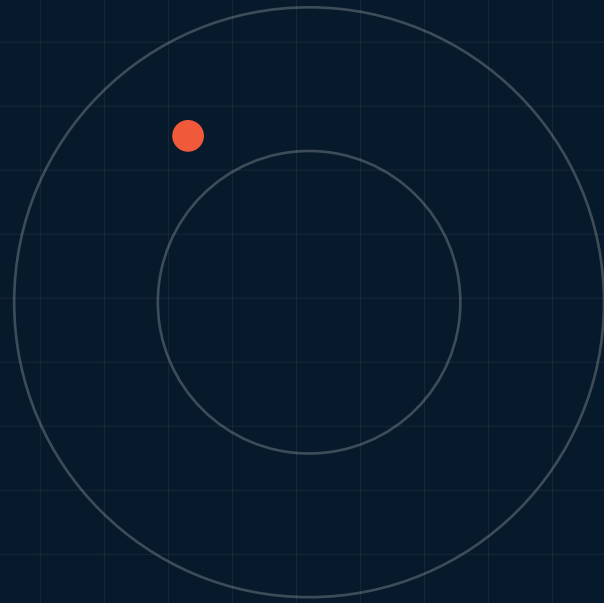




WHEN SPACE BECOMES INFRASTRUCTURE

Architecting Sustained Human Life Beyond Earth

ABSTRACT

Human exploration beyond low Earth orbit is moving from a sequence of bounded missions toward an operational environment that must persist, recover and grow. This note examines the architectural consequences of that transition: service continuity, maintainability, distributed autonomy, human-system integration and interoperability. The argument is deliberately system-level. The central design object is no longer a vehicle in isolation, but the network of interfaces and services that allows multiple vehicles, habitats, crews and operators to function as one dependable capability.

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01

THE DESIGN OBJECT IS CHANGING

The engineering logic of a short mission is different from the logic of a persistent operating environment. A bounded mission can be optimized around a defined duration, a known consumables model, scheduled ground support and a narrow set of objectives. A sustained presence must remain useful while hardware ages, crews rotate, software changes, logistics are delayed and new participants arrive with systems that were not designed together. [1]

NASA's current Moon to Mars Architecture makes this shift explicit through successive segments - Human Lunar Return, Foundational Exploration, Sustained Lunar Evolution and Humans to Mars - and through sub-architectures for power, mobility, transportation and utilization. The stated lunar-infrastructure objective is not simply repeated access; it is an interoperable environment in which industry and international partners can maintain continuous robotic and human activity. [2]

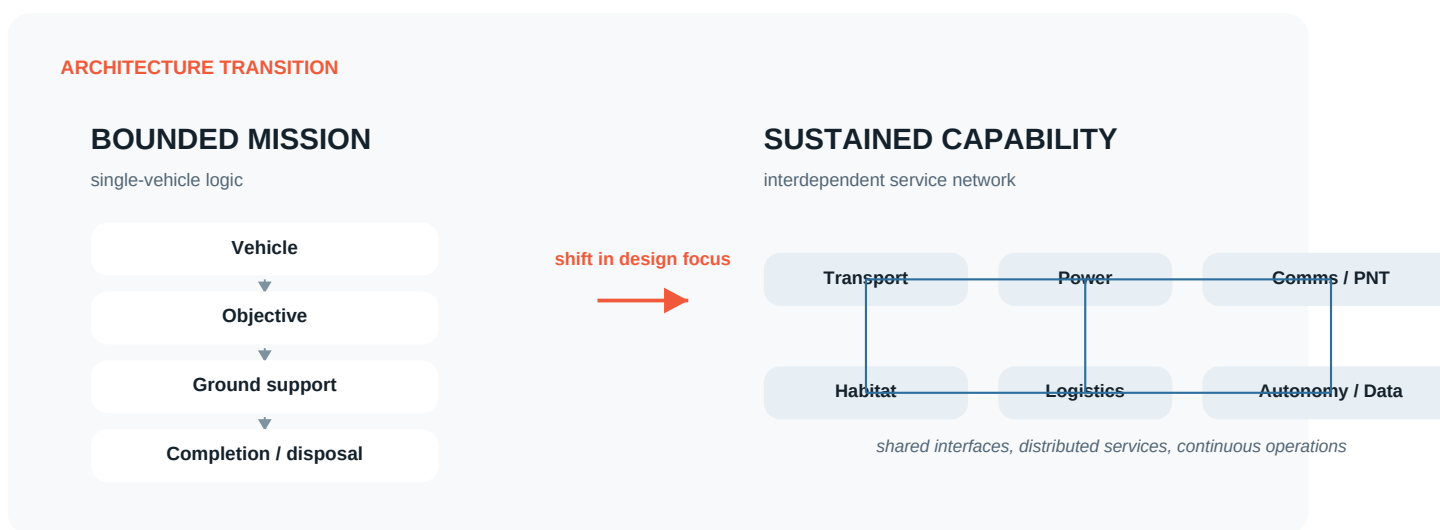


Figure 1. The design object expands from a mission chain to an interdependent operational ecosystem.

WORKING DEFINITION

In this paper, infrastructure means a persistent set of shared capabilities - physical, digital and operational - that can support more than one mission, user or vehicle and can be maintained or evolved over time.

02

RESILIENCE BEYOND REDUNDANCY

Redundancy remains essential, but a long-lived system cannot stop at the question "What takes over when unit A fails?" The harder question is what the architecture does after the spare is unavailable, the failure mode is ambiguous, or the repair window is measured in weeks rather than hours. For persistent infrastructure, resilience is the ability to preserve critical services, absorb a degraded state and recover useful capability without turning every anomaly into mission loss.

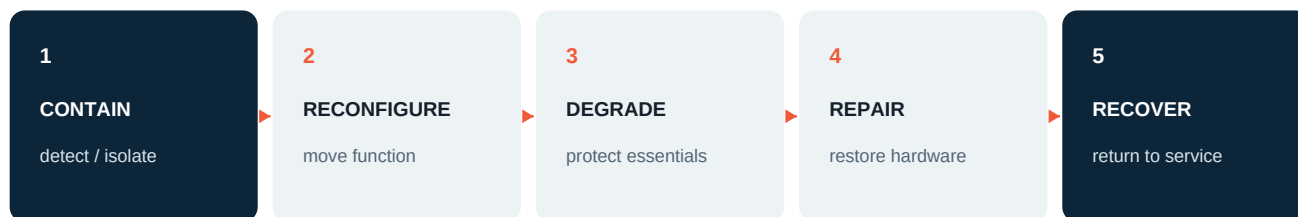


Figure 2. A resilience sequence for persistent infrastructure. Redundancy is captured inside containment; recovery requires additional architectural provisions.

That requirement changes practical design choices. Replaceable units need physical access. Fault-management software needs observable states and rollback paths. Critical services need load-shedding rules before an emergency occurs. Spares and tools become part of system architecture rather than logistics afterthoughts. The important metric is therefore not only component reliability, but the continuity of the service delivered to the crew or mission.

ENGINEERING CONSEQUENCE

For long-duration systems, "repairability" must be designed into geometry, interfaces, diagnostics, crew procedures and spares policy. A component that can technically be replaced but cannot be reached, isolated or verified in flight is not maintainable in operational terms.

DEGRADED-MODE PRIORITY

crew survival -> vehicle safety -> communications -> navigation -> minimum mission capability

03

AUTONOMY AS AN OPERATIONAL SERVICE

As missions move farther from Earth and operations become more distributed, the value of autonomy shifts from convenience to continuity. The relevant architecture is not an "AI spacecraft"; it is a layered control system in which deterministic safety functions remain authoritative while adaptive functions assist diagnosis, resource allocation and coordination. The boundary between those layers must be explicit, testable and recoverable. [3]

OPERATIONAL MATURITY

L1 AUTOMATED EXECUTION
predefined sequences

L2 ADAPTIVE RESPONSE
state-aware control

L3 ASSET COORDINATION
shared resources / tasks

L4 DECISION SUPPORT
risk / objective trade-offs

ONBOARD COMPUTING BOUNDARY

SAFETY-CRITICAL CONTROL
deterministic / verified

RECONFIGURABLE COMPUTE
fault recovery / workload migration

PERCEPTION & ESTIMATION
sensor fusion / anomaly cues

MISSION ASSIST
recommendations / prioritisation

Figure 3. Autonomy is useful when authority, fallback behaviour and verification boundaries remain visible to the system designer and operator.

For deep-space infrastructure, this layering also supports graceful degradation. A failed high-level autonomy service should not remove basic commandability; loss of a networked planning function should not compromise local safe-state control. Conversely, low-level deterministic functions should expose enough state to support higher-level diagnosis. The architecture is strongest when information can flow upward without allowing unverified authority to flow downward.

DESIGN TEST

For every autonomous function, ask four questions: What decision authority does it hold? What evidence can the crew or ground inspect? What is the fallback mode? How is the function isolated if its confidence or behaviour becomes unacceptable?

HUMAN PRESENCE IS A SPACECRAFT FUNCTION

A long-duration habitat cannot be treated as a pressure shell with habitability added later. The crew is part of the control loop: human performance depends on atmosphere, thermal conditions, radiation exposure, workload, interfaces, maintenance burden and the quality of environmental information available during nominal and off-nominal operations. NASA human-system standards and ECLSS practice reflect this integration through explicit requirements for atmospheric control, monitoring, water, waste, environmental limits and alerting.

[5] [4]

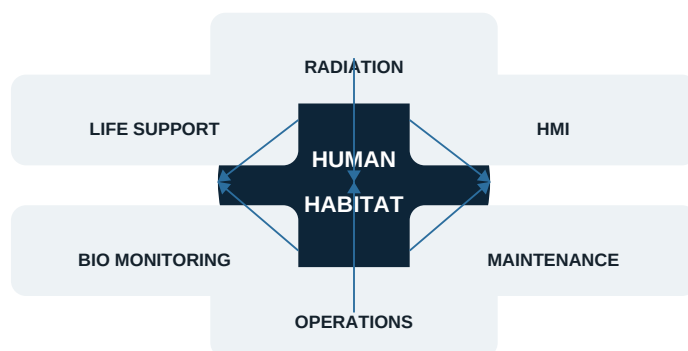
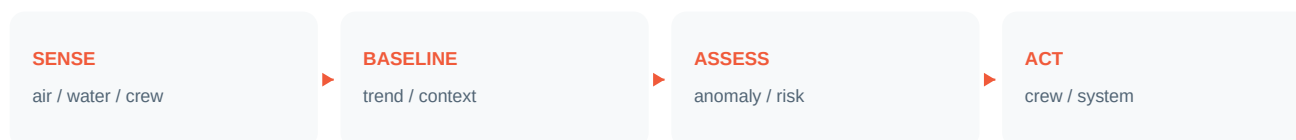


Figure 4. Habitability is an integrated system boundary, not a late-stage interior layer.

FROM SENSOR DATA TO OPERATIONAL HEALTH INTELLIGENCE



The opportunity is not to invent a single "health score," but to connect environmental, biological and operational trends in a way that improves detection and response. Any such model must preserve traceability to the underlying measurements and should support, rather than obscure, clinical and engineering judgement.

SHARED SERVICES CHANGE MISSION ECONOMICS

Repeated exploration becomes more scalable when every user is not required to rebuild the same foundational functions. Communications, navigation, timing, cargo delivery, power and data services are natural candidates for shared architectures because their value increases when multiple missions can consume them through known interfaces. ESA Moonlight and NASA's LunaNet work are concrete examples of this service-oriented direction for lunar communications and navigation. [7] [6]



Figure 5. A service stack for sustained presence. The layers are separable for procurement, but coupled in operation.

The practical implication is contractual as much as technical. Once a capability is consumed as a service, interface definition, performance envelopes, service availability and failure responsibility become architecture parameters. The mission designer must know not only that a network or power source exists, but what quality of service is guaranteed, under what conditions, and how the vehicle behaves when that service is degraded.

EXAMPLE

LunaNet is explicitly framed around mutually agreed standards and interfaces that allow multiple providers and users to participate in an evolving lunar network. ESA Moonlight similarly pursues lunar communications and navigation as a shared service rather than a mission-specific relay.

INTEROPERABILITY AT THE INTERFACES

A lunar ecosystem can become fragmented long before it becomes large. Docking, power, communications, software and data interfaces are expensive to change after hardware families are established. Early interface discipline therefore protects both competition and cooperation: organisations can differentiate internally while remaining compatible at the boundaries where vehicles and services meet. [8]

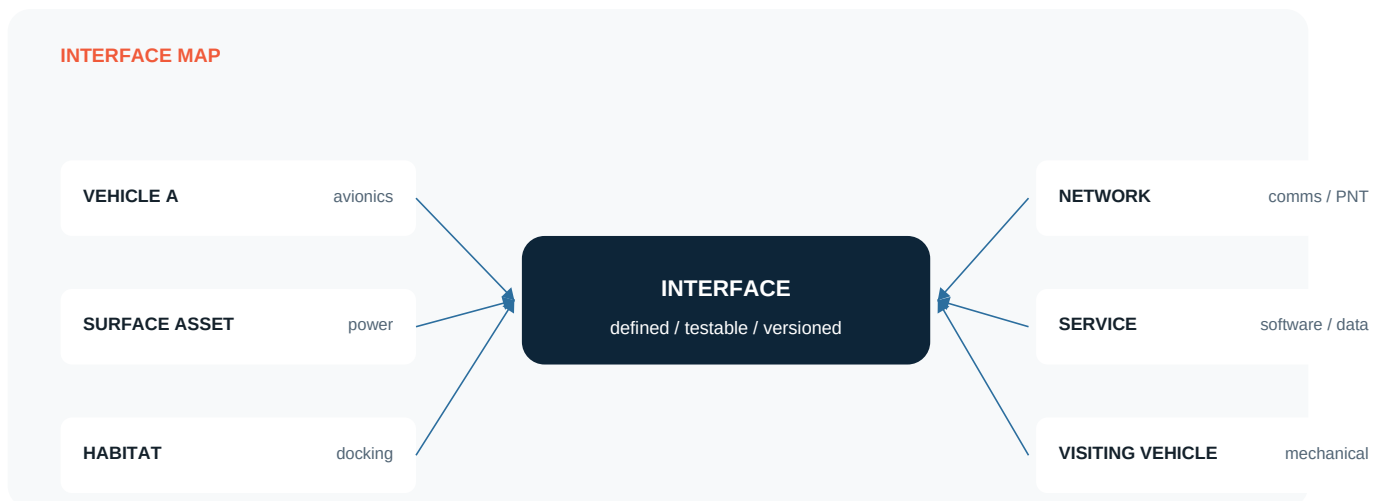


Figure 6. Interoperability concentrates design discipline at the boundary. Internal implementations can remain diverse.

NASA's international deep-space standards already cover avionics, communications, power, software and docking. The stated purpose is to enable independent development of compatible systems rather than to prescribe complete vehicle designs. That distinction is important: standards should reduce interface uncertainty without freezing innovation inside the subsystem. [8]

PROGRAMME IMPLICATION

Interface ownership should be treated as a programme-level responsibility. Every interface needs an authority, configuration status, verification method and change process. In a multi-partner architecture, unmanaged interfaces become hidden programme risk.

PROGRAMME AND INSTITUTIONAL IMPLICATIONS

The transition from missions to infrastructure does not require a single grand architecture. It requires a different set of programme questions. The most important decisions concern service continuity, interface ownership, maintainability and the distribution of authority between crew, software, ground and external providers.

SERVICE CONTINUITY

Define the minimum service that must survive a degraded state, then design the failure response around that service.

INTERFACE OWNERSHIP

Assign technical authority and configuration control before multiple partners begin detailed design.

MAINTENANCE PATH

Validate access, isolation, diagnosis, replacement and post-repair verification as one end-to-end operation.

AUTONOMY BOUNDARY

Separate deterministic control from adaptive support and make authority, confidence and fallback states observable.

HUMAN DATA

Connect environmental and biological trends without replacing engineering or clinical judgement with opaque scoring.

SERVICE CONTRACTS

Treat availability, latency, quality and failure responsibility as architecture parameters when infrastructure is externally provided.

SYNTHESIS

The decisive shift is not from one destination to another. It is from designing a mission that can succeed once to designing a capability that can remain useful, recover from failure and accept new participants over time.

Independent perspective. No institutional endorsement is implied.

08 REFERENCES AND SOURCE BASIS

The source base is intentionally limited to primary institutional material. These references support the factual descriptions of current exploration architecture, interoperability, human-system requirements and the transition toward shared lunar and post-ISS infrastructure. Interpretive statements in the paper are the author's own.

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AUTHOR NOTE

Rania Toukebri | Lead Spacecraft Architect | Programmes Leader | Space Systems & Strategy. This document reflects the author's independent professional perspective. References to agencies, programmes and standards are for technical context and do not imply endorsement by any employer, agency or institution.