Integrated System for Autonomous and Adaptive Caretaking (ISAAC)

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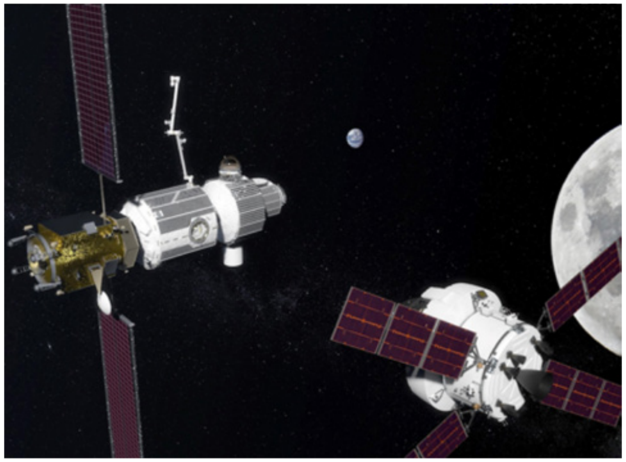
Customer: HEOMD / Gateway

- **What it is:**
  - A spaceport in lunar orbit that will serve as a gateway to deep space and the lunar surface
- **What Gateway provides:**
  - Support on aligning ISAAC-developed capabilities with evolving Gateway mission requirements
  - Technical information about Gateway design concept to support realistic simulation testing (e.g. in iPAS)
- **What ISAAC provides:**
  - Capabilities relevant to needs, use cases, and requirements for Gateway
  - Feasibility tests and relevance assessments inform Gateway systems engineering trade studies



The Concept: Autonomous Caretaking of Uncrewed Spacecraft

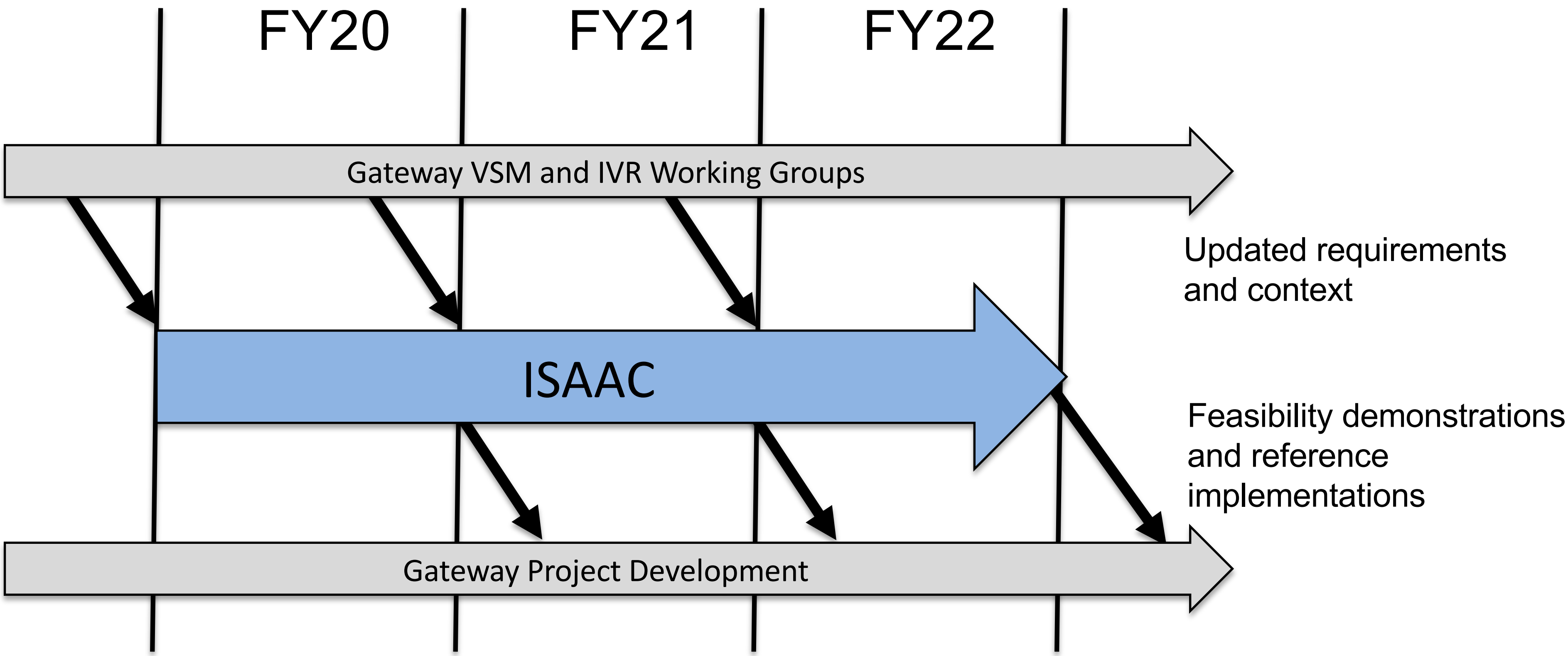
Description and Objectives

- Develop **autonomous caretaking** of uncrewed spacecraft
- Integrate autonomous robots, spacecraft infrastructure (avionics, sensors, network), and ground control
- Enhance **autonomous state assessment**, **logistics management**, and **fault management**
- **Focus on capabilities required for the Gateway** (Human Exploration Requirements HEOMD-004: GTW-L2-0044, 0047, 0050, 0142, 0143, 0145) and applicable beyond the Earth-Moon system.
- **Assess feasibility and relevance** for future deep space spacecraft.
- Extend the Autonomous System Manager (ASM) architecture to enhance **integrated analysis of data, operator productivity, and reliable coordinated execution** of system-level tasks.

Gateway Alignment and Infusion

- **Intra-Vehicular Robotics Working Group**
  - Chartered to provide a detailed specification of the interfaces between IVR and Gateway modules and systems
- **Vehicle Systems Manager Working Group**
  - Chartered to provide a detailed specification of the Vehicle System Manager and the overall Autonomous Systems Management Architecture
- **Alignment:**
  - ISAAC will need to respond to details emerging from the working groups
  - Working groups identify gaps and needs, set requirements, define problems
  - ISAAC will prototype solutions to solve problems and close gaps relevant to the scope of ISAAC, demonstrate those solutions, and establish feasibility
  - Building technologies in response to the Working Groups will best align ISAAC deliverables to Gateway needs
- **Infusion:**
  - We expect Gateway to implement flight flight versions of technologies developed by the ISAAC project after successful demonstrations

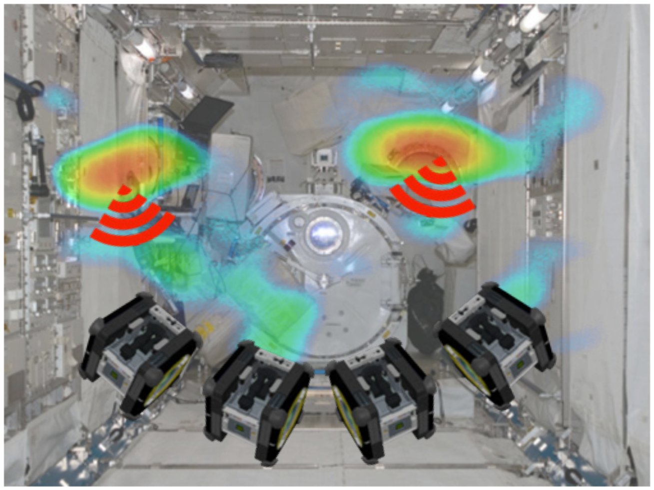
Ongoing Engagement with Gateway



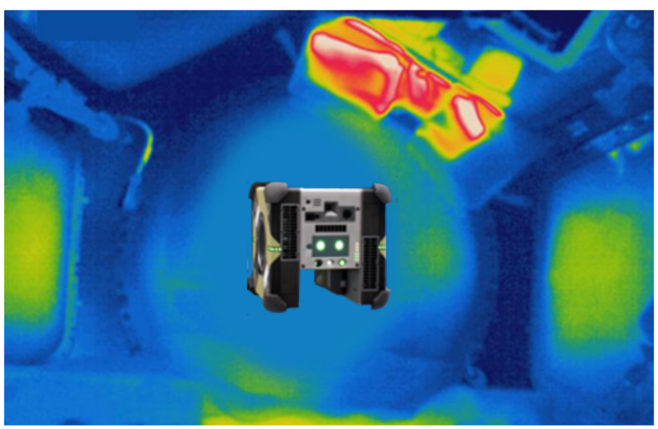
- **Ongoing Gateway engagement is critical**
  - Without ongoing input, ISAAC delivers the wrong thing
  - Without incremental output, ISAAC delivers too late

ISAAC Capability Areas

Autonomous State Assessment

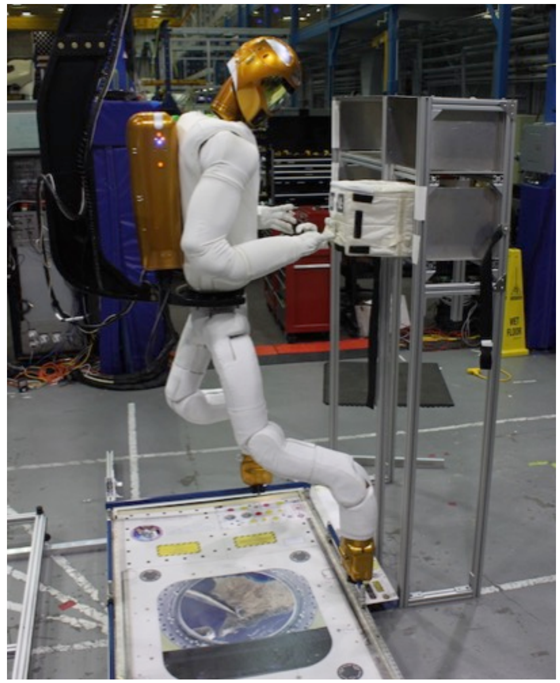


Localizing signal sources by analyzing signal strength variation



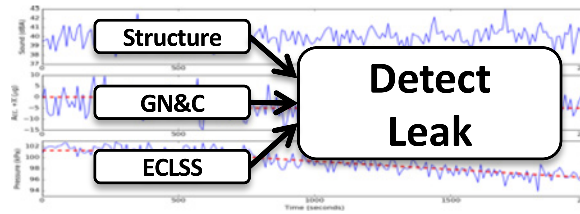
Habitat thermal mapping

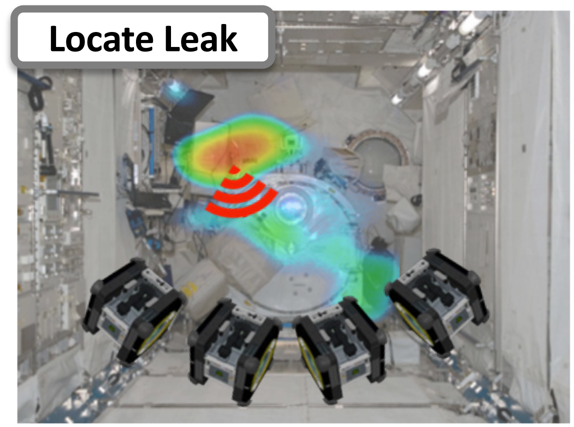
Autonomous Logistics Management



Robotic cargo transfer

Integrated Fault Management



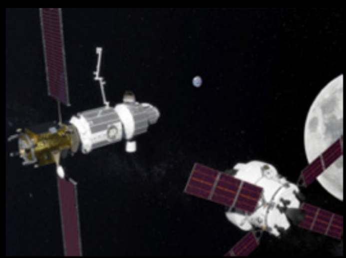


The Challenge

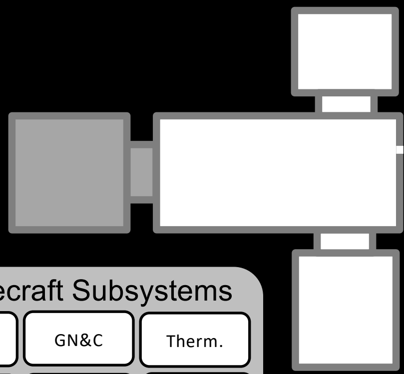
- **Duration and distance impact:**
  - **Reduce risk** through improved fault recovery during uncrewed phases
  - **Reduce cost** by enabling new design options
  - **Free up crew time** spent on maintenance and logistics
  - **Enhance utilization** during uncrewed phases

- **We need autonomous spacecraft caretaking during uncrewed periods**

Simplified Architecture



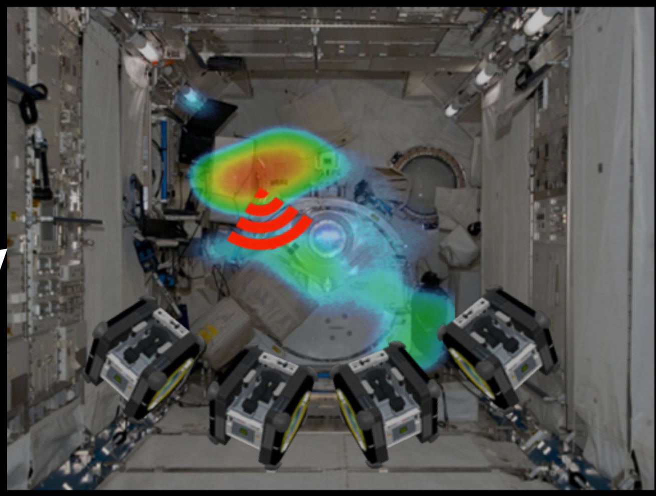
Gateway



Spacecraft Subsystems

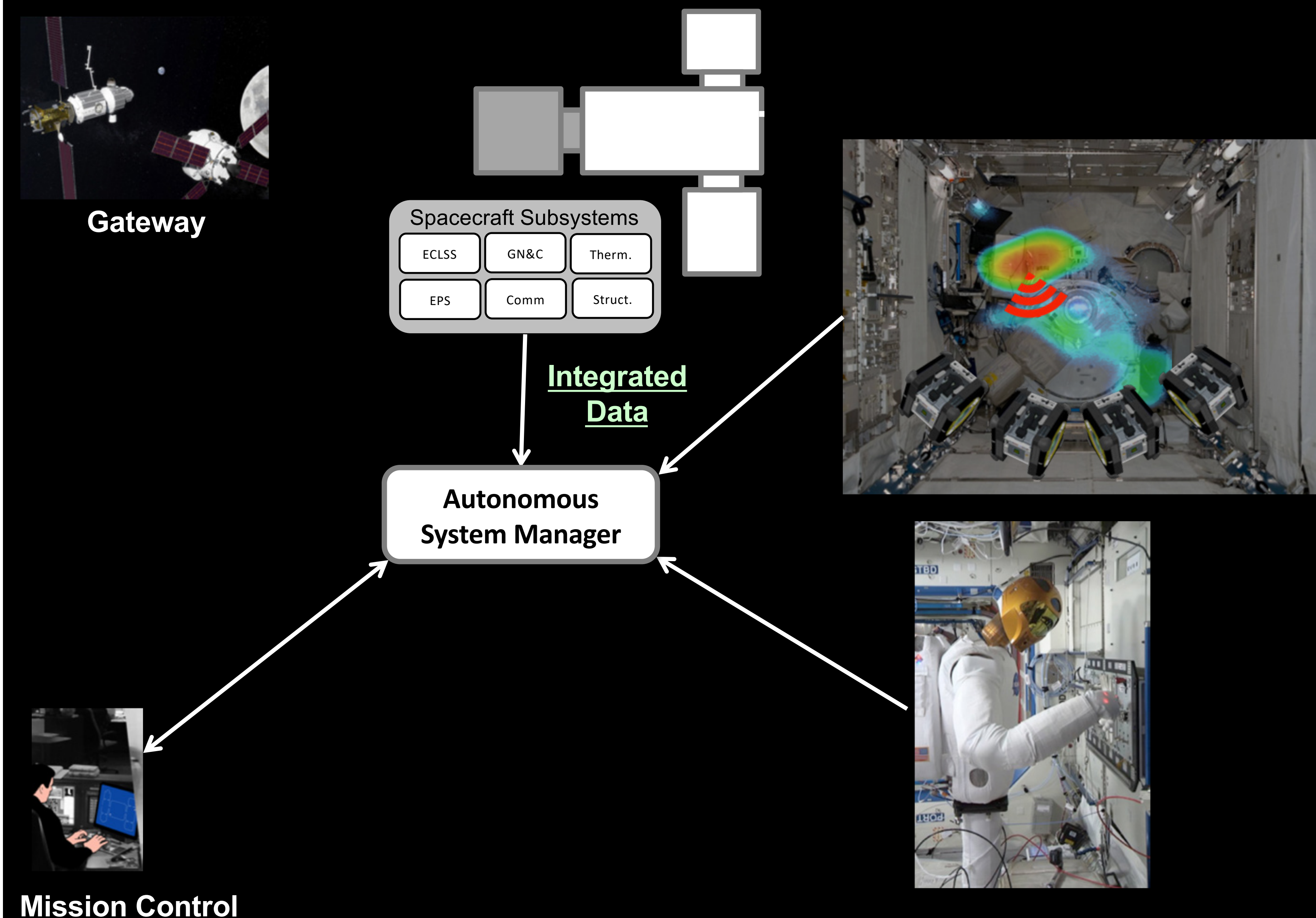
ECLSS	GN&C	Therm.
EPS	Comm	Struct.

Autonomous System Manager

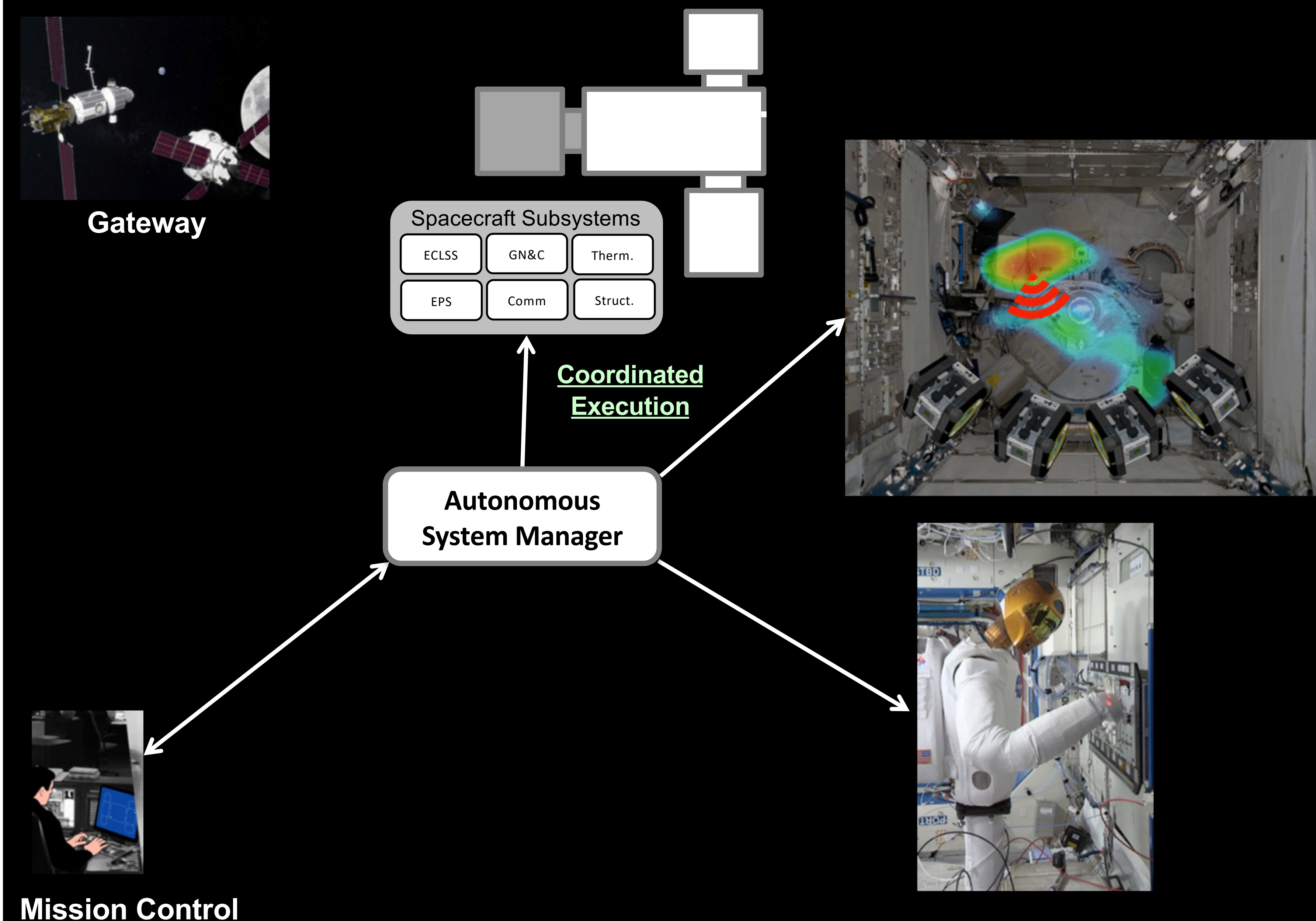


Mission Control

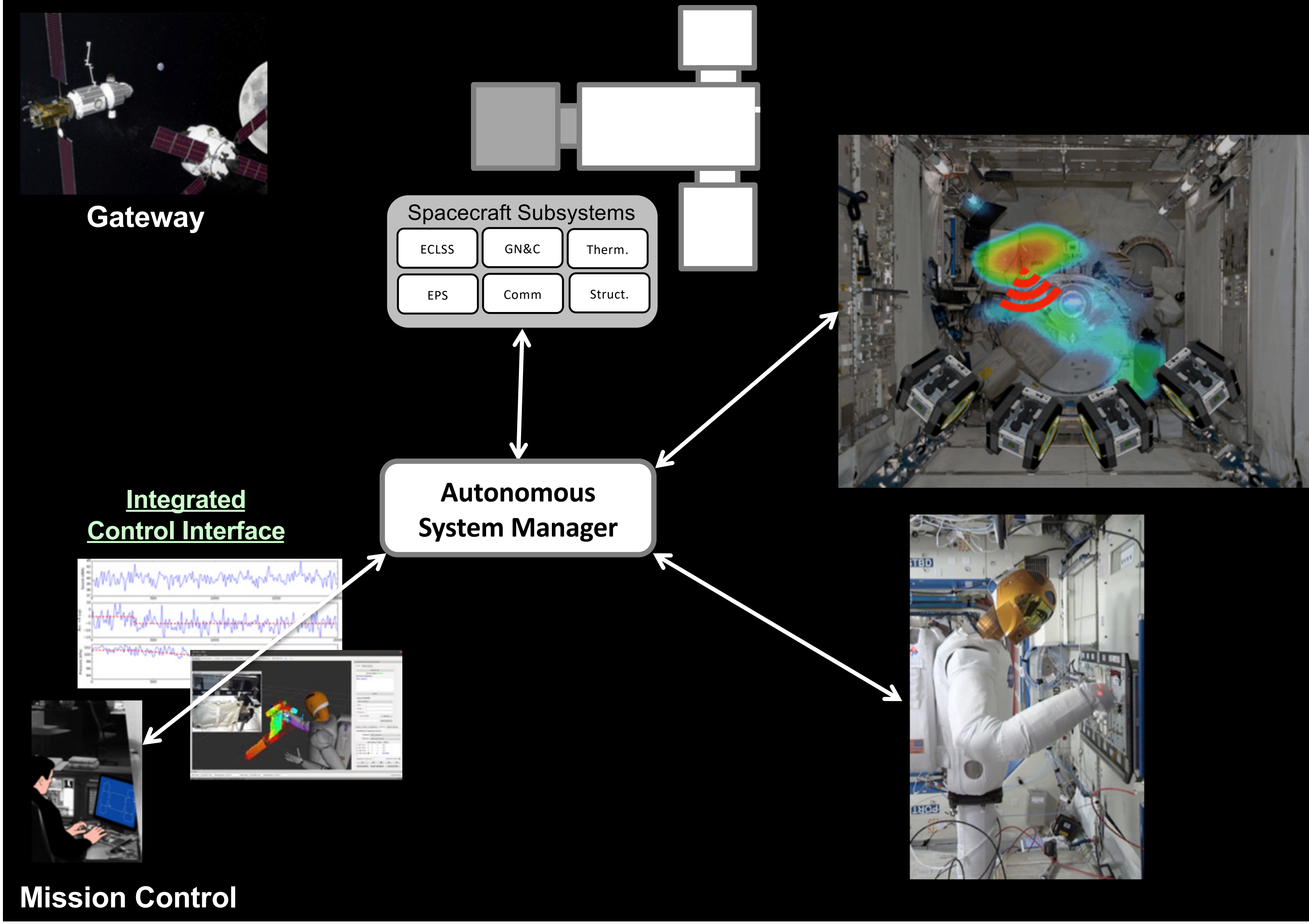
Thrust: Integrated Data



Thrust: Coordinated Execution



Thrust: Integrated Control Interface



What ISAAC Is and Isn't

- **ISAAC is about:**
  - Developing technical thrusts: Integrated Data, Coordinated Execution, Integrated Control Interface
  - Linking spacecraft subsystems and robots
  - Demonstrating capabilities using ISS, iPAS, and other testbeds
  - Assessing feasibility and relevance of capabilities for Gateway and future missions
  - **Developing critical technology for caretaking of uncrewed spacecraft**
- **ISAAC boundaries:**

Don't	Instead
Develop new robots	Leverage platforms developed by previous STMD investments. Make minor modifications where needed (e.g. add modified COTS sensors).
Rely on perfect availability of ISS resources	Maintain reserve against typical spaceflight delays; keep alternate testbeds and robot platforms in mind
Develop new core fault diagnosis and executive technology	Link existing core software to spacecraft subsystems and robots

Technical Thrusts and Capabilities

Capability Area	Technical Thrust: Integrated Data	Technical Thrust: Integrated Control Interface	Technical Thrust: Coordinated Execution
Autonomous State Assessment	√		
Autonomous Logistics Management	√	√	
Integrated Fault Management	√	√	√

Each year focuses on one technical thrust

Technical Thrusts and Capabilities

Capability Area	Technical Thrust: Integrated Data	Technical Thrust: Integrated Control Interface	Technical Thrust: Coordinated Execution
Autonomous State Assessment	√		
Autonomous Logistics Management	√	√	
Integrated Fault Management	√	√	√

Each year focuses on one technical thrust

Each year we build one capability, including:
- One or more demonstrations (ISS, iPAS)
- One or more assessments of feasibility and relevance for future deep space missions

Technical Thrusts and Capabilities

Capability Area	Technical Thrust: Integrated Data	Technical Thrust: Integrated Control Interface	Technical Thrust: Coordinated Execution
Autonomous State Assessment	✓		
Autonomous Logistics Management	✓	✓	
Integrated Fault Management	✓	✓	✓

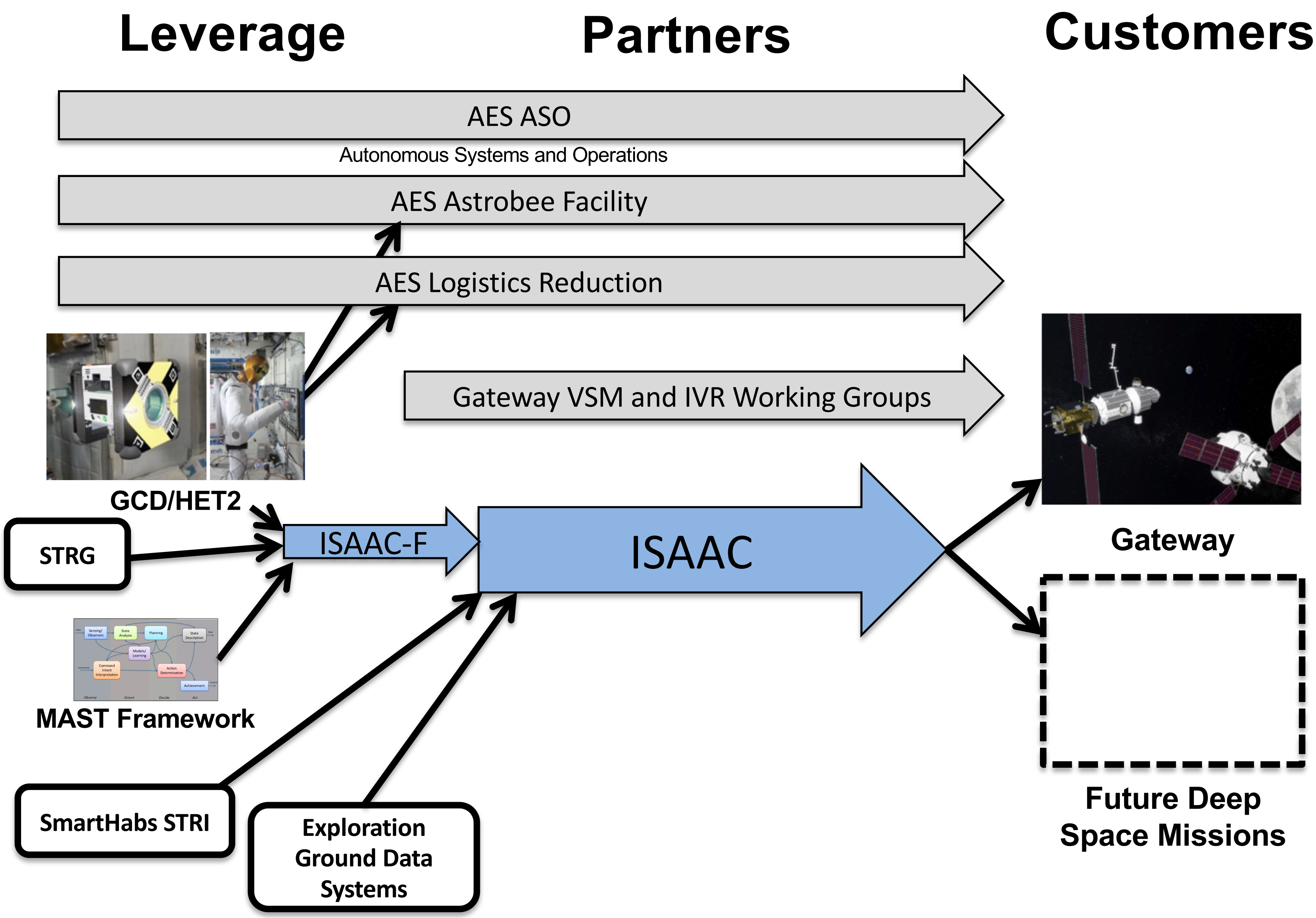
Each year focuses on one technical thrust

Capabilities that come later in the project can take advantage of more of the technical thrusts

Each year we build one capability, including:

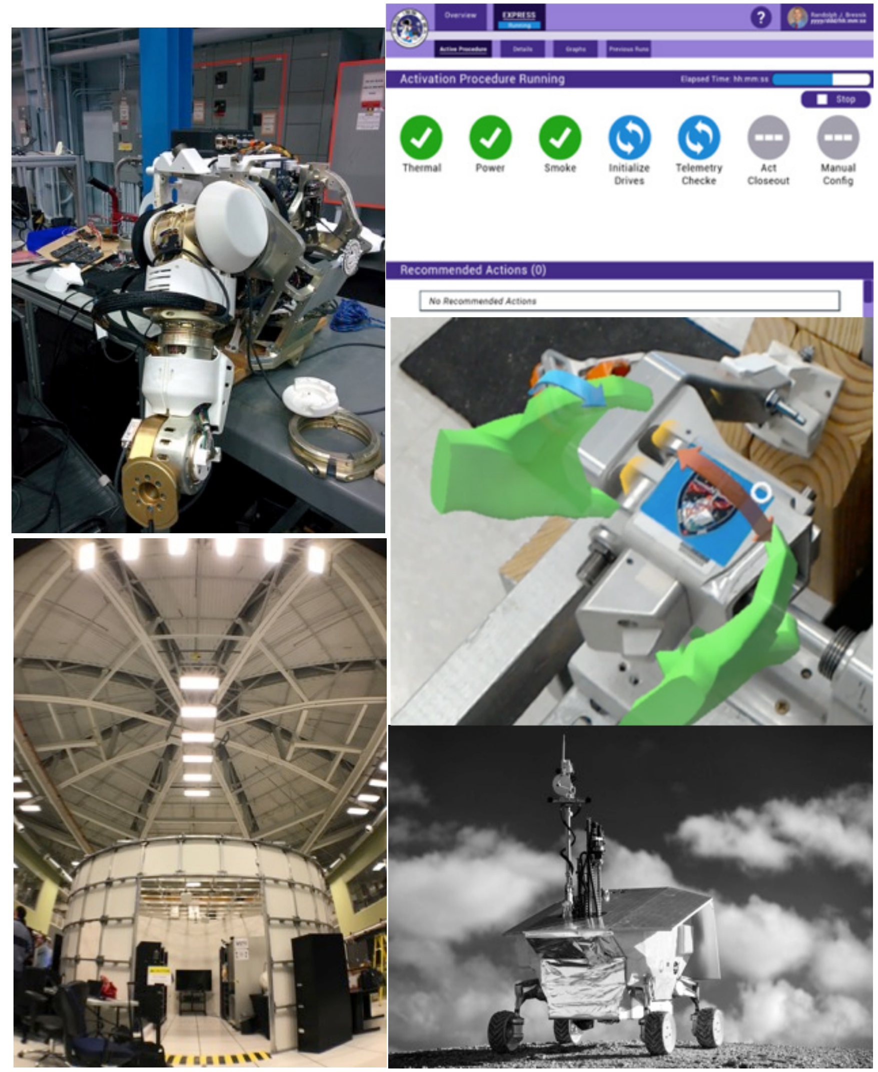
- One or more demonstrations (ISS, iPAS)
- One or more assessments of feasibility and relevance for future deep space missions

Partnerships



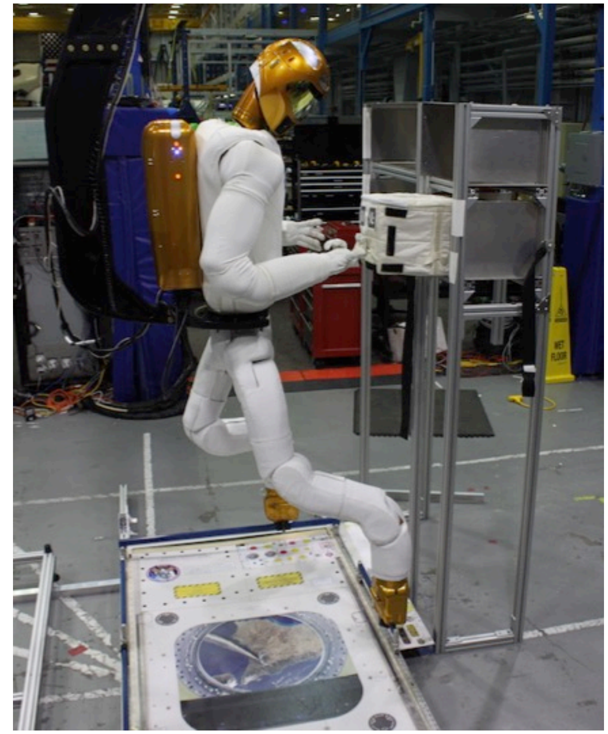
Partnerships: AES / Autonomous Systems and Operations (ASO)

- **What it is:** ASO is maturing technology by demonstration onboard ISS and Habitat analog testbeds, for infusion into future Exploration missions (e.g. Orion as part of EM-2, Habitat) and participating in evaluation of NextSTEP BAA Habitat designs
- **What AES/ASO provides:**
  - Fault diagnosis core technology (as matured through ACAWS)
  - Robust planning and execution core technology (e.g. PLEXIL)
- **What ISAAC provides:**
  - Links ASO technologies to a broader range of models, data, and commanding
    - Both spacecraft subsystems and autonomous robots
  - Essentially, enables broader impact

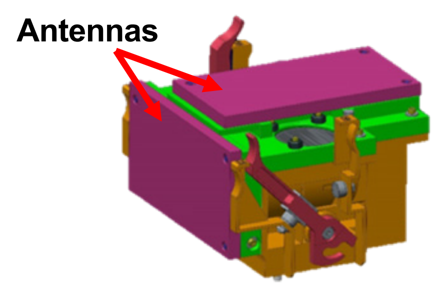


Partnerships: AES / Logistics Reduction (LR)

- **What it is:** AES/LR develops technologies that reduce logistical mass, volume, and the crew time dedicated to logistics management
- **What AES/LR provides:**
  - Renewal/support of Robonaut2 platform on ISS
  - RFID-Enabled Autonomous Logistics Management-2 (RFID Recon): RFID readers that integrate with Astrobee, enabling inventory tracking with a mobile inspector
  - REALM-6DOF: SBIR-derived WHISPER RF/infrared tag technology, in development, provides cm-level tag location accuracy
  - Robotic mobility manipulation technologies for autonomous cargo transfer
- **What ISAAC provides:**
  - Linking data from fixed, RFID Recon, and REALM-6DOF telemetry with other spacecraft and robotic data sets, improving its usefulness
  - Assess impact of RFID Recon and REALM-6DOF technology on autonomous robotic ops
  - Integration of spacecraft data with existing robotic autonomous command/control interfaces



Robonaut2



RFID Recon Astrobee Payload

Partnerships: AES / Astrobee Facility

- **What it is:** The Astrobee Facility maintains the Astrobee free flyer robot platform and supports guest science users
- **What AES/Astrobee provides:**
  - A unique free flying IVA robot testbed on the ISS
  - Associated ground testing facilities (MGTF and Granite Lab)
  - Integration and ops support
- **What ISAAC provides:**
  - Flagship guest science project increases Astrobee utilization and impact
  - ISAAC-developed capabilities will enhance the Astrobee platform, offering new opportunities for future guest science

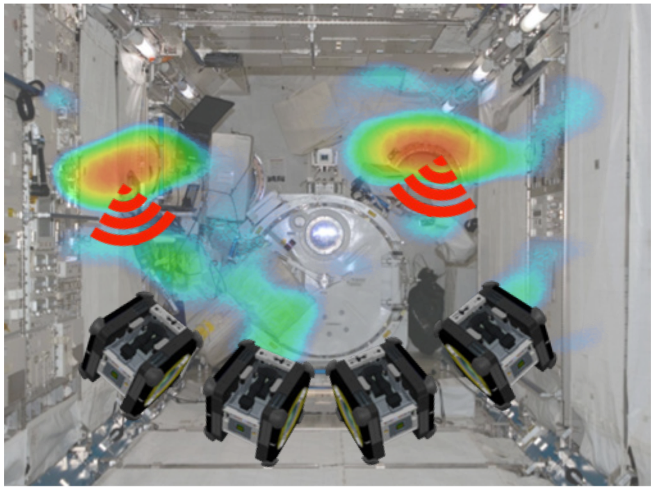
Preliminary ISAAC Demo Scope

- One demo per year
- One technical thrust emphasis
- Associated with an IVR use case

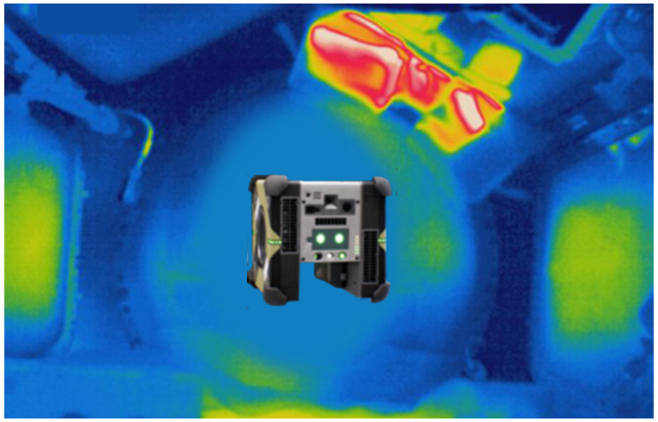
#	Year	Technical Thrust	Use Case
1	FY20	Integrated Data	*Autonomous State Assessment*
2	FY21	Integrated Control Interface	*Autonomous Logistics Management*
3	FY22	Coordinated Execution	*Integrated Fault Management*

Demo 1: Integrated Data Autonomous State Assessment (2020)

- **Location:** ISS (ground facilities as a fallback)
- **Goals:**
  - Build a 3D model of the ISS interior with co-registered data from multiple sensors. Possible map/sensor types:
    - Point: RFID reader
    - Area: Visual, depth, or thermal IR camera
    - Volume: Sound level, CO_2 level, wifi signal strength
  - Map visual texture at 1mm – 0.2mm
    - Full map "base layer" is visual texture draped over 3D geometry. Texture will likely have higher spatial resolution than geometry.
  - Anomaly detection for 3 types of anomalies using integrated data from robots and vehicle subsystems
    - e.g. hatch open/closed, temperature outside nominal range, item moved, cable disconnected, motor noise
- **Prior work:** Astrobee mapping ISS interior during commissioning phase (visual "sparse map")



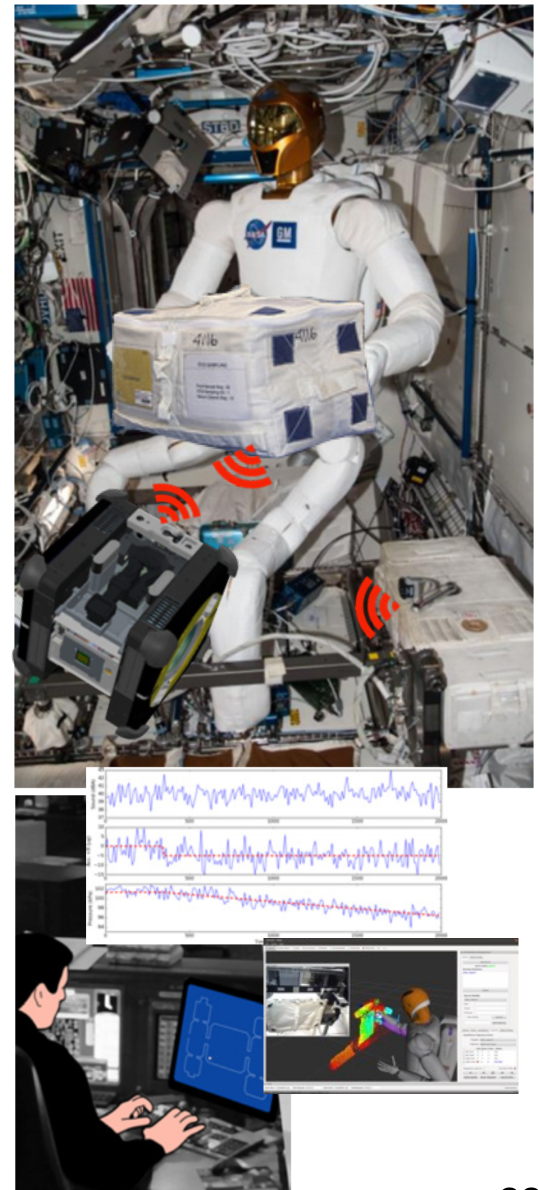
Localizing signal sources by analyzing RSS spatial variation



Habitat thermal mapping

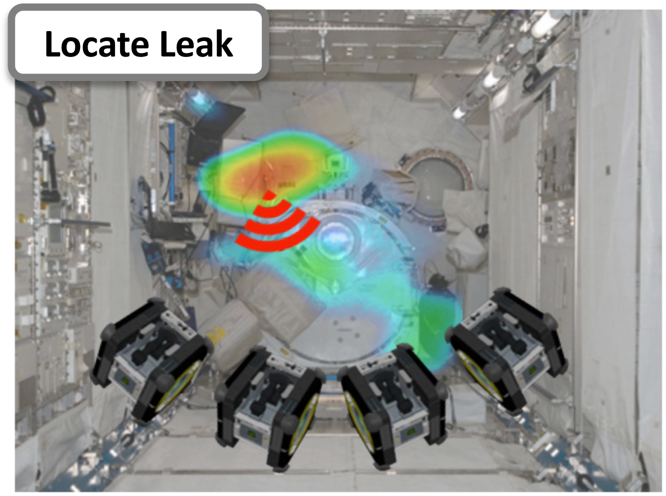
Demo 2: Integrated Control Interface Autonomous Logistics Management (2021)

- **Location:** ISS (ground facilities as a fallback)
- **Goals:**
  - Enhance cargo transport from FY20 LR-AL demo with new operator interface
    - Enhance user experience, make ops more effective
  - Improve situation awareness:
    - Vehicle subsystems and robots in one 3D environment
    - Plot telemetry from vehicle and robots in one view
    - Geometry, status, progress, steps of current plan
  - Unify remote commanding:
    - Enable at least one command type for each of three vehicle component types and two robots
    - Enable basic execution control for each robot: Execute single commands, run/pause/abort plan
- **Assets involved:** Robonaut2, Astrobee, RFID Recon payload, RFID-tagged cargo item, three vehicle subsystems (TBD)
- **Prior work:** FY20 AES Logistics Reduction Autonomous Logistics (LR-AL) demonstration- incorporate Robonaut2 & Astrobee in finding and retrieving a CTB on orbit (controlled from ground)

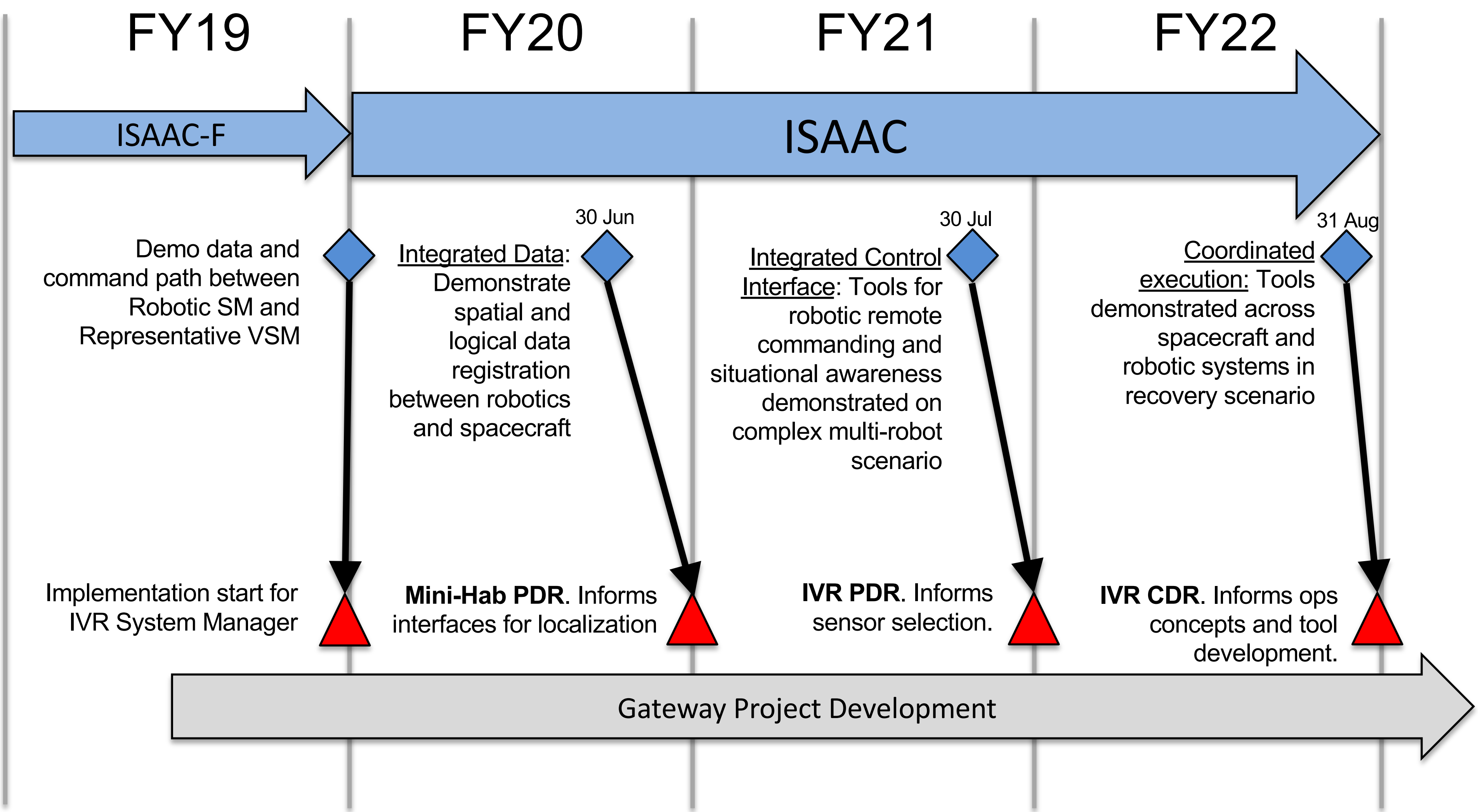


Demo 3: Coordinated Execution Integrated Fault Management (2022)

- **Location:** ISS (ground facilities as a fallback)
- **Goals:**
  - Demonstrate finding and patching a simulated leak ("recovery scenario")
    - Detect: Repeat FY19 iPAS leak detection demo with improved fidelity (e.g. updated details of Gateway design, latest version of MAST, improved filtering)
    - Isolate: Astrobee with a microphone payload, "leak" ultrasound source, 3D volumetric mapping
    - Recover: Robonaut2 close a hatch or patch the leak
  - Coordinated execution:
    - Automated generation of plans with actions for multiple agents and coordination between them
    - Distributed execution system capable of running multi-asset plans, including coordination
- **Assets involved:** Robonaut2, Astrobee, SoundSee payload, leak simulator (ultrasound source), three vehicle subsystems (TBD)
- **Prior work:** FY19 ISAAC demo, moving from pure simulation to include ISS and real robots



Milestones


FY19
FY20
FY21
FY22
ISAAC-F
ISAAC
Demo data and command path between Robotic SM and Representative VSM
30 Jun
Integrated Data: Demonstrate spatial and logical data registration between robotics and spacecraft
30 Jul
Integrated Control Interface: Tools for robotic remote commanding and situational awareness demonstrated on complex multi-robot scenario
31 Aug
Coordinated execution: Tools demonstrated across spacecraft and robotic systems in recovery scenario
Implementation start for IVR System Manager
Mini-Hab PDR. Informs interfaces for localization
IVR PDR. Informs sensor selection.
IVR CDR. Informs ops concepts and tool development.
Gateway Project Development

ISAAC project FY19

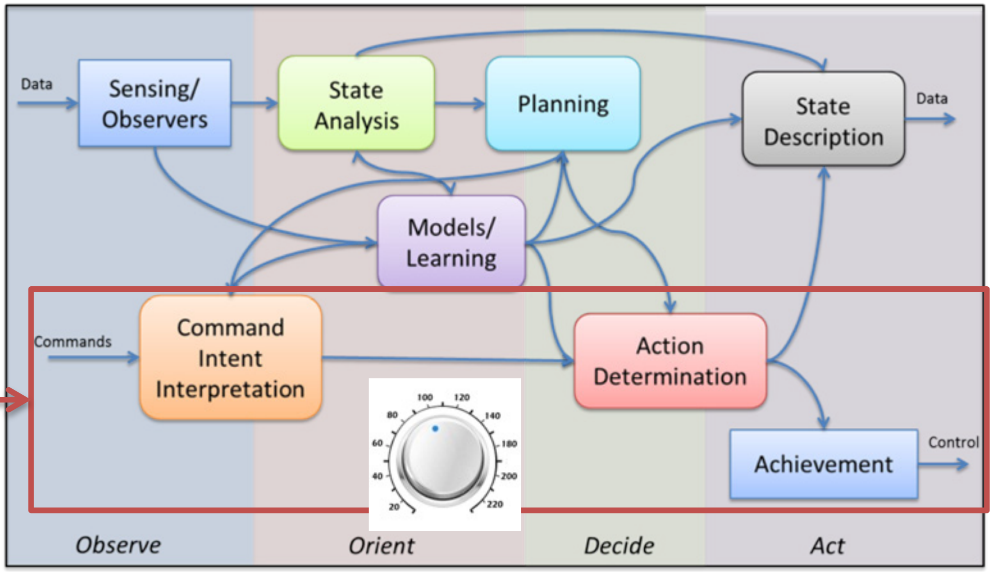
- **Game Changing Development Program "Formulation" project**
  - Goal: One year to figure out what a 3-year project should do, make sure we understand the problem before we propose solutions

- **Two thrusts:**
  - Technology development & integration:
    - Prototype autonomy framework and capabilities: MAST, MBFDIR
    - Gateway analog test environment: iPAS, Astrobee & Robonaut2 simulators
    - Demonstration: test with leak detection & localization scenario
      - Integrate robotic (mobile) sensor data with stationary spacecraft sensory information in a way that enables cross-subsystem analysis (e.g. for fault detection).
      - Emulate command and telemetry data flow based on the Gateway Autonomy and Flight Software concept of operations.
      - Autonomously select robot sensing actions based on a system-level objective, such as isolating a fault or locating a lost inventory item.
  - Project formulation:
    - Solidify infusion strategy, address stakeholder needs
    - Identify technical scope, evaluation criteria, work plan for FY20-22
    - **Present to STMD "DPMC" in August/September**

ISAAC Foundations: MAST

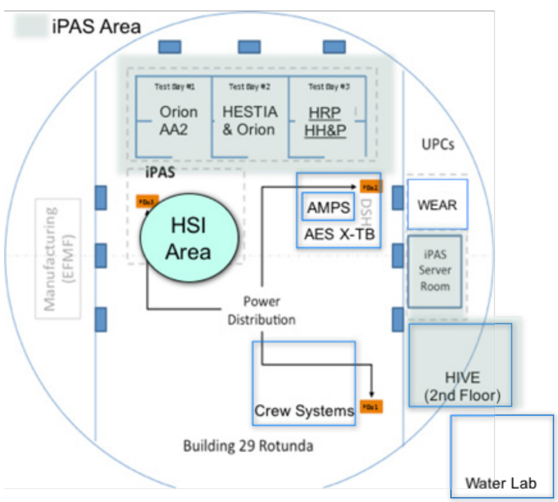
- The Modular Autonomous Systems Technology (MAST) framework supports an autonomous system management (ASM) architecture that:
  - Can be used for all classes of autonomous systems
  - Standardizes information sharing and interfaces between technologies
  - Designed around formal verification and validation principles

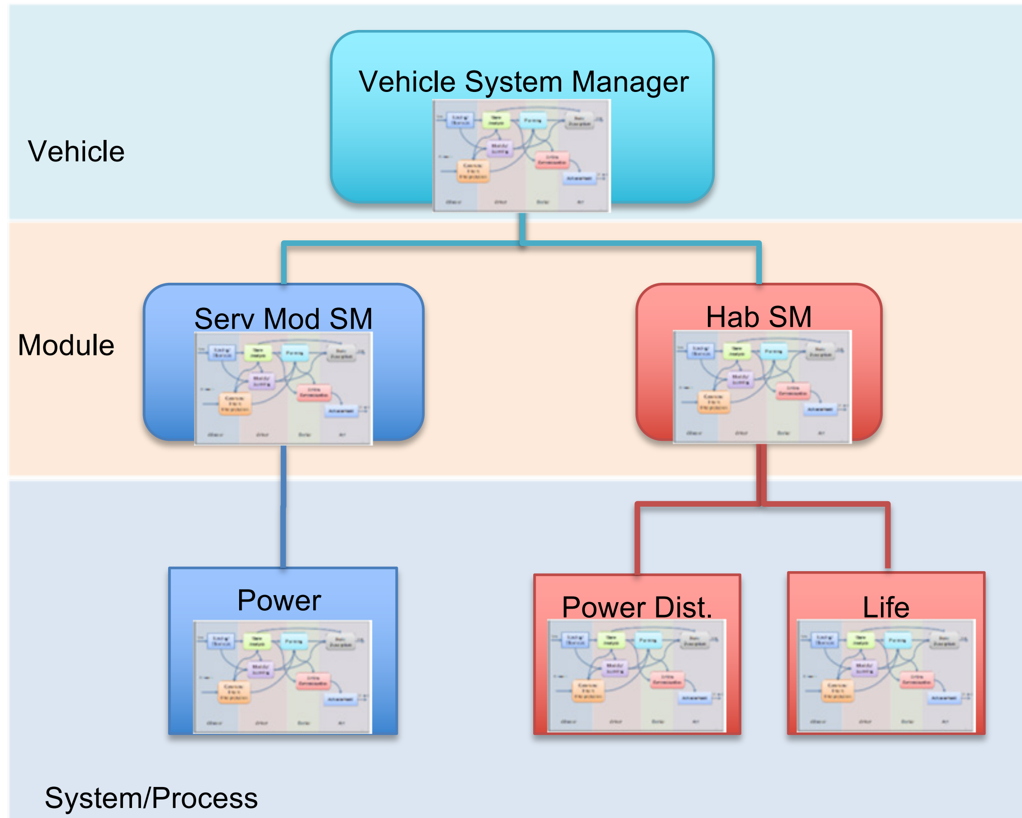
- Variable autonomy possible by figuring out how to throttle “actions”



ISAAC Foundations: FY18 MAST/ASM Demo

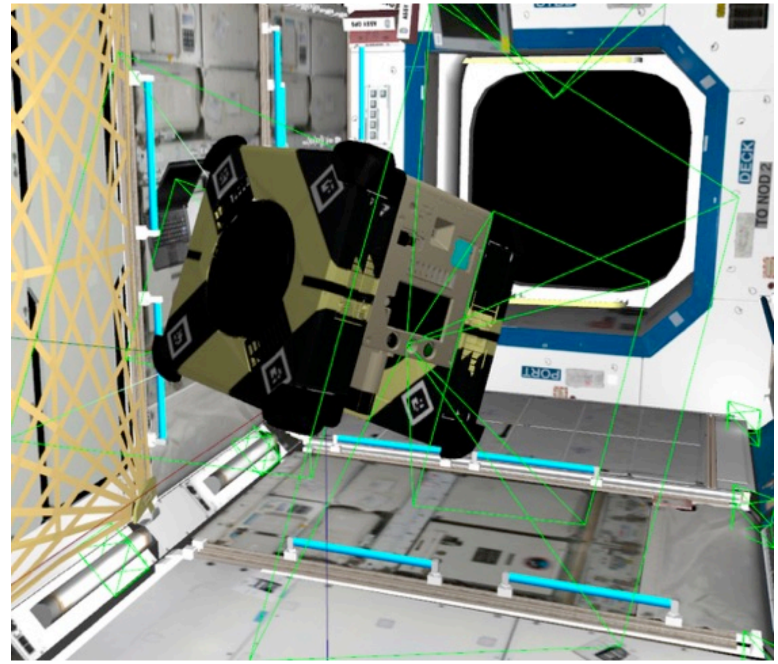
- **Developed a leak detection scenario**
  - Distributed autonomous functions
  - Used cognitive (learned) agents for detection
  - Tested ASM architecture command/telemetry flow





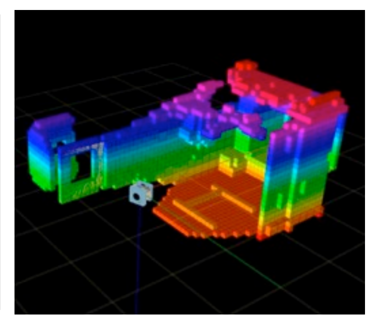
ISAAC Foundations: Astrobee Simulator

- Simulates Astrobee propulsion system, arm, color and depth cameras, inertial sensor, and environment
- Implemented as a set of plug-ins for the open source Gazebo robot simulator
- Easy to switch to different environments (ground labs, ISS, Gateway concept design)
- Easy to switch between simulator, real hardware drivers, or a mix (both provide the same ROS message interfaces to the rest of the system)
- Can simulate 10x faster than real time with sufficiently powerful GPU
- Leverages GCD investment in HET2 Astrobee project



Astrobee in Gazebo simulation of ISS environment

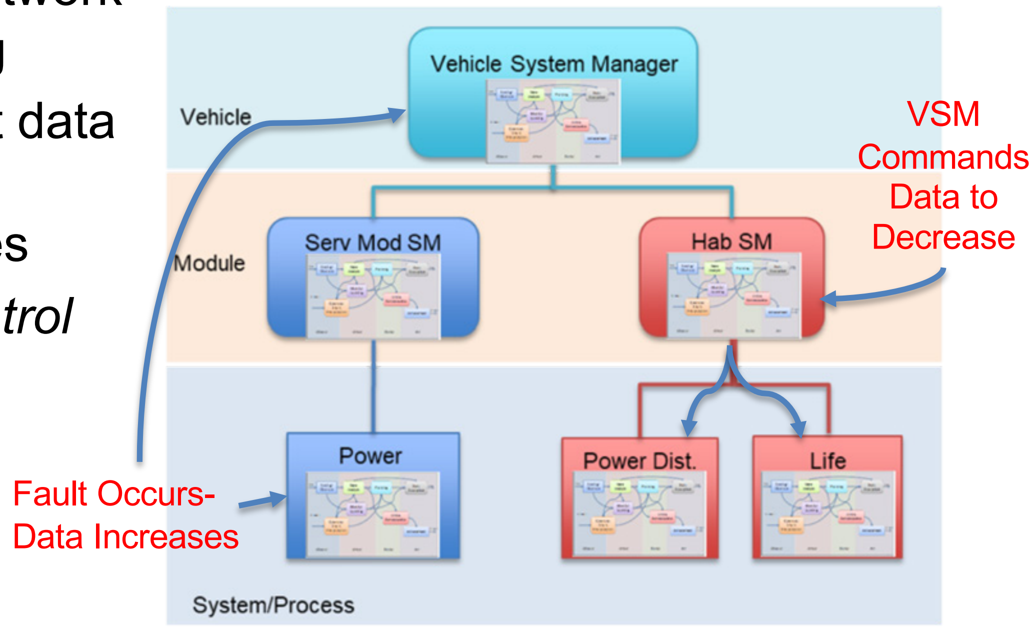
Simulated NavCam view



Obstacle map built from simulated HazCam point clouds

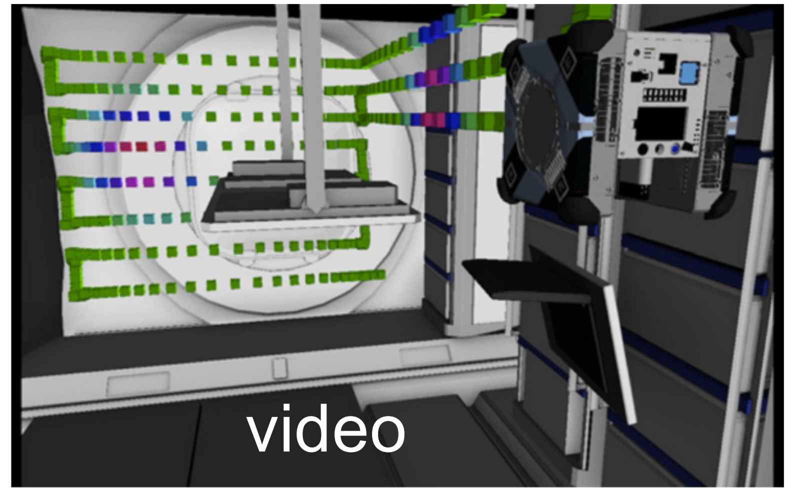
ISAAC Technology Development

- **Adaptive Data Filtering**
  - Bandwidth constraints and latency will dictate how much data will be able to be communicated to the ground
  - It is expected that more data will be generated by the spacecraft (including robots and payloads) than is possible to downlink and store
  - This technology allows for “dynamic” selection of data for downlink based on VSM command
  - Developed application to vary network bandwidth and latency for testing
  - Added to MAST ways to abstract data into categories and command data throttling on these categories
  - ***Benefit:*** *Provides method to control data downlink based on events*



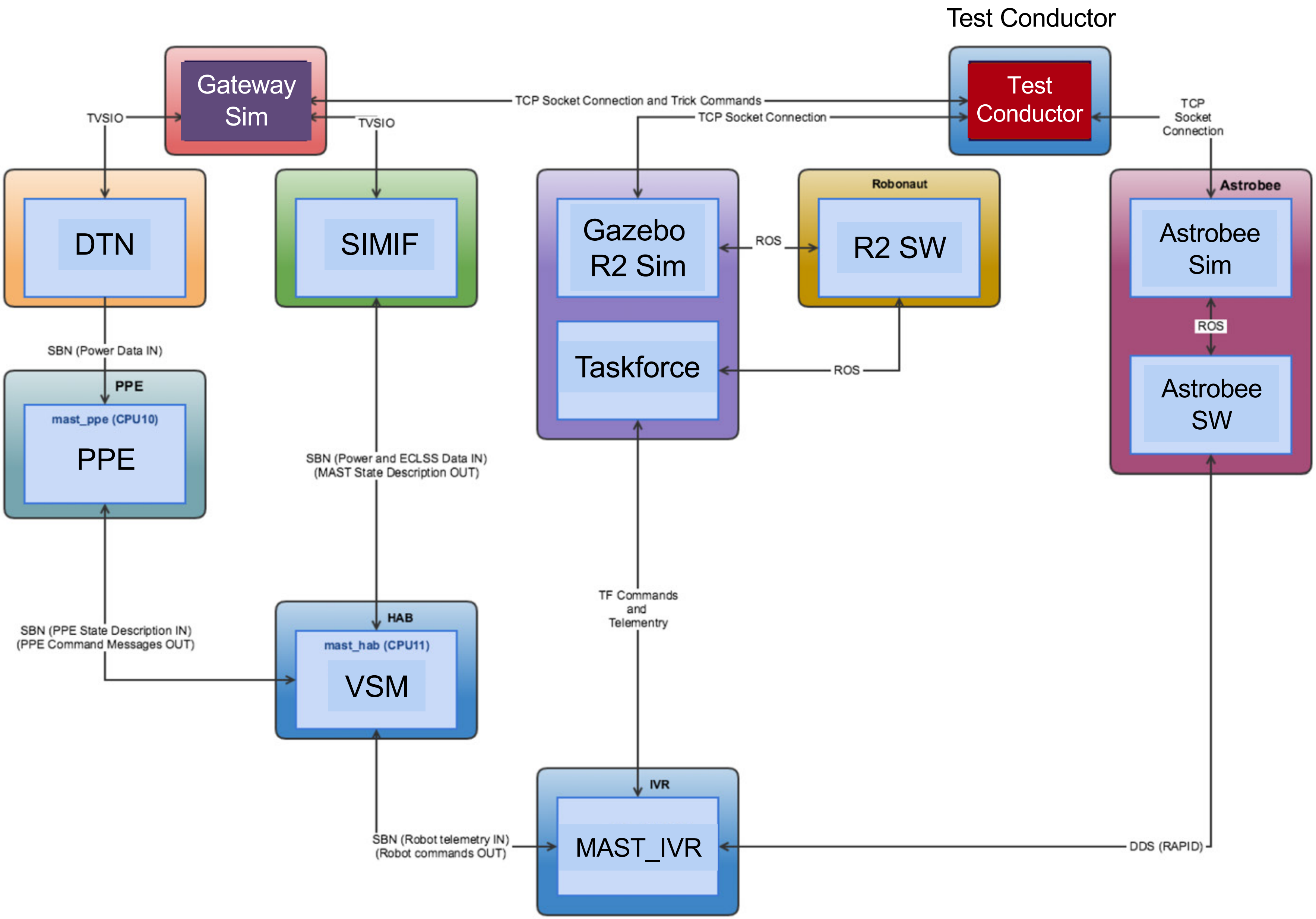
ISAAC Technology Development

- **Acoustic mapping with a free flyer**
  - Astrobee simulator environment
  - Gateway 3D VR model
  - Low fidelity ultrasonic noise sources
  - Low fidelity ultrasonic microphone model
  - Astrobee flies a coverage pattern
  - Map ultrasound intensity vs. location
  - ***Benefit:*** *Demonstrated autonomous spacecraft interior survey; enables ISAAC to improve the leak and sensor model fidelity within a framework that is already integrated*



- **Low fidelity sound and sensor models are the starting point**
  - Key is integrating vehicle systems and free flyer, commanding and telemetry
  - Future work will improve sound and microphone model, keep existing interfaces
  - We’ve had discussions with ultrasound subject matter experts about prior art

IVRSM and interface to ASM architecture



ISAAC FY19 Demo

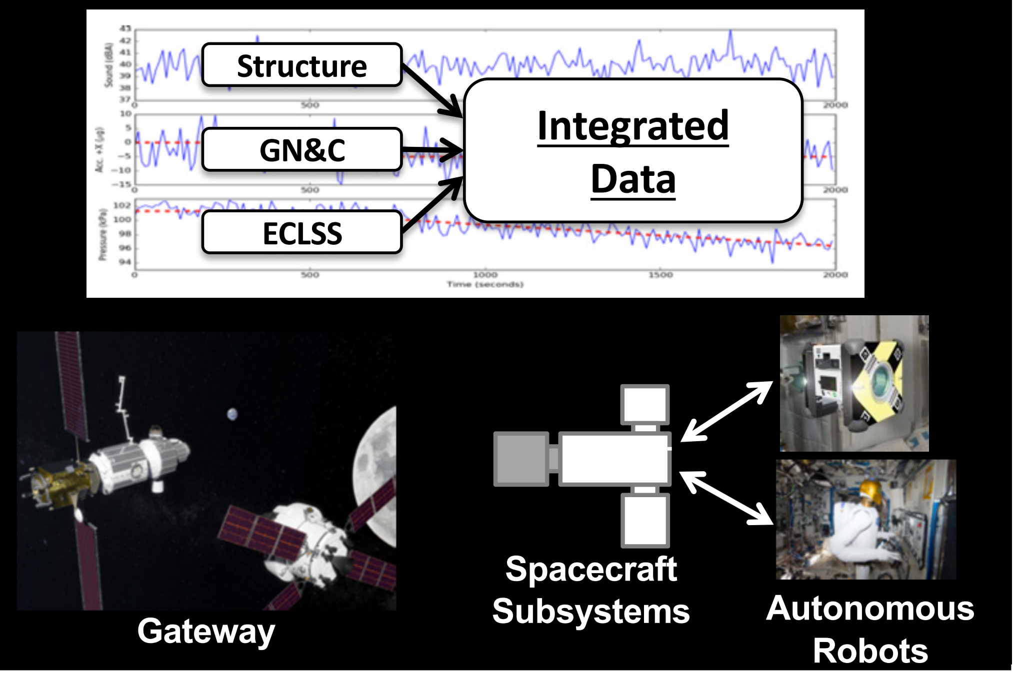
- **Milestone: September iPAS demonstration**
  - Test distributed framework with Vehicle System Manager (SM), Module SM, and Robot SMs (including an IVR SM)
  - Use case: leak detection and localization scenario
  - Additions of several SMs (including structural health monitoring) to fill out data integration efforts
    - Requires sufficient integration efforts with other groups
  - **Demonstrate: (sets up for ISAAC milestones in:)**
    - Scaling of ASM architecture, MAST (Year 1)
    - Data throttling over larger network (Year 2)
    - Data/command interface to ground through VSM (Year 2)
    - Robot data passing through ASM architecture (spatial integration will be incomplete) (Year 1)
    - Applicability to Gateway autonomy architecture (All)

Integrated System for Autonomous and Adaptive Caretaking (ISAAC)

PT: Terry Fong (Autonomous Systems)
Thrust Area: ST5
PM: Matt Deans (ARC)
Deputy PM: Julia Badger (JSC)
Centers: ARC + JSC

Description and Objectives

- Develop a **critical capability to support autonomous caretaking of exploration spacecraft while uncrewed**
- Integrate autonomous robots, spacecraft infrastructure (avionics, sensors, network), and ground control
- Enhance **autonomous state assessment**, **autonomous logistics management**, and **integrated fault management**
- Focus on **capabilities required for the Gateway** (Human Exploration Requirements HEOMD-004: GTW-L2-0044, 0047, 0050, 0142, 0143, 0145) and applicable beyond the Earth-Moon system.
- Enable **important assessments of feasibility and relevance** for the design of future deep space spacecraft.
- Extend **autonomous system manager architecture** to enhance integrated analysis of data, operator productivity, and reliable coordinated execution of system-level tasks.



Customers

- **Gateway.** ISAAC-developed capabilities directly relevant to HEOMD-004 and other requirements for Gateway.

Partners

- **AES Autonomous Systems and Operations.** Support fault diagnosis and planning+execution technologies used by ISAAC architecture.
- **AES Astrobee Facility.** Support Astrobee testbeds and ops.
- **AES Logistics Reduction**. Support Robonaut2 testbeds and operations. Collaborate on logistics demonstration.
- **Gateway Intra-Vehicular Robotics (IVR) and Vehicle System Manager (VSM) Working Groups.** Provide Gateway guidance.

Leverage

- **GCD/HET2.** Developed analog robot platforms for Gateway IVR.
- **MAST.** Developed system architecture that ISAAC will extend.

Technical Approach

- Focus on three technical thrusts:
  - Integrated Data: Link models and telemetry across multiple spacecraft subsystems and robots
  - Coordinated Execution: Enable higher-level commanding and effective collaboration
  - Integrated Control Interface: Enable mission control to understand and control integrated autonomous systems
- Perform tests with the iPAS facility (JSC) and on ISS
  - Leverage existing testbeds and robots developed with STMD support
  - Capstone demo on ISS: Link embedded sensors and multiple robots to detect, isolate, and patch a simulated leak
- Proposing ISAAC development in **FY20-22**
  - Deliverables staged to respond to relevant Gateway milestones
- **Investment is needed now in order to meet Gateway needs**