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On-Orbit Upgrade and Repair: The Hubble Space Telescope Example

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From the Hubble Space Telescope (HST) example, a model of a serviceable scientific mission is developed to study on-orbit repair and upgrading, including spacecraft repair, payload instrument upgrading, and bus subsystems upgrading. Mission utility is measured by the onboard payload instrument discovery efficiency. A Monte Carlo simulation is used to model uncertainty in the arrival of new technologies, random spacecraft failures, and catastrophic failures of a servicing operation. The value of the option to repair and upgrade, as well as the impact of different design choices, is investigated using actual data from the HST manned servicing missions. The main differences between manned and unmanned servicing missions are then analyzed in an attempt to derive conclusions for robotic on-orbit servicing of scientific missions. In light of the cases examined, designing for serviceability exclusively for satellite repair does not seem very valuable. In contrast, upgrading can significantly increase mission utility especially if the technology embedded in the serviceable modules is evolving rapidly. Technology upgrades via on-orbit servicing have been identified as a very promising concept. Large increases in mission utility can be realized for a cost significantly lower than the cost of replacing the whole satellite.

Nomenclature

$\mathcal{C}$ = cost function
$\mathcal{C}_{\mathrm{NewTech}}$ = cost of the new technology to be installed on the spacecraft
$\mathcal{C}_{\mathrm{OptTech}}$ = cost of the optimal technology to be installed on the spacecraft
$\mathcal{C}_{\mathrm{Repair}}$ = repair cost
$\mathcal{C}_{\mathrm{Serv}}$ = servicing cost
d = scientific instrument generation
N_B = generation of the onboard bus technology
N_B^d = state-of-the-art bus technology when an instrument d is invented
N^{ref} = reference parameter to define the decrease in utility caused by bus technology obsolescence
P_f^{Serv} = probability of failure of a servicing operation
P_S = probability of success of the observatory operation
P_S^{Serv} = probability of success of a servicing operation
T_B = mean time between arrivals of new bus technologies
T_I = mean time between arrivals of new instruments
u^d = utility rate per unit time with the instrument d
u_m^d = maximum utility rate per unit time with the instrument d
u_{NewTech} = utility rate per unit time with the new-generation instrument
u_{OldTech} = utility rate per unit time with the old-generation instrument
X_B = stochastic variable representing the arrival of a new bus technology
X_I = stochastic variable representing the arrival of a new instrument
ΔT = time until next scheduled repair

I. Introduction

ON-ORBIT servicing has been recognized as an interesting concept, covering applications such as mission life extension, refueling, repair, and upgrading. However, it represents such a large shift from current practices that its adoption as the new design paradigm will require a careful evaluation of its value and benefits in light of the many challenges still ahead. The present study proposes consideration of the satellite upgrade, which appears as one of the most promising applications of on-orbit servicing because it offers the unique opportunity to extend the capabilities of the system once deployed.

Multiple valuation studies have been carried out considering autonomous on-orbit servicing for various applications. In particular, the Spacecraft Modular Architecture Design for On-Orbit Servicing study, performed in 1996 by the Naval Research Laboratory,[1] focused on estimating the costs and benefits associated with the use of autonomous on-orbit servicing.

Saleh et al.[2] developed a new valuation framework based on real option analysis to account for the value of the flexibility offered by on-orbit servicing and applied it to mission lifetime extension. The conclusions emphasize the importance of accounting for the added flexibility in the valuation of on-orbit servicing. Using a similar approach, Lamassoure et al.[3] studied the refueling of satellites in orbit for a commercial mission facing uncertain revenues and for a thin military radar constellation with a dynamic distribution of contingencies. The study concluded that on-orbit servicing seemed promising for some conditions and that the value of flexibility can correspond to a large part of the total value of the mission.

An interesting contribution to the analysis of satellite upgrade using on-orbit servicing is the study of the upgrade of the global-positioning-system (GPS) satellites. A first publication[4] investigated the design modifications that would be necessary to make the GPS satellite serviceable. A second study[5] considered on-orbit servicing as an alternative to the phased replacement strategy currently adopted for the GPS system. The study identifies on-orbit servicing as an opportunity to keep up with the technology evolution while designing satellites with long design lifetimes.

Adopting a different approach to space mission upgrade, Chaize[6] studied the concept of staged deployment, which aims at improving

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the overall performance or capacity of a system of satellites by growing a constellation as necessary rather than directly designing the system for a full capacity.

The present study aims at investigating the value of on-orbit repair and upgrade of a scientific platform based on real data from the unique example of the Hubble Space Telescope servicing missions. Launched in 1990, the Hubble Space Telescope (HST) is the only example of an unmanned platform designed to be regularly serviced by the shuttle. A modular design was adopted to allow repairing the telescope, installing new payload instruments and regularly upgrading bus components to make Hubble a state-of-the-art scientific observatory. The Hubble Space Telescope is a unique opportunity to analyze a real serviceable platform and use real data to investigate the value of satellite upgrade using on-orbit servicing. Although it must be acknowledged that the HST servicing manned missions will likely not represent a standard on-orbit servicing scheme, in particular regarding the use of the shuttle vehicle, they offer the opportunity to apply the model to a real case example. The model can then be adapted to different missions by modifying cost, utility, and specific parameters to adapt them to the specific case studied.

The model has been constructed from the example of the Hubble Space Telescope and aims at estimating the value of serviceability for a scientific mission. A single instrument is assumed to be installed on the satellite. A utility metric is defined to capture the scientific return of the mission. Utility depends on the generation of the instrument installed on the satellite and on its compatibility with the other onboard bus subsystems. Three potential servicing operations are considered: the repair of the spacecraft, the installation of new instruments, and the upgrade of bus subsystems. The decision to upgrade or repair is made if the utility per cost metric exceeds a predefined threshold. Data from the Hubble Space Telescope are used to benefit from real inputs from an existing serviceable mission. In particular we used the probability of failure of the spacecraft, the instruments utility, and the servicing costs. A Monte Carlo simulation is used to model four sources of uncertainty: the appearance of a new instrument, the emergence of a new technology for a bus upgrade, the failure of the spacecraft, and the potential failure of a servicing operation. Different levels of flexibility are investigated from a non serviceable to a fully serviceable spacecraft.

The main questions investigated are the following:

1) What is the potential improvement in utility that can be achieved with serviceability?

2) What are the respective contributions from satellite upgrade and from satellite repair?

3) How does servicing risk affects the value of servicing?

4) What is the impact of the pace at which technology evolves?

5) What is the impact of the decision model defining what upgrade and repair are conducted?

6) To what extent can the data from the Hubble Space Telescope be used to derive conclusions on the value of unmanned on-orbit servicing?

The example of the Hubble Space Telescope is first reviewed to analyze the achievements of the repair and upgrade missions conducted with the shuttle. The model of a scientific mission developed from the HST example is then described. The value of repairing the spacecraft is then investigated before considering the option to upgrade against technology obsolescence. The impact of the criteria chosen to decide on which servicing missions to conduct and of initial design choices is explored. The main differences characterizing unmanned and manned servicing missions are then discussed. In particular, the impact of the risk and cost of a servicing mission on the value of serviceability is investigated. Finally the main limitations of the present model are presented.

II. Hubble Space Telescope

The Hubble Space Telescope was designed in the 1970s and deployed on 25 April 1990 by the Space Shuttle *Discovery*. A spherical aberration in the primary mirror was discovered immediately and corrected during the first servicing mission. A total of four servicing missions has been performed to make the Hubble Space Telescope a state-of-the-art observatory along the 13 years it has been operated.[7]

A fifth servicing mission was planned in 2005 to install new instruments and conduct repair operations. However, all plans were modified following the 2003 Space Shuttle *Columbia* accident with the grounding of all shuttle vehicles. The Hubble Space Telescope servicing missions were put into question mainly because of safety concerns for the shuttle astronauts. Different options are currently discussed including abandoning further HST servicing operations; conducting one more shuttle servicing mission, likely after a few successful Shuttle flights; and conducting a robotic servicing mission.[8,9] The option to continue maintaining and upgrading the Hubble Space Telescope is also compared to the alternative of investing in the development of a new modern platform.[10]

An interesting issue to the present study is the circumstances leading to the decision to design the telescope to be regularly serviced. First, the emergence of the shuttle, a reusable vehicle capable of reaching orbit and returning to Earth, was an enabler for on-orbit servicing. With the development of a reusable vehicle, two concepts were proposed: the telescope could be regularly returned to Earth using the shuttle to be repaired and upgraded on Earth, or the repair and upgrade operations could be done in orbit by astronauts. The second more innovative concept was chosen. However, if the shuttle has been an enabler of on-orbit servicing, it does not explain the need for serviceability. The rationale for designing the Hubble Space Telescope for serviceability was to reproduce in space the equivalent of an observatory on Earth. On Earth, instruments can be changed as more efficient instruments appear and as the state of knowledge evolves requiring different types of measurements or different targets to be studied. The HST modular design was chosen because it offers a way to adapt the observatory to the need of the scientific community and to prevent technical obsolescence over the long lifetime characterizing a space platform.

The example of the Hubble Space Telescope illustrates the large benefits derived from a serviceable platform that can be repaired and maintained but also upgraded to follow the evolution of technology and user needs.

A. Mission Salvage

The ability to service the Hubble Space Telescope made it possible to save the mission. The flaw in the primary mirror would have significantly reduced the scientific usefulness of the space telescope, and the failure of four of the six gyroscopes would have caused the mission to be lost.

B. Repair and Maintenance

Extensive maintenance operations were conducted to ensure the health of the Hubble spacecraft. Two characteristics of the repair missions should be emphasized. First, on-orbit servicing has allowed the repair of problems that were not expected in the initial design of the vehicle. The thermal blanket degraded faster than expected and had to be replaced after the astronauts on mission SM2 discovered the issue. It was not expected that the flexible structure of the solar panels would cause them to oscillate creating disturbances in the observations. Another illustrative example is the case of the gyroscopes that appear to be the largest failure point of the spacecraft and are failing far more rapidly than it was expected. Secondly, on-orbit servicing has provided a way to return the failed components back to Earth to study the causes of failure and find solutions to fix the unexpected problems. This was mainly possible because of the use of the shuttle.

C. Instrument Upgrade

The upgrade of the instruments extended the possibilities of the observatory by incorporating state-of-the-art instruments and new capabilities. A total of 12 instruments will be installed on Hubble offering improved performance and different observation capabilities.

D. Other Bus Upgrades

Upgrading other subsystems to implement new technologies has radically increased the performance of the observatory and made the installation of new instruments possible. The upgrade of the solar panels and the thermal system made it possible to operate up to four instruments simultaneously, compared to only two in the initial design. The performance of the spacecraft computer and the available onboard memory have greatly increased over time. The speed of the onboard computer and the data archiving rate have been multiplied by respectively 20 and 10 through the four servicing missions. Computer modules appear as good candidates for upgrade because of the fast pace at which computer technology evolves.

III. Model Description

From the Hubble Space Telescope example, a model of a serviceable scientific platform has been developed to investigate the value of repairing and upgrading a spacecraft in orbit. The framework used is explained in the following paragraphs.

A. Monte Carlo Simulation

A Monte Carlo simulation is used to take into account the different sources of uncertainty and estimate the value of the option to repair and upgrade. A probabilistic distribution is chosen to characterize each uncertainty parameter. At different points in time, called decision points, the space operator can choose either to repair, upgrade, or not alter the satellite. A simulation corresponds to one run of the model over a 15-year time frame. During a simulation, the total utility, the discounted costs, and the sequence of decisions chosen during the satellite lifetime are determined. At each decision point during the simulation, each uncertainty parameter is assigned a value that is a random draw within its distribution. Each run corresponds to a possible scenario of resolution of the uncertainty over the time horizon. In a Monte Carlo process, a large number of simulations are run to generate a representative set of possible outcomes. The distributions of utility and costs are derived from the frequency of occurrence in the large sample of simulations.

B. Uncertainty

Four sources of uncertainty are incorporated in the model: the uncertainty in the appearance of new instruments or new technologies and the uncertainty in the failure of the spacecraft or a servicing operation.

1. *Uncertainty in the Evolution of Instrument Technology*

A new instrument corresponds to a technological improvement and therefore an increase in the performance of the instrument. The arrival of a new instrument is uncertain and represented by the probabilistic variable X_I, with $X_I = 1$ when a new instrument is invented and $X_I = 0$ otherwise. X_I is assumed to follow a Poisson process with a mean time of arrival T_I. The probability of a new instrument being invented in the time interval dt is

$$P(X_I = 1) = (1/T_I)\,\mathrm{d}t \tag{1}$$

An instrument is characterized by its generation, which is its rank of appearance. The initial instrument installed corresponds to generation 1. If the current state-of-the-art instrument is generation d, a new instrument will be generation $d + 1$.

2. *Uncertainty in the Evolution of Technology for Bus Upgrades*

Evolution in technologies can lead to improvements in the performance of subsystems other than the payload. The arrival of such a new technology is uncertain and is represented by the probabilistic variable X_B, with $X_B = 1$ when a new upgraded module is available and $X_B = 0$ otherwise. X_B is assumed to follow a Poisson process with a mean time between arrival noted T_B. The probability of a new bus subsystem improvement being invented in the time interval dt is

$$P(X_B = 1) = (1/T_B)\,\mathrm{d}t \tag{2}$$

3. *Spacecraft Failure Rate*

The probability of a successful operation of the satellite decreases as the time elapsed since the last repair increases. The evolution of the probability of success of the operation of the satellite P_S, shown in Fig. 1, is taken from data on the Hubble Space Telescope reliability. A failure is assumed to prevent any observation to be conducted, and the spacecraft is of no utility to the user until the satellite can be repaired.

4. *Uncertainty in the Success of a Servicing Operation*

The probability of success of a servicing operation is noted P_S^{Serv}. The failure of a servicing operation is assumed to be catastrophic and to cause the loss of the target satellite. The satellite cannot be repaired and no additional utility is generated over the rest of the time horizon.

C. Flexibility

The baseline architecture chosen as a reference is a satellite that cannot be serviced. No repair and no upgrade are possible. With a serviceable architecture, three independent decisions are offered to the space operator.

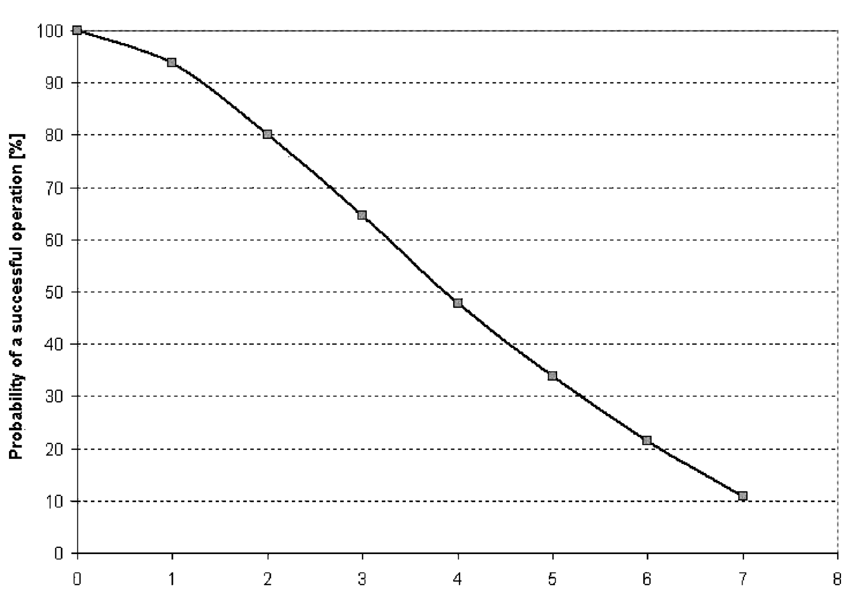

Fig. 1 Hubble Space Telescope reliability depending on the time elapsed since the last repair mission (Leckrone, D., NASA Goddard Space Flight Center, 2001).

1) Satellite repair: The satellite can be repaired restoring the reliability of the satellite to 1.

2) Instrument upgrade: A new instrument can be installed. Because a single payload slot is considered, the previous instrument is turned off and replaced by the new instrument. The payload state of the art is defined as the latest instrument invented. The onboard payload technology is the actual instrument installed on the satellite.

3) Bus upgrade: The space operator can upgrade the bus subsystems. Again the state-of-the-art technology refers to the latest innovation while the onboard technology is the last technology installed on the satellite.

The decision maker can choose not to service the satellite or to carry any combination of these three operations. A servicing mission requires a single visit to the target satellite, independently from the number of operations conducted.

D. Utility

We chose to characterize the utility of an instrument by its discovery efficiency, a metric related to the characteristics of the instrument. This measure, often used to describe and compare the capacity of observation cameras, is defined as the product of the field of view and the throughput of the instrument. The field of view characterizes the space that is viewed by the instrument, whereas the throughput is a measure of the detection sensitivity of the instrument.

The choice of a utility function is a difficult and critical step in the development of the model. Although it must be acknowledged that discovery efficiency does not fully characterize the scientific value of an instrument and cannot be used across all HST instruments (in particular the NICMOS camera was not considered because it operates over different wavelengths), it was preferred over other metrics, such as the number of publications, as it was more easily quantifiable.

Discovery efficiency values were chosen to characterize the cameras installed on the Hubble Space Telescope (WFPC1, WFPC2, ACS and WFC3) based on the data found. Table 1 summarizes the utility values used in the model. Using the utility data from the HST instruments, a utility curve is derived that extrapolates the utility for instrument generations that would appear after the last camera implemented on Hubble. The resulting utility curve is shown in Fig. 2.

Table 1 Estimates of the discovery efficiency and cost of the cameras installed on the Hubble Space Telescope (NASA Goddard Space Flight Center)

Camera	Utility	Cost, million $
WFPC1	1	130
WPFC2	14	127
ACS	110	75
WFC3	180	83

1. *Impact on Utility of the Upgrade of Bus Subsystems*

The discovery efficiency defined earlier is considered as the maximum utility the instrument can provide per year of operation. When a new instrument is developed, we assume that the instrument is designed for the current state-of- the-art bus technology. For example, the bus processor requirements of a new camera will correspond to the characteristics of the state-of-the-art processors implemented in newly designed satellites. The performance of an instrument is assumed to be optimal if the satellite bus subsystems incorporate technologies at least as efficient as the technology that was the state of the art when the instrument was developed. If a new instrument is installed and the bus subsystems are not upgraded to the state-of-the-art bus technology, the instrument is assumed to be constrained by the bus subsystems, and a lower utility is provided. The decrease in utility depends on the number of innovations that separate the onboard technology and the technology for which the instrument has been designed. The actual utility u^d gained for a year of operation of the instrument d is given by

$$u^d = u_m^d \exp\left[-\left(N_B^d - N_B\right)\big/N^{\mathrm{ref}}\right]^2 \tag{3}$$

where N_B^d is the generation of the bus technology that was the state of the art when the instrument d was developed.

2. *Impact of Servicing Missions on Utility*

If an upgrade mission is demanded, the increase in utility is taken into account in the period at which the decision to upgrade is made. Moreover, upgrading the satellite does not significantly impact the operation of the spacecraft, and no down time is considered. A preventive mission launched to repair the satellite before a failure occurs does not impact the operation of the satellite either, and a full utility is gained. In case of a satellite failure, no utility is gained over the period if the satellite is not repaired. If a repair mission is launched, the satellite is assumed not to be operational for 25% of the period to take into account the time to repair.

E. Costs

1. *Repair Cost*

The cost of repairing the spacecraft, not including the price of the servicing mission, is assumed to be proportional to the probability

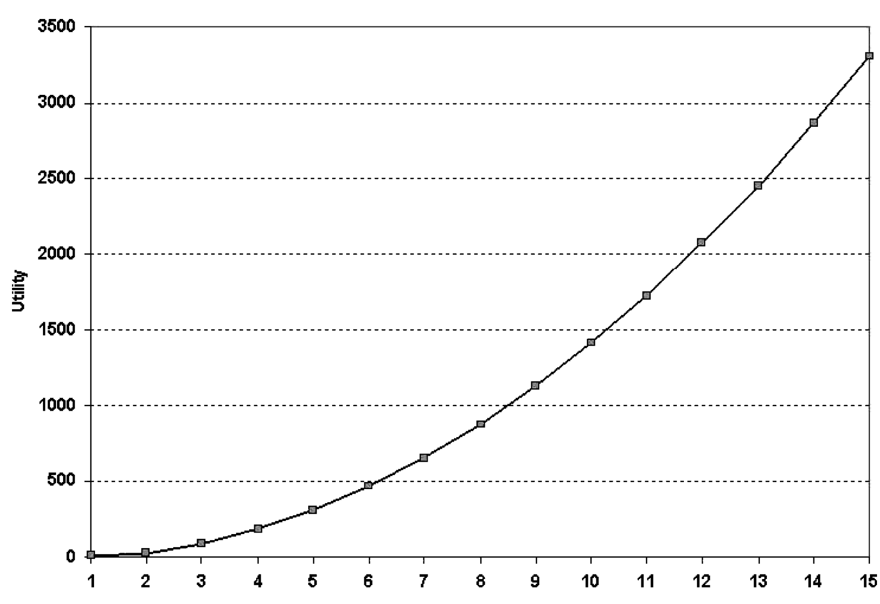

Fig. 2 Utility curve showing the improvement in utility as technology evolves.

of failure of the spacecraft. As a reference, we chose to set the cost of repairing the satellite four years after the last repair mission at $70 million, based on data from Hubble repair missions. The Hubble Space Telescope was repaired approximately every four years, and a typical repair cost is derived from the hardware and software expenses incurred during the servicing mission SM3A (Hubble Program Office).

2. Instrument Cost

Some estimates of the cost of the cameras installed on Hubble are shown in Table 1. The trend is toward a decreasing cost of the instruments, and each new instrument appearing after WFC3 is assumed to cost $100 million.

3. Other Cost Assumptions

The cost of the initial satellite is set at $1 billion similar to the cost of the Hubble Space Telescope. A cost penalty of 10% is assumed to design the satellite for serviceability. Operation costs are set to $21 million per year. Any bus upgrade is assumed to cost $20 million based on some estimates of the cost of bus upgrades on the Hubble Space Telescope. (The advanced computer was estimated at $7 million and new state recorders at $11 million.) Finally, similarly to the Hubble Space Telescope, it is assumed that the spacecraft does not have thrusters onboard to deorbit at end of life, and a servicing mission is required to place the dead satellite on a graveyard orbit or on a trajectory to reenter and burn in the atmosphere. This termination mission is not required if a catastrophic failure occurred during a servicing mission.

F. Decision Model

The decision model used to determine whether a repair or an upgrade mission is launched is illustrated in Fig. 3.

1. Scheduled Repairs

Scheduled repairs are planned to prevent the satellite reliability to decrease below 50%. This corresponds to regular repair missions every four years if no on-demand repair mission is carried out.

2. Decision Model Sequence

First the space operator examines whether a repair mission is required. A repair mission is needed if the satellite fails during the period considered, if the satellite has failed in previous periods and has not yet been repaired, or if a scheduled repair is planned to prevent the reliability of the satellite to drop below the predefined threshold.

Technology upgrade is then considered. An upgrade is decided if the utility per cost metric exceeds a minimum threshold. The utility per cost metric is defined as the ratio of the additional utility provided normalized to the utility gained with current technologies and the cost of upgrading. If a repair mission is necessary for the health of the spacecraft, the price of the servicing mission will be incurred whether the satellite is upgraded or not. Therefore, the cost of the servicing mission is not taken into account in deciding to upgrade. In this case the cost used to calculate the metric is only the cost of the new technology. The utility gained with an upgrade is multiplied by the probability of success of the servicing operation to take into account the risk of on-orbit servicing in the decision making. Different combinations of upgrades are considered with the installation of a new instrument if the state-of-the-art payload is not installed onboard the satellite or/and a bus upgrade if a new bus technology is available. The optimal decision concerning the upgrade of the satellite is derived.

If a repair mission is necessary, the decision maker must then decide if the utility gained by the repair is sufficient to justify the cost of servicing the satellite. The servicing mission is launched if the utility metric, defined as the ratio of the utility gained until the next scheduled repair ΔT and the total cost of the servicing mission, exceeds a minimum threshold. The period until the next scheduled repair is defined as the minimum between the time remaining until the end of the satellite lifetime and the time until the satellite was planned to be repaired. The utility corresponds to the utility of the optimal technology that will be installed. Costs include the price of the servicing mission, the cost of the repair units, and the cost of the upgrade if an upgrade was decided.

Depending on the decisions made for the upgrade and repair of the mission and on the success of a servicing mission at that period,

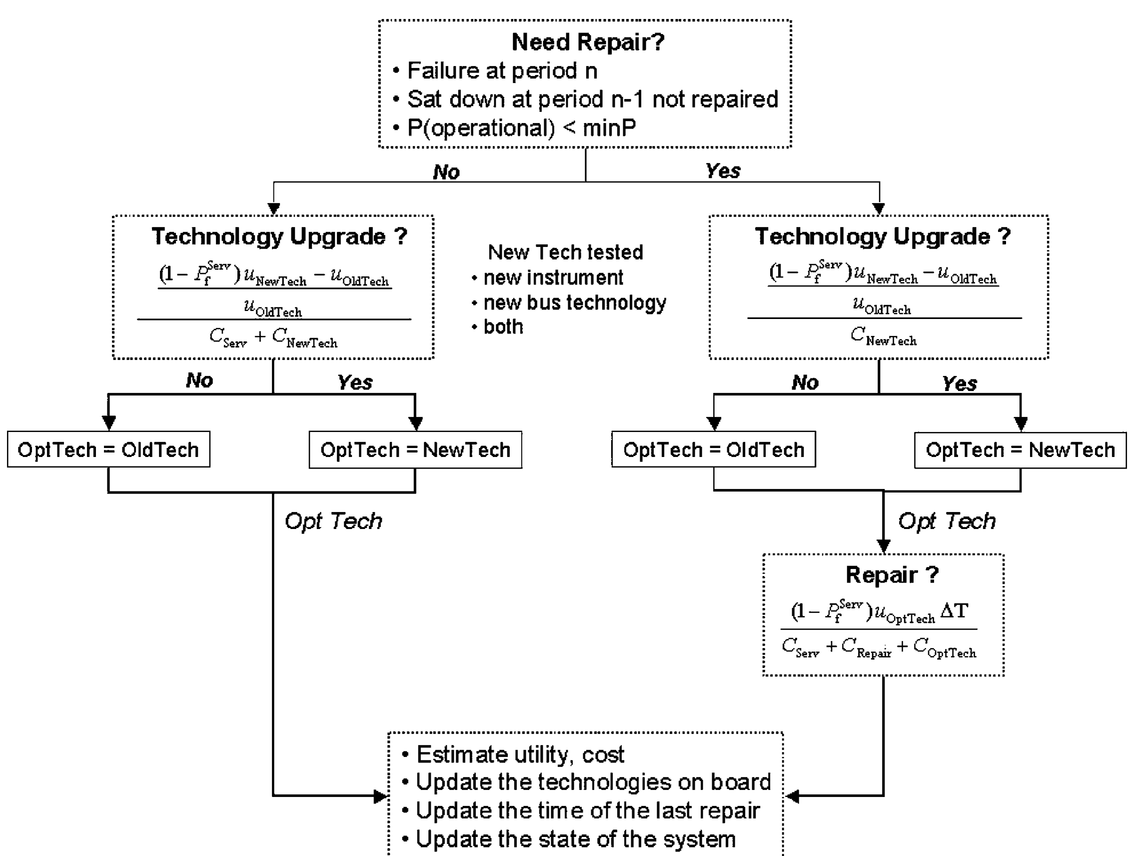

Fig. 3 Decision model for the repair and upgrade of the spacecraft.

the utility gained and the costs incurred over the period until the next decision point are calculated. The technology installed on-board and the reliability of the satellite are updated if necessary.

IV. Monte Carlo Probability Distributions

Figure 4 illustrates a typical result from the Monte Carlo simulation, showing the probability distribution of the total mission utility that can be achieved with a serviceable satellite, normalized to the utility provided by a baseline satellite. In this case, the satellite is always repaired and upgraded to the latest technology. There is no risk of failure when the satellite is serviced, and only the cameras installed on Hubble are considered as potential instruments. The probability shown on the *y* axis is calculated from the frequency of occurrence of a given utility value over the 1500 runs done during the Monte Carlo simulation. Significant improvements in utility can be realized. New instruments provide a huge improvement in performance sometimes multiplying discovery efficiency by a factor of 10. A maximum utility improvement of 2105 is achieved when a new instrument appears every year for the first four years, and the baseline satellite fails during the first year of operation. The scale is artificially large because of the utility metric chosen, and often we will consider the utility improvement as a percentage of the utility that can be gained in an ideal scenario that provides the maximum utility improvement. The scale in Fig. 4 has been rewritten in percentage of the ideal value, which is 2105 in this case.

The risk of catastrophic failure of a servicing mission causes a major change of the mission utility distribution as illustrated in Fig. 5. First, the mission utility for a serviceable satellite can be lower than the baseline utility because the mission might be lost

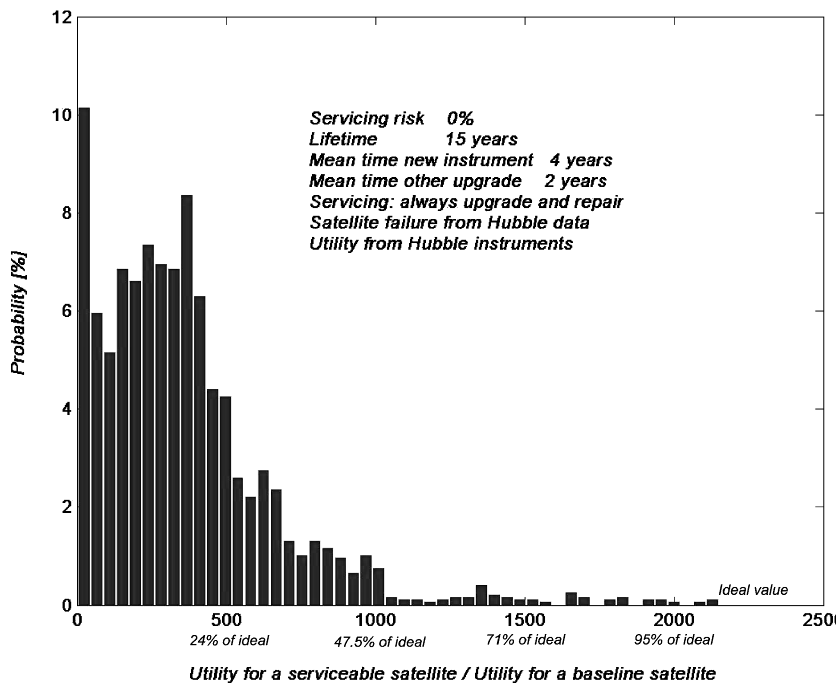

Fig. 4 Probability distribution of the improvement in utility achieved with a serviceable satellite.

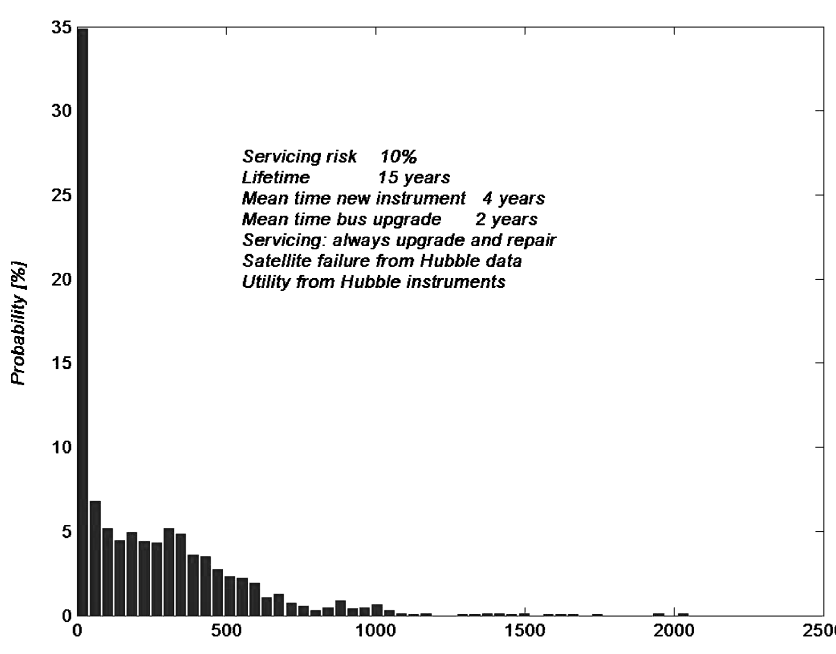

Fig. 5 Probability distribution of the improvement in utility achieved with a serviceable satellite assuming a 10% servicing risk.

during an upgrade mission. Therefore, on the contrary to the case of a servicing risk of 0%, the ratio of a serviceable satellite utility and a baseline satellite utility can be lower than 1. A peak at low mission utility values appears corresponding to scenarios for which the satellite is lost at some point in time during the time horizon. The probability distribution is flattened over the high utility values. For example, a 10% servicing risk causes the probability of multiplying the baseline utility by 500 to decrease from 4 to 2.5%.

V. Repair Missions

The Hubble Space Telescope has been designed to be regularly serviced by the shuttle. The reliability of the satellite drops below 50% after four years of operation if no repair is undergone. The implications of the design choices made for the Hubble Space Telescope and the value of the opportunity to repair are studied.

A. Impact of Satellite Failure on the Baseline Architecture

The utility distribution for a baseline satellite that cannot be repaired is shown in Fig. 6. It can be seen that the mean time for a satellite failure is 3.5 years, which means that because of the choices in the design of the Hubble Space Telescope a repair mission must be carried out on average every 3.5 years to maintain the scientific platform. Each peak in the distribution corresponds to one additional year of operation of the satellite. In all of the scenarios tested, the satellite never survives more than eight years.

B. Using On-Orbit Servicing for Satellite Repair

The value of repairing the satellite (on-demand and scheduled repairs) can be investigated independently from the upgrade option. The mission utility distribution for a serviceable satellite is shown in Fig. 7, assuming that the satellite is always repaired but never

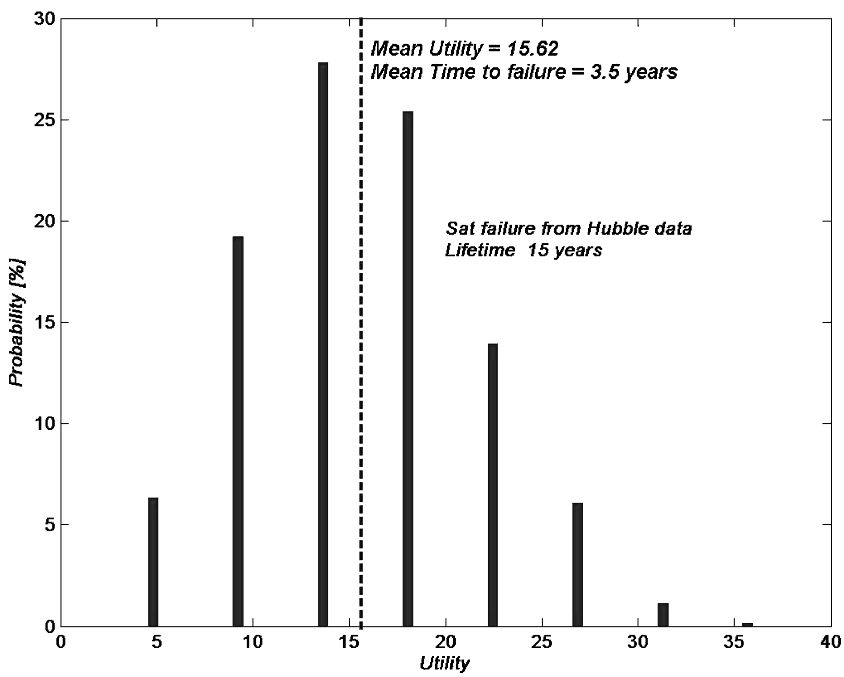

Fig. 6 Probability distribution of the mission utility achieved with a nonserviceable satellite. The probability of failure of the spacecraft is derived from the reliability of the Hubble Space Telescope.

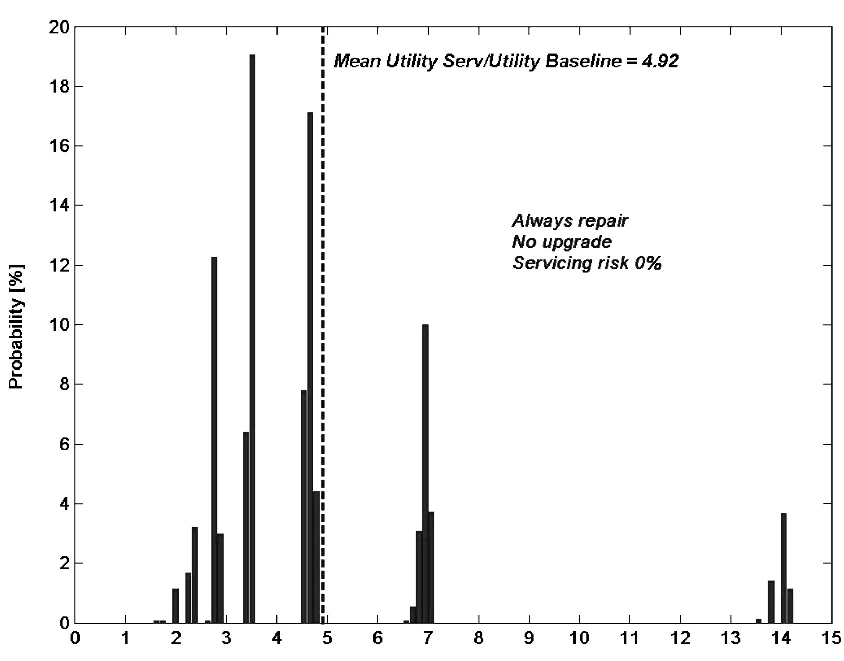

Fig. 7 Probability distribution of the improvement in utility offered by the option to repair. The probability of failure of the spacecraft is derived from the reliability of the Hubble Space Telescope.

upgraded. The distribution is discontinuous, with each peak corresponding to a different time at which the satellite first fails. On average, the utility gained over the mission is almost multiplied by five when the satellite is regularly repaired. Repairing the satellite always increases the mission utility compared to the baseline case because the satellite never survives the 15-year lifetime based on the design choices made if no repair mission is launched.

C. Impact of Servicing Risk on the Option to Repair

The same results are presented when a 10% risk of catastrophic failure during a repair mission is assumed. The distribution of mission utility is shown in Fig. 8. The utility generated over the satellite lifetime is on average four times higher than the baseline utility. However, there is a probability of about 8% to get a utility lower than without repairing the satellite. An average of 3.4 repair missions are carried out corresponding to an average mission cost of $2.3 billion.

VI. Satellite Upgrade and Instrument Technology Evolution

The value of technology upgrade is studied independently from satellite repair by considering a 100% reliable spacecraft. The satellite is assumed to be upgraded as soon as a new instrument or a new bus technology appears. The impact of the pace at which new instruments and new payload capabilities appear is investigated.

A. Impact of the Mean Time Between Appearance of New Instruments

The distribution of the utility that can be expected from a serviceable satellite is shown in Fig. 9 depending on the mean time between

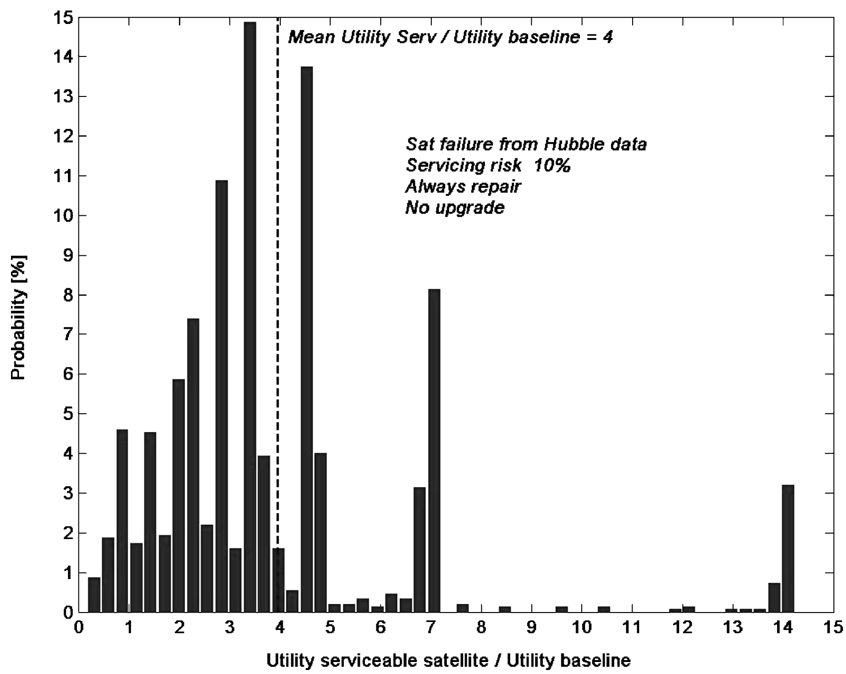

Fig. 8 Probability distribution of the improvement in utility offered by the option to repair. The probability of failure of the spacecraft is derived from the reliability of the Hubble Space Telescope. A servicing risk of 10% is assumed.

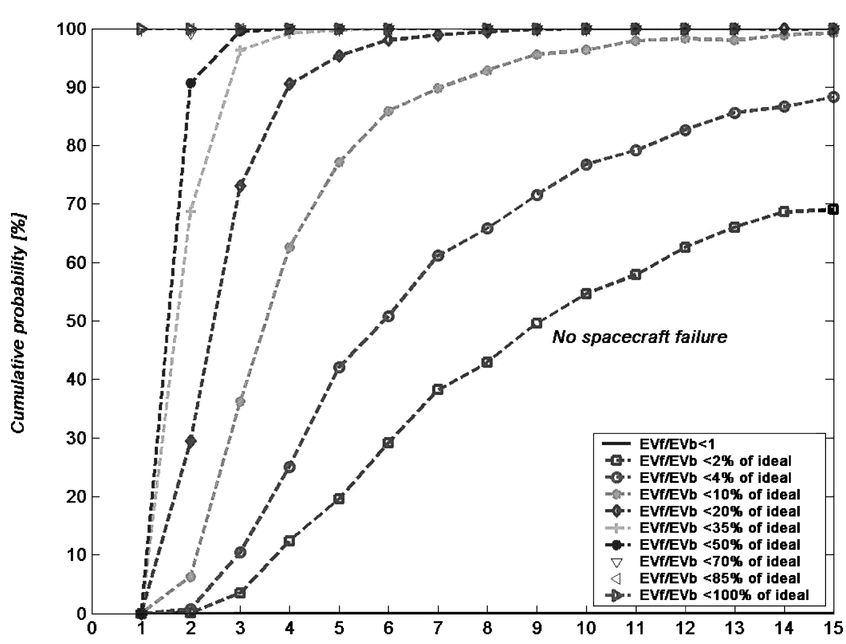

Fig. 9 Probability distribution of the utility offered by a serviceable satellite assuming a 0% servicing risk.

arrival of new instruments, assuming that an upgrade mission can be offered with a 0% risk of catastrophic failure. Utility values are normalized to the baseline utility and are represented as a percentage of the ideal value. Different reference utility levels are defined. The curves in Fig. 9 represent the probability of getting a utility below each of the utility reference levels chosen. The figure can be understood as a map showing the probability of getting a utility within certain predefined ranges. Because there is no risk of failure during a servicing mission, the utility gained with a serviceable satellite is always higher than the baseline utility. At one extreme, if a new instrument is available every year on average the space operator is assured to significantly improve the scientific return of the mission by getting at least 50% of the maximum utility improvement. As the time between new instrument arrivals increases, the potential improvement in utility decreases. The probability of being in the lowest range (at most 2% of ideal utility improvement) increases from 0% when a new instrument is available every year on average to 65% when a new instrument is available every 15 years on average. The value of technology upgrade increases as the pace at which technology evolves increases. Therefore, fast-evolving technologies such as computer hardware are very promising candidates for satellite upgrade.

B. Impact of Servicing Risk

Figure 10 shows the same utility map as Fig. 9 for a servicing risk of 10%. The probability of decreasing mission utility by regularly upgrading the satellite is significant. For a mean time of arrival between new instruments of one year, there is a 20% probability of decreasing mission utility by servicing the satellite. As the mean time between innovations increases, the probability of decreasing mission utility with a serviceable satellite decreases. In this case, the decision maker upgrades the satellite as soon as a new instrument appears. The faster is the pace of innovation, the more servicing missions are attempted, and therefore the probability of a servicing failure over the satellite lifetime increases. Two trends can be noted in the utility map. At low mean times between innovations, the distribution shifts towards higher levels of utility as the mean time between arrival of new instruments increases. At higher value of the mean time between innovations, the reverse effect is seen. This results from the interaction of two competing effects. If technology evolves faster, more instruments are available, and therefore more upgrade missions are launched. This translates to potentially higher mission utilities because more capable instruments are installed onboard. However, this also increases the risk of a servicing failure causing the loss of the satellite and decreasing the mission utility. With these two effects, a maximum utility is obtained when a new instrument is invented every two to three years on average.

VII. Upgrade Decision Model

The map of average utility gained and average cost incurred depending on the upgrade decision model chosen offers an interesting decision tool. Figure 11 shows such a utility cost map. As the upgrade metric threshold increases, the average cost and the average utility decrease. Such a map can be used by decision makers to determine an adequate utility threshold depending on total cost constraints or minimum utility levels. The point corresponding to the lowest cost and lowest mission utility represents a case for which no upgrade is performed. The first group of points offering a normalized mission utility close to 4% of ideal corresponds to the cases where one upgrade is carried out on average over the satellite lifetime. A significant increase in utility can be gained. As the upgrade metric threshold increases, the decision maker waits until a new innovation appears that offers enough capability to justify the cost of a servicing mission. Therefore the servicing operation is on average carried out later, which can explain the spread in the discounted costs. A more capable instrument is installed; however, it is installed later, and there is a lower chance that such an instrument is ever invented, which explains the spread in mission utility. A second group of points can be seen corresponding to an average of about 1.5 upgrade missions for a total cost around $2 billion. The same arguments can be used to explain the spread in utility: the upgrade metric threshold impacts the generation and capability of the instruments installed, the time at which the upgrade is carried out, and the probability of arrival of a new instrument offering enough capability to justify the servicing mission. If the upgrade metric threshold is further decreased, the average number of servicing missions demanded increases. The increase in utility and cost is large enough to see distinct points on the utility cost map. The average utility reaches a plateau when the upgrade is implemented as soon as the new technology appears.

VIII. Design Choices

Because of the reliability curve of the Hubble Space Telescope, a repair mission is necessary every three to four years on average to maintain the spacecraft operational. The impact of such design choices relating to the level of redundancy or the serviceability of the satellite is explored. A tradeoff exists between regularly repairing the satellite in orbit and designing the satellite for a higher level of

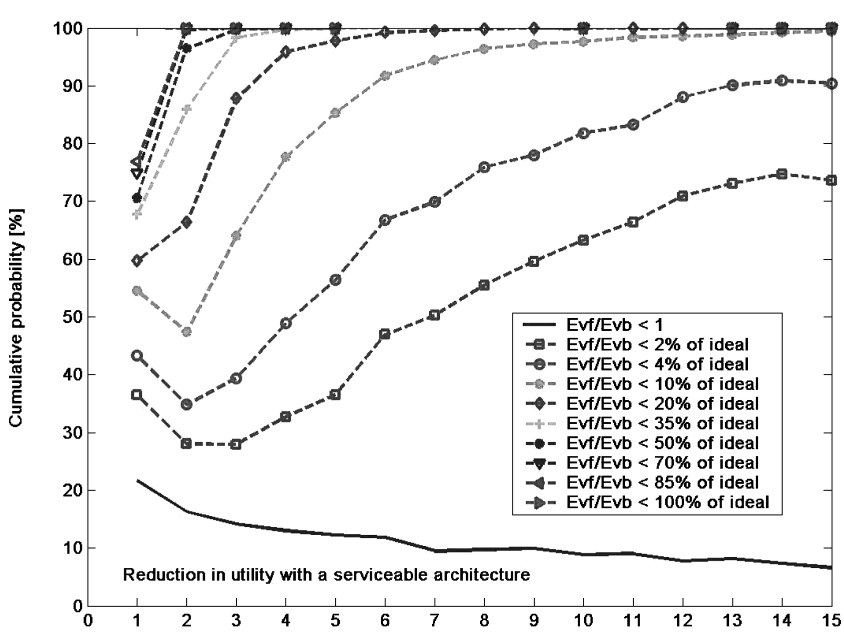

Fig. 10 Probability distribution of the utility offered by a serviceable satellite assuming a 10% servicing risk.

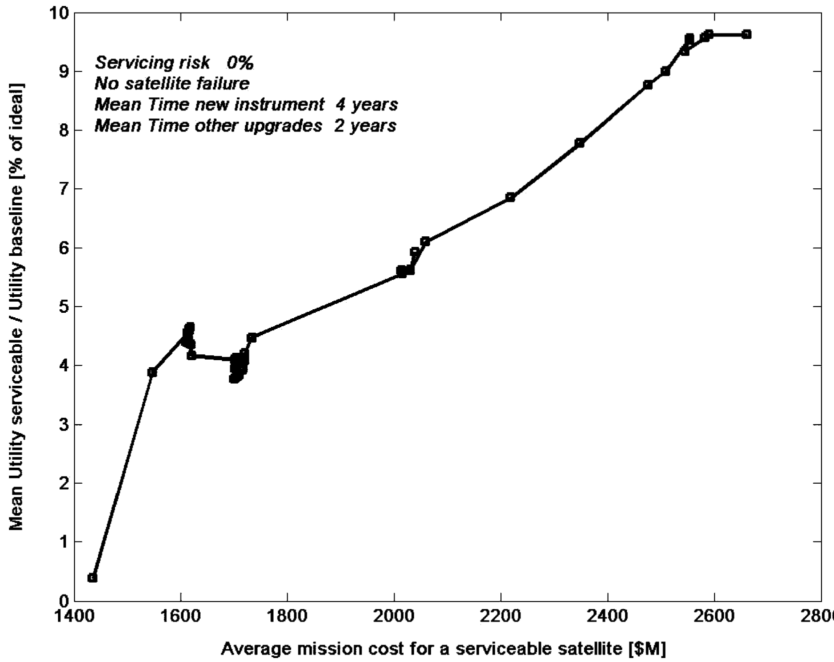

Fig. 11 Mean mission utility and average total mission cost for different upgrade thresholds assuming a 0% servicing risk. Only upgrade missions are considered, and the spacecraft is assumed to be 100% reliable.

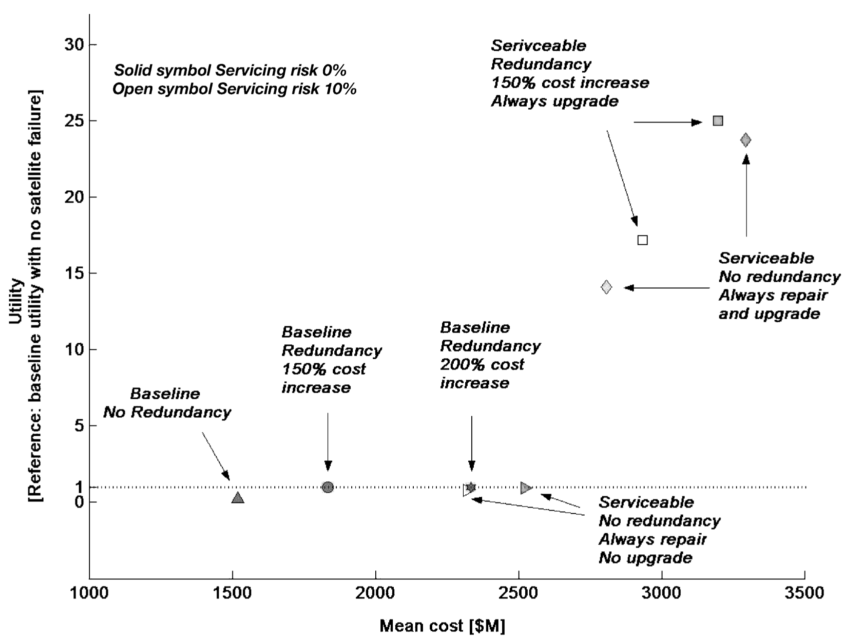

Fig. 12 Impact of various design choices on the mission utility and total cost of the architecture.

reliability. The effect of different design choices on mission utility and lifetime costs is shown in Fig. 12.

The following assumptions apply for the results shown in Fig. 12:

1) A baseline satellite refers to a nonserviceable architecture. (No upgrade and no repair are possible.)

2) For serviceable satellites, three cases are considered: a) "always repair—no upgrade," where the satellite is designed to be repaired but not upgraded in orbit, b) "redundancy—always upgrade," where the satellite is designed to be reliable (no servicing repair mission) and to be upgraded in orbit, and c) "always repair and upgrade," where the satellite is designed to be both repaired and upgraded in orbit. The decision model has been chosen so that, if the satellite is designed for such servicing missions, the satellite is always repaired when required and upgraded as soon as a new technology appears.

3) It is assumed that redundancy ensures a 100% reliable satellite but requires additional expenses in the initial satellite design.

4) As the impact of redundancy on spacecraft design cost is difficult to estimate, two cost penalty levels were shown as references: a cost penalty of 200% as an upper limit and a cost penalty of 150% as an intermediate value.

In Fig. 12, the mean utility is normalized to the average utility offered by a baseline redundant satellite. Let us first consider the architectures for which no upgrade is done. Designing for serviceability and regularly repairing the satellite is more expensive than designing for reliability even if redundancy doubles the initial satellite cost. Therefore it can be concluded that designing for serviceability exclusively for satellite repair does not seem viable, with the current assumptions and in particular with a servicing mission cost close to a shuttle launch price.

Let us consider next the architectures that can be upgraded, with the two alternatives: 1) a satellite designed for a high reliability for which servicing missions are exclusively carried out to install technology upgrades or 2) a satellite for which servicing missions are carried out both for repair and upgrading. If the cost penalty of designing for reliability is below 150%, redundancy appears as more efficient than on-orbit servicing repair and upgrading. The increase in cost incurred by the upgrading operations is higher for a redundant satellite than for a repairable satellite because repair and upgrade operations can be carried out during a single servicing mission and the servicer operation accounts for the major part of the servicing mission cost.

The higher utility offered by a reliable satellite compared to a serviceable satellite for a 0% servicing risk can be explained by the loss of utility incurred during satellite downtime before the repair servicing mission. Designing for serviceability exclusively for satellite repair does not seem a viable design choice with a servicing cost as high as the cost of a shuttle flight. If upgrade servicing missions are demanded, repairs can be conducted at the same time for a small increase in cost. Critical systems could therefore be designed for reliability, whereas noncritical subsystems or subsystems for which reliability is costly could be replaced during upgrade missions. For higher upgrade metric thresholds or if technology evolution is slower, fewer upgrade missions are demanded, driving design choices towards more reliability and less reliance on serviceability.

The tradeoff between designing for reliability and designing for serviceability is necessarily dependent on the characteristics of the case studied (cost, servicing, and technology assumptions). In particular, the price of the servicing mission, very high in this case because we are considering a shuttle flight, will have a major impact. However, the model can be adapted to the specific case studied and can provide useful insights into optimal design choices.

IX. From Manned to Unmanned Servicing Missions

The preceding results were based on the Hubble Space Telescope case that uses manned on-orbit servicing. The main parameters that can defer from manned to unmanned on-orbit servicing are discussed. In particular, the impact of servicing cost and servicing risk on the mission cost and utility are investigated.

A. Designing for Serviceability

The satellite must be designed to be serviced for both manned and robotic servicing operations. Astronauts have a limited mobility in space, and the modules must be designed to limit the number of operations and simplify access and maneuverability of the components. It is considered that the design for robotic servicing operations would not be radically different from what is currently done for astronauts. One of the best ways to design subsystems for extravehicular activities could be to make them compatible with robotic operations. The cost penalty for designing a satellite for manned and unmanned serviceability should not be radically different.

B. Scope of the Servicing Operation

One of the main differences between manned and unmanned operations is believed to be the degree of flexibility that can be achieved. Robotic missions are efficient for operations that are planned in advance and for which the satellite has been designed. However, if a failure or a problem occurs that has not been thought of in advance, it will be difficult for a robotic servicer to accomplish the operation. Humans can adapt to the situation and improvise. Some unplanned operations have been carried out by astronauts on the Hubble Space Telescope, such as the repair of a power unit box that was not initially designed to be serviced. The present model could be adapted to differentiate between subsystems that can and cannot be repaired by a robotic servicer, assigning a different probability of failure for each category.

C. Servicing Risk and Cost

One of the main reasons why the on-orbit servicing community examines the development of an unmanned infrastructure is to reduce the cost of servicing to make it affordable for most space missions. The development of a large demand for on-orbit servicing requires the cost of a servicing mission to be significantly lower than the cost of a shuttle flight. As far as servicing risk is concerned, it can be argued that manned operations might reduce the risk of a catastrophic failure during the servicing operation.

The impact of servicing risk and servicing cost on the demand for on-orbit servicing, the cost of the mission, and the utility gained over the satellite lifetime are studied in more details. The decision model chosen for the study requires a minimum utility of 22 to justify a repair expense of \$100 million and an upgraded utility of at least 1.2 times the current utility to justify an upgrade expense of \$100 million.

Figure 13 illustrates the corresponding evolution of mission utility and cost depending on the servicing infrastructure characteristics. Utility is normalized to the baseline utility. Servicing risk significantly reduces the mission utility. A 10% risk causes the mean utility to drop from 45% of ideal to 30% of ideal. The impact of servicing cost appears different at low and high servicing costs. At low servicing costs, utility is more sensitive to an increase in servicing

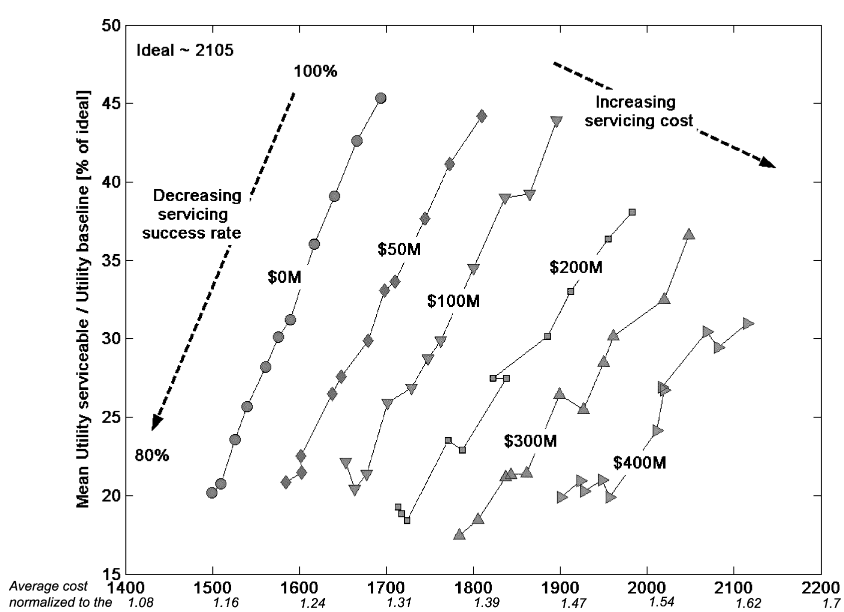

Fig. 13 Impact of servicing risk and servicing cost on the mission cost and utility of the serviceable architecture.

risk than in servicing cost. At high servicing costs, utility decreases rapidly as the cost of a servicing operation increases. At low costs of servicing, up to $100 million, the first new instruments are installed as soon as they appear providing a high utility. As the cost of servicing increases within this low range, the last upgrades are canceled, but the first upgrades are still carried out. The last instruments that are cancelled are those that were operating for a shorter period and for which the probability of appearance was lower. Therefore the drop in utility is small because the first upgrades are assured. If the cost of servicing is high, above $200 million in this case, only one or two upgrade missions are carried out. As the cost of servicing increases within this high range, the space operator has to wait until a more capable instrument appears that offers enough capability to justify the high servicing cost. At high servicing costs, the first upgrades that occur early on in the mission and that are the most probable to appear are not performed. Therefore, the loss in utility caused by an increase in servicing cost is larger.

X. Model Limitations and Future Work

Some limitations to the present model must be underlined as well as potential future refinements:

1) The sensitivity of the results and conclusions to some model assumptions must be investigated in more details, in particular the sensitivity to the spacecraft failure probability model.

2) The spacecraft failure model should be refined as the present model only accounts for catastrophic failures leading to the destruction of the mission. Two features could be integrated into the model: 1) the potential reduced satellite performance following a partial spacecraft failure, making the distinction between catastrophic and noncatastrophic failures; and 2) failures that cannot be repaired using on-orbit servicing, taking into account the degree of spacecraft serviceability (which will be dependent on the initial cost of designing for serviceability).

3) The utility model could be refined by considering more than one instrument and taking into account the added value of observations with different instruments.

4) As illustrated by the consequences on the HST mission of the shuttle grounding following the *Columbia* accident, the availability of the servicing infrastructure to perform the servicing mission is an additional source of uncertainty, which seems critical and should be taken into account in the model.

5) The tradeoff between regularly repairing the spacecraft and designing for reliability should be investigated in more details. In particular, efforts should be devoted to quantifying the impact of designing for a higher reliability level on spacecraft cost.

6) The HST servicing scheme is likely not representative of future typical servicing missions. The main differences between the HST servicing missions and likely characteristics of typical servicing missions should be analyzed to investigate their impact on the model assumptions and results.

XI. Conclusions

The value of technology upgrades on a scientific mission has been modeled, based on the case of the Hubble Space Telescope, a unique example of an unmanned scientific platform initially designed to be regularly serviced by the space shuttle. The impact of the repair of the spacecraft, the installation of new instruments, and the upgrade of bus subsystems are included. A Monte Carlo simulation is used to model uncertainty in the arrival of new technologies, random spacecraft failures, and catastrophic failures of a servicing operation. The installation of new more capable instruments and of new technologies to ensure compatibility of the bus with the upgraded payload can provide a huge increase in the scientific utility of the mission. A huge increase in mission utility can be achieved at a lower cost than if the satellite had been replaced. The value of upgrading increases as the rate of innovation accelerates. If a servicing mission is risky, a tradeoff appears between upgrading more often to achieve a higher utility and the increased risk of losing the satellite as the number of servicing missions increases. The decision model used by decision makers defines the upgrade strategy, which can vary between upgrading as soon as a new technology appears or waiting until the impact of the innovation is large enough to be considered worth the cost of the servicing mission. The main differences between manned servicing operations, similar to the maintenance operations conducted on the Hubble Space Telescope, and unmanned robotic missions are then examined. In particular, the impact of the risk and cost of servicing on the mission utility is investigated.

On-orbit upgrade appears as a promising operation in the case studied because the potential improvement in utility is large and there is no other method to achieve the same improvement in utility at similar cost and risk levels.

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