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SURVEY OF FLEXIBILITY IN SPACE EXPLORATION SYSTEMS

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ABSTRACT

An increasingly common objective in the design of new space systems is the property of flexibility, or the capability to easily modify a system after it has been fielded in response to a changing environment or changing requirements. The body of research on this topic has been growing, but substantial work remains in developing metrics for characterizing system flexibility and trading it against other metrics of interest. This paper samples from the history of space exploration to glean heuristic insight into characteristics of flexibility in space exploration systems and their potential application to future systems. Divided into categories of intra- and inter-mission modification, examples include the Hubble Space Telescope, *Mir* space station, International Space Station, Apollo, Space Shuttle, and robotic Venera program. In several cases, metrics are identified which show clear performance gains due to changes after a system is fielded, and in all cases, environment or requirement changes that prompted system change are identified. Also discussed are examples where flexibility proved critical to mission success. Modular design and separation of functionality are recognized as likely flexibility-enabling characteristics. Also, briefly discussed are examples of non-configurational (e.g. software and trajectory) flexibility in space exploration applications.

INTRODUCTION

In January 2008, NASA Administrator Michael Griffin spoke to the Space Transportation Association on the rationale behind NASA's choice of exploration architectures. In his speech, he cautioned against designing aerospace systems for very specific roles. He added, "Even though from an engineering perspective it would be highly desirable to have transportation systems separately optimized for LEO and deep space, NASA's budget will not support it. We get one system; it must be capable of serving in multiple roles ... We are designing today the systems that our grandchildren will use as building blocks, not just for lunar return, but for missions to Mars, to the near-Earth asteroids, to service great observatories at Sun-Earth L1, and for other purposes we have not yet even considered. We need a system with inherent capability for growth." [1]

Dr. Griffin's remarks highlight flexibility, an increasingly common objective for new space systems. Flexibility can be defined as the capability to easily modify a system after it has been fielded in response to a changing environment or changing requirements.[2] The body of research on this topic has been growing, but substantial work remains in developing metrics for characterizing system flexibility, constructing strategies for designing flexible systems, and trading this flexibility against other metrics. In this paper, we sample from space exploration history to glean heuristic insight into fundamental characteristics of flexibility in space exploration systems and their potential application to future space systems.

Before continuing, it is important to distinguish between flexibility and robustness. Both terms refer to the ability of a system to handle change, typically after it is fielded.[2] However, unlike robustness, flexibility implies that in the presence of requirement or environment changes, a user can exercise options to adapt the system. These adaptations can result in improving a performance metric in a given scenario or altogether changing system functionality. Thus, a historical examination of either robustness or flexibility would require an answer to the question of "Did requirements change?". In the context of flexibility, however, a question that must also be asked is "What actions or modifications did the user make in order to adapt to that change, and how effective were they?". Conceptually, the ideal flexible system is one for which a minimal change to the system itself enables a large change in functionality or performance.

Since modification is required for a system to demonstrate its flexibility, this paper makes a distinction between systems that are principally modified between missions and those that are modified during missions. In the case of the latter, which we refer to as intra-mission modification, examples exist such as the Hubble Space Telescope, International Space Station, and the *Mir* space station. In these cases, a one-of-a-kind system is fielded and then modified over time to adapt to a changing environment or requirements. In contrast, examples of the former, which we refer to as inter-mission modification, include the Space Shuttle, Apollo, and Venera programs. In these cases, multiple vehicles are fielded in series and are adapted from one mission to another during the course of the program. In both cases, decisions made at the design stage affect the system's ability to adapt to new mission environments and requirements.

CASES OF INTRA-MISSION MODIFICATION

Hubble Space Telescope

Perhaps the most famous astronomical instrument in history, the Hubble Space Telescope (HST) was launched on April 25, 1990, aboard the Space Shuttle *Discovery*. The original vision of Dr. Lyman Spitzer in 1946, the telescope took shape over several decades and was eventually designed in the 1970s for launch and servicing by the newly developed Space Shuttle. One of the best-known servicing missions, Servicing Mission 1 (SM1), installed equipment to correct for a spherical aberration in the HST primary mirror, dramatically improving the quality of the data returned from the $1.5 billion instrument[3]. Over the 18 years of Hubble's lifetime, four servicing missions have been performed, with a fifth planned for October 2008.

Shown in Table 1 is a summary of servicing accomplishments for Hubble spanning its entire lifetime. Shown in Fig. 1 is the data rate from Hubble

Table 1. Summary of Hubble Deploy and Servicing Mission Accomplishments. [3, 4, 5, 6]

Mission	Launch Date	Mission Duration	Payload Servicing	Subsystem Servicing
HST-Deploy STS-31	April 24, 1990	5.1 days		
HST-SM1 STS-61	December 2, 1993	10.8 days	WFPC2 COSTAR GHRS Redund. Kit	Solar Arrays and Drive Electronics Magnetometers Flight Computer Coprocessors Rate Sensor Units Gyroscopes and Electronic Control Units
HST-SM2 STS-82	February 11, 1997	10.0 days	NICMOS STIS	Fine Guidance Sensor Solid State Recorder Engineering Science Tape Recorder Reaction Wheel Assembly Optical Control Electronics Enhancement Kit Data Interface Unit Solar Array Drive Electronics
HST-SM3A STS-103	December 19, 1999	8.0 days		Gyroscopes Fine Guidance Sensor Transmitter Central Computer Solid State Recorder Electronics Enhancement Kit Battery Improvement Kits Thermal Protection
HST-SM3B STS-109	March 1, 2002	10.9 days	ACS NICMOS Cryocooler	Solar Arrays Power Control Unit Reaction Wheel Assembly
HST-SM4 STS-125	October 8, 2008 (planned)	11.0 days (planned)	WFC3 COS STIS ACS	Gyroscopes Fine Guidance Sensor Batteries Soft Capture Mechanism New Outer Blanket Layers

over its lifetime, and clear improvements exist at the completion of each servicing mission (with the exception of SM3A, which only conducted subsystem servicing and no payload servicing). Table 1 and Fig. 1 help illustrate important points about Hubble's utilization of on-orbit servicing:

- In addition to the difficult-to-quantify benefits of on-orbit servicing (in Hubble's case, salvaging a mission and reputation of an agency), measurable changes can occur in a system's performance and, by extension, value to users.
- Servicing can be used for at least four distinct purposes: Payload Upgrade, Payload Repair, Support System Upgrade, and Support System Repair. In the case of Hubble, the majority of servicing actions have been the repair or replacement of subsystem items. By the end of 2008, for example, all six gyroscopes and all solar arrays will have been replaced twice. In total, 28 subsystem servicing items are listed in the Table 1, compared to 11 payload servicing items.

The Hubble Space Telescope has clearly reaped benefits from its design and accommodation of on-orbit servicing. Interestingly, Avnet[7] suggests that the Hubble design for Shuttle servicing detracted from the success of the program in that the telescope was prevented from being launched into more scientifically and operationally favorable orbits and that the telescope was effectively grounded along with the Shuttle after the *Challenger* accident. Furthermore, if the quoted cost of a Shuttle launch ($450 million)[8] is multiplied by the number of servicing missions (five), the cost of servicing comes to $2.25 billion, which is $750 million higher than the original cost to build and launch the telescope. With this, it is important to distinguish between the value added due to servicing and the costs incurred. It is readily acknowledged that the design for servicing (and, by extension, flexibility) can incur significant costs, and it is the duty of the designer to select the scheme with the highest benefit-to-cost ratio. It can hardly be disputed that the benefits incurred by Hubble's design for servicing have been significant, and it is the question of whether the benefits were worth the cost that is often debated.

Mir

In February 1986, shortly before the end of its successful Salyut space station program, the Soviet Union launched the 25-ton base block to its *Mir* space station. Intended to be increased in size module by module, the *Mir* base block was built with six docking ports, and over its 15-year lifetime *Mir* would grow to over 125 metric tons in mass.[10]

The first module to be added to the *Mir* base block was Kvant 1, a relatively small 8-ton science module. Interestingly, Kvant 1 had originally been designed to dock with Salyut 7, but schedule delays forced it to be

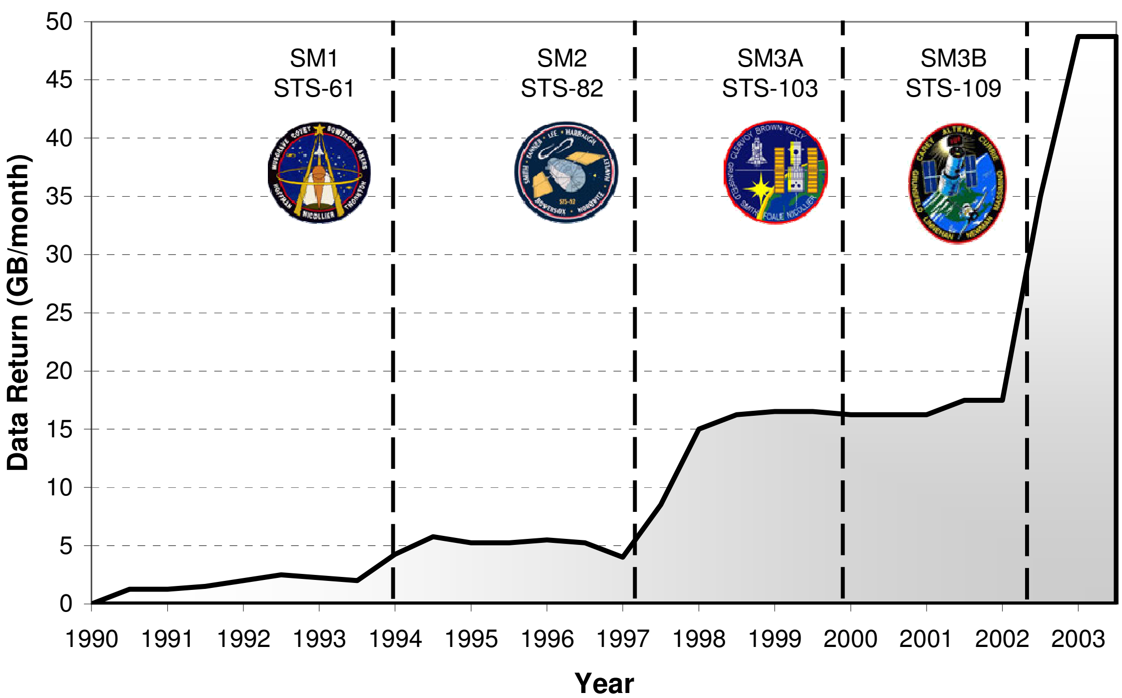

Figure 1. Hubble Space Telescope Data Return (adapted from Ref. 9).

remanifested for *Mir*. Plans existed to construct *Mir* out of similar small modules, but these plans were abandoned in favor of the larger 20-ton modules Kvant 2, Kristall, Spektr, and Priroda which would dock over the next decade.[11] It has been noted that the modular design of *Mir* allowed a flexible buildup capability that was responsive to funding and payload availability changes.[10] In large part because of the incrementalism allowed in the *Mir* buildup, assembly spanned ten years instead of the three originally planned. While in some ways this may be viewed as a drawback, it is also an indicator that flexibility allowed the project to be continued despite a series of unexpected events, and particularly despite the collapse of the Soviet Union. As summarized by former cosmonaut Anatoly Solovyov in 1999, "During these 13 years, at least two-thirds of all we've done and accomplished, we never planned to do. We never thought that the American Shuttle would visit the station, for example … We never thought about this at the beginning of the 1980s when we created the station." [12]

One interesting metric to examine from the perspective of flexibility is the power capability aboard *Mir* at different times in its development. As shown in Fig. 2, this capability increased and decreased at different points throughout Mir's life, starting at 9 kW in 1986 and peaking at about 39 kW in 1996. A major limitation to operations aboard Mir was the amount of power available.[10] Although maximum power generation was significant, solar incidence angles and array shading could reduce output by half.[11] As a result, most new elements delivered to *Mir* included additional solar arrays. The complex's first new solar array, delivered by Kvant 1, was added to the base block by spacewalking cosmonauts in June 1987. Both Kvant 2 and Kristall included solar arrays and more than doubled *Mir*'s maximum power output. During the five-year hiatus caused by the collapse of the USSR, power capability decreased significantly due to long-term solar array degradation. The launch of Spektr in 1995 nearly doubled the *Mir* power output, and the Cooperative Solar Array (CSA) was delivered by the Space Shuttle on STS-74 in 1996.

Important notes regarding the evolution of *Mir* power capability include the fact that additional capability was made possible by two means: docking of new modules and assembly of newly-delivered hardware by cosmonauts on spacewalks. Also, the power capability metric is interesting in that it clearly captures both the addition of capability and the degradation of that capability. Such degradation is likely to occur in the metrics of interest for flexible systems with long lifetimes and should be a consideration in their design.

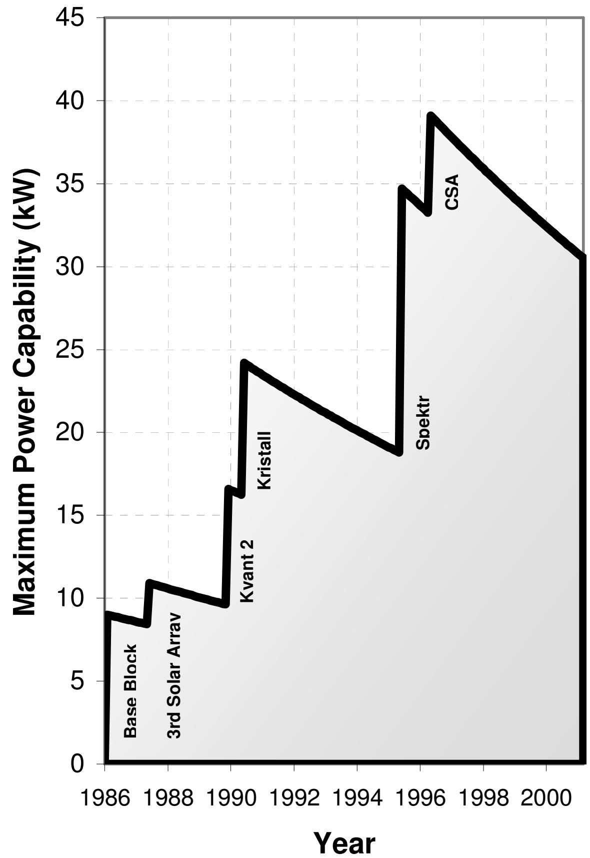

Figure 2. Evolution of Mir Power Capability (adapted from Ref. 11).

International Space Station

The most massive structure ever constructed in space, the International Space Station (ISS) has its origin in the Reagan Administration's 1984 directive for NASA to construct a manned space station within a decade. The modular space station, originally named Space Station Freedom as an affront to the Soviet Union, was to include international participation from Europe and Japan (announced in 1984 and 1989, respectively).[11] Substantial changes occurred throughout the 1980s, and soon after the collapse of the USSR, *Freedom* was renamed and it was decided to combine international plans for *Freedom* with Russian plans for *Mir-2*.[11]

ISS assembly was preceded by ten flights of the U.S. Space Shuttle to the Russian *Mir* space station, and the beginning of ISS assembly was marked in November 1998 by the launch of the *Zarya* Functional Cargo Block from the Baikonur Cosmodrome. Completion of ISS assembly is currently slated for December 2011 with the launch of the Multipurpose Laboratory Module on a Russian Proton rocket.[6]

While the long-term flexibility of the ISS has yet to be demonstrated (it is still undergoing its planned assembly), there are still two notes of interest regarding flexibility. First, the modular design of the ISS has allowed program managers flexibility in choosing which modules to fly and in what order. As a result, the ISS assembly sequence has been changed numerous times. For example, mission 15A delivering the final set of solar arrays was originally to be flown prior to the European and Japanese research modules but has been postponed until after the delivery of these modules.[6, 13] Additionally, although often to the chagrin of ISS engineers, the flexibility of the ISS assembly sequence has allowed several modular components (such as the U.S. Habitation Module, U.S. Propulsion Module, U.S. Centrifuge Accommodation Module, and Russian Science Power Platform) to be descoped without critical consequences. This suggests that flexibility of a modular system might be measurable, at least in part, by the number of distinct launch orders or scenarios that exist which ensure at least a given minimum performance capability.

Second, it is interesting to examine the growth of the ISS both in terms of mass and science return. As Fig. 3 shows, just as in the earlier discussion of *Mir*, the ISS exhibits changes in capability over time that have some correlation with growth in vehicle mass (i.e. the addition of pressurized modules and infrastructure). In the case of *Mir* shown earlier, this capability was measured in terms of power production. In Fig. 3, the capability depicted is NASA science return in terms of average crew time spent on research per week and number of science-related publications per expedition time period.[*] For reference, the U.S. *Destiny* Laboratory was added to the ISS in 2001, at the end of Expedition 1, and the mass plateau starting during Expedition 6 is the result of the grounding of the Shuttle fleet after the 2003 *Columbia* disaster. Due to limits on data availability, this plot extends only through Expedition 13 (September 2006).

As Fig. 3 shows, ISS mass has increased quite rapidly during assembly. ISS mass leveled off during the grounding of the Shuttle fleet since the Shuttle was the primary vehicle responsible for delivering new elements to orbit. During this time, science return per expedition declined due to the reduction in crew size to two instead of three; here, the ISS is operating under-capacity in terms of science return. Note that maximum crew research time per week occurred on Expedition 3, soon after delivery of the *Destiny* laboratory. A small decline in crew research time occurred by Expedition 4, although it is important to point out that during the ISS assembly phase, science investigations compete with assembly-related tasks for crew time.

Perhaps the most important point from Fig. 3 is the illustration of a time-delay characteristic. In the case of the ISS, addition of modules provides additional capability, but this capability may not be fully utilized until later expeditions (e.g. while equipment checkouts are performed and until later missions deliver investigation-specific equipment and personnel dedicated to performing experiments rather than installations). Furthermore, it appears from Fig. 3 that the returns of ISS science research in terms of publications are delayed in time by 1-2 years (roughly 2-4 expeditions), judging by the initial peaks in the crew research time and publication rate curves. Depending on the scenario, measurable returns for flexible systems may exhibit similar time-delay characteristics and should be considered when evaluating responses to system configuration changes. That is, even if a change to a fielded system could be made instantaneously, some observed effects of that change may take time to manifest themselves.

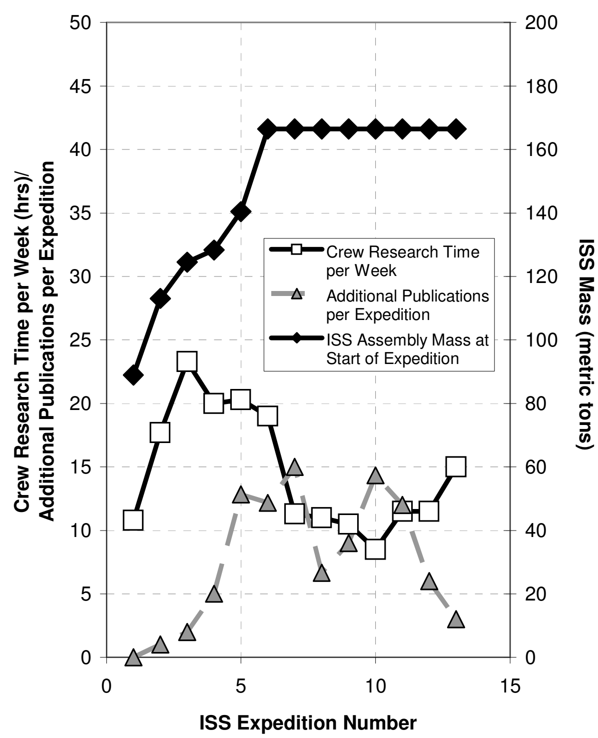

Figure 3. Evolution of ISS Mass and Research Returns.[14, 15, 16]

[*] Power capability and science return could be tracked for both *Mir* and the ISS; the choice to show power for *Mir* and science return for ISS is made for convenience for reasons of data availability.

CASES OF INTER-MISSION MODIFICATION

Apollo Program

Firm commitment for the historic Apollo program occurred on May 25, 1961, as President Kennedy announced a U.S. commitment to land a man on the Moon by the end of the decade. By 1973, the U.S. had spent $19.4 billion ($92.3 billion in FY08 dollars) on the Apollo lunar program and had landed twelve men on the surface of the Moon and returned them safely to Earth. In the process, the nation had also developed and proven an extremely capable – and flexible – manned space vehicle.

Table 2 illustrates the diversity of missions achieved with the Apollo vehicle through 1973. While most of these mission types were planned in advance, they were also enabled by the addition of major elements to the baseline Apollo command and service module (CSM). For all but one lunar mission, a lunar excursion module (LEM) was added, and for the J-type missions, a lunar rover was added to the LEM for enhanced surface exploration. While it may seem obvious that a LEM would be necessary to complete the campaign, the decision to separate the LEM functionality from that of the CSM largely enabled the elements to be developed and tested separately. For example, Apollo 7 and Apollo 8 were able to accomplish substantial program objectives without carrying a LEM, and a LEM was only added to missions when necessary for lunar landing (or LEM testing). This would not have been possible, for example, had a direct ascent architecture been chosen with integrated CSM and LEM functionalities.†

Furthermore, it deserves note that the C' mission type in Table 2 was not part of the original mission sequence. In August 1968, lunar module schedule slippage prompted studies to examine the feasibility of launching a CSM on a lunar orbital mission without a LEM.[17] With the successful completion of Apollo 7 in October 1968, the official decision to conduct a lunar orbital mission on Apollo 8 was made on November 12, 1968 – just five weeks before launch.[18] Thus, despite delays in LEM readiness, the Apollo program made progress in late 1968, and it is likely that this flexibility allowed the U.S. to meet President Kennedy's "in this decade" goal.[17] Again, it is unlikely that such flexibility would have been available had a monolithic direct-ascent vehicle been chosen.

† A direct ascent option might have been an example of a robust vehicle since it could perform a wide variety of missions, but it would have been essentially static with little modification among different mission types.

Table 2. Apollo Mission Type Designations.[19]

Mission Type	Flights	Trajectory	Purpose
A	Apollo 4 Apollo 6	Earth Orbital	LV and spacecraft development
B	Apollo 5	Earth Orbital	LEM unmanned flight evaluation
C	Apollo 7	Earth Orbital	CSM manned flight demonstration
C'	Apollo 8	Lunar Orbital	CSM manned flight demonstration
D	Apollo 9	Earth Orbital	LEM manned flight demonstration
E		Earth Orbital	LEM manned flight demonstration, augmenting mission type D objectives
F	Apollo 10	Lunar Orbital	LEM manned flight demonstration
G	Apollo 11	Lunar Landing	Manned lunar landing demonstration
H	Apollo 12 Apollo 13 Apollo 14	Lunar Landing	Precision manned lunar landing demonstration and systematic lunar exploration
J	Apollo 15 Apollo 16 Apollo 17	Lunar Landing	Extensive scientific investigation of Moon on lunar surface and from lunar orbit

As early as 1963, NASA engineers were considering options for extending Apollo hardware to missions outside of the lunar program shown in Table 2. These efforts resulted in the Apollo Extension System, Saturn/Apollo Applications Office, and finally the Apollo Applications Program (AAP). AAP proposals varied from telescope mounts on converted lunar modules[20] to manned Venus flyby missions using the Apollo CSM and a habitat module converted from a Saturn upper stage[21] (see Figs. 4 and 5, respectively). Although most of these proposals never flew, the sheer variety of credible designs might be taken as an indicator of the flexibility of the Apollo system. In the end, there were two post-lunar contributions that resulted from the AAP: Skylab and the Apollo-Soyuz Test Project.

Skylab was launched in May 1973 and housed three crews over its 6-year orbital lifetime. The bulk of the orbital laboratory was converted from the third stage of a Saturn V rocket, allowing for a spacious "two-floor" workshop. The laboratory also included an airlock module, Apollo Telescope Mount for sun observations, and a multiple docking adapter (MDA) to allow up to two Apollo spacecraft to be docked at once if necessary.

In order to accommodate Skylab missions, the Apollo CSM underwent 23 significant modifications, including the addition of power transfer capability, removal of one fuel cell, and removal of the high-gain antenna.[22] However, perhaps the most interesting modifications to the Apollo CSM were associated with the procedures developed for the case of a Skylab rescue mission. In such a contingency, plans called for a two-man crew to launch on the next available CSM. The projected time to prepare and launch the rescue vehicle was 45 days, although modifications to convert the command module to a rescue configuration were projected to take only 8 hours. These modifications included the removal of aft bulkhead storage lockers, installation of two additional crew couches, modification of life support and communications umbilicals, and the addition of an experiment return rack (see Fig. 6).[22]

In an often-overlooked event of the Skylab program, the Skylab rescue procedures were activated in August 1973 when leaks in two of four reaction control system (RCS) quads on the Skylab 3 CSM threatened the mission and put at risk the crew's safe return. It was feared that the cause of the RCS leaks was contaminated propellant, which would eventually render all RCS quads inoperative and make Earth return impossible. Upon failure of the second RCS quad, astronauts Vance Brand and Don Lind began preparations for a rescue mission using the Skylab 4 CSM. Although propellant contamination was ruled out as the cause within several hours and the rescue mission was not flown, it is likely that the option provided by the rescue mission provided the necessary time for engineers on the ground to evaluate the problem; otherwise, the Skylab 3 crew would likely have been ordered home immediately, prior to failure of any additional RCS quads.[22] Thus, in the case of Skylab, the flexibility of the Apollo CSM offered both long-period and short-period benefits. First, in a strategic sense, it eased the transition from lunar to space station missions. Second, as demonstrated by the Skylab 3 incident, the ability to quickly outfit the capsule for a rescue mission gave operators options in real-time that likely saved a mission from a premature end.

The final flight of the Apollo CSM occurred in 1975 as part of the Apollo-Soyuz Test Project (ASTP). From the perspective of flexibility, of interest in ASTP was the addition of a U.S.-built docking module to accommodate the different docking interfaces of the Apollo and Soyuz vehicles. In addition, the module carried communication equipment tuned to Soviet frequencies and provided an atmospheric interface since the American and Soviet vehicles utilized different atmospheric pressures. In terms of design philosophy, the docking module was built to accommodate any mission-specific equipment to minimize the number of modifications required of the Apollo CSM.[23] As with the lunar module and rover, this is another instantiation of the ability to add mission-specific modules to the basic Apollo vehicle.

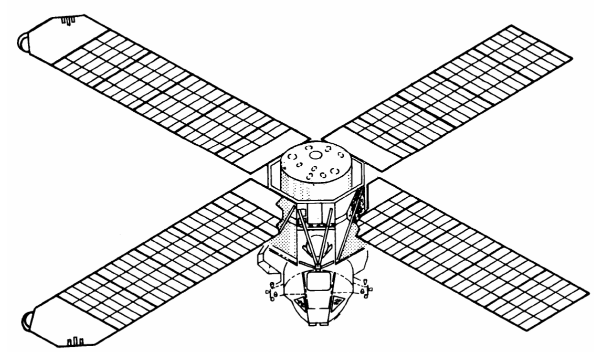

Figure 4. Lunar-Module-Based Apollo Telescope Mount Design dated April 1968.[20]

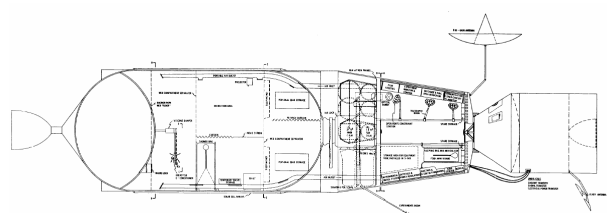

Figure 5. Proposed Apollo Configuration for a Manned Venus Flyby (dated February 1967).[21]

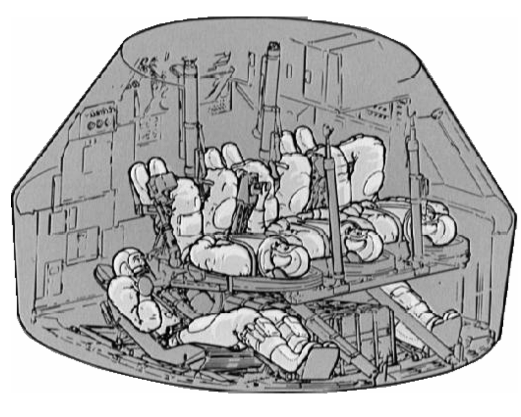

Figure 6. Cutaway View of Skylab Rescue Command Module (1973).[24]

Space Shuttle Program

Toward the end of the Apollo lunar campaign, on January 5, 1972, President Richard Nixon announced the approval of the Space Transportation System, or Space Shuttle, a system which would provide, according to NASA Administrator James Fletcher, "the means of getting men and equipment to and from space routinely, on a moment's notice if necessary, and at a small fraction of today's cost." This would be accomplished "within the framework of a useful total space program of science, exploration, and applications."[25] NASA's challenge following Nixon's announcement became one of transforming an expansive vision for the Shuttle into a practical reality under a highly constrained development budget. While the Shuttle never lived up to the cost and flight rates that were promised at the program's inception, it is notable that the design decisions made in the 1970s produced a system which even today is, arguably, unsurpassed in the variety of capabilities which can be fulfilled with a single space vehicle. With relatively few architectural modifications, the Shuttle has accommodated satellite deployment, satellite retrieval and servicing, launch of interplanetary robotic probes, classified Department of Defense missions, space station logistics and assembly flights, and a wide variety of science and engineering research missions. By the time of its planned retirement in 2010, the Shuttle will have endured and responded to nearly three decades of changes in requirements and environments. Many of these changes emphasized or deemphasized different types of missions at different times in the Shuttle's life.[27]

Evidence for changing mission requirements can be seen in Fig. 7, which shows the dominant Space Shuttle mission classifications by percent of missions flown spanning from 1981 through the end of 2007. For example, in 1984-1986, unmanned spacecraft servicing accounted for 69% of Shuttle missions, but by 1993-1995, almost the same percentage (67%) was attributed to dedicated research flights. In 1999-2001, 79% of flights were to an orbiting space station, and in 2005-2007 that number increased to 100%.

Each of these three spikes in mission type frequencies can be explained to a large extent by specific events driving decisions within the Space Shuttle program. For example, the *Challenger* disaster prompted presidential action to limit commercial communications satellite use of the Space Shuttle to only payloads with national security or foreign policy implications. The *Challenger* disaster also prompted many Department of Defense satellites to be launched on expendable launch vehicles instead of the Shuttle (including 20 Global Positioning System satellites).[26] This explains the decline in both unmanned spacecraft

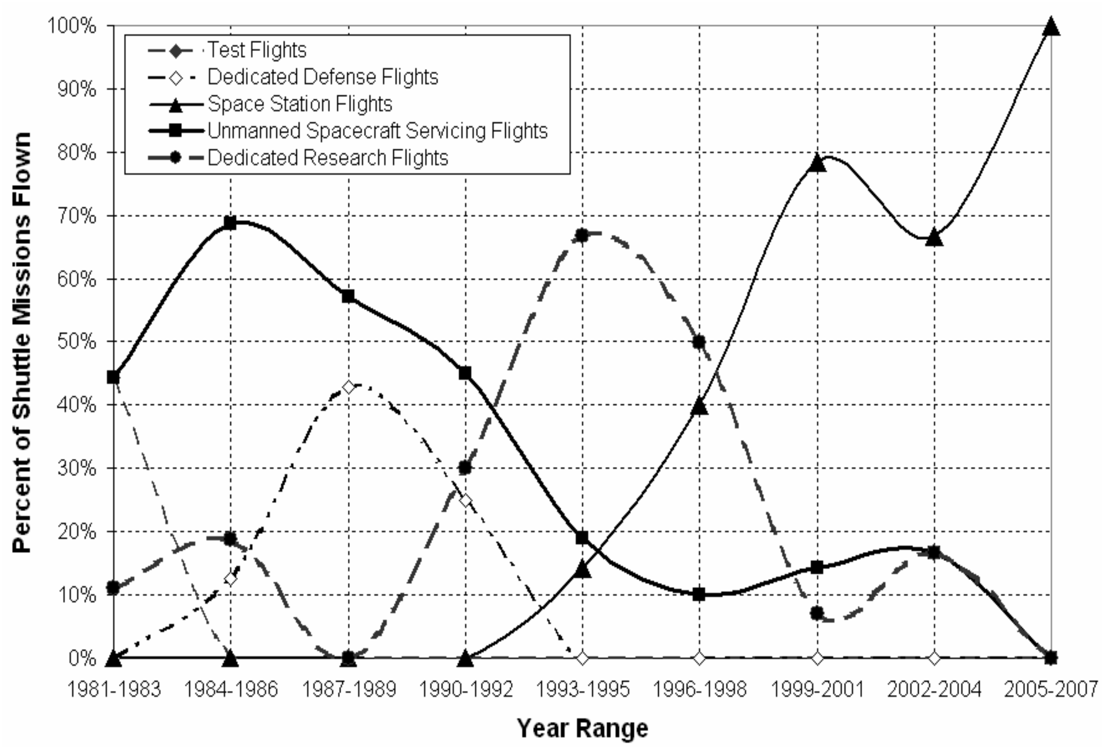

Figure 7. Time-History of Space Shuttle Usage by Primary Mission Type.[27]

servicing and defense flights after 1986. Also, the start of space station flights (first to Mir and then to the International Space Station) in the mid-1990s is tied to the maturation of plans for a space station and especially the invitation extended to Russia to join the international partners. Finally, the Columbia disaster in 2003 was a third major event which served as a catalyst for a new vision for the nation's space program which would retire the Shuttle in 2010 after fulfilling its commitments to International Space Station (ISS) assembly. As a result, every flight in 2005-2007 was destined for the ISS.

Interestingly, it has also been shown that over its history, not only has the Shuttle experienced three distinct periods of specific mission type predominance, but the dominant mission types in these periods have occurred in almost equal numbers. Ref. 27 shows that 31% of Shuttle flights have been to service unmanned spacecraft, 30% have been dedicated to research, and 28% have been destined for a space station. Overall, it is rather remarkable that the system was able to accommodate these changes in mission type, particularly since many were unexpected.

As suggested in Ref. 27, the Space Shuttle has employed several fairly standard elements which have been addable or removable depending on mission-specific requirements. For example, 63% of Shuttle flights are known to have carried the Remote Manipulator System (RMS), a robotic arm enabling satellite capture and space station assembly missions. Additionally, in the 1990s, three orbiters were modified such that their airlocks were mounted externally with the Orbiter Docking System (ODS), which included a docking interface to enable missions to the ISS and *Mir* space stations. The Spacelab and SPACEHAB modules were both pressurized facilities that fit within the Shuttle payload bay and enabled dedicated long-duration research flights. Also, the Extended Duration Orbiter (EDO) pallet first flown in 1992 included a set of cryogenic hydrogen and oxygen tanks that could be added to the Shuttle payload bay to extend mission durations by 6 days. Additional examples of mission-specific elements are identified by Ref. 27, and these examples are of interest because they identify the engineering articles that were added to the Shuttle on a mission-by-mission basis to allow the program to flexibly respond to the dynamic mission requirements indicated by Fig. 7.

Venera Program

While all examples of flexible space exploration systems have thus far been limited to manned or Earth-orbiting missions, examples do exist of flexibility in unmanned planetary probe programs. The most interesting of these is the early Soviet Venera program, which between 1970 and 1981 accumulated 9.7 hours worth of measurements and data from the surface of Venus. Of particular interest is the evolution of the Venera vehicle through the missions preceding the first successful Venus landing.

As early as 1960, the USSR was making plans to send unmanned probes to Mars and Venus. However, knowledge about Venus' environment was far from mature. Surface temperature estimates in 1961 ranged from 30°C to 330°C. Korolev's designs for Venus probes in the 1950s assumed pressures up to 5 atm and temperatures up to 75°C. An early Venus probe that launched (but failed to leave orbit) in February 1961 included a dome structure intended to float in Venus' oceans. Even as late as 1967, the Venera 4 descent craft included a dissolve-on-contact sugar lock to release a transmitter in the event of a splashdown on Venus.[28] In reality, Venus is almost 100,000 times

Table 3. Evolution of Venera 3MV Lander Designs.[28,30,31]

Mission	Launch Date	Atmospheric Entry Date	Design Temp.	Design Press.	Number of Instruments	Comments
Venera 3	Nov. 1965	March 1966	80°C	5 atm	7	Likely entered Venus atmosphere, but contact lost 2 weeks before entry
Venera 4	June 1967	Oct. 1967	300°C	18 atm	5	Lost at 25-27 km altitude
Venera 5	Jan. 1969	May 1969	320°C	36 atm	6	Lost at 16-26 km altitude
Venera 6	Jan. 1969	May 1969	320°C	36 atm	6	Lost at 10-12 km altitude
Venera 7	Aug. 1970	Dec. 1970	540°C	180 atm	3	Descent vehicle landed on its side, indicated 92 atm, 475°C environment
Venera 8	March 1972	July 1972	490°C	105 atm	7	Successful; transmitted for 63 min.

drier than Earth[29] and sports surface temperatures of 475°C and pressures of 92 atm. Simply realizing the hostility of this operating environment was a challenge faced by the early Venera program.

Table 3 shows the progression of Venera missions leading up to the first fully successful landing and operation of Venera 8 in July 1972. It should be noted that this list is not comprehensive; many vehicles destined for Venus in the 1960s suffered from launch or injection failures before leaving Earth's sphere of influence. Additionally, Table 3 does not show the series of successful missions which followed Venera 8, namely Venera 9-14. The table ends at Venera 8 in part because it represents the final convergence onto the correct Venus environmental conditions. However, Venera 8 was also the last of the 3MV generation of Soviet planetary probes originally approved in 1963; Venera 9 began what was designated the 4V1 generation of spacecraft.

Significant success for the Venera program began in March 1966 with Venera 3, the first mission listed in Table 3. Although contact was lost with Venera 3 prior to entry, it is likely that the entry was on-target and the first of its kind on Venus. By the time of the Venera 4 launch in 1967, the Soviet scientific community began to believe that Venus was a much harsher environment than originally anticipated, and the vehicle was designed to withstand 18 atm and 300°C conditions. This vehicle failed due to the fact that atmospheric conditions were harsher than anticipated. Venera 4 and 5, which arrived in 1969, suffered similar failures despite being designed to withstand higher pressures and temperatures.[28]

The ultimate in pressure and temperature capability for Venus – and the first vehicle to transmit from the Venusian surface – came with Venera 7 in 1970. This vehicle was designed to withstand an incredible 540°C, 180 atm environment. However, this came at the sacrifice of scientific instruments, and only temperature sensors, a barometer, and a radar altimeter were carried. Additionally, to maximize the time available on coolant, the spacecraft bus providing support during interplanetary cruise was retained during much of atmospheric entry rather than being jettisoned prior to entry. Upon landing, Venera 7 detected the 92 atm, 475°C environment, which would enable engineers to properly design the remainder of what became an overwhelmingly successful Venera program.

From the perspective of flexibility, the Venera program is an outstanding illustration of environment uncertainty and the requirement to be able to modify a design to adapt to this environment (or, in this case, one's best knowledge of this environment). Venera was very much an evolutionary program that, in its first several missions, actively traded pressure and temperature capabilities against science return in order to converge upon a suitable design.

NON-CONFIGURATIONAL FLEXIBILITY

The focus of this paper's discussion of flexibility has been on configurational changes made to a vehicle mid-flight or between flights. It deserves note, however, that additional interesting examples of flexibility, or modifications to a system after it has been fielded, exist in terms of software and trajectory updates to exploration systems.

In one example, new autonomous navigation software known as Field D* was uploaded to NASA's Mars Exploration Rovers in July 2006, over two years after the vehicles' successful 2004 landing. The new software allowed the rovers to accomplish autonomous global path planning, a necessity since commands sent from controllers on Earth take up to 26 minutes to reach Mars. The previous autonomous navigation algorithm, the Grid-based Estimation of Surface Traversability Applied to Local Terrain (GESTALT), proved to have shortcomings in scenarios where the rovers were attempting to navigate through dense clusters of rocks. The new Field D* software was complex enough to require a full flight upload as opposed to a simpler software patch.[32] This example is interesting with respect to flexibility because it shows an example of new technology being applied to a system that had far outlived its planned lifetime (the original lifetime of the Mars Exploration Rovers was planned at 3 months, and they continue to function as of the writing of this paper, over 4.5 years later).

Additionally, in terms of trajectory flexibility, the design of interplanetary trajectories for robotic probes typically allows significant flexibility for mid-course retargeting. For example, on robotic Mars missions, final landing site selection typically does not occur until a few months before landing. Also, the active redesignation of landing sites during lunar or Mars descent for hazard avoidance purposes (e.g. for the NASA ALHAT human lunar landing technology project[33]) is an example of changing a pre-planned trajectory in real-time in response to new information about the vehicle's environment. This shares many conceptual similarities with flexibility in the configurational sense treated in this paper.

CONCLUSIONS

Overall, this paper has sampled from the history of space exploration to highlight examples of flexible systems and examine the circumstances that underscored their flexibility. Prime examples were divided into categories based on whether their flexibility was demonstrated during a continuous mission (intra-mission modification) or whether it was demonstrated among multiple flights of the same basic vehicle (inter-mission modification).

In the category of intra-mission modification, the Hubble Space Telescope was presented as the classic example of a serviceable space system. Data return rate was tracked as a performance metric and as a surrogate measure of the value returned from the observatory that showed sharp rises with the addition of new components. Observations were also made on the relative frequency of payload and support system servicing. Next, the *Mir* space station was presented, and maximum solar array output was tracked as a function of time. This metric exhibited the interesting property of degradation over time. Additionally, changes in space station construction plans were mentioned, including the discontinuation of 8-ton Kvant-1 class modules and the effects of the collapse of the Soviet Union. These events are examples of environment and requirement changes that *Mir* successfully withstood. Thirdly, the International Space Station was presented in terms of its performance to date. Like *Mir*, the modular nature of the station allowed significant changes to occur in the assembly sequence and number of modules launched. Additionally, ISS metrics of interest demonstrate the potential existence of time-delayed outcomes in flexible systems, a characteristic that should be considered when appropriate in any such analysis.

In the category of inter-mission modification, the American Apollo program was presented as flexible in several ways. First, the separation of landing functionality into a lunar module allowed parallel development and testing of the command and lunar modules and in many ways is responsible for the timing of the Apollo 8 mission that enabled President Kennedy's lunar landing goal to be reached. Additionally, advanced but unflown concepts of the Apollo Applications Program were presented, as were the successful Apollo-derived Skylab and Apollo-Soyuz Test Project missions. Included in this discussion was the criticality of the Apollo command module's flexibility in its potential to act as a rescue vehicle for the Skylab 3 mission. In addition to Apollo, data was presented on the division of Space Shuttle missions by category over time, showing a clear dominance of different mission types at different times in the vehicle's history. Furthermore, some of the mission-specific elements added or removed from the Shuttle to enable these missions were identified. Finally, the Soviet Venera program was shown to exhibit an evolutionary development, using the same basic 3MV vehicle design to adapt to wildly changing knowledge of the conditions at the surface of Venus.

In addition to the two basic intra- and inter-mission categories, a short discussion acknowledged the strong ties between configurational flexibility (the primary focus of this paper) and space exploration examples in software and trajectory flexibility.

Perhaps the most interesting note to make applies to all the examples discussed in this paper. Generally speaking, flexibility tends to be difficult to assess because it deals with a system's ability to respond to scenarios that may never have been envisioned by the system's designers.[‡] Because of this, the system's flexibility is only exhibited in the presence of unplanned events (i.e. changes in environment or requirements). For all the systems considered in this paper, such unplanned events occurred, and flexible responses were able to be observed. Had these events not occurred, these responses would not have been observed, and similarly, since flexibility must be taken with respect to the perturbing event, it is difficult to say with certainty how flexible these same systems would have been to other unplanned events. This fact further highlights the need for more study into how to design the property of flexibility into space systems.

In conclusion, this paper has highlighted some of the most interesting examples of flexibility in the history of space exploration. A number of key flexibility characteristics have been identified in a heuristic fashion, and it is hoped that this insight will serve as a further contribution to the study and design of flexible space systems.

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[‡] Further complications occur because the response modes that the system operators take may also have never been envisioned originally.

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