year seats, HPC hours, and inference-grade GPU leasing

Front-loaded in Year 1 for analysis tools, with a second bump in Years 2-3 for cloud compute during AI training and HIL testing

C. Software			**USD ($)**	**USD ($)**	
MATLAB/Simulink	3.5	years	5000.00	17500.00	License with some add-ons required for 3 years
ANSYS Fluent	3	years	65000.00	195000.00	Enterprise CFD license for 3 years
Computers	5	computers	5000.00	25000.00	Computers required for CFD, CAD, and AI software
Additional Software/Storage Space/Etc.	1	n/a	35000.00	35000.00	Storage ~ $30k, other softwares for AI, sensing, etc.
Software Total				**$ 272,500.00**	, total software cost over 3.5 years

Budget Summary



Total Cost (w/o salaries)	**FTE (Weeks)**	**USD ($)**
	3718.00	$ 710,656.00
Total Cost (w/ salaries)	**Salaries ($)**	**Total ($)**
	$ 6,058,500.00	$ 6,769,156.00

Agenda

Thank you!

AMCC-AAC

Autonomous Magnetized Cryo-Couplers with Active Alignment Control for Propellant Transfer

Backup

Computer Vision

Autonomous coupling powered by a blend of AI and traditional Methods

April Tags

AprilTags are compact, low-data markers ideal for our 50 mm tag area. We place three uniquely IDed tags based on the coupler's geometry. Knowing their 3D positions allows us to estimate the coupler's center from just one tag, with more tags improving accuracy.

Detection involves converting the image to grayscale and matching binary patterns. A red-to-white mask enhances tag visibility against the background.

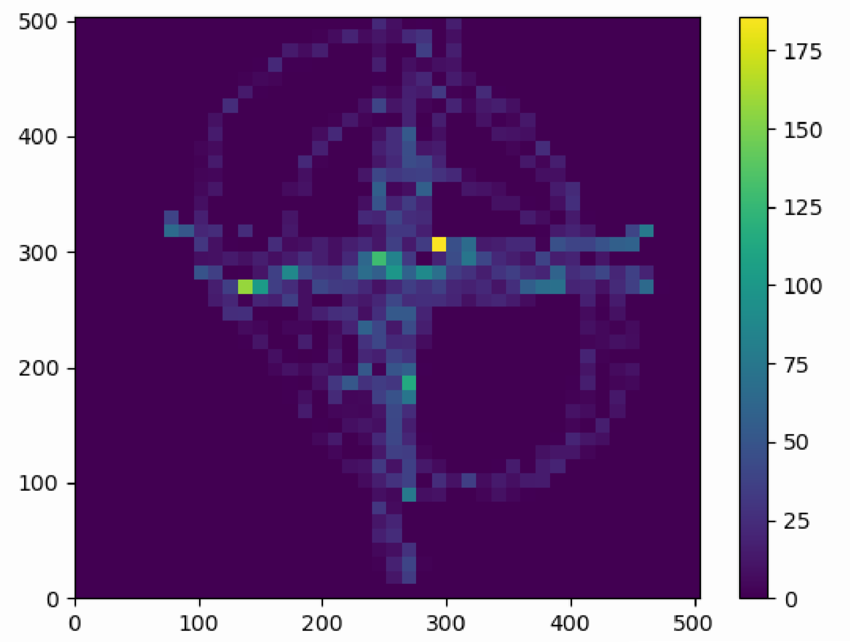
Computer Vision

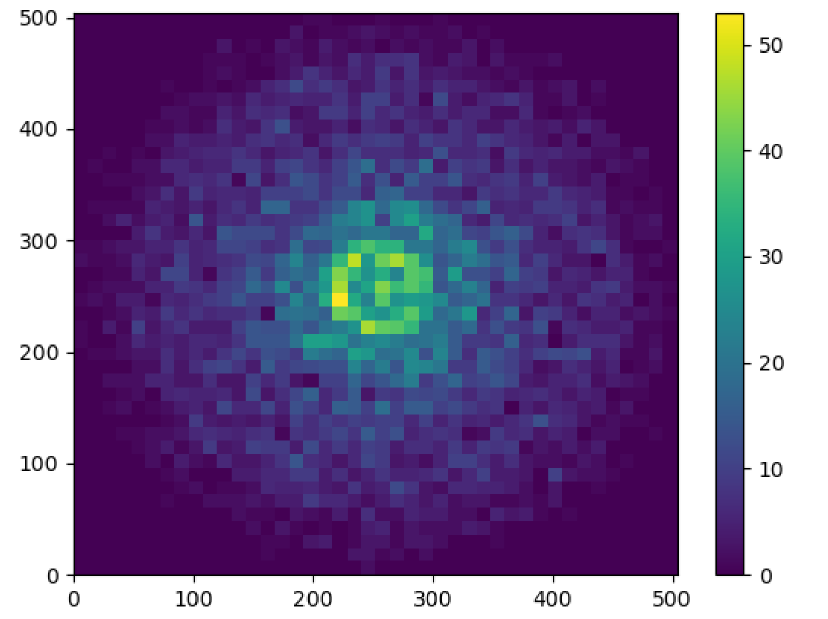
Autonomous coupling powered by a blend of AI and traditional Methods

Data Collection

We propose collecting training data by recording a video of the coupler from various angles, then converting each frame into an image.

This method can lead to bias in the training data. To address this, the application of image rotations to the data, can be used to even out the center point distribution, improving coverage of different coupler positions and orientations.





Computer Vision

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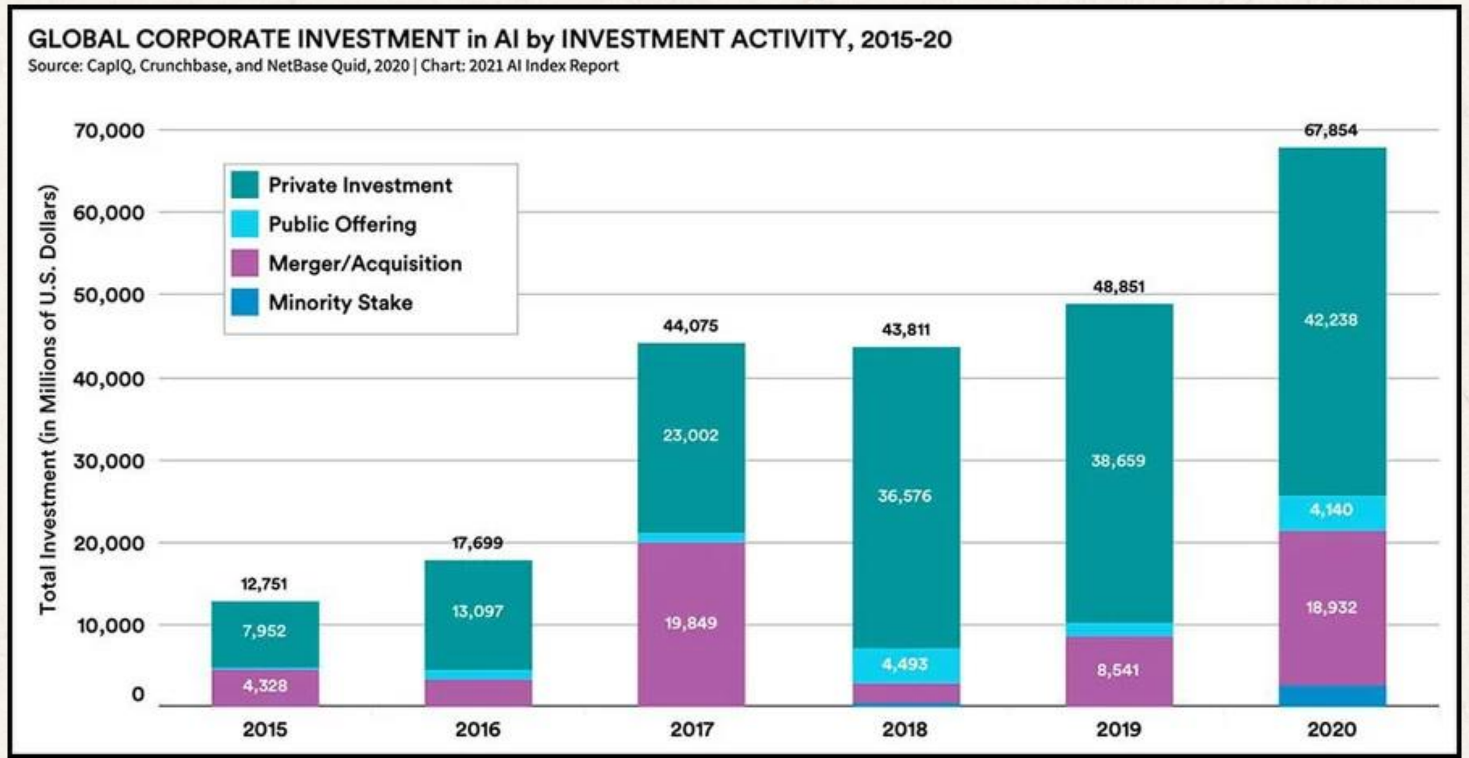

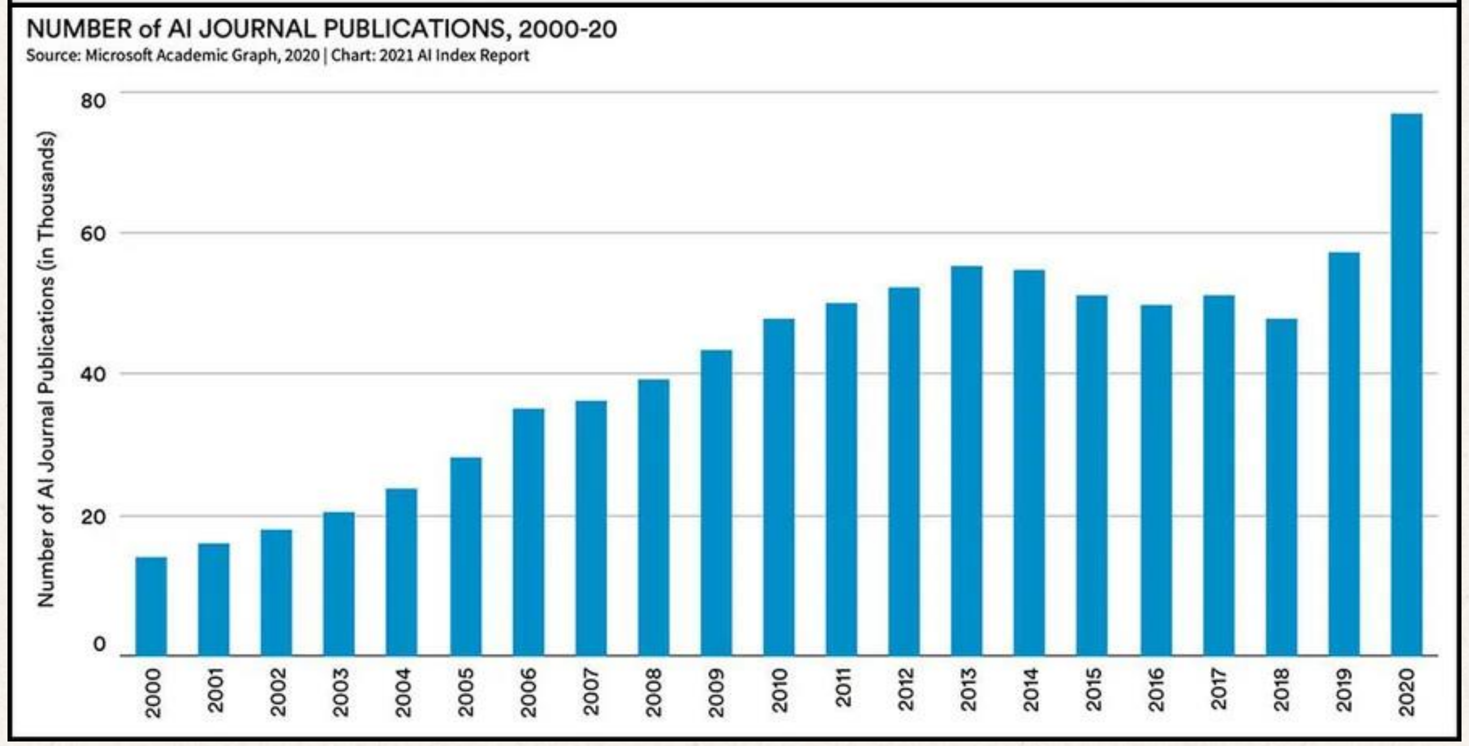

Why AI?

AI isn't something we should rely on blindly. It's a rapidly evolving tool that makes autonomous systems more robust, adaptable, and accurate.

With the rapid advancement of AI in recent years, sooner rather than later, AI will catch up to modern methods of computer vision.

Computer Vision

Autonomous coupling powered by a blend of AI and traditional Methods

Improvements

Training on high-quality photos (not video frames) will improve model accuracy.

Testing smaller tags, new placements, and color designs can boost detection.

Lidar Integration: Using 3D lidar data alongside vision adds spatial context for more precise localization.