The NSBE Aerospace Systems Conference (NSBE-ASC) is a scientific and technical conference of the professionals, focused on aeronautical and astronautical disciplines. The conference highlights the scientific and engineering contributions of Black aerospace professionals. Attendees explore the scientific and engineering contributions of aerospace professionals, while collaborating and exchanging technical data on the world as leading aerospace programs! The conference includes industry executives and experts from Lockheed Martin Corporation, NASA, The Boeing Company, United Technologies Corporation, Medgar Evars University, NASA Michoud Assembly Facility, and Franklin Institute Science Museum- including NASA Administrator, Major General Charles S. Bolden. National Society of Black Engineers (NSBE) Aerospace Systems Conference (ASC) occurred Saturday, September 16 – Monday, September 18, 2023, at the University of Houston.

(Lessons Applied to---)
From HMI to AI: Operations Complexity with Lunar In-Space Assembly

(Comprehensive Space Studies Vitae: Tracking A Journalist's Investigative Perspective on Lunar Missions)

Ronald H. Freeman, PhD

Editor-in-chief, Journal of Space Operations & Communicator

Chair, Space Operations & Support Technical committee

NSBE_ASC Pathways Into A Personal Journey of Aerospace Science Studies

NSBE-ASC Presentations, 2010- 2020

2010 "Improving Flight Survey through Aircraft Simulation Instruction"

2012 "The Role of Innovation Networks in commercializing Aerospace Industry"

2014 "Developing Commercial Crew Transportation Capability through Technological Milestones"

2016 "Managing Rocket Engine Complexity: A Phenomenological Study of Combustion Instabilities"

2018 "Developing Safety in Technology Innovation Programs: A Case Study in Rocket Propulsion"

2020 "Adaptive Safety Management in Commercial Aerospace Industry"

Lessons Learned

2010--- Simulation Instruction reveals points of task complexity and problem solving.

2012--- Program cancellation or failure creates loss of value, an intangible cost accrued to risk-adverse stakeholders which suggests a need for Risk Management.

---Risk management includes leveraging strategies of Insurance and Knowledge-Sharing(or Knowledge Brokering).

--- Explore Stakeholder Analysis per valuation changes to performance, cost, and scheduling goal prioritization.

2014 ---Mission lifecycle downstream problem-solving, both costly and time-consuming, may be lessened with upstream hardware components subject to performance challenges (models and simulation augment experiments) and TRL maturation.

NSBE_ASC Pathways Into A Personal Journey of Aerospace Science Studies

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2014 ---"Developing Commercial Crew Transportation Capability through Technological Milestones"

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2018--- "Developing Safety in Technology Innovation Programs: A Case Study in Rocket Propulsion"

Lessons Learned

2014--- Innovation combines both technology and scalability into a mission-related ecosystem (e.g. cubesat constellation in LEO)

2016--- System complexity has traditionally been associated with behavioral impact of increasing component numbers. Emergent, unpredictable, and uncoordinated behaviors arise from component-component interactions. This results in microdynamics of propulsion complexity, as experienced in Apollo Combustion Instabilities.

----Simulations and models complement experiments In Cis to develop control methods (e.g. Flow solver coupled to algorithms. Input-Output models of control routines may be due to Lack of Filters for frequency oscillating perturbations.

2018 ---Propulsion management strategies indicate system level testing before component-testing.

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NSBE_ASC Pathways Into A Personal Journey of Aerospace Science Studies

NSBE-ASC Presentations, 2010- 2020

2018 "Developing Safety in Technology Innovation Programs: A Case Study in Rocket Propulsion"

2020 "Adaptive Safety Management in Commercial Aerospace Industry"

Lessons Learned

2018 ---Acoustic coupling between the lox feed-line and combustion chamber indicated CI observed phenomena, indicating propellent flow, narrowing problem domain to injectors or nozzles. Design analysis became the tool of problem solving.

2020---Technical systems prone to failure are complex, tightly-coupled systems making the chain of events for disaster incomprehensible to the operators. The use of redundancy exacerbates the problem—adding more complexity.

--- Software and its interactions with hardware build systems with a level of complexity and coupling where the interactions among components (often controlled by software) cannot all be planned, understood, anticipated, or guarded

--- Safety goals are structured notationally across the activities of system life cycle and across a hierarchy of levels from system to components, And, stakeholders negotiate at each stage of the life cycle a safety decision.

Agenda

1. Introduction and Historical Perspective “Mission-Pull” of ARTEMIS Technologies
2. From HMI to AI: Operations Complexity with Lunar In-Space Assembly, 2023
   --- In-orbit manual assembly (HMI) of space station truss
   --- In-orbit autonomous assembly (RMI) of space station truss
   --- System of systems architecture (AI) of space station
3. Conclusion

Lessons Learned to Apply
"From HMI to AI: Operations Complexity with Lunar In-Space Assembly, 2023"

1. Systems complexity suggests complexity in operations, indicating systems usage between system user and the "machine" system. Human (user)-Machine Interactions indicates their role in operations complexity.

Introduction

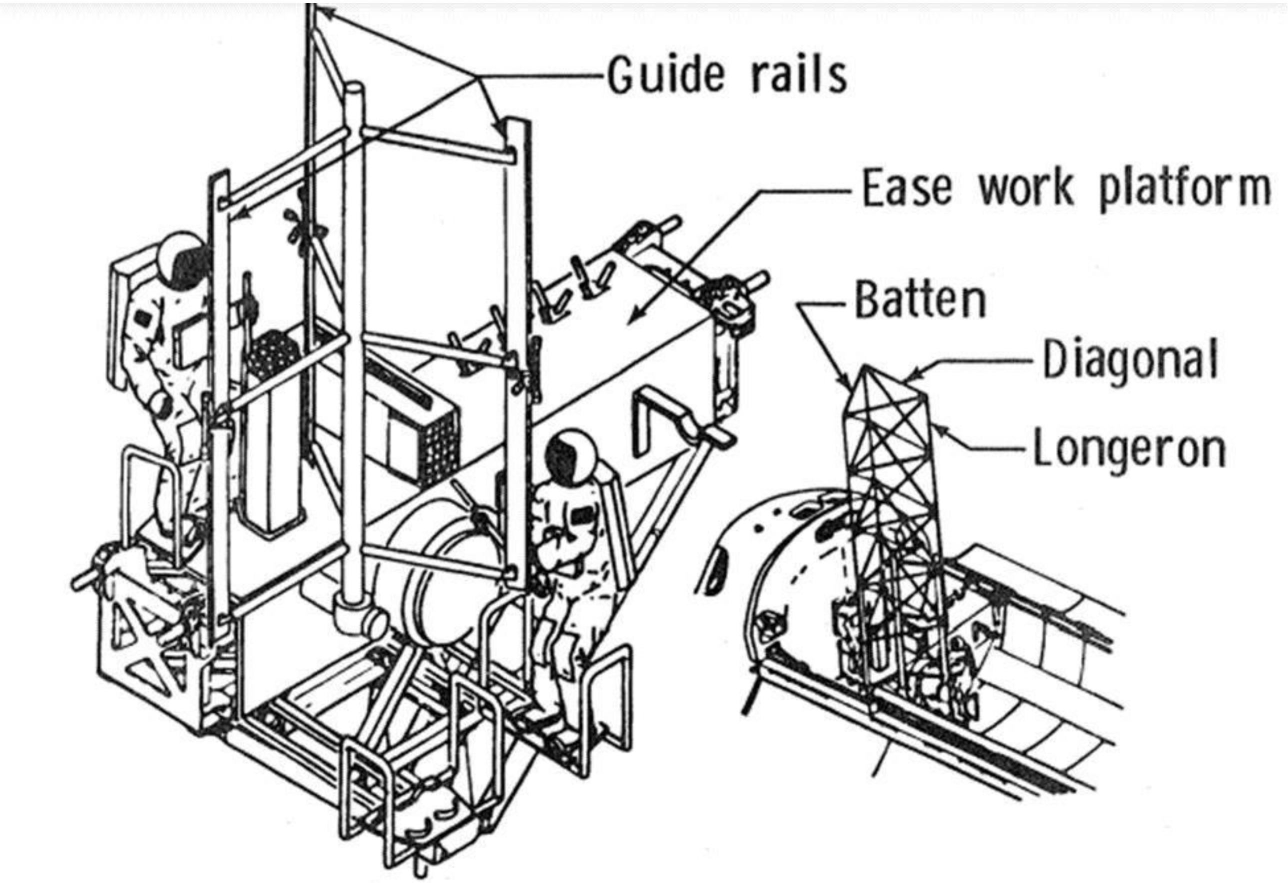
Operations complexity

-----System usage (technology-task fitness) and problem solving (HMI)

------ Situational awareness and decision-making per

1. Skills
2. Rules
3. Knowledge (AI agents)

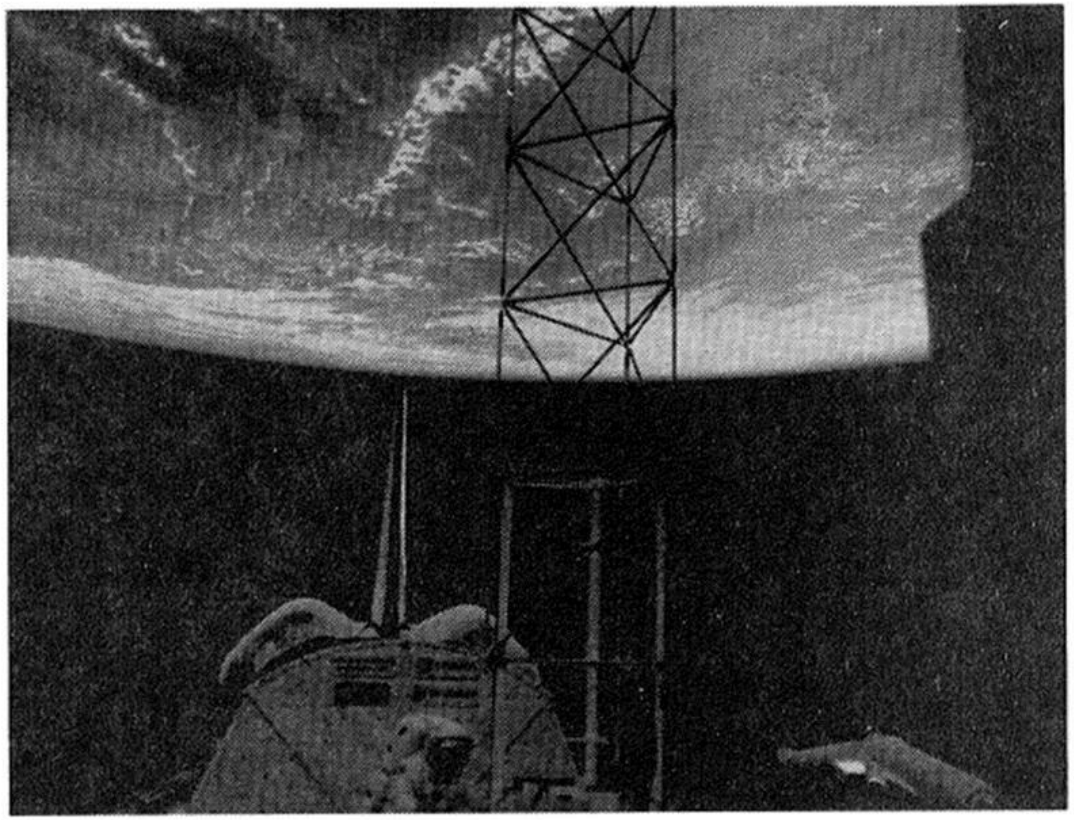
2. In-Orbit Manual Assembly (HMI) of Space Station Truss


Guide rails
Ease work platform
Batten
Diagonal
Longeron

Assembly Concept for Construction in EVA of Space Structures
(Neutral Buoyancy Simulations (NBS))

Figure.- ACCESS (Truss Under Construction

Two astronauts first deployed a 10-foot revolvable assembly fixture consisting of a central tubular mast and three guide rails. Using prepackaged joints and members, they assembled a bay of the truss on the guide rails manually rotating the assembly fixture to access the three sides of the truss. When the bay was completed, it was raised and supported on the top half of the guide rails. This process was repeated to build 10 bays of the structure.



3. **In-Orbit Manual Assembly (HMI) of Space Station Truss**

NBS vs In-orbit Truss Assembly

Preliminary results

Task	Time min: sec		
	NBS	NBS	Flight
	Avg all tests	Trained	Trained
Setup	4:00	3:04	3:31
Assemble 10 bays	30:13	21:44	25:27
Disassemble 10 bays	18:45	15:00	18:52
Stow and close up	5:23	4:30	4:41
	58:21	44:18	52:31

Space Weather: "The Dust Problem"

Apollo 17 Complaints of EVAs in Space Environment
Fatigue apparent from the intensive use of hand and wrist muscles in this assembly process. Clogging of joints and mechanisms, human health toxicology, false instrument readings, vision obscuration, abrasion of surfaces, failures of seals, and thermal control.
Walking or rover movements of stir up dust that travels ballistically and sticks to anything and everything due to lack of atmosphere.
Tiny shards of rock permeating Lunar Module interiors, coating helmet visors, jamming zippers, and penetrating layers of protective spacesuits material.
Unable to put their gloves back on after three days because lunar dust had degraded the seals.

The need for robotic assistants due to high cost and risk of human EVAs.

Over the four years of this Technology Maturation Program project, JPL will develop a small-scale dexterous archetype initially based on the existing Limbed Excursion Mobile Utility Robot (LEMUR II) platform. This robot is a 10kg-class robot with 6 high-dexterity limbs that have been explicitly designed to accommodate both mobility and manipulation. In addition, the limbs have been designed to accommodate a quick-connect modular toolset for additional operational flexibility.

ISS construction required 80 launches on several kinds of rockets over a 12-year period. The International Space Station has conducted 29 debris avoidance maneuvers since 1999, including three in 2020

By relieving astronauts of the more time consuming or mundane activities, these robotic archetypes increase the safety and productivity of various EVA operations. Specific technologies needed for such robots include the development of the hardware and algorithms necessary for locomotion in an environment like the International Space Station (ISS), which is characterized by a trusswork and rail substrate in micro-gravity. However the optimal number and types of archetype robots must be established and the proper extents of the individual archetypes must be explored.

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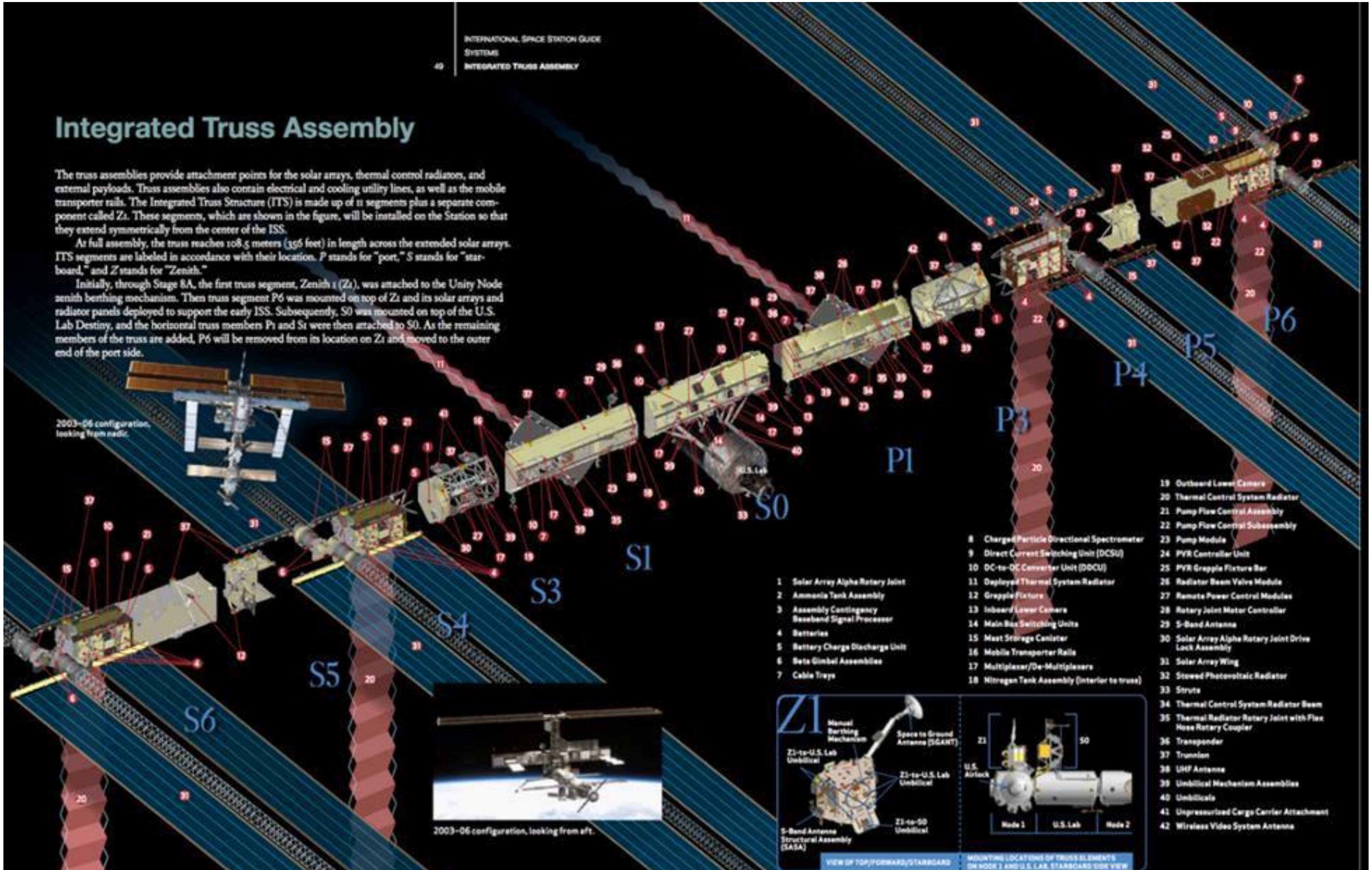

International Space Station Guide
Systems
49 Integrated Truss Assembly

Integrated Truss Assembly

The truss assemblies provide attachment points for the solar arrays, thermal control radiators, and external payloads. Truss assemblies also contain electrical and cooling utility lines, as well as the mobile transporter rails. The Integrated Truss Structure (ITS) is made up of 11 segments plus a separate component called Z1. These segments, which are shown in the figure, will be installed on the Station so that they extend symmetrically from the center of the ISS.

At full assembly, the truss reaches 108.5 meters (356 feet) in length across the extended solar arrays. ITS segments are labeled in accordance with their location. *P* stands for "port," *S* stands for "starboard," and *Z* stands for "Zenith."

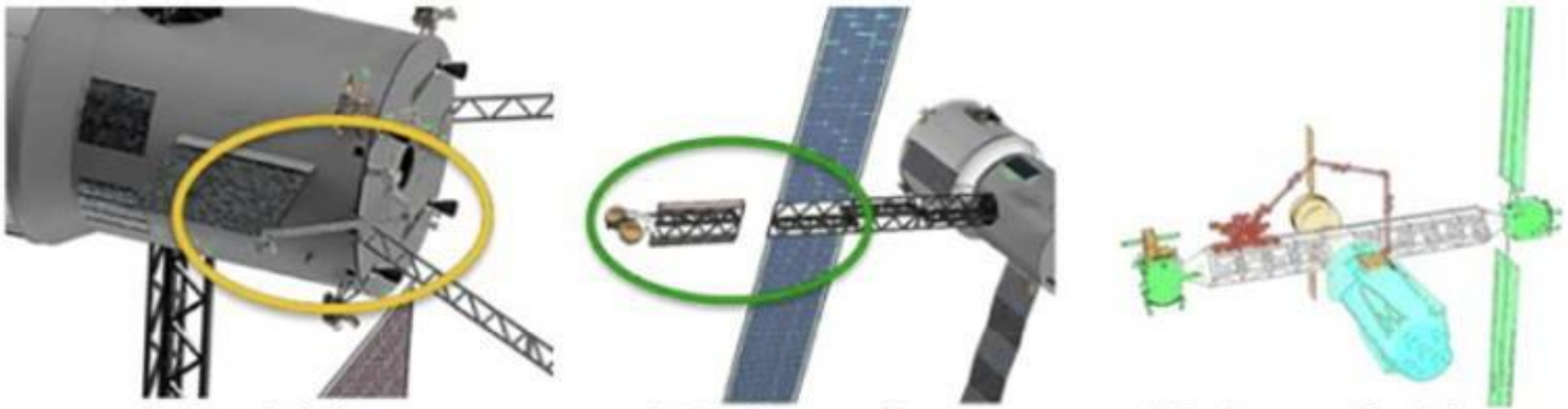
Initially, through Stage 8A, the first truss segment, Zenith 1 (Z1), was attached to the Unity Node zenith berthing mechanism. Then truss segment P6 was mounted on top of Z1 and its solar arrays and radiator panels deployed to support the early ISS. Subsequently, S0 was mounted on top of the U.S. Lab Destiny, and the horizontal truss members P1 and S1 were then attached to S0. As the remaining members of the truss are added, P6 will be removed from its location on Z1 and moved to the outer end of the port side.

2003–06 configuration, looking from nadir.

2003–06 configuration, looking from aft.

In-Orbit Autonomous Assembly (RMI) of Space Station Truss

Space autonomous assembly robot includes onboard robotics, free-flying assembly agents, and persistent assembly platforms.



(a) Onboard robotics (b) Free-flying assembly agents (c) Persistent assembly platforms

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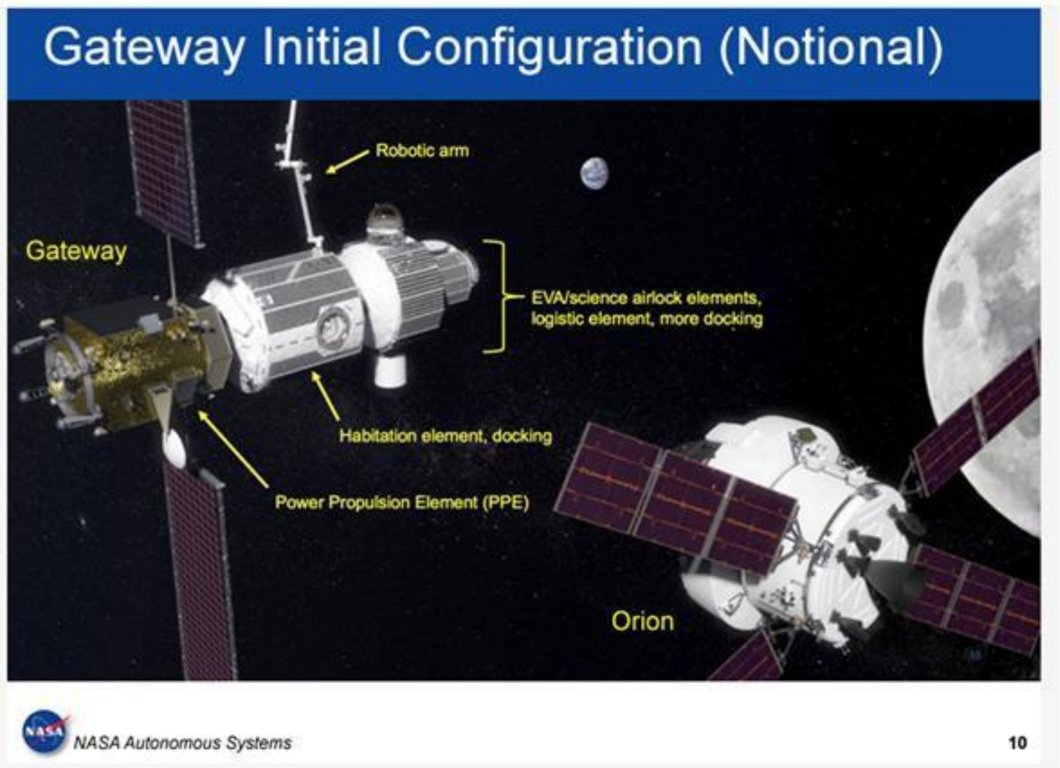
In-Orbit Autonomous Assembly (RMI) of Space Station Truss

LOP-Gateway without Truss



LOP-Gateway with Truss

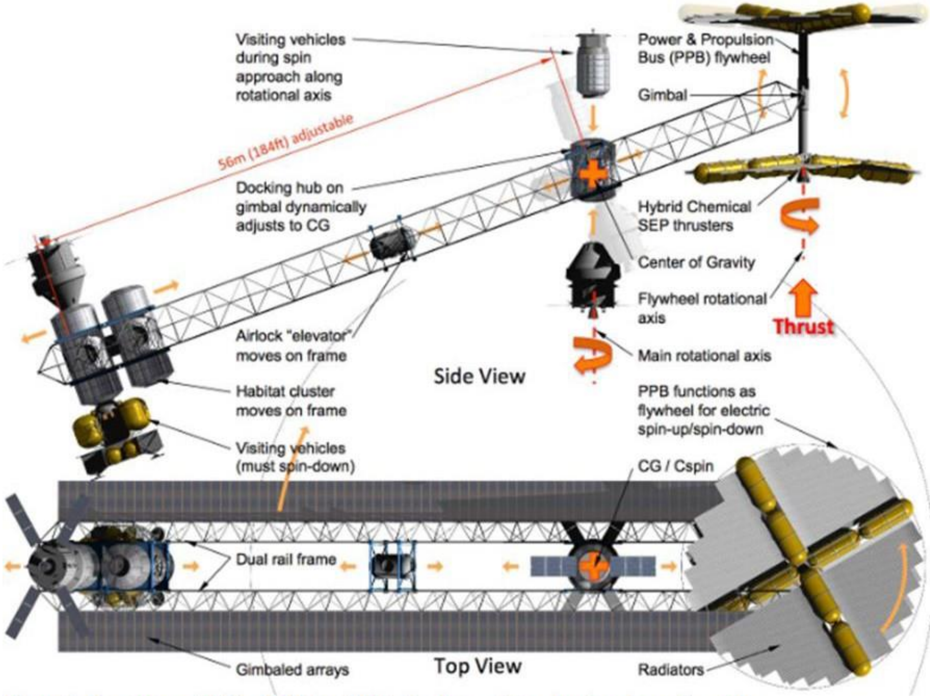
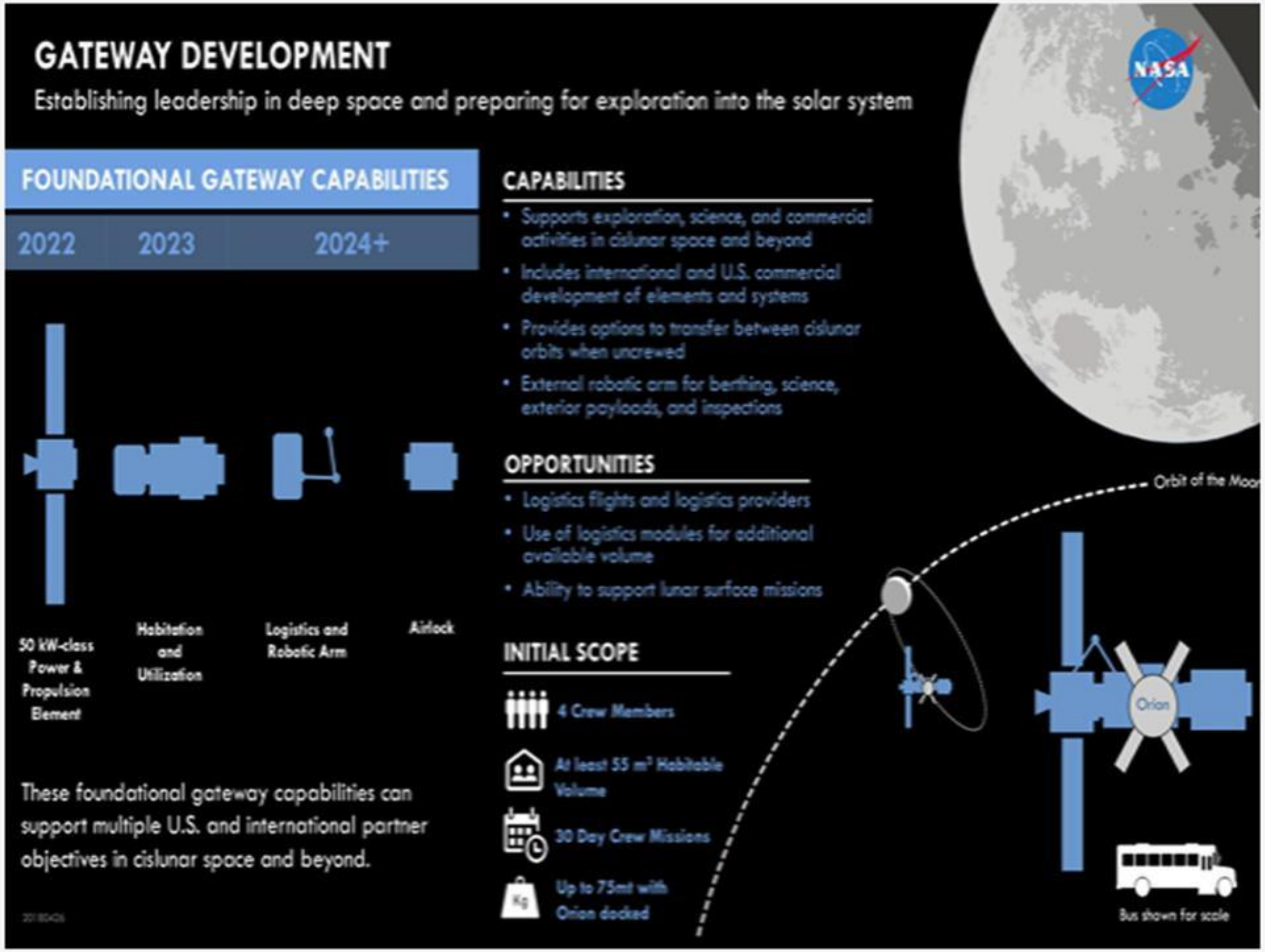
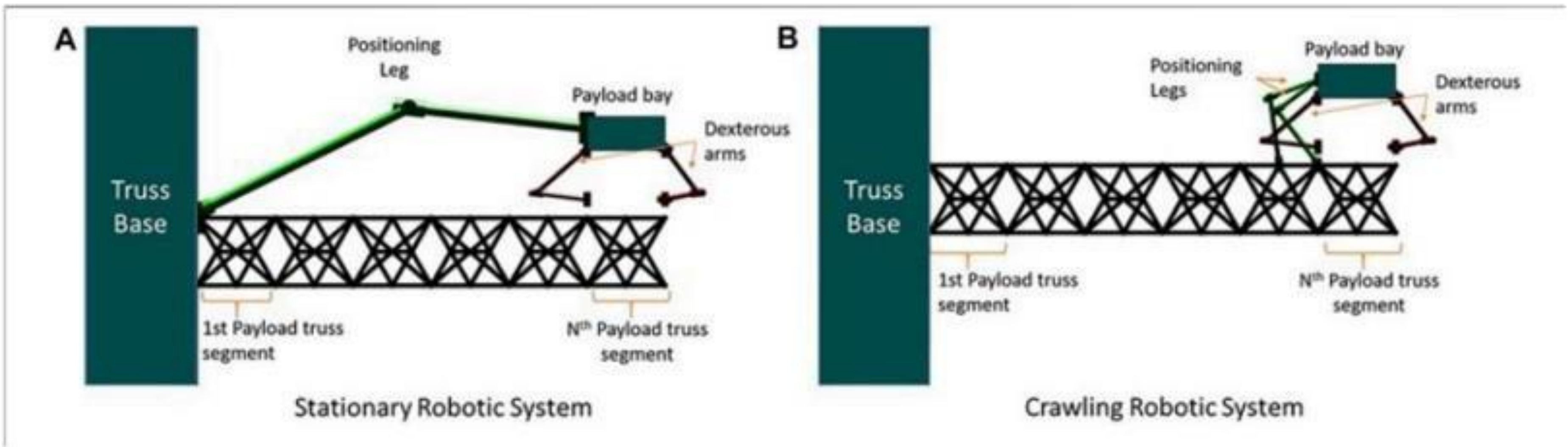


Figure 6: Our proposed "Sling" Option GGT side view and top view in spin configuration

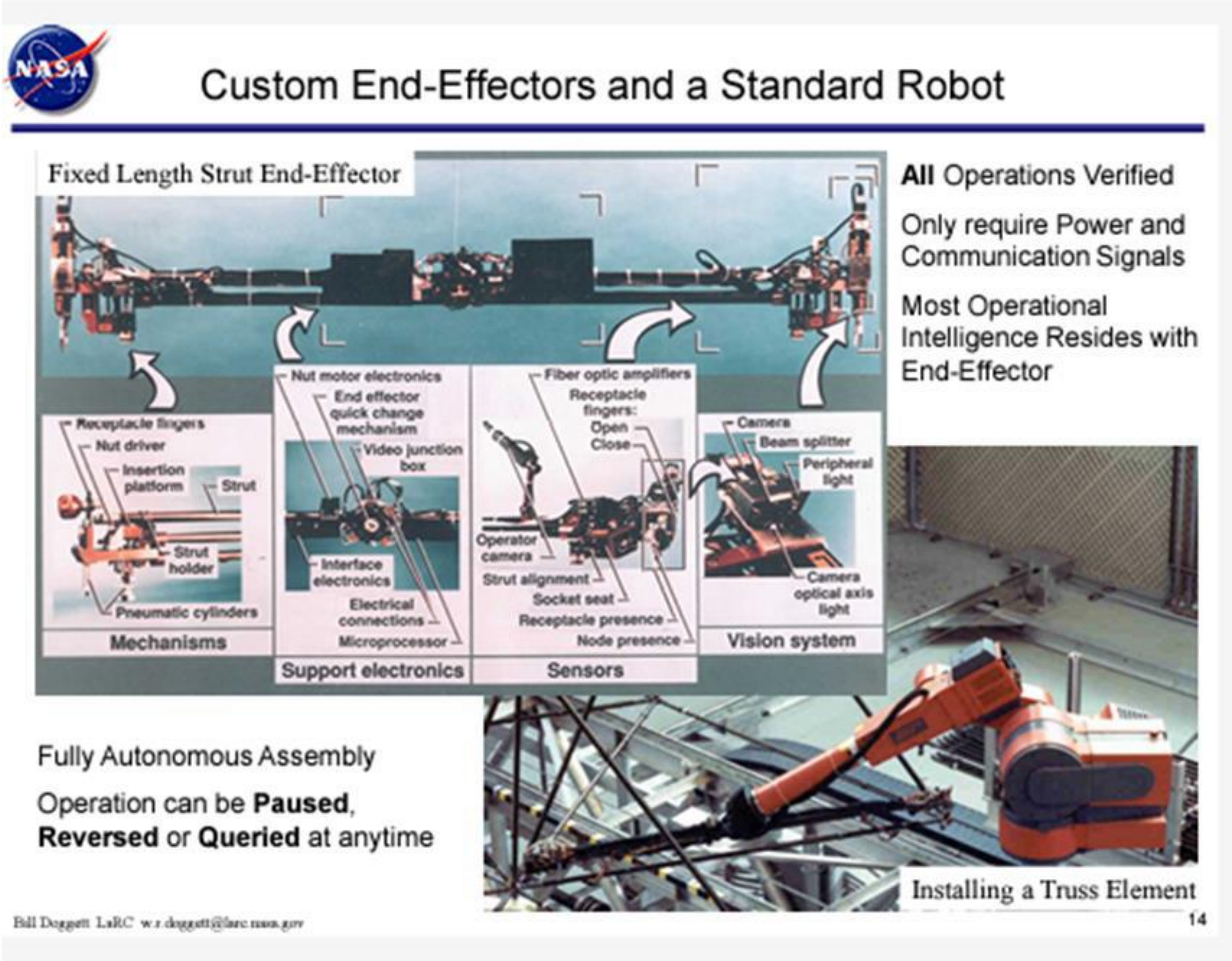

GATEWAY DEVELOPMENT
Establishing leadership in deep space and preparing for exploration into the solar system
NASA
FOUNDATIONAL GATEWAY CAPABILITIES
2022
2023
2024+
50 kW-class Power & Propulsion Element
Habitation and Utilization
Logistics and Robotic Arm
Airlock
These foundational gateway capabilities can support multiple U.S. and international partner objectives in cislunar space and beyond.
CAPABILITIES
• Supports exploration, science, and commercial activities in cislunar space and beyond
• Includes international and U.S. commercial development of elements and systems
• Provides options to transfer between cislunar orbits when uncrewed
• External robotic arm for berthing, science, exterior payloads, and inspections
OPPORTUNITIES
• Logistics flights and logistics providers
• Use of logistics modules for additional available volume
• Ability to support lunar surface missions
INITIAL SCOPE
4 Crew Members
At least 55 m³ Habitable Volume
30 Day Crew Missions
Kg
Up to 75mt with Orion docked
Orbit of the Moon
Orion
Bus shown for scale

Unlike ISS assembly by astronauts with robotic manipulators, robotic ISA allows for complex structures to be assembled without the need for EVAs.

Robotic ISA requires design for both the structure and the robotic assemblers, the latter being either Stationary, Crawling, or Free-flyers. The robotic system with a stationary base has manipulator(s) rigidly attached to a single location on the base structure and a workspace directly linked to the length of the manipulator. Thrusters are used in unattached Free-flying robotic systems to move the robot body around the workspace. Crawling robotic systems with more manipulators attached at designated footholds, move the robot body along the structure base.



(A) Stationary robotic system (B) Crawling robotic system.


Custom End-Effectors and a Standard Robot
Fixed Length Strut End-Effector
All Operations Verified
Only require Power and Communication Signals
Most Operational Intelligence Resides with End-Effector
Receptacle fingers
Nut driver
Insertion platform
Strut
Strut holder
Pneumatic cylinders
Mechanisms
Nut motor electronics
End effector quick change mechanism
Video junction box
Interface electronics
Electrical connections
Microprocessor
Support electronics
Fiber optic amplifiers
Receptacle fingers:
Open
Close
Operator camera
Strut alignment
Socket seat
Receptacle presence
Node presence
Sensors
Camera
Beam splitter
Peripheral light
Camera optical axis light
Vision system
Fully Autonomous Assembly
Operation can be Paused, Reversed or Queried at anytime
Installing a Truss Element
Bill Doggett LaRC w.r.doggett@larc.nasa.gov
14

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The Gateway will 1. test technologies and operational procedures requiring new technologies, on autonomous systems to run scientific experiments onboard; 2. perform system health management, including caution and warning; 3. manage autonomous data and other functions. Technologies will augment the crew's abilities, allow autonomy from Earth-based Mission Control and coordination with the Orion crew capsule, lunar landers, and their various systems and subsystems.

Primary Robotic Technologies

1. Dexterous and effector manipulation technology
2. Robot collaborative operation technology
3. Human-robot interaction technology
4. Autonomy and mobility requirements
   ---- Autonomic decision-making and data analysis
   ---- Fault detection and safe behavior mode
   ---- Deploy hybrid assembly and safe manufacturing processes
   ---- Robot navigation
   ---- Microgravity movement
5. Assembly dynamics and control technology
6. Metrology and assembly operation management technologies
7. Integrated management technology
8. Assembly dynamics and control technology
9. Metrology and assembly operation management technologies

Table 1. Summary of ANALOG-1 objectives

	ANALOG-1 Objective	Addressed in ANALOG-1 ISS
1	To demonstrate the control of a complex lunar surface rover/robot, specifically relating to dexterous manipulation in performing geological and technical tasks.	Fully addressed with exception of the technical tasks *Data was collected on the durations associated traversing between sampling sites, description of the sampling site by the crew member, collection and retrieval of the sample, including any incidents of 'errors' such as dropping the sample*
2	To obtain data on the task duration (navigation, hazard avoidance, sampling, site survey) during a lunar / geology exploration mission, following different strategies and evaluate the differences, especially in terms of speed of execution/reactivity.	Site survey, sampling and navigation addressed, however with reduced representativeness *Data collected included the specific time of each operation as well as the duration of traverses, interaction with operations teams (about path planning, science context, sampling)*
3	To evaluate the benefits for orbital control vs ground control, by comparing quantitatively efficiency vs time to complete activities as well as qualitatively the operations efficiency	Not addressed as ground control was not included *This objective relating to comparison between ground control and orbital control was not addressed in this ISS part of the experiment due to the highly constrained time available for the experiment. However, the data collected may be used as a refence data set to compare with the results of the ground experiment to be undertaken in the summer of 2022 on Mt. Etna, as part of the ARCHES activity (Wedler et al. 2021).*
4	To demonstrate and evaluate the versatility of the developed tools and techniques on rover/orbital control station side by performing tasks in unstructured (geology) and structured (system maintenance) environments	Unstructured tasks were not addressed *As with objective 3, the versatility aspect was not addressed, as only data related to the geological activity was collected. Data concerning a maintenance activity, i.e., an unstructured task, was not collected.*
5	To further define and evaluate the scientific geological exploration processes, team interactions, timeline, tools and techniques;	Addressed, however with reduced representativeness *Analysis of the data (including telemetry, timing, and traverse path executed) collected by the tools available to the astronaut, e.g., 3DROCS and MOF, together with team interaction metrics (as described in objectives 6 and 7).*
6	Evaluate the scientific decision-making process during teleoperation in selecting more promising geological samples with the purpose to address defined scientific questions.	Fully addressed *Data collected here included noting the time and content of the description by the crew member of the sample site (contextual information) through audio recording of the space-to-ground interaction, together with audio recording of the interaction between the members of the in-scenario science team.*
7	To further evaluate efficiency of having a geology trained astronaut	Addressed, however with reduced representativeness *The fundamental hypothesis for the scientific part of the experiment was that 'a geologically-trained astronaut equipped with immersive tools would enable a more efficient and effective interaction with the science backroom on the ground'. Applicable metrics relating to the estimation of efficiency in this regard can be found in Burghart et al. (2008). Questionnaires were also completed by the astronaut and science team members.*

RMI: #2 Robot collaborative operation technology

#4 Autonomy and mobility requirements

#5 Assembly dynamics and control technology

#8 Assembly dynamics and control technology

Case1. (Probability Reliability Assessment).
To overcome difficulties in decision-making under significant uncertainties, risk informed decision making (RIDM) is employed. Overall functional safety management (FSM) includes the RIDM and periodic risk reassessments based on performance monitoring of programmable control and protection systems (i.e. the installation as well as faults and failure). Periodic tests are performed to detect dangerous hidden faults in a SIS so that, if necessary, a repair can restore the system to an "as new" condition or as close as practical to this condition. These tests must be done every TI hours to detect the dangerous failures (DU) that have not been detected by the automatic diagnostics implemented in the SIS. When calculating Probability of Failure of a Safety Instrumented Function (SIF**)**, the most

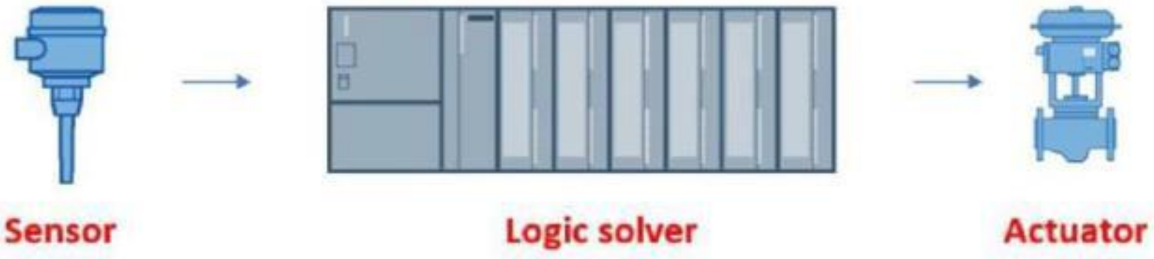

Figure 4. A Generic Safety Instrumented System

The integrity and performance of the safety instrumented function depends on a large number of factors, and it is measured by the so-called "Safety Integrated Level" (SIL) which are covered by various international standards such as IEC-61508 (for all industries), IEC-61511 (for the process industry), IEC-62061 (for machinery safety), IEC-61513 (for the nuclear industry) or ISA-84[16]. Some of the main factors that influence the performance of the SIF are the following:

- The technology used: the quality of the components and the manufacturer, the safe and dangerous failure rates, the capacity of automatic diagnostics of the components, etc.
- The architecture used: component redundancy, common cause failures, etc.
- The response time of the components, the time to be repaired and restoration time to normal operation.

Freeman, R. H. (2021). Safety Management II: Risk mitigation of geospatial threats from space weather intrusion. In *ASCEND 2021* (p. 4181).

4. **System of systems architecture (AI agents) of space station**

- Architecting a complex space mission involves various multi-disciplinary decisions variables and variations along any of these decision variables results in a distinct architecture [2], where the system roles and their interactions with other systems could vary drastically and cause substantial fluctuations in the behavior of the systems and the outcome of the mission. This makes space systems design a typical System-of-Systems (SoS) problem. The collection of systems that constitute a SoS exhibit traits of operational and managerial independence, geographic distribution, emergent behavior, and evolutionary development.
- Autonomously assembled robots have certain autonomous decision-making capabilities. With sensors and memory, the intelligent system, control-manage their state and surrounding environment. Predetermined rules utilize the data to execute tasks or diagnose faults for further corrective actions.
- Control algorithm for the system's execution of autonomous tasks may bs used to evaluate the impact of delays in the development of individual systems on the schedule of the whole SoS.
- Algorithms and those used by other researchers can be incorporated into a processing pipeline, and those attributes added to the database, so that multiple attributes can be compared. Therefore, algorithms create a preliminary space architecture database for which to retrieve useful sources of data and be used to feed a set of SoS tools.
- The increase in size and complexity of aerospace applications indicate certain managing constraints, including (1) information originating from multiple sources, often with diverse representations, cause useful data for trade space analysis to be overlooked; (2) unexpected interactions not identifiable are generated due to system complexity; and (3) continuous development of new methodologies causes a common knowledge database to non-exist.

AI agents of space systems design and increased automation

- To support both decision making in early stage of space systems design and increased automation, extraction of necessary data is required to feed working groups and analytical methodologies. Artificial Intelligence agents can be trained to recognize information coming from standardized representations (e.g. Model Based Systems Engineering diagrams).
- Building an enriched database of space architectures is at the core of a new AI technology for topic discovery. AI topic agents are based on the NASA 2020 Technology Area Roadmap ontology.
- Once deployed, each AI agent analyzes millions of paragraphs in the 60,000 papers, and returns a similarity score for each, depending on how closely the paragraph reflects the topic. The technology uses abstracts that generalize a concept being scored from samples, words and patterns in language.
- The technology for concept detection derives from work in neural networks, Natural Language Programming (NLP) and computational linguistics. In training, the agents learn words and patterns, stored as an array that indicates the concept or topic.
- To ensure the quality of the research collected, the content was curated by NASA and stored in the NASA Technical Reports Server (NTRS) repository.

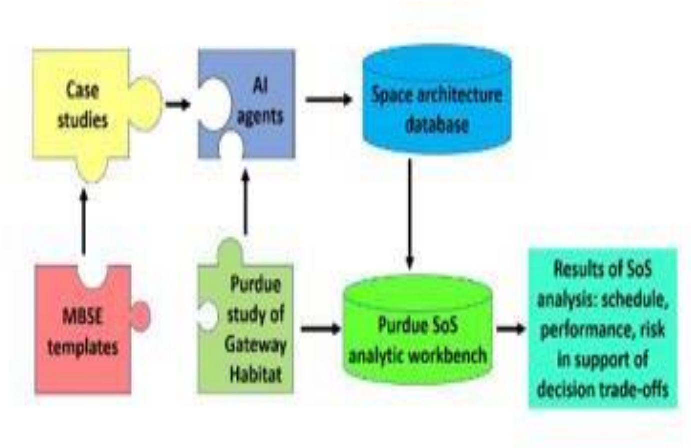

Figure. Based on case studies, with possible information in MBSE format, the AI agents build a database that feeds tools in the AWB for SoS analysis.

AI: **Systems Operational Dependency Analysis**

- Systems Operational Dependency Analysis (SODA) assesses developmental risks and uncertainty in time and resources on the operational aspects of complex system architectures. In SODA, the parametric model of system behavior shows operational dependencies between the systems.

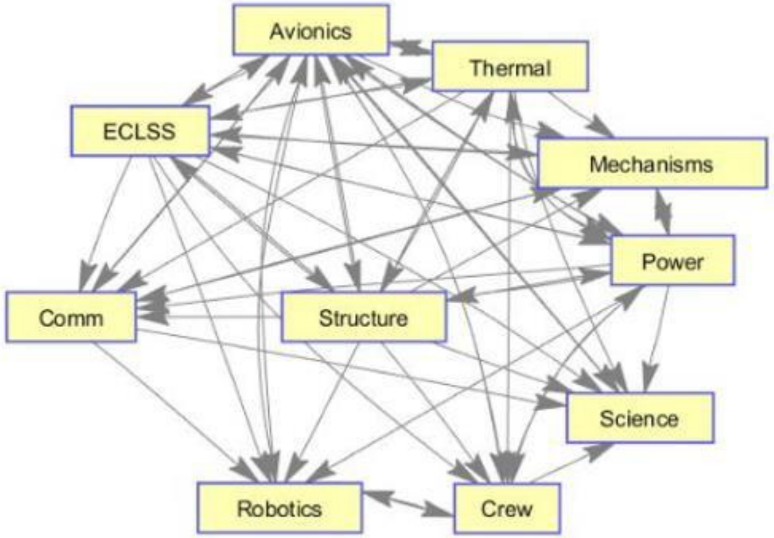

Figure. Operational dependency network for a habitation module.

AI: Systems Developmental Dependency Analysis

- The Strength of Dependency (SOD) in SDDA model evaluates the fraction of development time of a system that is dependent on inputs by other systems. SDDA's partial developmental dependencies account for the punctuality of a system development. The Criticality of Dependency (COD) indicates the level of punctuality below which partial parallel development of systems is not acceptable, and where a task needs to be fully completed before subsequent tasks can begin.

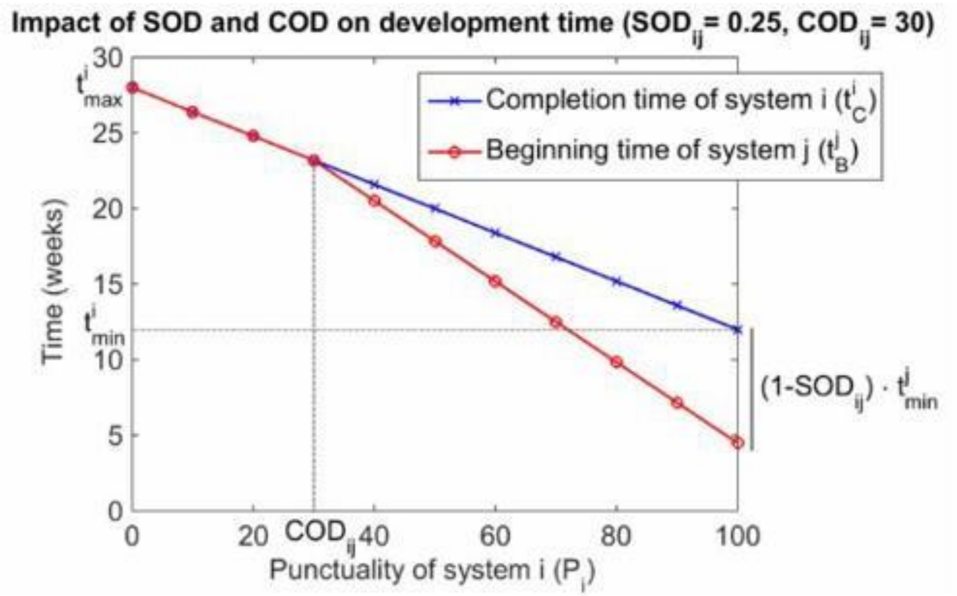

Figure. Completion time of system i and beginning time of system j in function of the parameters of the developmental dependency between the two systems. Due to partial dependency, system j can begin its development before completion of system i, unless i is critically late.

Conclusion

- To identify design-affiliated knowledge structures, at aggregated system levels, system usage is re-framed in terms of HMI (and, technology task fitness or TTF).
- In the case of ISS construction, to model the construction of the station's micro-gravity, astronauts were trained in erecting the station's truss in a Neutral Buoyancy Simulation.
- Unlike the environment of ISS construction, astronaut EVAs of the lunar orbit-based Gateway construction will be challenged particularly by the "Dust Problem" as reported by apollo 17 astronauts.
- Either robotic assistants or fully autonomous robots should function as a superior alternative to astronaut EVAs.
- To assure reliability of autonomous In -Space Assembly robotics, performance of many of the primary robotic technologies have been verified on the International Space Station.
- Robot-Machine (Space Structure) Interactions (RMIs) will be teleoperated by either Earth-based Mission Control or a Gateway installed-complex control station.
- Fully equipped with sensors, situational awareness will be controllably managed with the system's risk-informed decision-making capabilities and hidden fault-detected per a safety instrumented system.
- Ongoing discovery of new technologies and advanced mission concepts almost in real time advances development of ARTEMIS Program with employment of Artificial Intelligence agents,
- Whereas autonomous robots importantly accelerates executes of ARTEMIS Program, Artificial Intelligence indicates a paradigmatic shift.