Abstract—The future of large spacecraft assembly, maintenance and servicing can benefit from the techniques and technologies of the past, present, and future. Not only can existing concepts and hardware be used to reduce implementation costs, but they can also point to deficiencies, which require further attention and development. This paper reviews relevant design trades, tasks and experience associated with actual Shuttle, Mir, and ISS missions as well as some credible developmental projects that were not actually flown. It includes an illustrated summary of some of the latest designs in use for fasteners, mechanical joints, electrical connectors, fluid connectors and related components. Interfaces common to both manual EVA and robotic handling are noted. References are supplied to aid the reader in pursuing additional details. These assembly, maintenance and servicing technologies have application not only to LEO, but also for large spacecraft beyond LEO.

INTRODUCTION

It can be argued from an engineering perspective that ideal spacecraft should be small, low cost and readily disposable or replaceable to address fault tolerance. Unfortunately, spacecraft designed to these capabilities tend to perform very specialized and limited functions. When more robust objectives are defined that exceed a single launch vehicle, in-space assembly and maintenance become viable alternatives. Long life and total value may also influence the choice of methods to manage obsolescence and failures.

Assuming that attempt opportunities are robust and readily available, basic design trades tend to assess risk and productivity relative to current and future success and are ultimately measured in terms of cost and time.

One of the first choices in the implementation of large spacecraft structures is the selection of the scope and method of component integration prior to launch. The range of options varies from permanently fixing all but a few interfacing components to totally accessible piece part assembly and maintenance. Neither option is ideal or compares equivalent metrics. Examples of high initial integration allowing immediate use are as diverse as typical struts with added detailed outfitting. As the number of handled parts increases, risk and unproductive time also increase. The evolution of the mixed levels of serviceability of the Hubble Space Telescope (HST) illustrates yet another important example.

Until such time as space based human and robotic labor is widely available, pre-integration and deployment automation should be maximized. "Manual" labor is best employed when otherwise impossible concepts are to be attempted or major cost or mass savings result from assembly and maintainability.

The question of humans and/or robotics as the implementing agents for a given set of tasks is best resolved after conceptual attempts at independent automation and integration. When concepts for the end product conclude that external aid is required, interfaces suitable for both agents should be provided. The ultimate selection is likely to occur in the distant future and may include a mixture of implementation techniques. Neither option is assured at this time. Until transport and safety are taken for granted, the availability of humans is only likely to occur when dictated by broad public benefits requiring in-situ intelligence, mobility, dexterity and adaptability. Projected investments in advanced robotics will also continue to limit alternatives. If humans are present, the natural tendency to exchange human time and risk for the cost and mass of automation is sure to continue. With humans on site, a blending of both capabilities is the only credible and proven option. For unforgiving environments, simplicity and flexibility usually provide the margin of ultimate success.

In parallel with high-level concepts, the initial design of large spacecraft structures often starts with relatively small components. When used in large numbers, these small elements rapidly add up in terms of cost, mass, volume and handling time. Existing experience has largely focused on making manual crew operations feasible and basic mechanisms functional. There has been little opportunity to tackle topics like robotic compatibility, unit mass or unit cost. In all cases, human and robotic operations must address factors such as visibility, handling compatibility,
physical access volume, coarse/fine alignment, initial capture, final mating/locking force reaction and post installation environmental protection. Of equal importance are considerations of maintainability and response to failures. In general, implementing robotic compatibility also tends to enable human interaction. While it is tempting to rely on these same items for future spacecraft, it should be remembered that few of the designs are penalty free. What follows is a sampling and critique of some of the currently utilized hardware and their usage challenges.

MAGNETIC RESTRAINTS

Based on the principle of a ball and socket joint, Russia utilizes permanent magnets for rapid and simple mechanical connections. These connections have been used on Mir and ISS to restrain portable cameras and environmental exposure experiments, but are readily suited for other applications. After mating, the ball fitting and shaft can be rotated 360° and pivoted ±45° for position refinement. The magnetic force holding the ball can be released by leverage of the shaft against the base collar. Design options include fixation purely based on magnetic attraction or magnetics backed up by circumferential latches controlled by a rotating collar. Ball size is typically 35mm diameter, but larger articles of approximately 100mm diameter have also been demonstrated. This interface is already proven for crew manual operations and is a potentially good candidate for compatibility with robotic handling.

ELECTRICAL CONNECTORS/CAPS

When data or power cannot be transferred by radio frequency or by microwave beam and electrical cabling and connectors are necessary, there are many existing examples to consider. Inserts provide the capability to handle pin/socket connections, co-axial lines and fiber optics. Both U.S. and Russian connectors are depicted below. Large high torque fittings and those with limited access may require supplemental tools. Though not shown, simpler and less expensive wing tabbed connectors are also frequently used for U.S. EVA. Typical accessories include dust and impact protection caps for each connector half as well as fabric thermal covers. Some designs are adapted from commercial products while the majority is custom built for compatibility with manual crew operations. Fabrication materials tend to be either aluminum or stainless steel. When used in large numbers, the mass of these metallic designs can be burdensome. Lighter materials and wider use of mass production components should be considered. None of these designs are specifically designed for robotic handling and the fine alignment required for initial mating makes such compatibility quite challenging. Self-aligning blind mate connections are dually applicable when integrated with mechanically adequate mate/demate provisions.

CABLE RESTRAINTS
Loose cables must be prevented from interfering with nearby mechanisms or entangling crew and robotic operations. When routing locations can be pre-planned, fixed position releasable restraints are used. For standalone or unanticipated lines, Velcro covered by beta cloth for atomic oxygen and ultraviolet radiation protection used to be the restraint of choice. The current preference is for a simple and reusable copper wire tie from the Russian space program. Neither concept is known to be robotically compatible however.

![Figure 5 - Cable Clamps](image)

![Figure 6 - Cable Wire ties](image)

**ROBOTIC MANIPULATOR INTERFACES**

Like humans, small fine dexterous manipulators and large robotic arms usually require special aids to enable equipment handling. Besides mechanical attachment fixtures for force and torque reaction, visual alignment targets are often necessary. Fasteners placed the center of these fittings allow an end effector to drive a threaded shaft and mate or release the handled equipment. The microconical, micro-square and H-fittings are used on ISS orbital replacement units and are the results of past attempts at commonality. The larger flight releasable grapple fixture (FRGF) is still widely used and has evolved into options. Latches which provide ascent/entry and on-orbit cargo restraint are available in many forms. Some like the passive latch are not intended for release except for contingency jettison. Nominally actuated latches have active motors for automated operations (ISS capture latch assembly and Shuttle payload retention latch assembly - PRLA). Many include manual backup overrides for fault tolerance. Not shown are designs from the flight support structures of HST, SPARTAN, the ISS high-pressure gas tanks or the appendages of serviceable spacecraft like GRO and UARS. While the cost and complexity of latch automation is significant, it does reduce the risk and time of human and robotic involvement. Such specialized automation is a viable alternative when a component already features significant structural mass/strength for its basic function.

![Figure 8 - H-Fitting](image)

![Figure 9 - FRGF](image)

**AUTOMATED AND MANUAL LATCHES**

Latches which provide ascent/entry and on-orbit cargo restraint are available in many forms. Some like the passive latch are not intended for release except for contingency jettison. Nominally actuated latches have active motors for automated operations (ISS capture latch assembly and Shuttle payload retention latch assembly - PRLA). Many include manual backup overrides for fault tolerance. Not shown are designs from the flight support structures of HST, SPARTAN, the ISS high-pressure gas tanks or the appendages of serviceable spacecraft like GRO and UARS. While the cost and complexity of latch automation is significant, it does reduce the risk and time of human and robotic involvement. Such specialized automation is a viable alternative when a component already features significant structural mass/strength for its basic function.

![Figure 10 - ISS Capture Latch Assembly](image)

**MECHANICAL INTERFACES**

To rigidly secure infrequently released articles, manual fasteners are often used. Bolted fasteners usually shift the involvement of automation to crew or robotically handled power tools. For most U.S. and Russian bolts, extended height hex headed interfaces are utilized. The flat-to-flat dimensions across the hex are commonly either 7/16 inch or 12mm (respectively). Self-locking, captive threads and torques less than 25 ft-lbs are normal for manual compatibility and productivity. By combining multiple bolts, the super bolt concept allows high loading upon a single shaft while the individual bolts within normal
engagement torques. The expandable diameter fastener (EDF) can be applied to rigidize and lock precisely aligned holes. Pip pins perform the same function for looser and more temporary connections. As expected, both EDF’s and pip pins are only appropriate for shear loading unlike the tensile capabilities of threaded bolts. Specialty restraints like the Russian ball and socket fitting with threaded collar are applicable to base structures under high loads. In this design, a spring detent captures the ball while the floating collar aids alignment and final mating. While all these items are more or less optimized for human actuation, the implementation of full robotic compatibility is still outstanding.

Figure 12 – Extended Height Hex Bolts

Figure 13 – Superbolt

Figure 14 – EDF

Figure 15 – Pip Pin

Figure 16 – Russian Mech

Figure 17 – ISS Ammonia Connection

Figure 18 – ISS Ammonia and O2/N2 Connectors and Caps

**FLUID CONNECTORS**

Safely managing gaseous and fluid line connections is not easy. High-pressure lines should be vented before mating or demating to prevent leaks and excessively stiff handling. Ventable caps are needed to keep unmated fittings clean and leak proof. The illustrations depict the ammonia line connectors/caps of ISS and the nitrogen connectors of the manned maneuvering unit (recently upgraded for ISS and Shuttle O2/N2 lines). The cryogenic and propellant recharge fittings of UARS, GRO and SHOOT showed even more promise but were never actually used on-orbit.

**BODY RESTRAINTS**

Unless gravity is available to aid mobility and restraint, any work agent will require structural attach points to enable their tasks. Without a readily replaced propulsion supply, free flying work aids will remain limited to simple inspections or crew safety protection. The current primary means of body restraint involve handrails, foot restraints and rigidizing waist tethers. These same aids are also viable for use by surface roaming robotics. From the vehicle designer’s perspective, the associated penalties are largely mass and strength demands placed upon the basic vehicle structure. If the large footprint and mass of other restraints is to be avoided or something with a more rigid grasp than a tether loop is desired, the EVA connection mechanism (ECOM) can be used. It mates to an active latching probe and can be used for equipment transport or body positioning. Rather than cluttering up a spacecraft’s exterior with unique structures, a compromise technique whereby a large manipulator provides positioning and restraint for an end mounted human or dexterous robot is often employed. This technique can also be reversed where the human/robot remain in a fixed location and the manipulator presents the item to be worked upon. The risk is that failure of the manipulator will preclude access to an important worksite. Wide ranging and low impact alternatives like magnetics, slidewires and manual cranes are also credible. By limiting the actuation loads and repetitions of external worksites, many of these restraints can be avoided totally. By sculpting fundamental exterior
structures to meet the grasp and load needs of simple mobility, yet more burdens can be avoided. The key is to address the limitations of humans and robotics as a significant and integrated influence from the beginning. If treated as secondary to other structural considerations, the impacts will mount.

Figure 19 - ISS and Shuttle Foot Restraint Sockets

Figure 20 - ISS Foot Restraint Probe and Socket Joint

Figure 21 - Handrail

Figure 22 - ECOM

DOCKING MECHANISMS

The idea of truss members for large structures has seen mixed results. When compacted into a canister and linearly deployed, success has been repeatable for solar array wings, large antennas and tether experiments. With fixed assembly jigs, humans and robots can also create simple and long linear trusses (ACCESS, STS-61B, 1985). Techniques, which reserve humans for failure intervention or final securing of large assemblies, have been even more successful for Russia (15m Ferma-Postroite, Salyut 7, 1986; ERA, Mir, 1988; 14.5m Sojora, Mir 1989; Rapana, Mir, 1993; Ferma-3, Mir, 1996). The concept of using humans for repetitive and unrestrained truss assembly was shown feasible by STS-61B (EASE, 1985) and STS-49 (ASEM, 1992), but was never an appropriate use of this valuable resource. Until human labor is abundant, automated and robotic agents are more appropriate for the nominal handling of large and simple trusses. Humans should be focused upon the more complicated vehicle outfitting and tending to unforeseen problems faced by the robotic laborers.

As learned from the manually assembled truss of STS-49, any assembly agent will face real challenges. Because of the need for post-mating structural rigidity and precision, the initial alignment and attachment of the larger joints was complicated by the undamped instability of long struts. This imposed extra handling time and frequent aid from a spanner wrench for final torquing of the lock collar. Water tank viscosity during pre-flight testing obscured the actual flight performance and must be addressed through better joint strut compliance before future attempts.

The recent invention of inflatable rigidizable struts has considerable promise to address the joint compliance issue as well as overall stowage and automated deployment. Switching from aluminum walled strut tubes to lighter and more fragile composites may reduce system mass, but it adds considerable risk to assembly handling, complicates automation and continues to burden stowage provisions.

Figure 23 - APAS Docking Mechanism

TRUSS STRUCTURES

For docking of large structures, the Russian designed automated peripheral attachment structure (APAS) is most widely used on ISS. Earlier probe and cone units are also still used on the Russian segment. The ISS common berthing mechanism (CBM) allows a large manipulator to attach and release modules with gentler forces. Other designs are contemplated for future vehicles, but will most likely have to deal with ISS compatibility for some time to come. Docking adapters for the ISS interim control module has been contemplated that may enable other applications.
OTHER FASTENING TECHNOLOGIES

One of the more inventive means of dealing with structures through electron beam technology has been externally demonstrated by the Russian and Ukrainian space programs. The Paton Institute of Kiev is proficient at creating welded joints and coatings (Salyut 7, 1984 and 1986). In conjunction with MSFC, an updated experiment almost flew on the Shuttle in the late 1990’s. The challenges for this technology have always included safe containment of hot splatter, weld integrity verification and multi kilowatt power portability.

Both NASA and Russia have also studied space compatible chemical bonding. The early Shuttle program studied on-orbit heat shield tile installation. After the Progress resupply vessel impacted Mir’s Spektr module in 1997, RSC Energia and NASA collaborated on leak repair equipment. This concept was based upon a two-part epoxy, a mixing/dispensing device and various patches. International efforts continue to develop similar equipment for future contingency response onboard ISS. Because of time and temperature restrictive curing and the permanent nature of this technology, it tends to be more conducive to maintenance than assembly.

CONCLUSIONS

Even with the repetition and evolution of past designs, there are no easy or obvious means for large spacecraft assembly and maintenance. The factors that motivate and influence the initiation of this type of venture can include scarce resources, jobs, defense, prestige and international cooperation. There is no single equation that dictates the selection of the many implementation options. Past experience, sound judgement and iterative validation are occasionally aided by breakthrough technologies and materials. Actual engineering design and implementation is best focused upon using the right tools for the right reasons. It is essential to balance simple automation, advanced robotics and human capabilities while allowing for inevitable failures and workarounds. Cost, mass, volume, time and risk can be tackled by careful selection from the techniques and technologies of the past, present and credibly projected future. To complement more comprehensive references, this paper has attempted to present a portion of the relevant experience for consideration.

REFERENCES

[1] NASA CP-2490, Space Construction Conference Proceedings, August 1986
[2] AIAA Conference on Structural Dynamics Issues of the ISS, April 1988
[3] Assembly, Installation and Repair Works in Outer Space, NPO Energia, 1988
[4] Satellite Services Working Group Reports, 1989
[5] NASA-STD 30550 Robotic Systems Integration Standard, Vol. I, 28 May 1991
[6] EVA Results of Shuttle Mission STS-37, 22nd ICES, July 1992
[7] EVA Operational Enhancements and ASEM, 22nd ICES, July 1992
[8] JSC-20466, EVA Tools and Equipment Reference, 1993
[9] SSP-30256, ISS EVAS Interface Control Document, 1998

Richard Fullerton is currently on a rotational assignment to NASA Headquarters as a project manager for advanced EVA research and development. He has served in the NASA Johnson Space Center from 1982 supporting Shuttle, Shuttle-Mir, and International Space Station EVA and program management. He has a BS in Mechanical Engineering from Texas A & M University.

Robert C. Trevino, P.E. is an engineer in the EVA and Spacesuit Systems Branch, crew and Thermal Systems Division, NASA Johnson Space Center. He has supported Shuttle, payload, and International Space Station EVA operations and hardware development since 1980. He has a BS in Aerospace Engineering from the University of Texas and a MA in Public Management from the University of Houston. He is also a licensed Professional Engineer.