An Open Avionics and Software Architecture to Support Future NASA Exploration Missions

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**NASA’s Exploration Roadmap**

**EXPANDING HUMAN PRESENCE IN PARTNERSHIP**

*CREATING ECONOMIC OPPORTUNITIES, ADVANCING TECHNOLOGIES, AND ENABLING DISCOVERY*

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**Phase 0**
Continue research and testing on ISS to solve exploration challenges. Evaluate potential for lunar resources. Develop standards.

**Phase 1**

**Phase 2**
Complete Deep Space Transport and conduct yearlong Mars simulation mission.

**Phase 3 and 4**
Begin sustained crew expeditions to Martian system and surface of Mars.

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Now
Using the International Space Station

2020s
Operating in the Lunar Vicinity (proving ground)

After 2030
Leaving the Earth-Moon System and Reaching Mars Orbit

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Phase 1 Plan
Establishing deep-space leadership and preparing for Deep Space Transport development

<table>
<thead>
<tr>
<th>Deep Space Gateway Buildup</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EM-1</strong></td>
</tr>
<tr>
<td><strong>2018 - 2025</strong></td>
</tr>
<tr>
<td>SLS Block 1</td>
</tr>
<tr>
<td>Crew: 0</td>
</tr>
<tr>
<td>CMP Capability: 8-9T</td>
</tr>
<tr>
<td><strong>Gateway (blue)</strong></td>
</tr>
</tbody>
</table>

**Known Parameters:**
- Gateway to architecture supports Phase 2 and beyond activities
- International and U.S. commercial development of elements and systems
- Gateway will translate uncrewed between cislunar orbits
- Ability to support science objectives in cislunar space

**Open Opportunities:**
- Order of logistics flights and logistics providers
- Use of logistics modules for available volume
- Ability to support lunar surface missions

These essential Gateway elements can support multiple U.S. and international partner objectives in Phase 1 and beyond.
## (PLANNING REFERENCE) Phase 2 and Phase 3
Looking ahead to the shakedown cruise and the first crewed missions to Mars

<table>
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<tr>
<th>Transport Delivery</th>
<th>Transport Shakedown</th>
<th>Mars Transit</th>
</tr>
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<tr>
<td><strong>Year</strong></td>
<td><strong>EM-6</strong></td>
<td><strong>EM-7</strong></td>
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<tr>
<td>2027</td>
<td>SLS Block 1B Cargo P/L Capability: 41t TLI</td>
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</tr>
<tr>
<td>2028 / 2029</td>
<td>Logistics</td>
<td>DST Logistics &amp; Refueling</td>
</tr>
<tr>
<td>2030+</td>
<td>DST: shakedown in cislunar space</td>
<td>DST: Mars transit and return to DSG in NRHO</td>
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</table>

### Known Parameters:
- DST launch on one SLS cargo flight
- DST shakedown cruise by 2029
- DST supported by a mix of logistics flights for both shakedown and transit
- Ability to support science objectives in cislunar space

### Open Opportunities:
- Order of logistics flights and logistics providers
- Shakedown cruise vehicle configuration and destination/s
- Ability to support lunar surface missions

**Reusable Deep Space Transport supports repeated crewed missions to the Mars vicinity**
Deep Space Gateway Conceptual Drawing
• NASA's Advanced Exploration Systems (AES) division is pioneering innovative approaches and public-private partnerships to rapidly develop prototype systems, advance key capabilities, and validate operational concepts for future human missions beyond Earth orbit.

• AES activities are related to crew mobility, habitation, vehicle systems, robotic precursors, and foundational systems for deep space.

• AES infuses new technologies developed by the Space Technology Mission Directorate and partners with the Science Mission Directorate to address Strategic Knowledge Gaps for multiple destinations.

• AES is leading NASA’s Deep-Space Gateway & Transport (DSG&T) Efforts.
AES Avionics & Software (A&S) Project

• AES Avionics & Software (A&S) Project Goal:
  – Define and exercise an avionics architecture that is open-source, highly reliable with fault tolerance, and utilizes standard capabilities and interfaces, which are scalable and customizable to support future exploration missions

• A&S Drivers:
  – Technology Transparency
    • The underlying hardware should not have any impact on an application either during development or execution
    • Code reuse and portability
  – Reliability and Maintenance
    • Operate in the presence of failures so that Maintenance Free Operating Periods (MFOPS) can be achieved
    • Provide autonomous operations
    • Minimal number of unique spares
  – Incremental Update & Certification - Designed for Growth and Change
    • Applications can be inserted/ altered with minimum impact on other systems and on the supporting safety case
    • Flexible scheduling to meet the deadlines of all the applications for each viable configuration and when system is upgraded
AES Avionics & Software (A&S) Project

• A&S Focus Areas and Objectives:
  – **Command & Data Handling (C&DH)** - Define a reliable, high-performance & modular C&DH architecture and build HW catalog
  – **Software** - Provide a reusable software architecture and tools suitable for human-rated missions
  – **Human Interfaces** - Identify, integrate & test human interface technologies that are scalable, sustainable, and evolvable to support future exploration
  – **Communication and Wireless Systems** - Enable interoperable, wireless & networked communication for inter/intra-vehicle systems
  – **Systems Engineering and Integration (SE&I)** - Model, build & test flexible and robust integrated vehicle systems

• A&S Benefits:
  – Results in an open architecture that allows use of hardware from multiple vendors
  – Enables use of evolving (near-launch) technology
  – Ability to upgrade capabilities and infuse new technologies with cost effective validation
Avionics & Software Architecture

Best-Effort (IEEE 802.3)
(Crew interfaces and science)
- Classical LANs can run isolated from or overlapping TT/RC network.
- COTS hardware easily upgraded.

Time-Triggered (SAE AS6802)
(Vehicle Command and Control)
- All messaging is into/out of C&DH system.
- Periodic and generally low bandwidth.

Effectors
- Heaters
- Pumps
- Valves
- Motors

Periodic and generally low bandwidth.
< 5 Mbit/s

Rate-Constrained (A664-p7)
(Asynchronous critical systems)
- Traffic shaping and policing ensures successful message delivery.
- Provides event-driven communication between synchronization domains.

High Speed Serial
(P2P, minimal networking)
- Provides >1Gbit/s point-to-point or (possibly) networked messaging.
- Mostly related to off-board communication.

Onboard Displays

Onboard Gateway

IEEE 802.11

Cameras, Audio, and Portable Devices

Classical Ethernet LAN

Direct audio/video signals

Sensor Data
(High rate)
- Optical navigation
- Autonomous systems

Sensor Data
(Low rate)
- Star tracker
- IMU/SIGI
- Sun sensor
- Thrusters
- Temperature
- Humidity
- Oxygen, CO₂
- Flow rate
- Voltage

Transponders (SDR)
- S-band, Ka-band, X-band, Proximity (UHF)

RF Equipment
- Amplifiers, switches

Voting at Interface

Rate-constrained traffic can be used by subsystems traditionally limited to P2P comm.

Command/Telemetry Processing

Equipment unique cabling

Data Recorders

Docking Interface

Data Recorders

Command/Telemetry Processing

DTN Storage/Processing

RF Equipment

Voting at Interface

[1] Rakow, Glenn Spacecraft Crew-Vehicle Avionics Networks and Communication Flow
# Blueprint of the Architecture: Distributed Integrated Modular Avionics (D-IMA)

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<tr>
<th>Description</th>
<th>Rationale</th>
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<tr>
<td><strong>Distributed</strong></td>
<td>• Resources (both hardware and software) are physically distributed</td>
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<tr>
<td></td>
<td>• Reduce harness mass</td>
</tr>
<tr>
<td></td>
<td>• Provide for local control of local functions</td>
</tr>
<tr>
<td></td>
<td>• Lowers flight computer load</td>
</tr>
<tr>
<td><strong>Integrated</strong></td>
<td>• Multiple functions of different criticalities running on separate, high integrity, partitions</td>
</tr>
<tr>
<td></td>
<td>• Re-locatable functions not limited to a single line replaceable unit (LRU) boundary</td>
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<td><strong>Modular</strong></td>
<td>• Standard interfaces/Virtual Backplane</td>
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<td></td>
<td>• Provides for composability</td>
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<tr>
<td></td>
<td>• Allows for hardware reuse</td>
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<tr>
<td></td>
<td>• Allows for software reuse</td>
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<tr>
<td><strong>Avionics</strong></td>
<td>• Board level building blocks used to assemble boxes into systems</td>
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<td></td>
<td>• Allows for multiple vendor hardware components</td>
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**Diagram:**

- **Processors**
- **Network**
  - **D-IMA Smart System**
    - Controller Type a
    - Controller Type b
    - TTE (NIC)
    - Processor
    - Bus I/F
    - Power
    - Remote Interface Unit
  - **IMA Networked System**
    - Common Avionics Enabler
    - Sensor & Effectors $\alpha$
    - Sensor & Effectors $\beta$
Brain of the Architecture:
NASA’s Core Flight Software (CFS)

- Core Flight Software (CFS) is a NASA-developed asset for spacecraft flight software reuse that is available as open-source:
  - [http://sourceforge.net/projects/coreflightexec/](http://sourceforge.net/projects/coreflightexec/)

- Productized real-time flight software developed over several years by Goddard Space Flight Center to serve as reusable software framework basis for spacecraft missions, test missions, real-time systems

- AES has since advanced the product line, including achieving human-rating, as a reusable software solution for future exploration missions

- CFS provides a published service layer (cFE) and an Operating System Abstraction Layer (OSAL) for common services to run on multiple platforms and with several operating systems
  - Pub/Sub message bus, time services, events, tables, file, task execution

- CFS provides common reusable spacecraft functions as open-source or government-purpose applications
  - Scheduler, commanding, telemetry, communication, data recording, limits, system health, sequences
• CFS also provides a mechanism to link distributed CFS instances called Software Bus Network (SBN), including an SBN library (SBN-lib) for non-CFS applications that need access to software bus data.
Some CFS Supported Platforms: Non-Exhaustive

• CFS has been ported to work on many processors...

  BAE RAD750
  LEON3
  Space Micro Proton 400K
  Raspberry Pi
  AITECH SP0-100
  Intel x86
  Maxwell SCS750

• ...and with many operating systems, both real- and non-real-time

  VxWorks
  Linux
  RTEMS
  Raspbian
  Green Hills
  XENOMAI
  PikeOS
Backbone of the Architecture: Time-Triggered Ethernet

- Time-Triggered Ethernet (TTE) is compatible with, can coexist with on the same physical media, and expands classical Ethernet with services to meet time-critical or deterministic conditions, supporting three message types:

  - Time-triggered (SAE AS6802): Sent over the network at predefined times and take precedence over all other message types
    - Occurrence, delay and precision of messages are predefined and guaranteed
  
  - Rate-constrained (ARINC 664 p7): Used for applications with less stringent determinism and real-time requirements
    - Bandwidth is predefined and guaranteed for each application and delays/jitter have defined limits
  
  - Best-effort (IEEE 802.3): Follow classical Ethernet policy
    - Use the remaining network bandwidth and have lower priority than TT or RC messages

- TTE Standards exist or are in-work and NASA supports development of an open TTE Standard
  - SAE AS6802 – Time-Triggered Ethernet
  - European Cooperation for Space Standardization (ECSS) ECSS-E-ST-50-16 – Time-Triggered Ethernet
  - Consultative Committee for Space Data Systems (CCSDS) Sub-Network Services WG

Sikorsky S-97 RAIDER

NASA's Orion Spacecraft
Reliability and Robustness: Triplex Voting Architecture

- Developed a 1-Byzantine Fault tolerant voting architecture using TTE and CFS using current COTS technologies
  - Three Onboard Computers (OBC)
  - Three High-Integrity (command/monitor) TTE Switches
  - Remote Interface Units (RIU)

- Architecture is scalable through additional network planes, high-integrity devices, etc.

- Approach uses TTE for data distribution and sync and built CFS apps to do so

- Benefits of the voting architecture:
  - Enables the use of COTS single board computers
  - Eliminates need for separate cross-channel data link
  - Eliminates need for separate timing hardware

The Crew Element: Human Interface Architecture

- Developed a human interface architecture to reduce barriers between the crew and the vehicle

- Core component is the Human Interface Management Computer (HIMaC) that acts as a Display Server, Telemetry/Command Exchange Server and Audio/Video Server
  - HIMaC is tied to flight software bus network and supports different traffic classes

- Architecture consists of open interface standards to provide flexible and reconfigurable peripherals
  - Displays, Controls, Wearables, Audio, Video, Virtual/Augmented Reality

- Provides a robust approach to data security

- Designed to be scalable, sustainable, and evolvable enabling support for system build up, upgrades and extensions
Can You Hear Me Now?: Wireless and Communication Architecture

- The communication links that the architecture is designed to support include:
  - DSG ↔ Earth
  - DSG ↔ Lunar Surface
  - DSG ↔ Visiting Vehicle
  - DSG ↔ Proximity/Wireless Communications (i.e. Extra-Vehicular Activity (EVA))

- Architecture supports several standard wireless standards and technologies for internal spacecraft and proximity communications
  - IEEE 802.11 Family
  - 5G Technology (LTE)
  - Wireless Sensor Networks
  - Radio Frequency Identification (RFID) for both logistics and sensing

- Candidate standards and technologies have been identified, are still being evaluated, and have not been finalized
  - Optical communication is also being looked at for DSG

- Will leverage the Interagency Operations Advisory Group (IOAG) Service Catalog and Consultative Committee for Space Data Systems (CCSDS) Standards

- Internetworking capabilities are a requirement, and must operate in the presence of time delays and outages
  - Delay/Disruption Tolerant Networking (DTN) is the solution
Connecting to the Solar System Internet (SSI): Delay/Disruption Tolerant Networking (DTN)

- Delay/Disruption Tolerant Networking (DTN) is an AES developed protocol suite that extends the terrestrial Internet capabilities into highly stressed data communication environments where the conventional Internet does not work
  - These environments are typically subject to frequent disruptions, unidirectional/asymmetric links, long delays and high error rates

- DTN is being standardized by the Consultative Committee for Space Data Systems (CCSDS) and the Internet Engineering Task Force (IETF) DTN Working Groups

- NASA’s Interplanetary Overlay Network (ION) DTN implementation is open-source software:
  - [https://sourceforge.net/projects/ion-dtn/files/](https://sourceforge.net/projects/ion-dtn/files/)

- Some of the benefits of DTN include improved operations and situational awareness, interoperability and reuse, space link efficiency, utilization and robustness, security and quality-of-service
Putting it All Together: Systems Engineering and Integration (SE&I)

• Determined the necessary avionics functions for architecture, allocated the functions to abstract systems and implemented the systems to perform the functions

• Modeled the avionics and software architecture using Model-Based Systems Engineering (MBSE) tools using the Systems Modelling Language (SysML) throughout life-cycle

• Led the migration of other spacecraft subsystems to run CFS applications on path-to-flight processors and connect to the architecture
  – Power, Environmental Control and Life Support System (ECLSS), Vehicle Autonomy applications, etc.

• Conceptualized mission scenarios to exercise/stress the architecture through both simulation and testing
An Enabling Architecture: Supporting Future Autonomous Systems

• As human exploration moves farther out into space, the need for autonomous systems significantly increases
  – Many functions of the current Mission Control Center (MCC) will need to move onto the spacecraft

• AES, STMD and others within NASA are researching various autonomy applications that could be used as part of the Deep-Space Gateway and Transport efforts

• NASA is also closely tracking commercial developments that could support autonomous systems

• The developed avionics and software architecture will serve as a platform to exercise autonomy applications and concepts
  – Exercise onboard autonomous Integrated Vehicle Health Management (IVHM) applications
  – Explore distributed and centralized autonomy concepts
  – Build crew and ground operator familiarity and comfort with autonomy applications
  – Provide reliable command/control capabilities for spacecraft subsystems
  – Provide additional processing/storage for less-capable systems
  – Monitor subsystems and serve as an operations advisor

• Open architecture will also serve as a technology development platform to help establish partnerships and collaborations to further enhance architecture
  – Support Academia, International Partner or commercial technologies
Avionics & Software Architecture

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Effectors
- Heaters
- Pumps
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- Motors

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High Speed Serial
(P2P, minimal networking)
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- Optical navigation
- Autonomous systems

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(Low rate)
- Star tracker
- IMU/SIGI
- Sun sensor
- Thrusters
- Temperature
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Distributed Processing
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- Propulsion
- ECLSS

Onboard Gateway

Classical Ethernet LAN

Classical Ethernet LAN

IEEE 802.11

IEEE 802.11

Wireless Devices

Servers

Real-time Audio/video streaming

Radio Equipment

RF Equipment

Amplifiers, switches

Data Recorders

Command/ Telemetry Processing

DTN Storage/ Processing

Voting at Interface

Transponders (SDR)
S-band, Ka-band, X-band, Proximity (UHF)

installation and cabling

Unique cabling

Command/ Telemetry Processing

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Distributed Processing

< 5 Mbit/s

> 100 Mbit/s

< 10 Mbit/s

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Key Takeaways

• The AES A&S project has developed an Avionics & Software architecture that is:
  
  – Open-source, with standard capabilities and interfaces
  
  – Highly reliable with 1-Byzantine fault tolerance
  
  – Scalable and customizable to support future exploration missions such as the Deep Space Gateway and Transport
  
  – Built on a foundation of NASA’s Core Flight Software (CFS) and Time-Triggered Ethernet (TTE)
  
  – Realizable with currently available COTS technology and supports multi-vendor hardware
  
  – Fully modeled in SysML, implemented and tested in relevant environments
  
  – Designed to support various autonomy technologies that will be needed for deep-space human exploration