Random Access Frames (RAF): Alternative to Rack and Standoff for Deep Space Habitat Outfitting

A. Scott Howe, PhD\textsuperscript{1} and Raul Polit-Casillas\textsuperscript{2}

Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109

A modular Random Access Frame (RAF) system is proposed as an alternative to the International Standard Payload Rack (ISPR) for internal module layout and outfitting in a Deep Space Habitat (DSH). The ISPR approach was designed to allow for efficient interchangeability of payload and experiments for the International Space Station (ISS) when frequent resupply missions were available (particularly the now-retired Space Shuttle). Though the standard interface approach to the ISPR system allowed integration of subsystems and hardware from a variety of sources and manufacturers, the heavy rack and standoff approach may not be appropriate when resupply or swap-out capabilities are not available, such as on deep space, long-duration missions. The lightweight RAF concept can allow a more dense packing of stowage and equipment, and may be easily broken down for repurposing or reuse. Several example layouts and workstations are presented.

Nomenclature

\begin{itemize}
  \item AES = NASA Advanced Exploration Systems project
  \item COTS = Commercial Off-The-Shelf technology
  \item CTB = Cargo Transfer Bag
  \item D-RATS = NASA Desert Research and Technology Studies field analog tests
  \item DSH = Deep Space Habitat
  \item ECLSS = Environmental Control and Life Support System
  \item EXPRESS = “EXpedite the PRocessing of Experiments for Space Station” payload standard
  \item GMWS = General Maintenance Workstation
  \item HDU = Habitat Demonstration Unit
  \item ISIS = International Subrack Interface Standard
  \item ISPR = International Standard Payload Rack
  \item ISS = International Space Station
  \item IVA = Intravehicular Activity
  \item LEO = Low Earth Orbit
  \item LOC = Loss Of Crew
  \item LOM = Loss Of Mission
  \item MOT = NASA Deep Space Habitat Missions Operations Test
  \item QC = Crew Quarters
  \item RAF = Random Access Frames
  \item SLS = Space Launch System
  \item TRWS = Telerobotics Workstation
\end{itemize}

I. Introduction

The International Space Station (ISS) uses a modular layout standard called the International Standard Payload Rack (ISPR), that consists of refrigerator-sized identical cabinets to organize internal outfitting. The ISPR system was conceived by space architects (Jones 2009) as a means to organize infrastructure, equipment, payloads, science experiments, stowage, logistics, and internal outfitting using swappable rack modules delivered by the Space Shuttle. Since the ISS was permanently located in Low Earth Orbit (LEO), frequent visits by the Shuttle allowed for

\begin{itemize}
  \item[1] Senior Systems Engineer, a.scott.howe@jpl.nasa.gov, 4800 Oak Grove Drive, Pasadena, California 91109
  \item[2] Space Architect, raul.polit-casillas@jpl.nasa.gov, 4800 Oak Grove Drive, Pasadena, California 91109
\end{itemize}
frequent resupply and swapping in and out of payloads and experiments. However, with the end of the Shuttle program, the ability to deliver rack-sized modules was reduced to infrequent visits by the Japanese- and European-built supply vessels, which themselves were on their way out. Regardless of whether frequent resupply vessels are available for maintaining the original purpose of the ISPR system in LEO, it can be said that the ISPR system may be inappropriate as far as deep space missions are concerned. Deep space missions are currently facilitated by Orion and Space Launch System (SLS) transportation architecture, which assumes less frequent launches and reduced opportunities for resupply. In addition, large ISS-style hatches may not be available on deep space habitats or vehicles. Therefore the need arose to develop a new system of internal outfitting organization, based less on resupply than on repurposing.

In 2011 the NASA Advanced Exploration System (AES) Logistics Repurposing project was organized and took over Logistics-2-Living efforts (Howe, Howard 2010), as well as pursued new concepts for establishing modularity and organizational approaches to internal equipment and outfitting (Shull, et al 2012). In parallel, workstations and crew functions evolved from NASA’s Desert Research and Technology Studies (D-RATS) were used as a basis for RAF workstation configurations. University teams under NASA’s eXploration Habitat (X-Hab) Academic Innovation Challenge built upon the Logistics Repurposing work. The Random Access Frame (RAF) system came out of these efforts.

This paper will briefly describe the ISPR concept appropriate for LEO facilities like the ISS, and then discuss the various studies and efforts that have gone into the development of the RAF system for Cis-lunar space and beyond in Deep Space Habitats that are inaccessible to frequent resupply.

II. ISPR System

The ISPR system consists of two main components – refrigerator-sized rack modules that plug into standoff structures containing infrastructure elements. Figure 1 (left) shows a cross-section of four ISPR rack modules (green) installed between four standoff frames (gray), defining a square volume corridor for crew occupancy. Racks are removed or installed by tipping the unit into the central corridor, and floating it through the end hatch of the module (Figure 1, right).

Figure 1: Cross-section of ISS modules showing the International Standard Payload Rack (ISPR) method of organizing equipment and logistics (left, shown as green modules attached to gray standoff structure) – rack modules can be swapped in and out with frequent Shuttle resupply (right)

The ISPR system has standard interfaces for power, data, thermal, fluid, gases, fire suppression, and other subsystems that each rack can plug into on basis of need. In actuality, though some racks were indeed swapped in and out, many of the racks were permanently installed and the most convenient swappability occurred on a smaller level by means of the “EXpedite the PRocessing of Experiments for Space Station” (EXPRESS) payloads, Shuttle middeck lockers, equipment, and avionics based on the International Subrack Interface Standard (ISIS).
Equipment, workstations, stowage, and logistics elements pack tightly into module

Stowed workstations

Similar to compact library shelving, unneeded RAF frames and their attached cargo are moved to the side

Work volume and corridor space are created on-the-fly in a random access fashion

Access corridors can be widened for work activities, or reduced to minimal functionality

Work activities and access must be correographed to eliminate bottlenecks as RAF frames are shuttled out of the way during operations

Work volume removes crew member from main corridor freeing up clutter and allowing for more efficient packing of equipment and stowage

Figure 2: Random Access Frame (RAF) concept
III. RAF System

The Random Access Frame (RAF) system came from the difficulty to resupply vehicles and habitats on deep space missions, and the need to be more clever at tightly packing volumes with more stowage and logistics. The system is based on ISIS and EXPRESS payload modularity, building on previous standards, but avoiding the large ISPR rack bulk. In this section we discuss the RAF random access concept, modularity, tertiary structure for outfitting, utility hookups, and kit-of-parts concepts.

A. RAF Concept

One method for packing supplies in a container might be to coordinate the placement of items in reverse order from when they are expected to be used, then maximize volume by packing it completely full – the crew would simply “eat their way” into the container, expanding the available volume as they go. This method however poses problems in contingency situations, where something is needed deep in the container before it was scheduled to emerge. Sometimes the item that is needed might lead to Loss Of Crew or Loss Of Mission (LOC/LOM) scenarios requiring that all the bales, boxes, and packages stuffed in front of the needed item be removed and relocated temporarily to another location until the item is found. This problem can pose significant risks to the crew in limited volume vehicles, and in some circumstances may prove to be an impossible task.

What is needed then is random access to all stowage and equipment to allow the crew to retrieve any item at any time, regardless of the planned timing that it was supposed to be used. Unfortunately complete random access requires open volume corridors between every shelf, similar to a warehouse or library, which would be an inefficient use of volume. The RAF concept solves this dilemma similar to the way random access shelving systems are used in libraries – by solid packing all the shelves together (Figure 5) except for a single corridor – random access is achieved by shifting the shelves sideways and creating new corridors on demand.

Not only stowed equipment and logistics, but also entire workstations can be solid packed in this way. Figure 2 (top) shows a solid-packed bank of RAF frames loaded with equipment. A crew member wishing to use the workstation would shift frames to the side (Figure 2, middle), and create a working volume off the main corridor (Figure 2, bottom). In most cases only the volume of a single corridor or workspace needs to be kept free from stowage and equipment, but that volume can be shifted anywhere along the bank of RAF frames.

![Figure 3: RAF system modular options](image-url)

Bare RAF frame
CTB stowage
Shuttle middeck lockers mounted to frame
Cargo netting
Isogrid panels for mounting avionics, electronics, and other equipment
Disassembled kit-of-parts can be repurposed
Isogrid or cargo netting panels repurposed
Unfolded CTB becomes dual-use partition or radiation shielding (can be used as water wall elements)
Using the ISIS standard modularity, a variety of means for mounting, connecting, and stowing equipment, avionics, and logistics packaging can be accommodated (Figure 3). The RAF frames are innately constructed from kit-of-parts components, allowing for disassembly and re-use. Initially, RAF frames can allow for tight packing of the pressure vessel, with a smaller free volume than what the ISS usually accommodates (Figure 4, left, and Figure 5). As stowage and logistics items are consumed the volume opens up to allow for additional permanent functions, such as Crew Quarters and wardroom (Figure 4, middle). When all logistics packaging is disassembled and repurposed, RAF frames can all be pushed to the side out of the way, or disassembled and used for other purposes (Figure 4, right).

**Figure 4**: Wireframe ISS module illustrating RAF method of organizing equipment and logistics (left) – as supplies are used (middle), RAF frames move to the side to open up volume (right)

**Figure 5**: ISS-type module wireframe with RAF frames and equipment packed more densely than ISPR system is capable of achieving
B. Deployable Tertiary Structure

Part of the RAF research included investigating how to provide additional deployable tertiary structure that folds out on demand (Figure 6). Such a capability would allow for collapsible workstations, that are only deployed on demand or assembled from repurposed elements as the mission progresses.

![Figure 6: Random access corridors and deployable tertiary structure](image1)

C. Utility Hookups for Sliding Frames

The RAF concept calls for keeping a standoff structure (or alternatively a longeron truss) upon which the frames can slide on rails. However, contrary to the ISPR system, utility hookups need not be stuffed through the standoff – RAF will use flexible cable and hose carriers spanning between frames to allow a serial bus approach to power, data, fluid, or gas supplies (Figure 7). These carrier systems have been used in industrial applications for many years, and are an efficient way to keep units connected even when they are movable or subject to kinematic motion. It is assumed that particularly densely connected equipment, such as Environmental Control and Life Support Systems (ECLSS) would need to be permanently fixed at the end of the pressure vessel where it does not need to be moved in the RAF system.

![Figure 7: Flexible cable and hose carrier system](image2)
D. Kit-of-Parts Assembly

Modular kit-of-parts designed for disassembly, re-assembly, and multi-use incorporate the lessons learned in Logistics-2-Living experimentation. Entire RAF frames loaded with stowage can be broken down into dual-use components and repurposed later in the mission (Figure 8). One scenario suggests that a deep space mission begin with full Cargo Transfer Bags (CTBs) and kit-of-parts RAF frames, where core mission equipment remains packed in the configuration – as logistics are consumed, repurposed unfolded CTB sheets and RAF frame components can be re-assembled into scientific workstations that will be needed upon reaching the destination.

IV. Example RAF-based Workstation Designs

The RAF system investigation resulted in design concepts for several specific applications. Designs for generic stowage concepts, a Telerobotics Workstation (TRWS), a Virtual Window, Crew Quarters, and General Maintenance Workstation (GMWS), were explored.
A. Stowage System

The most basic unit of stowage assumed the use of Cargo Transfer Bags (CTBs). The design of stowage systems required random access for each of the CTBs, but also required a method for selectively removing CTBs without losing control of all the other stacked CTBs. The result was a double-loaded RAF frame with cargo netting. The netting could be released selectively, freeing up a single row of CTBs (Figure 9).

B. Telerobotics Workstation (TRWS)

A TRWS design was conceived that packed six flat-screen displays with CPU into a single RAF frame. The workstation in stowed configuration is very slim (Figure 10, left), but opens up when in use (Figure 10, right). In Cis-lunar Deep Space Habitat studies (Griffin, Smitherman, Howe 2013), a repurposed ISS node 1 was fitted with RAF frames. While stowed the frames stayed clear of side hatches, but could be spread out in front of the hatches while in use. This concept allowed for dual use of volume for the TRWS, RAF access corridors, and also for egress to the node side hatches (Figure 11). Additional uses for the TRWS includes as an Intravehicular Activity (IVA) workstation for monitoring and controlling habitat functions, and also for virtual window purposes.

Figure 10: Telerobotics Workstation in stowed configuration (left) and deployed configuration – six flat-screen displays and work surface fold out, with CPU mounted behind (right)

Figure 11: Cross-section of ISS-type module showing TRWS deployed and in use
C. Virtual Window

Another application for RAF frames is a deployable virtual window. Using roll-up screens and digital projectors, camera views from the outside can be augmented and enhanced with star catalogs and overlayed text to help crew members gain a sense of position and overall orientation in relation to earth and the mission destination. Virtual windows can also be used to project streaming navigation video from remotely piloted robotic probes and vehicles (Howe, Kennedy, Gill, et al 2013) or for entertainment purposes. In the RAF approach, eight RAF frames line up with each other in each of the four bays of a cylindrical habitat, and stow compactly in their own rows (Figure 12, right). When deployed, roll-up screens are attached to the neighboring frame and slid sideways to create the projection surface (Figure 12, left). In use, the crew member remains in the center of the four screens in a surround position (Figure 13).

Figure 12: Virtual Window consisting of eight RAF frames with digital projectors and screens stretched between them – digital projectors can project augmented reality star maps (left), and stow into compact configuration (right)

Figure 13: Virtual Window in use
D. Crew Quarters

A simple Crew Quarters configurational study was performed, where unfolded CTB rectangles are used as doors between RAF frames. Additional CTBs can be repurposed for privacy as needed along the sides. A Crew Quarters using the RAF concept would keep dedicated walls for personal use, but allow the volume to be collapsed when not in use.

Figure 14: Crew Quarters (CQ) in deployed (left) and stowed (right) configurations -- uses empty CTBs unfolded to make privacy partitions

E. General Maintenance Workstation (GMWS)

Several generations of GMWS were explored during mission operations tests in NASA’s Habitat Demonstration Unit (HDU) during NASA Desert Research and Technology Studies (D-RATS) 2010, D-RATS 2011, and NASA Mission Operations Tests (MOT) 2012 (Howe, Kennedy, Gill, et al 2013; Gill, et al, 2011; Kennedy, et al, 2011; Tri, et al, 2011). Lessons learned from these prototypes (Figure 15) were applied to an RAF version of a GMWS.

Figure 15: Habitat Demonstration Unit (HDU) General Maintenance Workstation prototypes -- Desert Research and Technology Studies (D-RATS) 2010 (left), D-RATS 2011 (middle), and Mission Operations Test (MOT) 2012 (right)
Dual RAF frames
Stowage volume for softgoods or secured bulk items
Stowed glovebox pop-out
Volume for permanently mounted avionics, compressed air tanks, and other equipment
Glovebox pop-out for manufacturing and particulate containment
Shuttle middeck lockers mounted to frames – can be mounted for front or back access
Cable and hose carrier

Figure 16: General Maintenance Workstation (GMWS) main glovebox in stowed (top) and deployed configurations (bottom) – main glovebox is for particulate containment while working on manufacturing and small parts repairs
Dual RAF frames

Stowage volume for softgoods or secured bulk items

Stowed work surface functions as a minor glove box access to particulate containment volume

Cable and hose carrier

Shuttle middeck lockers mounted to frames – can be mounted for front or back access

Additive manufacturing (3D printer) unit in stowed configuration. Alternatively, the unit may be installed between the RAF frames in place of 2-3 middeck lockers

Particulate containment volume becomes open work surfaces if needed

Deployable work surface

Additive manufacturing unit printhead frame shown in deployed configuration – for long parts the printhead frame can be mounted further up the RAF frame (provided part accuracy can be maintained)

Additive manufacturing unit part build table shown in deployed configuration – feedstock filament spools mounted underneath

Figure 17: GMWS minor glovebox work surface and additive printer in stowed (top) and deployed (bottom) configurations
The RAF version of the GMWS consisted of Shuttle middeck lockers mounted between two RAF frames. The workstation featured a particulate containment glovebox (Figure 16, top stowed, bottom deployed) and various work surfaces and fold-out maintenance equipment such as an additive manufacturing (3D printer) unit (Figure 17, top stowed, bottom deployed). Using the modular kit-of-parts approach, the workstation can be disassembled, reconfigured, or added onto depending on the need at hand.

For example, the deployable additive manufacturing unit consists of actuators, controllers, and feedstock spools built into the same kit-of-parts. While stowed the unit folds up against the surface of the RAF frame (Figure 18, top left), opening up to create a print volume on demand (Figure 18, top right). The part table is actuated up or down (Figure 18, bottom left) during the print process (Figure 18, bottom right). In cases where long parts are needed, the unit can be dismantled and remounted to allow for a larger print volume.

Figure 18: Additive manufacturing unit (3D printer) stowed (upper left), deployed (upper right), adjusting height (lower left), and printing (lower right)
V. RAF Test Unit

An RAF test unit was constructed using the help of California Polytechnic University of Pomona (Calpoly Pomona) architecture students Brice Colton, Brianna Wiley, Garrett Sanne, and Martin Saet (under professor Michael Fox in the department of architecture). The unit was constructed under NASA’s eXploration Habitat (X-Hab) Academic Innovation Challenge managed by the National Space Grant Foundation. The full-sized test unit consisted of a test unit enclosing RAF frames (Figure 19, left) for the purpose of demonstrating sideways translation, assembly, disassembly, and repurposing of parts in various test environments.

![Figure 19: Test unit enclosing RAF frames fitted with Shuttle middeck lockers (left), with actual test article readied for neutral buoyancy tests at University of Maryland’s neutral buoyancy facility (right, photo by David Akin)](image)

Proposed tests will include neutral buoyancy (Figure 19, right) stowage and outfitting in University of Maryland’s neutral buoyancy facility (also performed within an X-Hab Challenge project under professor David Akin), and eventual zero-gravity flights.

The test article is constructed of Commercial Off-The-Shelf (COTS) industrial kit-of-parts structural units, which though oversized for space use, are assumed to be considerably lighter than equivalent ISPR rack systems – each RAF frame weighs about 31kg in a skeletal approach without heavy enclosures (Figure 20). So far the test units have gone through several iterations optimizing the roller translational functionality constrained within the COTS system and university teams are able to participate in NASA’s overall mission in the critical path through the X-Hab project (Howe 2012).

As of this writing, the prototype test unit has provided a means of exploring kit-of-parts assembly for structural frames, and reduction of friction in translational devices (wheels, sliders, etc). More work will be needed to gradually get the RAF prototype up to a dependable state.
VI. Future Considerations

Additional research included ideas for launch stowage configurations. For example, should all the parts, equipment, and logistics be shrink-wrapped and suspended with a low center of gravity for launch and then assembled during the long transit period by the crew?

As of this writing, RAF roller systems, handles, and powered vs manual translation have not fully been resolved. For example, it is not clear whether the proposed placement of handles and restraints will be sufficient for a crewmember to provide the right amount of force to move the frame – other potential solutions could include rotating handles in a gearbox system for precision positioning. It is assumed that more data will be available when the neutral buoyancy tests are completed, and perhaps eventual zero-g parabola tests. Another aspect that needs to be studied further includes disruption of air flow, shifting center of mass, and crush hazards for crewmembers.
Reconfigurable 3D printing or additive manufacturing units may need to be enclosed to capture stray material or outgassing. An accordion-type concept was briefly studied, but more work needs to be done to fit additive manufacturing equipment to an RAF frame.

Durability of RAF systems has not yet been addressed. This issue will be addressed in future research.

The kit-of-parts system making up the RAF frames could be printed using additive manufacturing (Figure 21) and later shredded in a heat melt compactor for recycling of filament feedstock. Extra heavy structure can be used during the launch phase when all outfitting must withstand launch loads, but once the habitat reaches orbit heavy parts can be scavenged one by one and replaced with lighter printed parts. The material saved during the gradual replacement process can then be used to print mission-specific scientific equipment or workstations.

Figure 21: Additive manufacturing tests of kit-of-parts systems performed at Marshall Spaceflight Center that could be used for reconfigurable internal outfitting

Figure 22: Deep Space Habitat cross-sections showing RAF advanced habitat outfitting (by Martin Saet)
Calpoly Pomona architecture student Martin Saet used the RAF concept to visualize a habitat module fitted with comfortable, luxurious outfitting. Tightly packed habitat modules gradually open up and become more volumous as supplies are consumed during long-duration missions. The various positions of the RAF frames create a dynamic spatial volume that changes day by day, leading to a healthier crew (Figure 22).

Figure 23: Advanced habitat outfitting using RAF concepts (by Martin Saet)

In Martin’s future visualization, virtual window technology is mapped to the inside hull beyond all the equipment and outfitting using flexible tiled display systems. Combined with the constantly changing volumes generated by shifting RAF frames, the virtual window background psychologically extends the cramped volume of the habitat beyond the actual physical hull boundary.

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