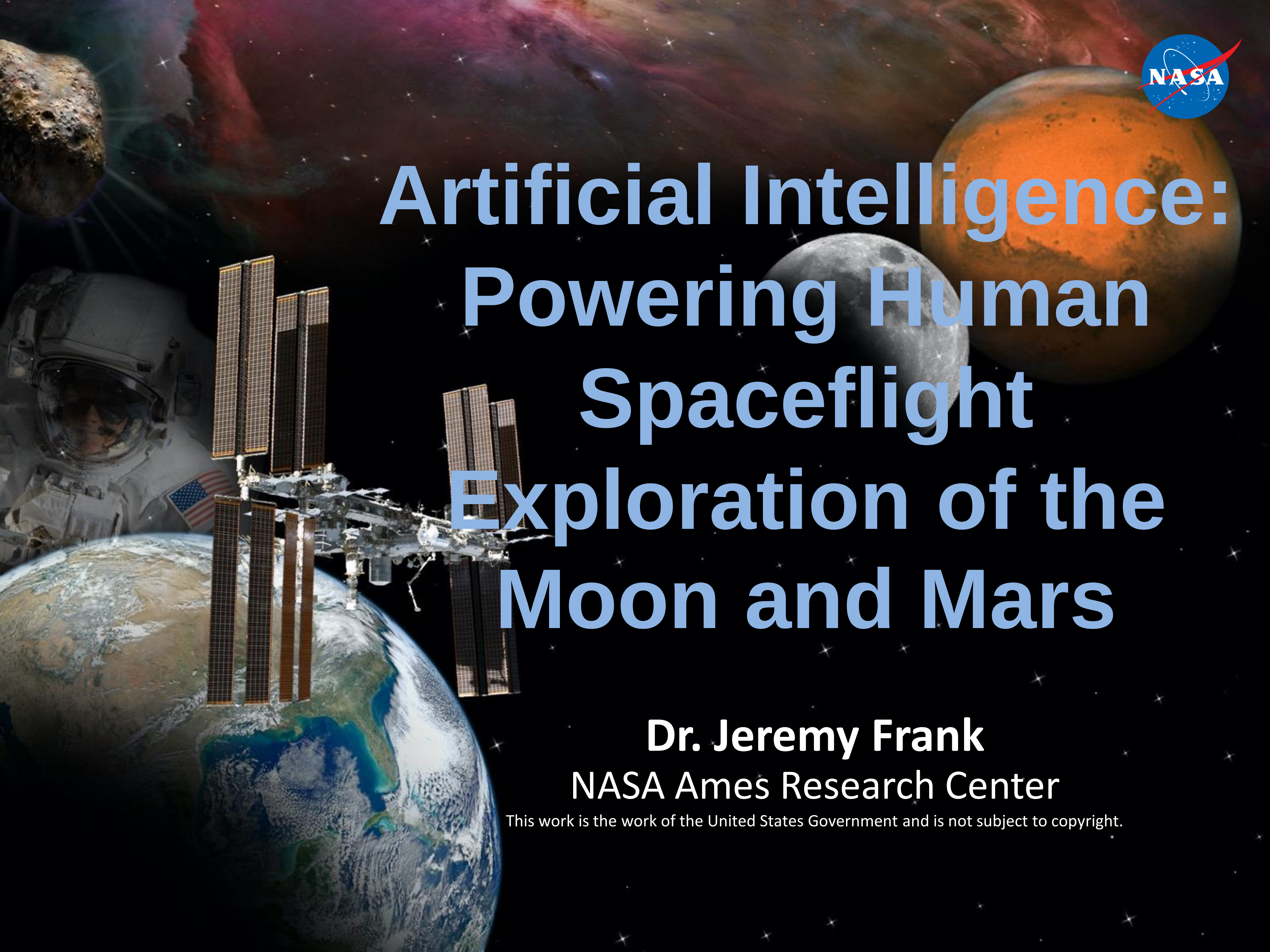

Artificial Intelligence: Powering Human Spaceflight Exploration of the Moon and Mars

Dr. Jeremy Frank
NASA Ames Research Center

Overview

1. Human Spaceflight Exploration

- Mission Operations Functions
- Human Exploration Destinations
- Motivations for Artificial Intelligence

2. Artificial Intelligence Technology

- Planning
- Plan Execution
- Fault Management
- Associated Technologies

3. NASA Investments

- NASA Technology Development

1. Human Spaceflight Exploration Needs

Mission Operation Functions

Monitoring

- **What is the state of the spacecraft?**
- Process and abstract data from sensors.
- Group resulting information into displays.
- Displays are specific to major spacecraft system and/or phase of mission.
- Monitoring ensures plans are being performed as expected, and spacecraft state is known.

Planning and Scheduling

- **What is the spacecraft doing and when?**
- Plans are created to achieve specific objectives.
- Plans are created days to weeks ahead of time.
- Plans are often created for major spacecraft subsystems separately, then integrated.
- Unexpected events or faults may require replanning on shorter time scales.

Status	Procedure	Rationale
This Week (GMT 2014/342 - 2014/348)		
Requested	ISTAR Total Organic Carbon Analyzer: TOCA - Waste Water Bag Changeout (Med Ops 6.3.350)	Required every 6 runs and prior to next run
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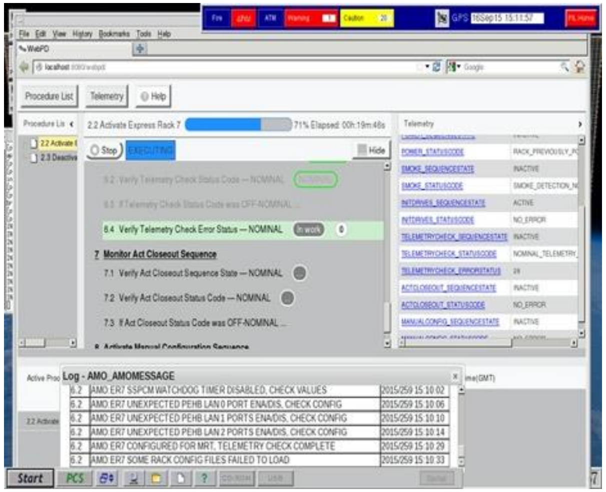
Recommended	ISTAR Total Organic Carbon Analyzer: TOCA - Water Sample Analysis From TOCA Sample Analysis Bag (Med Ops 6.3.300) (for Hot PWD)	Required monthly (alternating between the hot and ambient ports)

Mission Operation Functions

Execution

- **What is the next activity to perform?**
- Execution involves issuing commands to spacecraft subsystems and ensuring results are as expected. (See Monitoring)
- If unexpected events occur, replanning may be needed. (See Planning and Fault Management)



2.2 Activate Express Rack 7 — 71% Elapsed: 00h:19m:48s

6.2 Verify Telemetry Check Status Code — NOMINAL

6.3 If Telemetry Check Status Code was OFF-NOMINAL ...

6.4 Verify Telemetry Check Error Status — NOMINAL

7 Monitor Act Closeout Sequence

7.1 Verify Act Closeout Sequence State — NOMINAL

7.2 Verify Act Closeout Status Code — NOMINAL

7.3 If Act Closeout Status Code was OFF-NOMINAL ...

8 Activate Manual Configuration Sequence

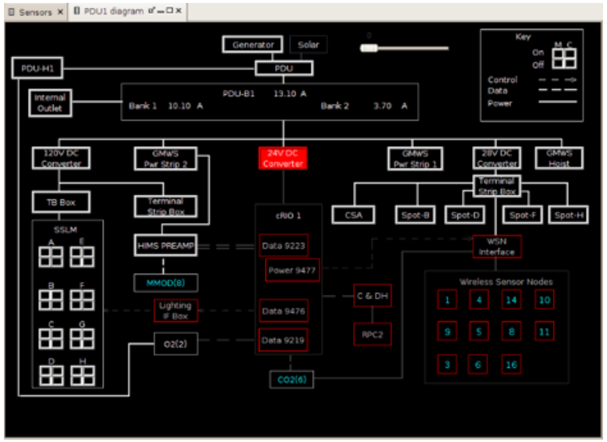
Telemetry	
POWER_STATUSCODE	RACK_PREVIOUSLY_P
SMOKE_SEQUENCESTATE	INACTIVE
SMOKE_STATUSCODE	SMOKE_DETECTION_N
INTDRIVES_SEQUENCESTATE	ACTIVE
INTDRIVES_STATUSCODE	NO_ERROR
TELEMETRYCHECK_SEQUENCESTATE	INACTIVE
TELEMETRYCHECK_STATUSCODE	NOMINAL_TELEMETRY_
TELEMETRYCHECK_ERRORSTATUS	29
ACTCLOSEOUT_SEQUENCESTATE	INACTIVE
ACTCLOSEOUT_STATUSCODE	NO_ERROR
MANUALCONFIG_SEQUENCESTATE	INACTIVE

Log - AMO_AMOMESSAGE

```
6.2  AMO ER7 SSPCM WATCHDOG TIMER DISABLED, CHECK VALUES            2015/259 15:10:02
6.2  AMO ER7 UNEXPECTED PEHB LAN 0 PORT ENA/DIS, CHECK CONFIG       2015/259 15:10:06
6.2  AMO ER7 UNEXPECTED PEHB LAN 1 PORTS ENA/DIS, CHECK CONFIG      2015/259 15:10:10
6.2  AMO ER7 UNEXPECTED PEHB LAN 2 PORTS ENA/DIS, CHECK CONFIG      2015/259 15:10:14
6.2  AMO ER7 CONFIGURED FOR MRT, TELEMETRY CHECK COMPLETE           2015/259 15:10:29
6.2  AMO ER7 SOME RACK CONFIG FILES FAILED TO LOAD                  2015/259 15:10:33
```

Fault Management

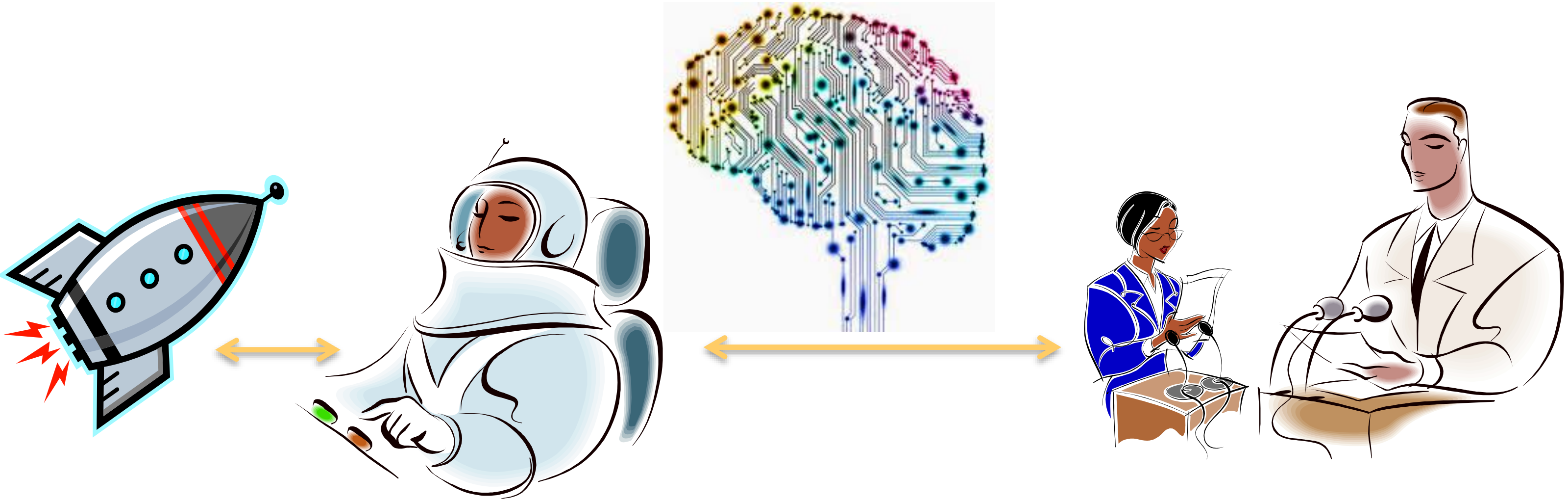
- **Is something wrong? What are the impacts?**
- Fault management involves the detection and isolation of faults (See Monitoring).
- Fault management also involves determining the consequences of faults.
- Recovering from or mitigating faults involves replanning. (See Planning)



Motivations for Artificial Intelligence

Enabling human spaceflight autonomy requires:

- A new balance of responsibility between crew and ground.
- A new balance of responsibility between crew and vehicle.
- New concepts of operations to fit new division of labor.
- Application of AI technology to automate systems, augment crew expertise and knowledge, and reduce crew workload.



2. Technologies

Planning and Scheduling

Purpose

- **Build a plan by choosing activities** to achieve goals.
- **Build a schedule** by ordering activities and choosing activity start times.

Functions

- Choose and order **activities.**
- Determine how to meet **constraints on activities.**

Absolute time	*Take image between 10:00 and 10:30 a.m.*
Relative time	*Take image at least 5 minutes after turning spacecraft*
Resources	*Battery state of charge must be above 65%*
Resources	*Two instruments can't be used simultaneously*

- Ensure activity **effects** satisfy activity **conditions.**

Preconditions	*Power must be on for instrument to take image*
Effects	*Image reduces available storage by 10 Mb*

- **Validate plans or schedules** to identify constraint / condition violations.

Task Execution

Purpose

- **Carry out a plan** using an appropriate execution strategy.
- Execution strategy incudes **discrete** and **continuous** control.

Functions

- Executive processes a timeline, or set of tasks, to perform.
- Executive **starts** tasks, **stops** tasks, and **monitors** execution.
- Executive performs continuous adjustment of parameters.
- Executive may need to handle **conditionals** (branches, loops), failures / contingencies, and other features.
  - Start time *Start actions after they are scheduled to start*
  - End time *Check action completion status when they are scheduled to end*
  - Condition *Do not start actions when it is unsafe (delay if needed)*
  - Condition *Terminate actions if specific unexpected events occur*

Fault Management

Purpose

- Monitor system to determine whether **faults** have occurred.
- Determine what faults have taken place.
- Assess remaining system **capability**.

Functions

- Detects when a system is **off-nominal.**
  - Off-nominal behavior may (but need not) signify impending faults.
- **Detect** the presence of faults.
- **Isolate** faults by eliminating possible candidates.
  - It may be not always be possible to uniquely isolate the fault in all cases.
- Determine the **consequences** of faults.
  - Loss of capability or redundancy may preclude accomplishing the current plan.
- Trigger **safing, recovery** actions or **replan** if mission objectives can no longer be met**.**

Associated Technology Needs

Human Interfaces

- Includes decision support for planning interfaces and fault management, and situational awareness for plan execution.

Flight Software Integration

- Autonomous spacecraft require integration of each autonomy capability with flight software.

High Performance Computing

- AI software require sufficient on-board computational resources (CPU, memory, bandwidth).

Machine Learning

- Adapt to changing operational environment and spacecraft performance changes using machine learning technology, both in the control center and ultimately onboard spacecraft.

Challenges for Artificial Intelligence

System Interaction

- Many disparate AI components must interact with each other, with underlying flight software

Human-Machine Interaction

- AI capabilities must be designed to facility human-machine interaction, both for crew and for flight controllers.

AI Engineering Best Practices

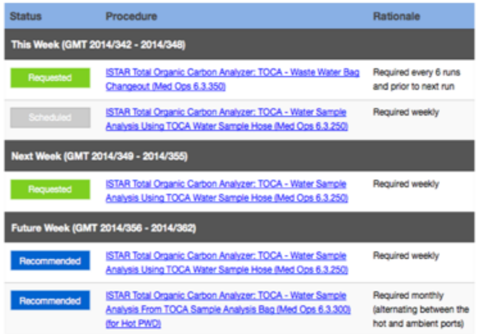
- Best practices are needed for engineering AI systems to operate in resource-constrained environments (CPU and memory limitations)
- Best practices for building AI applications are also needed (e.g. modeling)

Autonomous Mission Operations: Projects

Autonomous Mission Operations: Capability Demonstrations

AMO TOCA SSC

- ISS demonstration of Crew Decision support for spacecraft habitation systems



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AMO EXPRESS

- ISS demonstration of Automation and Decision support

Advanced Caution and Warning (ACAWS)

- Orion Decision support for dynamic spacecraft operations

Vehicle System Management (VSM)

- Orion and Gateway spacecraft autonomy

In-Vehicular Robotics

- In-Vehicle robot task and motion planning

Autonomous Mission Operations: Projects Overview

	SSC	TOCA	Orion ACAWS	Robotics	AMO EXPRESS	Hab. VSM	Orion VSM
Monitoring	✓	✓	✓	✓	✓	✓	✓
Planning		✓		✓		✓	
Execution	✓			✓	✓	✓	
Fault Management		✓	✓			✓	✓
Anomaly Detection		✓				✓	
User Interfaces	✓	✓	✓		✓		
Flight Software					✓	✓	✓
Machine Learning		✓				✓	

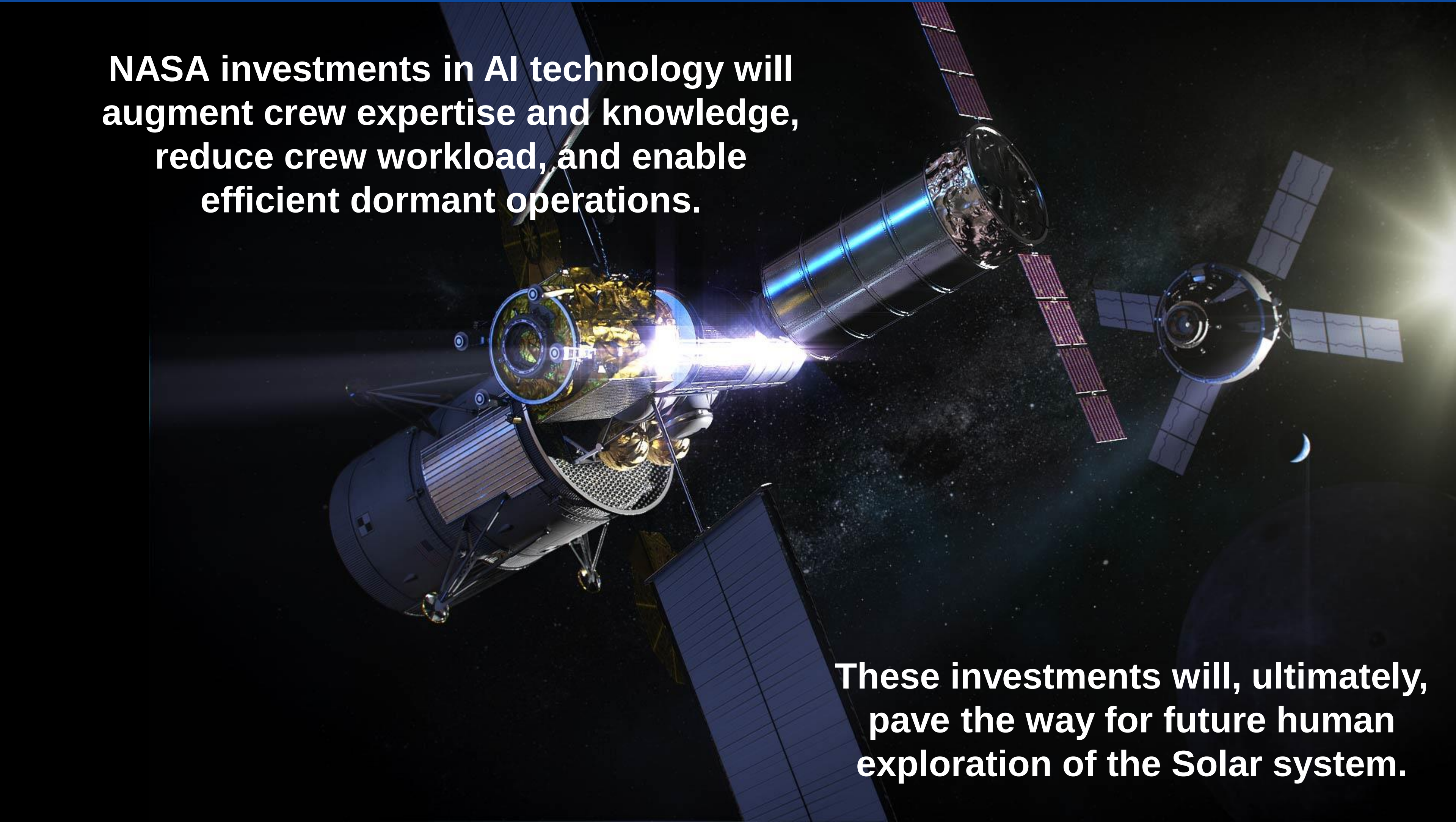
Navy / Air Force vs Space: Similarities

Navy / Air Force	Space
Ground systems automation	Ground systems automation
Commander decision aids	Astronaut decision aids
Crew size reduction	Smaller crews to Mars
Vehicle autonomy	Spacecraft / Robot autonomy
Variable communication coverage (e.g. GPS denial)	Variable communication coverage (LEO vs deep space)
Risk of upgrades to ongoing missions	Risk of upgrades to ongoing missions
High communication latency (e.g. submarines)	High communication latency (deep spacecraft)
Risks to crew	Risks to crew

Navy / Air Force vs Space: Differences

Navy / Air Force	**Space**
Large fleet size	Small fleet size
High system diversity	Low(er) system diversity
High operating time => fewer defects	Lower operating time => more defects
High value from modest gains (accrued over large fleet)	Less value amortized from modest gains (due to fleet size)
Highly regulated	Few/no regulations
High compute power available	Low compute power available
Mostly known environment	Less known environment

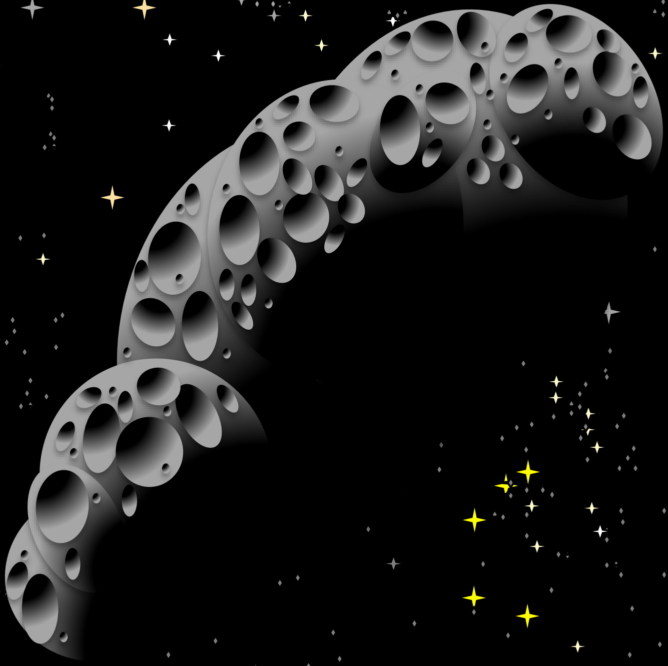
Conclusions



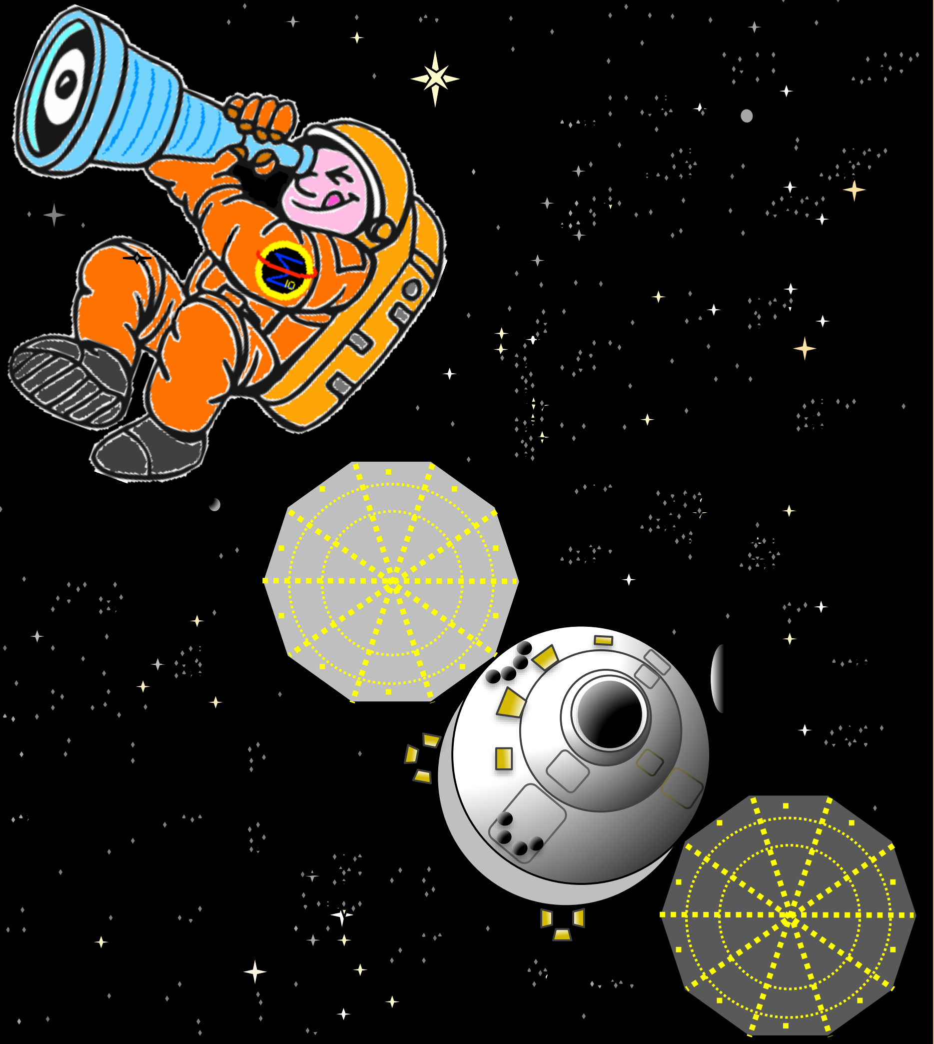
NASA investments in AI technology will augment crew expertise and knowledge, reduce crew workload, and enable efficient dormant operations.

These investments will, ultimately, pave the way for future human exploration of the Solar system.

Autonomous Mission Operations



Thank you!



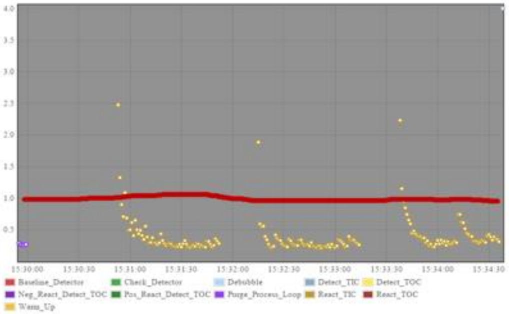
AMO TOCA SSC

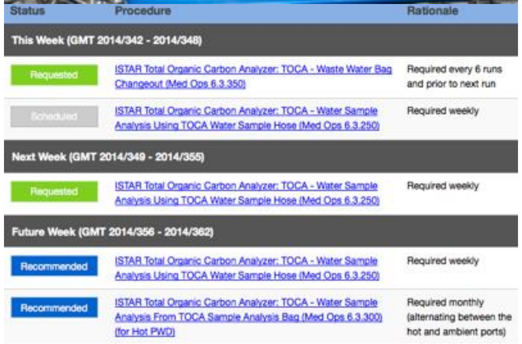
Evaluate astronaut’s ability to autonomously manage spacecraft systems.

- AI Technology: Planning, Monitoring, Fault Management
- Associated Technology: Human Interfaces

ISS Systems: TOCA and SSCs

- Water Quality analyzer, used/operated 1-2 times / week
- Crew non-critical (office) computers used for multiple functions
- Several fault modes, some experienced regularly on orbit
- Deployed software onboard ISS (on non-critical computer network); crew managed systems for 7 months.





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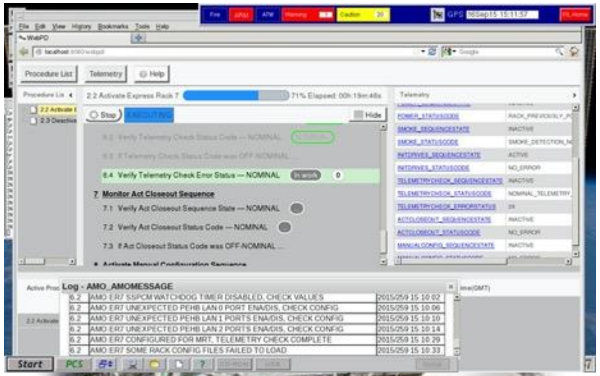
AMO EXPRESS

Evaluate astronaut’s ability to autonomously manage spacecraft systems.

- AI Technology: Execution
- Associated Technology: Human Interfaces



2.2 Activate Express Rack 7 71% Elapsed: 00h 19m 48s

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6.3 If Telemetry Check Status Code was OFF-NOMINAL ...
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7 Monitor Act Closeout Sequence
7.1 Verify Act Closeout Sequence State — NOMINAL
7.2 Verify Act Closeout Status Code — NOMINAL
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8 Activate Manual Configuration Sequence

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SMOKE_SEQUENCESTATE	INACTIVE
SMOKE_STATUSCODE	SMOKE_DETECTION_N
INTDRIVES_SEQUENCESTATE	ACTIVE
INTDRIVES_STATUSCODE	NO_ERROR
TELEMETRYCHECK_SEQUENCESTATE	INACTIVE
TELEMETRYCHECK_STATUSCODE	NOMINAL_TELEMETRY_
TELEMETRYCHECK_ERRORSTATUS	28
ACTCLOSEOUT_SEQUENCESTATE	INACTIVE
ACTCLOSEOUT_STATUSCODE	NO_ERROR
MANUALCONFIG_SEQUENCESTATE	INACTIVE

Log - AMO_AMOMESSAGE

```
6.2  AMO ER7 SSPCM WATCHDOG TIMER DISABLED, CHECK VALUES          2015/259 15 10 02
6.2  AMO ER7 UNEXPECTED PEHB LAN 0 PORT ENA/DIS, CHECK CONFIG     2015/259 15 10 06
6.2  AMO ER7 UNEXPECTED PEHB LAN 1 PORTS ENA/DIS, CHECK CONFIG    2015/259 15 10 10
6.2  AMO ER7 UNEXPECTED PEHB LAN 2 PORTS ENA/DIS, CHECK CONFIG    2015/259 15 10 14
6.2  AMO ER7 CONFIGURED FOR MRT, TELEMETRY CHECK COMPLETE         2015/259 15 10 29
6.2  AMO ER7 SOME RACK CONFIG FILES FAILED TO LOAD                2015/259 15 10 33
```

ISS Systems: Payload Racks.

- Payload equipment racks operations is operator intensive, subject to many operational constraints.
- These racks can be controlled by computers and plan execution software (Timeliner) onboard ISS.
- Developed Timeliner scripts to implement conditional plans to power on the racks.
- Developed displays to provide crew with situational awareness of state of executed state.

Orion Advanced Caution and Warning System (ACAWS)

Evaluate astronaut's ability to autonomously manage spacecraft systems.

- AI Technology: Fault Management
- Associated Technology: Human Interfaces

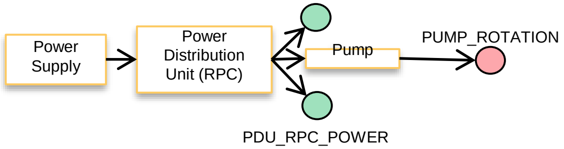
Orion: NASA's next human-capable spacecraft

- ACAWS presents Orion system Loss of Capability and Loss of Redundancy information to flight controllers and crew.
- Tested using the live downlink from Exploration Flight Test 1 from pre-launch through post-landing.
- Subsequent testing in simulation environments with flight controllers and crew.

Orion Vehicle Systems Management

Evaluate autonomous spacecraft fault management.

- AI Technology: Fault Management
- Associated Technology: Flight Software

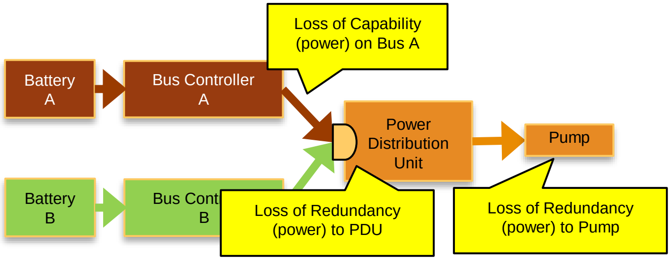


● FAIL Test
○ PASS Test

	PDU_Bus_Power	Pump_Rotation	PDU_RPC_Power
Pump.Mechanical_Failure		1	
Power_Supply.Fail_to_Gen_Power	1	1	1
RPC.Fail_Open		1	1

Orion: NASA’s next human-capable spacecraft

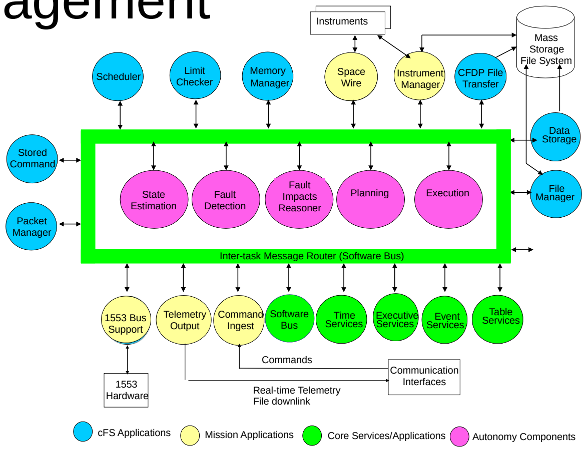
- The Orion model and architecture being scaled to Artemis 1 (first Lunar mission), and ultimately Artemis 2 (first crewed Lunar mission)
- Integrated and ran Orion ACAWS on embedded computers running real-time operating systems.



Habitat Vehicle Systems Management

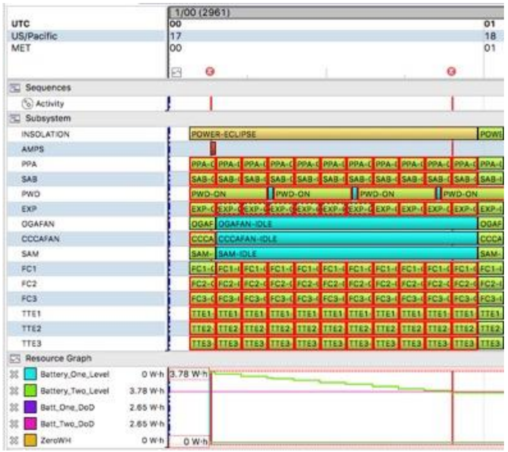
Evaluate autonomous spacecraft mission operations.

- AI Technology: Planning, Execution, Fault Management
- Associated Technology: Flight Software



Gateway: Human outpost in Lunar orbit

- Gateway will be dormant (uncrewed) 10-11 months out of the year.
- Developed and tested a Vehicle Systems Management (VSM) for Gateway, managing many spacecraft subsystems (power, thermal, life support).
- Integrated and run VSM on embedded computers running real-time operating systems.



In-Vehicle Robotics

Evaluate autonomous robotic planning and execution.

- AI Technology: Planning, Execution.

Gateway: Human outpost in Lunar orbit

- Dexterous Manipulators and other service robotics will enable Gateway dormant operations and assist crew.
- Demonstrated manipulator robot planning and execution in the presence of unexpected events and faults.

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NASA Artemis Overview