HUBBLE SPACE TELESCOPE

DAWN OF THE ERA OF SERVICEABLE SPACECRAFT

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DAWN OF THE ERA OF SERVICEABLE SPACECRAFT

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The Hubble Space Telescope (HST), scheduled for launch in late 1988, is the first spacecraft designed for extensive on-orbit servicing. The launch of this vehicle will usher in a new generation of spacecraft: spacecraft designed to include on-orbit servicing as an integral part of their operational plans. The HST's operational plan calls for servicing to be performed during planned maintenance missions scheduled at periodic intervals throughout its projected lifetime, and during any unscheduled contingency maintenance missions.

The maintenance philosophy of the Hubble Space Telescope is based on removal and replacement of orbital replaceable units (ORUs). Therefore, appendages, instruments, and pieces of equipment which might fail, become obsolete, or outlive their missions during the Telescope's projected lifetime of fifteen years were made into ORUs: by definition, easily and safely replaceable on-orbit by an extravehicular (pressure-suited) astronaut.

The ORU changeout philosophy provides for a variety of spacecraft enhancements. The most obvious of these is the replacement of failed units to allow mission continuation. Additional enhancements include the replacement of existing units with newer, upgraded equipment to improve mission performance, and the replacement of existing instruments with instruments that will perform altogether different missions.

As could be expected, many lessons have been learned in designing, building, and testing this first product of a new era of spacecraft design, and many more lessons will be learned during the actual maintenance missions. As a result, many cost saving design precedents have been established for future serviceable spacecraft. This paper will explore the lessons learned on Space Telescope as they can be applied to the design of future serviceable spacecraft.

To begin with, let me discuss ORU philosophy, or how spacecraft builders and designers decide which items of hardware should be made replaceable on-orbit, and to what level of each subsystem the components should be divided into ORUs.

A vehicle designed for periodic servicing can avoid significant cost and weight impacts by incorporating fewer redundant systems. The serviceable spacecraft should have as ORUs all those critical subsystems which cannot be guaranteed with a high degree of certainty to perform acceptably throughout the spacecraft's lifetime. In most cases, this will turn out to be every critical subsystem on the vehicle.

In those places where on-orbit replacement is not practical (such as in wiring paths), redundancy sufficient to ensure acceptable performance for the mission lifetime should be incorporated. Depending on the level of risk acceptable to the spacecraft operator, even where ORUs are utilized, redundant systems sufficient to sustain satisfactory performance between scheduled maintenance missions should be employed.

As on-orbit servicing becomes more routine and less costly (as it will from a space-based facility), maintenance missions can be scheduled on an as-needed basis, and the need for redundant ORU systems can be eliminated.

As to the level within a subsystem that the components are divided into ORUs, wherever there is a significant discrepancy between the reliability of the subsystem as a whole and one of its parts, that part should be made into a separate ORU. Similarly, this philosophy should be applied to each level of "parts"; that is, if, within any of the subsystem parts there exists a large discrepancy between the reliability of the part and one of its "sub-parts", that "sub-part" should be broken out into a separate ORU.

This ORU philosophy gradually evolved during the course of the Hubble Space Telescope's design, development, fabrication, assembly, and verification process. Whereas the HST program had to pay the high price of learning these lessons through numerous hardware modifications to make already-built units on-orbit replaceable, future spacecraft for years to come will reap the benefits.

One of the most basic considerations to take into account when designing a spacecraft for on-orbit servicing is the environment in which the servicing will take place. The most important aspects of the space environment as they relate to on-orbit spacecraft repair are zero-gravity, vacuum, and extreme temperature variations. The implications of working in zero-gravity involve the need to employ stability aids for both the crew and loose equipment, as well as mobility aids for crew movement about the vehicle. The relaxed or neutral body position in zero-gravity is also a factor as the body becomes less erect but slightly taller, with the arms floating at shoulder height and the legs somewhat bent at the knees and hips. Working in a vacuum requires the crew to wear massive, bulky pressure suits, which demand strength and stamina to perform in for any length of time. Maneuverability and flexibility of the suit is limited, dexterity of the gloves is limited, side-to-side and up-and-down fields of view are restricted, and the size of the suit constrains access in confined areas. Thermal cycling on-orbit (28.5 degree inclination low earth orbits see temperatures ranging from about -200°F to +250°F every 90 minutes) impacts the design of tools and equipment that must function and survive in the extreme hot and cold temperatures they will encounter during maintenance tasks.

Adequate workspace accessibility is a crucial element in the design of serviceable spacecraft. All servicable hardware should be designed and located to be accessible, allowing for crew anthropometric ranges and pressure-suited envelopes. Accessibility consists of several facets: access to the workspace, access within the workspace, and access to specific interfaces (such as fasteners and connectors) within the workspace. Each of these facets must be addressed in the serviceable design.

To allow access to each workspace, mobility aids (handrails) should be placed on the vehicle in such a way as to provide translation paths from the vehicle's berthing attach points to the various worksites. The distance between handrails along a translation path should never be more than three feet. Foot restraint receptacles (small, lightweight, and relatively inexpensive) should be placed wherever potential worksites are envisioned, and such that adequate access for all operations can be achieved without having to rely on an automated positioning system (such as the Shuttle's Remote Manipulator System). Upper and lower hinge door stays, integral to each equipment bay and capable of maintaining a stable work surface on the bay door, should be incorporated on all equipment bays having serviceable hardware located on their doors; bays having no serviceable hardware on their doors should have just one integral door stay. This will eliminate the need for portable door stays or tethers to be carried and installed by the crew. Door stays should be detented for optimal access to bays and doors.

Access within the workspace must be provided with respect to dimensional envelopes of the smallest and largest (NASA typically uses 5th precentile female and 95th percentile male) pressure-suited crewpersons's hand, arm and whole body as appropriate. Tasks that involve whole body access require a working envelope of approximately 48 inches in diameter. Access within the workspace for the full range of motion of servicing tools must also be provided.

Access to interfaces within the workspace is critical to servicing task performance. This includes reach and visual access to fasteners, connectors, and controls, and visual access to labels, markings, displays, and alignment features. Tool access to fasteners and drive mechanisms should be straight-in, and hand-tightened connectors should be adequately spaced to allow access by a pressure suit gloved hand. The worksite design must take into account the impact of weightlessness on body posture, and the constraints of working in the spacesuit.

The need for visual access at the worksite implies the requirement for adequate illumination. Illumination can be provided in a number of ways: sunlight/earth albedo, service facility-based lighting (such as Shuttle payload bay floodlights), spacesuit helmet-mounted lights, portable work lights, and vehicle-mounted lights. Sunlight/earth albedo is cyclical (with the exception of sun-synchronous orbits) and depends on vehicle orientation with respect to the sun/earth; service facility-based lighting may not be adequate to fully illuminate recessed worksites (such as inside bays); helmet-mounted lights provide small area spot-lighting; portable work lights can provide spot-lighting or flood-lighting but should be easily mountable on the vehicle and not require precision positioning; vehicle-mounted lights should be provided based on the worst case scenario that no other lighting may be available. These should provide wide area flood-lighting for maximum effectiveness, and be on-orbit replaceable. The minimum necessary illumination for translation paths is 3 foot-candles; for worksites, 30 foot-candles; and for safety critical areas, 50 foot-candles.

The design of mechanical fasteners should be standardized to the maximum extent possible to minimize the number of tools required to actuate them, as well as to simplify procedures. The fasteners should be captive to the vehicle (e.g., keyhole-slotted bolts, J-hooks) and offset enough from the side of the unit to be easily engaged without interference between the tool and the unit. Bolt heads should be at least 5/16 of an inch high to prevent tool sockets from inadvertently slipping off during actuation. The amount of torque required to release and tighten fasteners should also be standardized to eliminate the need for multiple torque-limiters and to simplify procedures. The Space Telescope has a number of latches which require torquing to a maximum of 35 foot-pounds for full engagement, but it is desirable to restrict the torque requirements to the limit attainable using a power tool (currently about 20 foot-pounds).

Electrical and radio frequency connectors should either be mounted in connector drive mechanisms (where connectors are numerous) or be hand-tightenable with self-locking devices to ensure engagement and prevent backing off during launch vibrations. Hand-tightened connectors must be adequately spaced to allow access by a pressure suit gloved hand. Connectors should be located such that they can be mated/demated while the unit is already/still fastened down. This eliminates the need for attempting to make the connections while simultaneously stabilizing the unit. Hand-tightenable connectors should be accompanied by connector maps, alignment marks, and identification labels, and their adjoining cables should be equipped with integral restraining devices to keep them out of the unit removal/replacement envelope and to aid in proper replacement. Cable harnesses should be flexible enough as to not restrict unit removal or replacement, nor prevent equipment bay doors from opening to their maximum angles.

Maintenance mission simulations and the Space Telescope assembly process have shown that the most difficult HST changeout operations are those associated with insertion of the large instruments (such as the Axial Scientific Instruments, the Fine Guidance Sensors, and the Wide Field/Planetary Camera). Very precise alignment is required for the insertion of these instruments through the aft shroud orifices and into their guiderails. An improved design from both the perspective of crew operations and instrument protection would incorporate a high alignment-to-installation tolerance ratio, such as would be achieved with a wedge-shaped instrument and receptacle, eliminating the need for any type of guiderails, since the receptacle itself acts as an alignment guide.

Alignment guides (such as picture frame corners) should also be used to assist the astronaut in positioning other ORUs for fastening to the vehicle. The larger the unit, the more desirable such alignment aids become.

Color-coding should be used wherever possible for ease and speed of recognition. Green signifies a safe condition; red signifies warning, danger, emergency; orange-yellow signifies caution. On the HST, all safe crew translation aids were painted yellow for brightness and thermal reflectivity reasons. Labels should be printed with high contrast between characters and background, preferably black on white, except in the case of cautions (black on orange-yellow) or warnings (white on red).

The use of automation and robotics in conjunction with the human role in servicing should be explored as smarter, faster, more efficient and versatile machines become available. Robots and teleoperated systems are very attractive for utilization in the performance of tedious, repetitive and unsafe tasks, and for performing tasks in extremely contamination-sensitive environments.

Early in the design phases of any serviceable spacecraft, analyses of task feasibility should be performed for the proposed maintenance missions. These analyses should include physical simulations of the tasks performed under mock weightless conditions (i.e. neutral buoyancy simulations), in order to provide timely functional critiques and design recommendations which will help to optimize the spacecraft's serviceability.

As mentioned briefly in the preceeding text, commonality should be incorporated as much as possible in every area of the serviceable spacecraft's design: boxes, fasteners, connectors, and so on. This cuts down on the number of tools required for maintenance missions, as well as reducing the amount of crew training required for any particular task. But commonality should be striven for among all serviceable spacecraft, to the extent of attaining interchangeability of parts, and common interfaces with existing and future servicing hardware and support equipment, along with the shared tools and common training. In order to realize the full economic and operational benefits of on-orbit servicing, the builders of present and future serviceable spacecraft must work together now with each other and with the present and future providers of orbital service to achieve standardization and commonality in spacecraft designs, as well as definition of interfaces with and requirements on servicing hardware and systems. By applying the lessons of yesterday, we can realize the full potential of spacecraft servicing for tomorrow.