Random Access Frame (RAF) System Neutral Buoyancy Evaluations

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The Random Access Frame (RAF) concept is a system for organizing internal layouts of space habitats, vehicles, and outposts. The RAF system is designed as a more efficient improvement over the current International Standard Payload Rack (ISPR) used on the International Space Station (ISS), which was originally designed to allow for swapping and resupply by the Space Shuttle. The RAF system is intended to be applied in variable gravity or microgravity environments. This paper discusses evaluations and results of testing the RAF system in a neutral buoyancy facility simulating low levels of gravity that might be encountered in a deep space environment.

Nomenclature

CTB	=	Cargo Transfer Bag
EAM	=	NASA Exploration Augmentation Module
ECLSS	=	Environmental Control and Life Support System
EMC	=	Evolvable Mars Campaign
HAT	=	NASA Human Spaceflight Architecture Team
ISPR	=	International Standard Payload Rack
ISS	=	International Space Station
L2L	=	Logistics to Living
LEO	=	Low Earth Orbit
RAF	=	Random Access Frame

I. Introduction

As part of the research conducted for deep space habitation, including lunar surface, Cis-lunar, Mars transit, moons of Mars, Mars surface, and beyond, it has been expedient to develop an internal outfitting scheme that could replace the current International Space Station (ISS) rack & standoff concept. The rack system was designed for easy swap out of large, refrigerator-sized hardware units when the now obsolete Shuttle-delivered replacements arrived on a somewhat regular schedule. Moving beyond Low Earth Orbit (LEO), it will become more and more difficult to resupply medium and long-duration missions that are further and further away from Earth. One of the first things to consider for more autonomous missions is the re-use of whatever equipment or material on hand, that has already been processed, manufactured, and paid for, lifted out of the gravity well. An effective multi-use strategy include Logistics-2-Living concepts (L2L) that design a dual use into every onboard item, such as cargo

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bags converting into partitions or furniture, and re-arrangeable kit-of-parts elements that can be configured for the job at hand (Howe & Howard 2010; Shull, et al 2012).

NASA Deep Space Habitat layouts used the heritage International Standard Payload Rack (ISPR) system to create new workstations (Griffin, et al 2013; Howe 2014) that maximize work surface area and dual-use volume from a rack-sized unit. Taking the L2L concepts and deployable ISPR workstations a step further, the Random Access Frame (RAF) concept was developed, which allows for denser packing of modules, better access to stowed items, and mutli-use of volumes.

II. Random Access Frame (RAF) Concept

The RAF system (Howe & Polit-Casillas 2014) is similar to a movable library shelving system that provides for only one access corridor at a time. The single corridor uses up less volume and allows for tighter packing of habitation and logistics elements (Figure 1). RAF technology can be used for random access shelving, deployable tertiary structures, and to optimize kit-of-parts assembly.

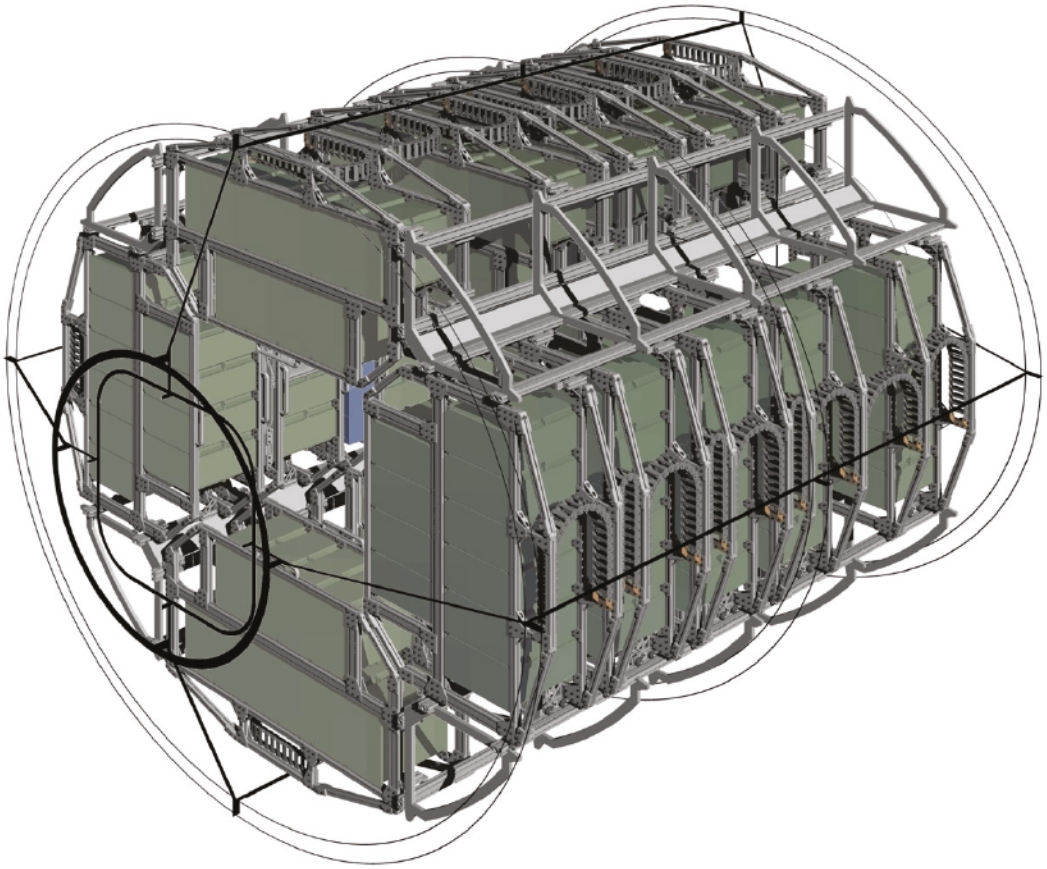

Figure 1: ISS-type module wireframe with RAF frames and equipment packed more densely than ISPR system is capable of achieving

A. Random Access Shelving / Deployable Tertiary Structures

RAF frames can be moved laterally, opening up access corridors on demand (Figure 2, Figure 3). This allows for stowage and equipment to be solid-packed into the volume, but also provides for access to every piece of equipment or stowage item without having to restack or reorganize the placement. Once a corridor is opened up between any two frames, the items stowed on either frame facing the corridor is easily accessible for inspection or use.

While useful spaces in Earth buildings are characterized by floor area, astronaut crew members have stressed that work surface area is most important in zero-gravity conditions. This means that rather than characterize a zero-g volume as lacking orientation, the clever use of floors, walls, ceilings, etc as work surfaces define the usefulness of a

space. In the RAF system, fold-out tertiary structure that stows into the frames provide opportunities for dedicated work surfaces that can be exposed on demand. Deployable workstations (Figure 3) multiply the available surfaces.

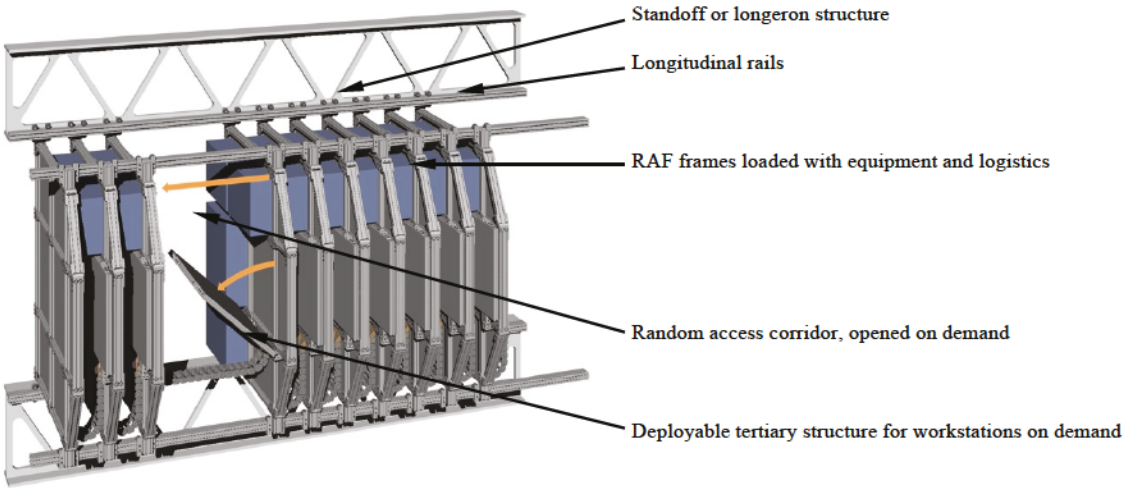

Figure 2: Random access corridors and deployable tertiary structure

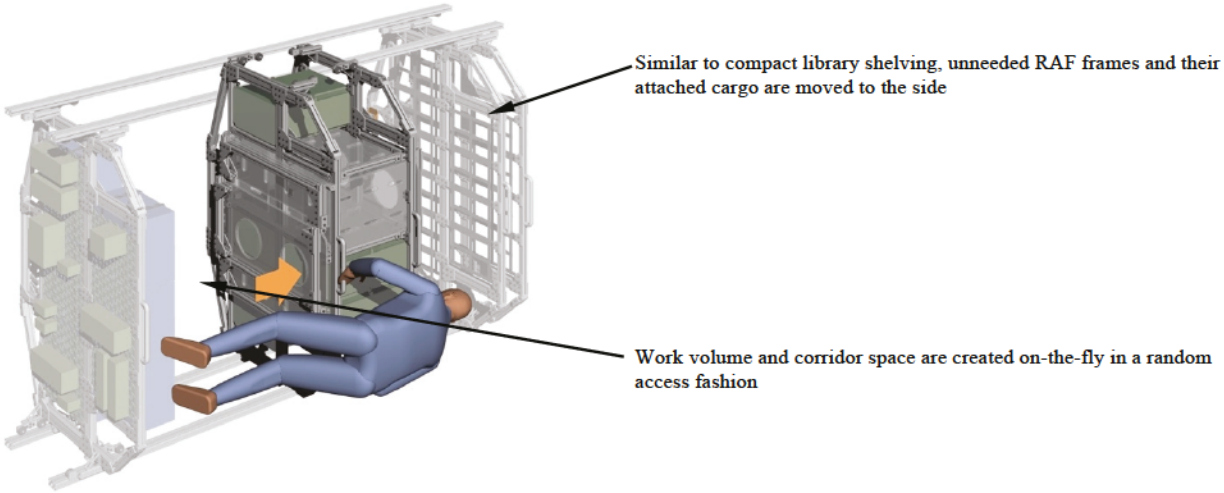

Figure 3: Random Access Frame operation

B. Kit-of-parts Assembly

An additional characteristic of the RAF concept is that all frame and infill materials are designed as a kit-of-parts for assembly, dis-assembly, reconfiguration, and reuse. Many modular options are available (Figure 4) that can be reconfigured for different functions later on. In particular, frame and infill components could be melted down after their primary use has been fulfilled, the material going toward the production of additive manufacturing feedstock. With printed parts that can be recycled back into feedstock, numerous mass-saving strategies can be put into play. For example, on long-duration missions heavy frame members can be installed that can withstand launch loads, for the purpose of stowage and tightly packed logistics, with only a bare minimum of workstations at the beginning. Once the launch has ended, the heavy members can be replaced one by one with lighter counterparts that are more appropriate in microgravity conditions, and the melted down heavy parts provide feedstock for the manufacture of tools and equipment that will be needed at the destination. Since a long-duration transit misstion could last six months, there will be plenty of time to swap out all the heavy members and print out parts to assemble complete science workstations, gloveboxes, instrument casings, and even small spacecraft and rovers.

A recyclable kit-of-parts outfitting system paves the way for more robust in-space manufacturing, where feedstock is extracted from the environment in regolith, atmospheric gases, and even enzymes and bioengineered organisms.

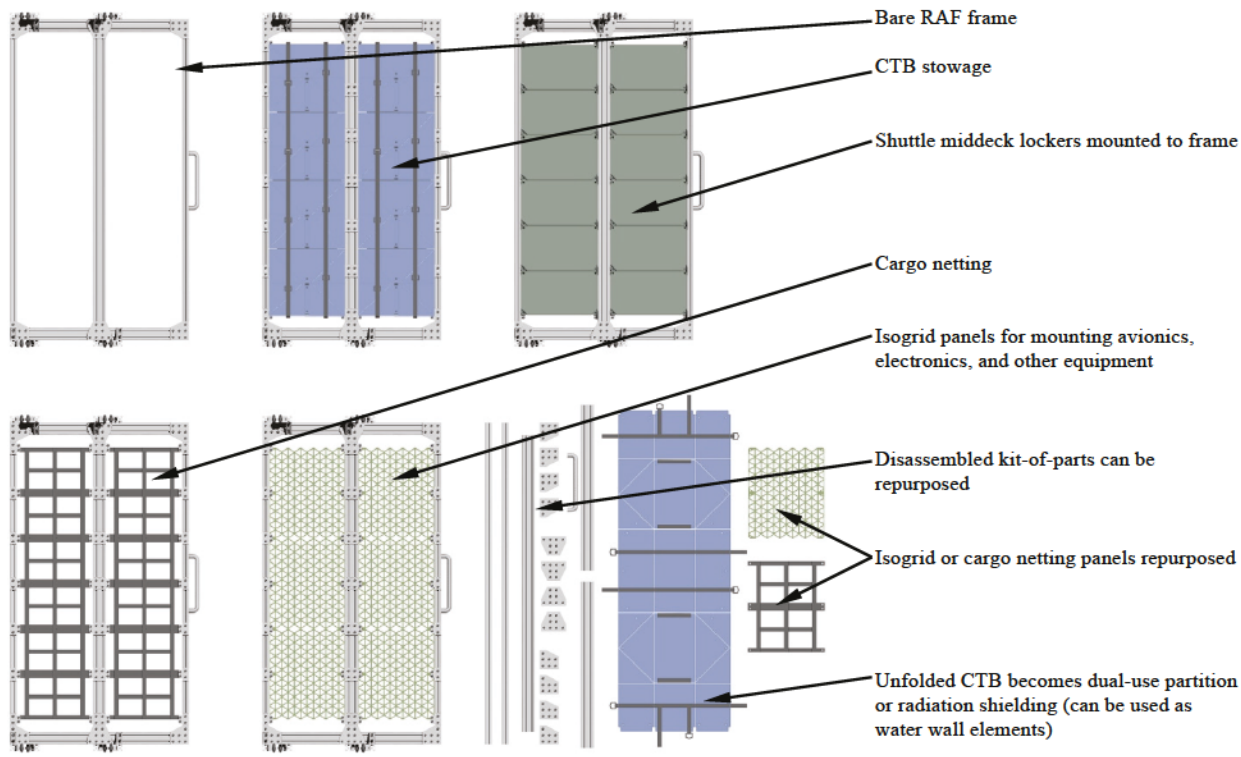

Figure 4: RAF kit-of-parts options

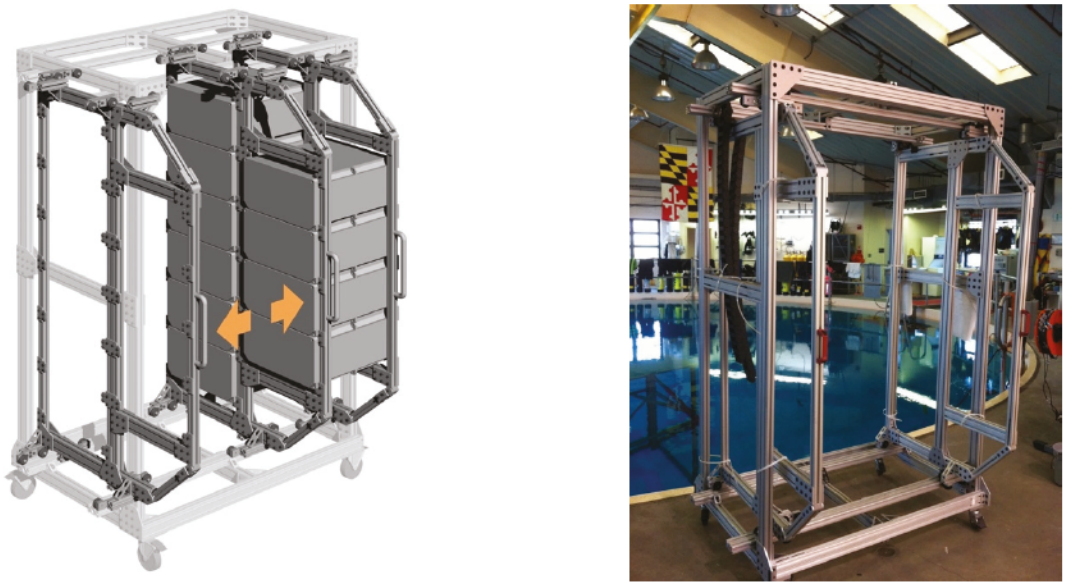

Figure 5: Test unit enclosing RAF frames fitted with Shuttle middeck lockers (left), with actual test article readied for neutral buoyancy tests at University of Maryland's neutral buoyancy facility (right, photo by David Akin)

III. Neutral Buoyancy Evaluations

The Random Access Frame (RAF) system was tested in habitat prototypes and as stand-alone test articles. A test unit was initially designed and built by CalPoly Pomona students (Brice Colton, Brianna Wiley, Garrett Sanne, and Martin Saet), that could be fitted with heritage Shuttle middeck lockers, Cargo Transfer Bags (CTBs), and equipment racks (Figure 5). The test unit was delivered to University of Maryland in order to undergo neutral buoyancy testing.

A. eXploration Habitat (X-Hab) Academic Innovation Challenge

In late 2013, the University of Maryland received a "X-Hab 2014" grant from the National Space Grant Foundation for the neutral buoyancy examination of habitat design, focusing on using body segment parameter ballasting in underwater simulation to investigate details of habitability design in microgravity, lunar, and Mars gravity conditions. As an additional detailed test objective under X-Hab 2014, the Jet Propulsion Laboratory (JPL) oversaw the design and development of the CalPoly Pomona-built prototype RAF test stand for habitat storage, which was delivered to the University of Maryland Space Systems Laboratory (SSL). As shown in Figure 5, the frame was outfitted with two flat panels mounted via wheeled tracks, which could be manually moved back and forth at will. The focus of this testing was the evaluation of RAF operations in neutral buoyancy simulations of microgravity, focusing on operation of the tracked elements, retrieval and stowage of cargo transfer bags (CTBs), and reconfiguration of internal RAF volume into crew quarters via the use of unfolded CTB fabric panels for privacy screening.

B. RAF Neutral Buoyancy Test Fixture Design

Early systems testing of the RAF structure as delivered identified some issues with the implementation of the track system. While the concept of four-point rolling suspension of the individual frames was straightforward, it proved to be impossible to effectively move the panel from one point to another using only a single (external) grasp point, which would be needed in an underwater or zero-g environment. A number of "trial and error" approaches to revisions of the roller configuration were tried, to no effect. Rather than continue experimentation, the University of Maryland team went back to first principles to analyze the fundamental mechanics of the situation to come up with viable configurations for use.

1. Frame Mechanism Analysis

A key part to the use of the RAF is smooth and uninhibited motion while reconfiguring the frames. In an ideal design (Figure 6), it would also require minimal force to intentionally reconfigure the frame layout. In order to understand what forces (Figure 7) need to be reacted out of the system by the bearings, the following analysis was performed.

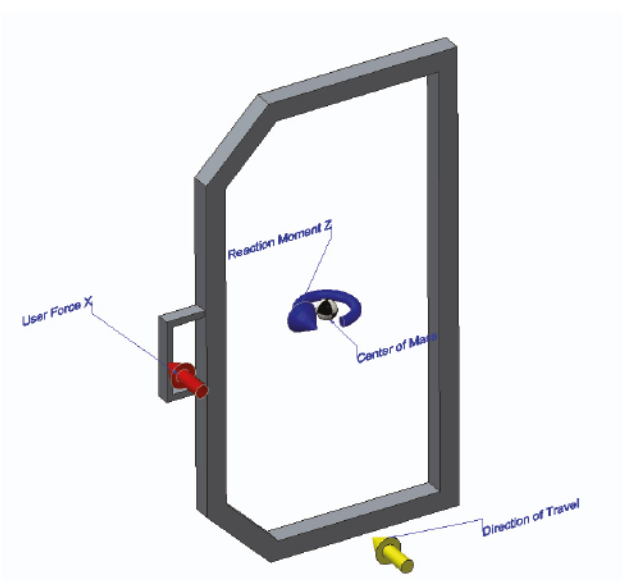

Figure 6: Ideal forces during reconfiguration

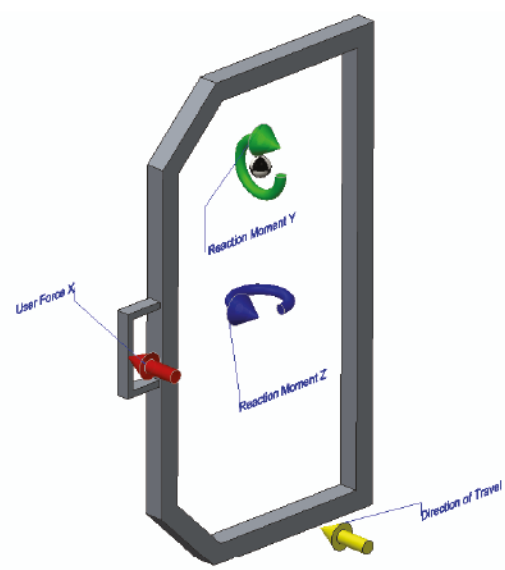

Figure 7: Primary forces on the pallet

During ideal motion the user will pull the frame in the intended direction by the handle; applying a force coincident with the center of mass except for a single offset. This will generate a single moment about the center of mass and accelerate the frame along the tracks.

However, the center of mass will not be co-planar with the user's force due to the equipment on the frame. This offset will cause an additional moment about the Y axis. These two moments are the largest forces to be reacted by the frame's bearing mechanism. Of course there will still be forces in the Y and Z axes as well as a moment about the X axis, so these directions will need to be constrained.

During testing, the initial prototype frame would quickly bind in place. The first prototype used a series of rollers located at each corner of the frame (Figure 8), which was found to cause an issue. These provided linear reaction forces along the Y and Z axis, as well as a reaction moment about the X axis, but provided little torsional support about the Z or Y axis.

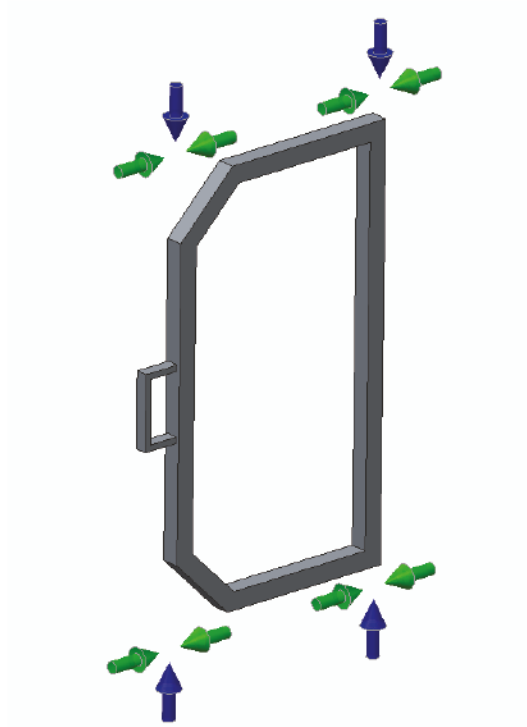

Figure 8: Initial location of the linear bearings.

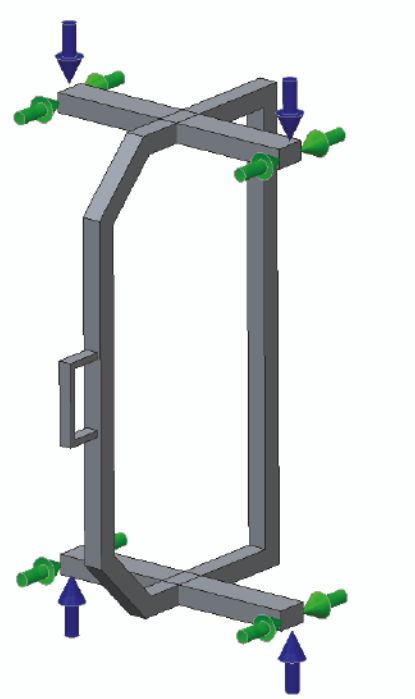

Figure 9: Reconfigured location of the linear bearings

The design was altered to provide the necessary reaction forces by rotating the plane on which the linear bearings sat on. A cross bar was added on the top and bottom of the frame and the bearings were relocated accordingly (Figure 9). This design performed better, however it would still jam under large forces. It was determined that the flex of the frame and the slop in the linear bearings would allow all four bearings to flex and bind.

Pre-loading all of the linear bearings was not practical because of the size of the RAF. Since this test setup was designed for use on earth, the binding problem can be modeled as a classic "slip-tip" problem and calculated as such.

2. *Slip-Tip calculations*

The moments at the corner results in the equation (1). The $F_{gravity}$ term is due to the mass and $F_{applied}$ is due to the force required to push the divider.

$$F_{gravity} * a - F_{applied} * h > 0 \qquad (1)$$

It is assumed the restraining forces on top are zero. This is a conservative estimation, as this would only occur in the worst case. This also implies that the friction forces on the top are also equal to zero (Figure 10).

$$F_{restrain1} = F_{restrain2} = 0 \qquad (2)$$

$$F_{friction1} = F_{friction2} = 0 \qquad (3)$$

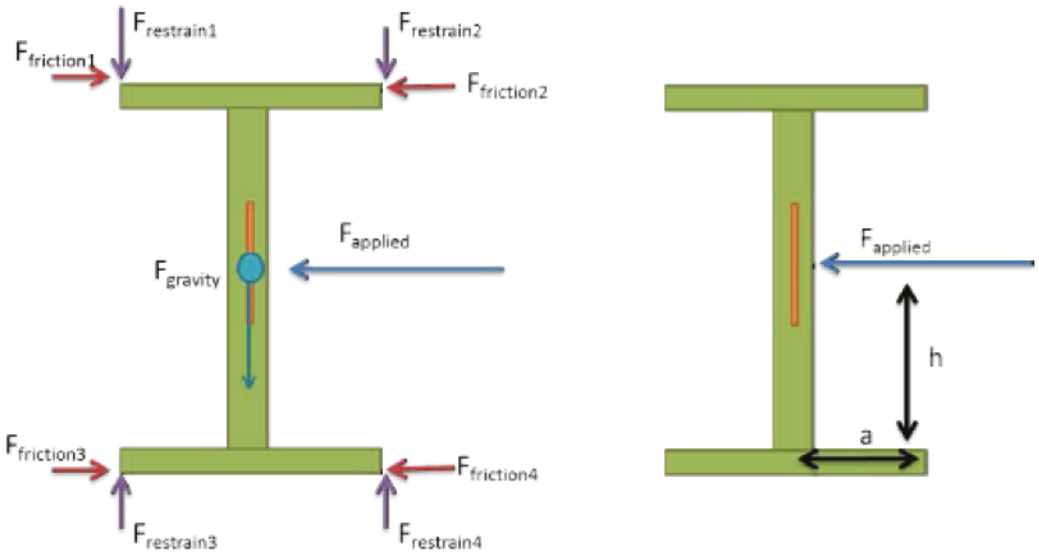

Figure 10 Free-body diagram for forces on RAF pallet

The force applied must be at least that of the friction force in order for the divider to move.

$$F_{applied} = F_{friction3} \qquad (4)$$
$$F_{friction3} = F_{gravity} * \mu \qquad (5)$$
$$F_{applied} = F_{gravity} * \mu \qquad (6)$$

Substituting (6) into (1) results in a relationship between slip and tip based on the geometric properties.

$$F_{gravity} * a - F_{gravity} * \mu * h > 0 \qquad (7)$$
$$a - \mu * h > 0 \qquad (8)$$
$$a > \mu * h \qquad (9)$$

A friction coefficient of 0.2 and a height of 3 feet were used. This results in a being a minimum of 0.6 feet. A factor of safety of two was applied and each slider bar, twice the calculated a, was made to a total length of 2.4 feet. This distance also ensured that if CTBs were attached to the frame and the divider they wouldn't be crushed into each other.

3. *Slip-tip Results*

This solution proved functional for basic analysis, however may not be suitable for use on orbit. The crossbar will complicate the packaging of the pallets inside of the RAF, making the minimum distance between pallets very large, or requiring multiple bearing beams to run the length of the RAF. Both of these solutions can be heavy and may still bind. Instead, we suggest a different approach to improve packaging and reduce weight.

The basic moments about the Y and Z axis can be reacted out through of a rack and pinion system along all four corners of the pallet (Figure 11). Each pair of pinion gears, connected by a shaft running the length of each side, will couple the motion of each corner. This coupling will allow the primary moments to be reacted out of the pallet without the need for extra leverage from extended surfaces. Coupled rack and pinion shafts provide the opportunity to add several beneficial features to the design.

By adding brakes to the shaft, the user can now lock each frame in place inside the tracks. This feature could be triggered by a mechanical release on the handle or even electronically. With the known geometry of the pinion gear located along the RAF track, the clutch could be designed to move the frames in known absolute increments. This system also makes automation a possibility. Motorizing a shaft can allow a user to command frames into place and even move entire stacks of frames along the track at once, further reducing reconfiguration time.

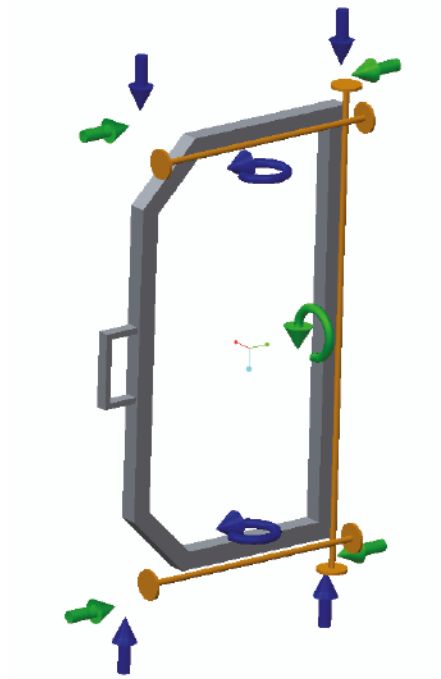

Figure 11 Suggested rack and pinion design for RAF frame

C. Random Access Frame (RAF) Neutral Buoyancy Evaluations

The purpose of the neutral buoyancy testing was to determine how the RAF would be operated under microgravity conditions. The RAF was modified with four low-friction sliding interfaces on structures along the truss as illustrated in Figure 9 above, and was tested in the Neutral Buoyancy Research Facility at the University of Maryland, using three cargo transfer bags (CTBs) built to NASA design standards at UMd. The RAF test unit was positioned at the bottom of the 25 ft. deep water tank, and held in place by its in-water weight. The CTBs were fitted with rudimentary internal shell structures to help maintain their shape, and were neutrally buoyant. The CTBs were placed on the structure, two on the divider and one on the frame itself. The test subject was ballasted so they were also neutrally buoyant.

The first evaluation (Figure 12) was to determine if the test subject could easily and safely slide the divider. They were able to move the divider back and forth with one hand on the divider handle, to control the divider, and another on the RAF frame, to push/pull against. During this motion, the test subject's unrestrained feet would go into the structure. While the length of the spreader bar with the slider pads prevented the divider from lying flush with either side of the frame, it also prevented the CTBs and the test subject's feet from possibly being pinned. As the RAF design progresses, footholds preventing this involuntary motion may become necessary. The test subject reported that they were able to hook their toes on the bottom portion of the frame, preventing this unwanted body reaction motion.

During the initial slider test, the test subject had to push against the RAF frame while moving the divider. While the current length of the RAF allows a test subject to reach the divider and the frame side at the same time, this may not always be the case. Longer RAFs will need to have additional hand and/or foot holds to push/pull against. The location and quantity of these holds will require further testing.

The second test (Figure 13) had the test subject remove a CTB from the frame and then replace it. The test subject went into the internal volume of the RAF structure in order to detach the CTB, which was hooked onto the RAF divider with a cord hooked into the handles on either side of the CTB. The current testing configuration allowed enough space between the divider and the frame for the test subject to easily fit; the spacing available was adequate to allow the test subject to access the inside of the CTB via a zipper pocket without needing to remove it from the frame. Alternative methods for attaching the CTBs to the frame which will prevent the need to enter the frame should be studied. While the original concept used Velcro-type material for restraining the CTBs on the RAF frame, this proved to be wholly inadequate in the neutral buoyancy testing.

Figure 12: First test in neutral buoyancy tank

Figure 13: Second test in neutral buoyancy tank

Further testing will be done to investigate the use of the RAF for separate activities such as for the creation of crew quarters. CTBs can unfold to a single large rectangle. These rectangles can be placed onto the RAF to form a privacy screen or room walls. This will allow larger rooms to be quickly converted to smaller rooms, such as crew quarters, and then easily reconfigured back to a large single room. Additional testing can be done to determine how unfolded CTBs can be repositioned on the RAF to create a small volume such as currently used on ISS for crew quarters.

IV. Mission Applications

RAF system and internal layout concepts can be custom-designed for long-duration missions. CalPoly Pomona student Martin Saet began with the underlying lateral sliding system to create a series of box cabinets to serve as infill (Figure 14). A box design will avoid some of the binding issues experienced by the University of Maryland tests, which can also apply the proposed rack and pinion improvements. The inside surface of the pressure shell is lined with flexible digital displays to seamlessly project a variety of background environments to relieve crew stress on long-duration missions. RAF box frames move in front of the projections, giving the impression of hidden features in a virtual environment that will take time to explore.

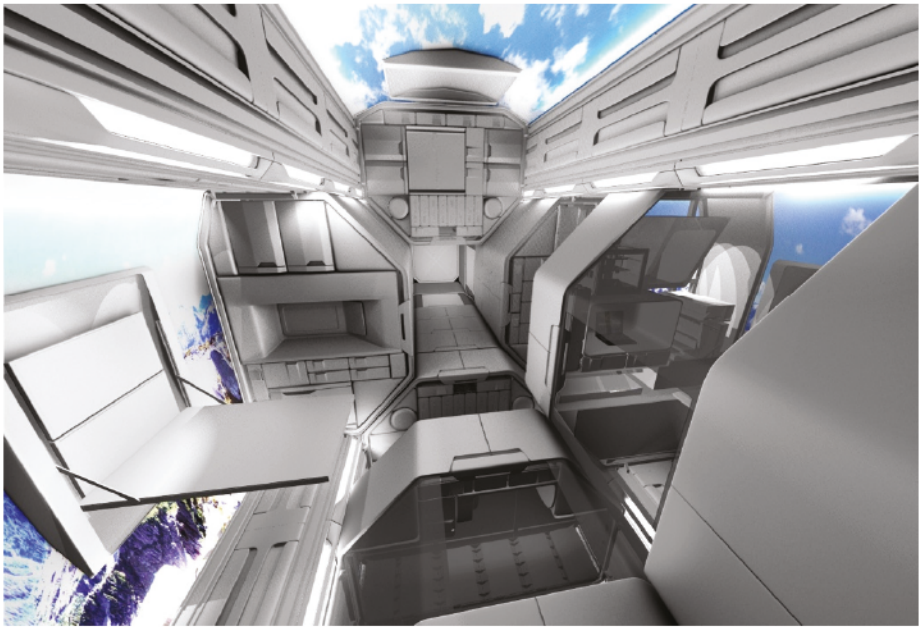

Figure 14: Advanced habitat outfitting using RAF concepts (by Martin Saet, California Polytechnical University Pomona)

V. Conclusion / Discussion

The original RAF test unit as built by the CalPoly Pomona students functioned as designed in a full single gravity environment but failed when additional simulated microgravity constraints were placed upon it. The University of Maryland team was able to adapat and redesign the original unit until it functioned as intended using single point grasp and repositioning. The neutral buoyancy tests resulted in a proposed design solution that could lend itself toward slim stacking frames, and also could be applied to automated or remote operation of frame repositioning. Though some of the efforts initially resulted in failure, some difficulties were overcome through testing in the neutral buoyancy environment, and other challenges identified. The RAF system has been proven to have potential as an internal outfitting solution on deep space habitats.

Future research may include construction of the proposed rack and pinion system designed by the University of Maryland team, zero gravity parabola flights, automation of frame repositioning, and potential installation on the ISS or planned Exploration Augmentation Module (EAM).

Acknowledgments

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