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Satellite Constellation Architecture and Design to take Advantage of On-Orbit Servicing and Repair

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SATELLITE CONSTELLATION ARCHITECTURE
AND DESIGN TO TAKE ADVANTAGE OF
ON-ORBIT SERVICING AND REPAIR

By

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Abstract

Access to space is becoming less expensive, which is allowing smaller companies with big ideas, such as on-orbit servicing and repair, to enter into the space industry. On-orbit servicing and repair provides capabilities, such as towing, refueling, inspections, and physical repair, to add additional life to on-orbit satellites by resolving life-limiting issues. On-orbit servicing and repair is technically possible, but there is still one major issue that continues to stifle the on-orbit servicing and repair market -- "satellites are not built with servicing in mind" (Parker, 2015).

The on-orbit servicing and repair industry is stagnate due to a challenging conundrum. Potential satellite customers are unwilling to pay for on-orbit servicing or repair until the capability is successfully demonstrated on-orbit. Unfortunately, it is difficult for the industry to prove the capability without customers willing to take a little risk. This "chicken and egg" scenario leaves several satellite manufacturers unwilling to change their satellite architectures and designs to accommodate on-orbit servicing and repair. This paper attempts to show the "how" and the "why" the space industry should change their architectures and designs to enable on-orbit servicing and repair.

There are many satellite bus components/consumables, including software, that could fail and shorten a satellite's life. However, the bus components/consumables that fail the most, batteries, solar arrays, propellant, reaction wheels, and power distribution components, are best suited for on-orbit servicing and repair. These five bus components/consumables, in addition to the satellite as a whole, will require several design changes specific to each bus component, which will drive new or updated requirements for each. Additionally, to increase the effectiveness and efficiency of on-orbit servicing and repair, satellite architectures will require changes, such as an on-orbit depot, on-orbit warehouse, and on-orbit gas tank.

The consequence of changing satellite design will affect satellite ground testing. The on-orbit servicing and repair processes, such as rendezvous, docking, and EMI/EMC will require testing between the on-orbit servicer and its customer satellite. The on-orbit servicing and repair capability provides the satellite manufacturer the ability to reduce qualification testing, run-time testing, and burn-in testing. This capability increases the probability that redundancy for these five bus components/consumables is no longer required, which reduces the hardware cost and testing schedule for each satellite. On-orbit servicing and repair creates seven new risks -- do no harm, debris and contamination, on-orbit servicer reliability, politics, cyber security, liability, and unintended consequences -- that must be mitigated.

Two simple business cases demonstrate the possible value of this new capability. The business case for Low Earth Orbit (LEO) does not provide a return on investment, because on-orbit servicing and repair in LEO is too difficult and too expensive to justify an investment. On the other hand, the business case for Geosynchronous Orbit (GEO), in two distinct scenarios, does provide a return on investment. Those two scenarios are a beginning of life anomaly, and an extension of life.

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Introduction

The space industry is evolving. Satellites are becoming smaller, and cheaper to build, with decreasing launch costs. The reduction in costs has brought new companies into the space industry. The majority of these new companies are start-up companies, and they have many creative ideas that take advantage of the benefits of space, which could dramatically change the way the Department of Defense operates in and views space.

One of those creative ideas has been the concept of on-orbit servicing (OOS), which is not the first time that this capability has been discussed. The National Aeronautics and Space Administration (NASA) repaired the Hubble telescope "during five separate servicing missions between 1993 and 2009 … [to replace] mechanical parts and two scientific instruments, but also in-space repairs for two existing instruments" (Redd, 2015). The Hubble telescope was built "flexible enough to accommodate a variety of unforeseen repairs and upgrades" (Redd, 2015), and allowed astronauts to conduct the servicing and repairs. Those NASA missions to repair the Hubble telescope are an example of human OOS. The latest advances in technology and coinciding cost reductions have made the concept of robotic OOS more viable in the space industry. A concept that takes OOS one-step further is on-orbit repair (OOR). Today, most experts agree that OOS is a non-invasive way to provide satellite life extension, inspections for anomaly diagnosis, and towing satellites from one orbit to another. OOR adds the ability to provide physical manipulations of a satellite to resolve anomalies, and/or upgrade existing components with the latest technology, by using "robotic arms that are even more mobile than human arms" (Cantieri, 2017).

The scope of this paper includes both on-orbit servicing and on-orbit repair. It will describe the feasibility of robotic on-orbit servicing/repair (OOS/R) for satellite bus components/consumables only, and the effects of OOS/R on satellite architecture and design using a systems engineering approach.

In order for the space industry to accept OOS/R, changes to the current satellite architecture will be required. Slightly modifying the satellite's architecture will increase the effectiveness of OOS/R. It is important to note that architectures utilizing OOS/R will be different in GEO and LEO due to the differences in orbital mechanics. The GEO OOS/R architecture could include an on-orbit depot to conduct servicing and/or repair, an on-orbit warehouse to store ready-to-use component replacements, and an on-orbit gas tank to easily provide additional fuel to satellites in need. The LEO OOS/R architecture would include none of those additional pieces.

OOS/R can mitigate many different types of satellite anomalies. In order to maximize OOS/R effectiveness, while minimizing changes to current satellite architecture and design, the most frequent on-orbit anomalies are the best candidates for OOS/R. The five bus components/consumables that experience the most frequent on-orbit anomalies are the batteries, solar arrays, loss of propellant, reaction wheels, and power distribution components. These bus components/consumables, as well as the overall satellite design, will require changes to enable OOS/R. Modifying ground testing will need to occur to ensure OOS/R success.

The architecture and design changes have the potential to create new risks that require mitigation. Do no-harm, debris and contamination, servicer reliability, politics, cyber security, liability, unintended consequences, and communication delays are eight risks of varying consequence and likelihood. Subjective risk analysis has shown several medium risks, but no high risks for OOS/R.

Causing the slow growth of the OOS/R market over the last decade is the chicken and egg conundrum. There are very few customers for OOS/R companies because those customers want to see the technology proven before taking on additional risk for their satellites, but OOS/R companies cannot show that their technology works without a few customers (Roesler, Jaffe, Henshaw, 2017). There have been several on-orbit demonstrations, but there has yet to be a customer that is willing to pay for OOS/R services. In addition, satellite builders are reluctant to make design changes in their satellites to accommodate OOS/R because the OOS/R business model did not provide a worthwhile return on investment. Fortunately, for the OOS/R market, this is shifting, as improved technology and lowered costs have opened the door for a profitable business case. A couple of companies have accepted the concept of OOS/R for their current satellites on-orbit, and it will not be long before more companies join the OOS/R movement.

On-Orbit Servicing and Repair

The term on-orbit servicing "refers to operations conducted on in-orbit spacecraft intended to accomplish some value added task. While most may think that this implies use of robotics to mechanically assist a satellite in need, it also refers to activities such as providing 'life extension' or performing visual inspections" (Benedict, 2013). NASA was the first to conduct OOS/R in 1984 "when the 14th Space Shuttle flight retrieved Palapa B2 and Westar 6, two failed communication satellites whose identical anomalies had left them stranded in useless orbits far below their intended geosynchronous target" (Parker, 2015). NASA also conducted human on-orbit repair on the Hubble Space Telescope during several shuttle missions between 1993 and 2009. Therefore, the concept is not new, but what is new, is the ability to use robotics in space to conduct semi-automated OOS/R commanded from the ground. The maturity of robotics has now made OOS/R more realistic. Human OOS/R has its benefits, but it is not a practical long-term solution due to the high risk to human life. In addition, while human OOS/R in LEO has been accomplished, sending humans out to GEO is extremely hazardous.

Multiple demonstrations and prototypes, both on the ground and on-orbit, by multiple companies and Government agencies have shown that the robotic technology is viable, and with minimal risk. "To do even the most basic operation on a satellite, a robotic repair vehicle must be able to manipulate a very expensive, relatively fragile device under challenging conditions" (Roesler, Jaffe, Henshaw, 2017). The Defense Advanced Research Project Agency (DARPA) has implemented a technique called compliance control "to ensure the robot is gentle enough to manipulate client spacecraft components without damaging them" (Roesler, Jaffe, Henshaw, 2017). Robotics manipulation is just one process. There are other elements of the OOS/R process.

The ability of the on-orbit services to rendezvous and dock with a satellite is critical. On-orbit servicers need diagnostic capability, which could include cameras, microphones, probes, and telemetry, tracking, and commanding (TT&C) and data-bus connectivity with the anomalous satellite. Minimal debris generation by the on-orbit servicers is very important. Debris can cause issues on-orbit that could outweigh the benefit of OOS/R capability. The entire OOS/R process includes all of these factors, and Figure 1 depicts this process.

Identifying a service or repair issue on the satellite is the first step. This step is relatively easy, since anomalies are self-detected on-board the satellite, and anomaly information is transmitted to the ground. Determining whether the anomaly could be resolved with an on-orbit servicer is a challenge. Therefore, to gather additional information to determine whether the on-orbit servicer can resolve the anomaly, an on-orbit servicer would travel to the anomalous satellite and conduct further diagnostic testing.
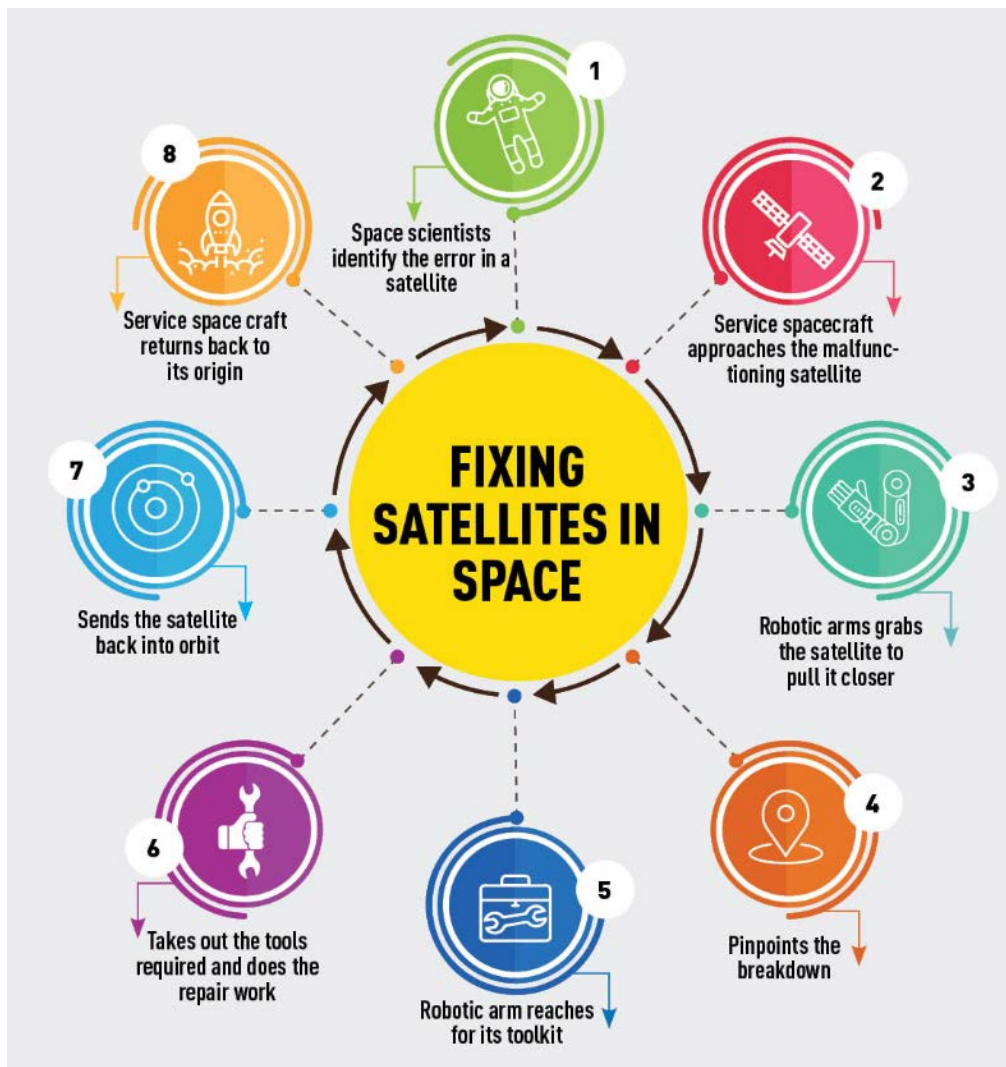

Figure 1 – On-orbit Service or Repair Process (Choudhary, 2018)

If the issue can be resolved, the next steps (steps 2 and 3 in Figure 1) is for the on-orbit servicer to rendezvous with the anomalous satellite, where the on-orbit servicer would conduct proximity operations in-order-to physically dock with the satellite. Proximity operations and docking are high-risk activities that require a well thought-out Concept of Operations (CONOPS) before execution. Ground simulations would help to mitigate that risk, but there will be physical contact between the two satellites.

It is conceivable that the OOS/R customer may desire that the OOS/R take place in a safer orbit or an orbit where debris is less of an issue. To enable this desire, after the on-orbit servicer physically docks with the customer satellite, the on-orbit servicer would need to tug the anomalous satellite to the desired orbit before the service or repair could take place.

In the fourth step, the on-orbit servicer will collect further diagnostic information through cameras on the end of long robotic arms that provide valuable imagery. If the on-orbit servicer can plug into the anomalous satellite's TT&C data bus though an external interface, the on-orbit servicer will be able to gather current TT&C information, and run diagnostic scripts on the flight software. If the anomalous satellite has lost transmit capability, it would be impossible for ground crews to know how to resolve the issue. In this case, the on-orbit servicer can transmit the anomalous satellite's diagnostic data to the receiving antenna on the ground. Once the ground has the data, the root cause can be determined, and a corrective action plan developed. The ground system includes a combination of transmit and receive antennas, data processing facilities, and the satellite command and control facilities.

Utilizing the robotic capability to service or repair the issue utilizing a correction action plan are the fifth and sixth steps. The on-orbit servicer will use several different tools on the end of the robotic arms, depending on the job that it needs to accomplish. The ground will control the service or repair using autonomous and semi-autonomous control. The on-orbit servicer has complete control without human involvement on the ground during autonomous operations. In semiautonomous operations, both the on-orbit servicer and a human on the ground conduct the service or repair. Simple service or repair operations could use autonomous operations. High-risk operations would benefit from semiautonomous operations, or human "in-the-loop" operations to stop an activity if there is an emergency. Lastly, during the service or repair, debris mitigation is required, since debris generation is a risk to the customer satellite, on-orbit servicer, and neighboring satellites in the same/similar orbit.

After the on-orbit servicer resolves the anomaly, it will undock from the repaired satellite, and the repaired satellite will return to normal operations (step 7 in Figure 1). If a different orbit was required for safety reasons, the on-orbit servicer will return the repaired satellite to its original orbit once the service or repair is complete. Finally, in step 8, the on-orbit servicer returns to its baseline orbit or moves on to its next customer.

Experts in the industry believe that rendezvous and docking are the highest risks, not the robotic technology. Several companies and Government agencies are conducting research and development to improve rendezvous and docking systems. In addition, the entire space industry would benefit from a standardized CONOPS.

Stakeholder Analysis

The OOS/R market has many stakeholders, and some stakeholders have more influence than others do. A stakeholder analysis provides context and identifies possible issues or risks in the OOS/R market. In 1991, Aubrey L. Mendelow, from Pennsylvania State University, created a stakeholder analysis methodology that categorized a stakeholder's "Power (the ability to influence our organization strategy or project resources) and Interest (how interested they are in the organization or project succeeding)" (Eriksen-Coats, 2018). The stakeholder analysis below utilizes Mendelow's method.

The OOS/R market has two distinct parts, the commercial sector, which operates to provide capability for a profit, and the Government sector, which operates to provide capabilities for the nation. This paper focuses on the commercial market and the U.S. Government. Both are important, but the commercial market currently controls the OOS/R market. Congress, the media, NASA, Department of Defense (DoD), National Labs, satellite manufacturers, OOS/R companies, bus component manufacturers, the launch community, and potential customers are the primary stakeholders. Uniquely, NASA and the DoD could both be creators of on-orbit servicers and customers of OOS/R. Figure 2 below depicts the stakeholder analysis graphically using Mendelow's matrix.

Congress plays a large role in defining federal policies for the commercial sector, and regulations and budgets for NASA, the DoD, and the National Labs. Agendas of the members of Congress drives their support decisions. Members of Congress are supportive when an OOS/R company is within their district and generating jobs for their constituents. Increasing taxpayer burden or spending too much money lessens the support of our members of Congress. Members of Congress vary in their interest level, but they have significant power. This puts Congress in both the Keep Satisfied and Manage Closely quadrants.

The media may be neutral, supportive, or disapproving. Their support is difficult to determine because the media can be biased. Therefore, for the purposes of the stakeholder analysis, we will assume the media is neutral in their support. Their interest level varies depending on what is currently occurring in the OOS/R market. Unlike Congress, the media has little power. Although they have the ability to sway public opinion, it is unlikely that media can influence how dollars are spent. Therefore, the media is in the both the Monitor and Keep Informed quadrants.

NASA has been studying, and implementing OOS/R capabilities for more than two decades, so their support is positive, and their interest level is high. Their level of power is debatable, but given their ability to obtain and spend billions of dollars of public funds each year, their power is considered high. This puts NASA in the Manage Closely quadrant.

The DoD has been interested in OOS/R for a shorter time than NASA but they are a similar stakeholder. The DoD's interest has increased recently because of the practicality and potential benefit to their missions. They command a large budget and greatly influence the space industry. Therefore, the DoD is in the Manage Closely quadrant.
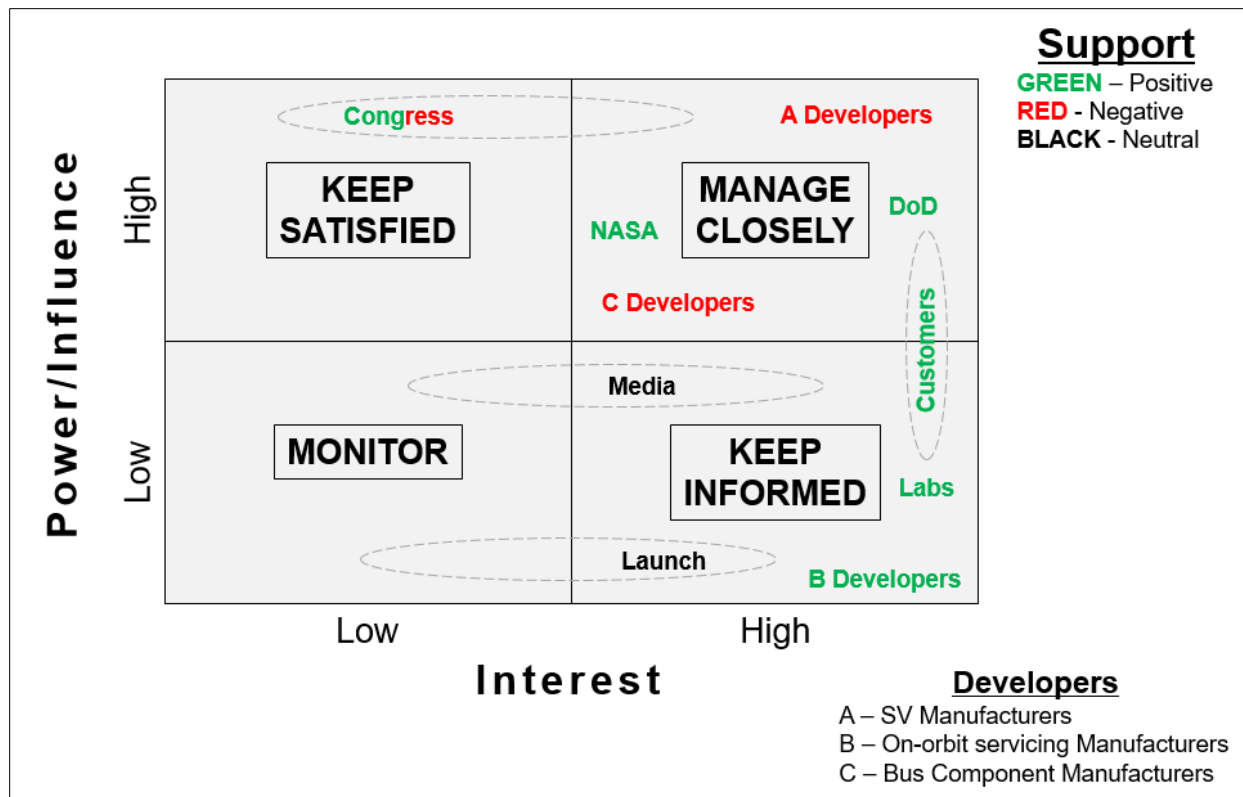
Figure 2 – Stakeholder Analysis

The National Labs, which include DARPA, Sandia Lab, Air Force Research Lab (AFRL), Navy Research Lab (NRL), and Army Research Lab (ARL), among others, are all supportive of OOS/R. The National Labs are currently sponsoring several research projects and prototypes in space, which demonstrates their interest level is high. DARPA, in particular, is leading the way in developing the OOS/R capability on several projects, and advocating for international OOS/R standards. The National Labs power, however, is low because they lack the funding to influence industry and commercial decisions. The National Labs is in the "Keep Informed" quadrant.

OOS/R can possibly hurt satellite manufacturers' profit margin. There is a belief that OOS/R could lead to smaller satellites that last longer on-orbit, and drive down the overall demand for satellites. Satellite manufacturer's remain skeptical of the technology and business model and question the ability to make a profit. Most satellite manufacturers are currently negative towards OOS/R, but this could change over time. Satellite manufacturers' interest in OOS/R is high, because they are watching the market to see where potential customers may lean. OOS/R companies need satellite manufacturers to change their satellite architecture and design to enable OOS/R, which would stimulate industry growth. Therefore, satellite manufacturers hold significant power in the industry. If satellite manufacturers do not see the value in OOS/R, and do not re-design their architecture and designs to accommodate OOS/R, it is possible that this industry could be short lived. Satellite manufacturers are in the "Manage Closely" quadrant.

OOS/R companies are supportive of their own industry, and highly interested in the success of the OOS/R market. However, their power is low because the current market does not fully support OOS/R as a viable business solution. Until more customers emerge, their power will remain low. Therefore, OOS/R companies are in the "Keep Informed" quadrant.

Bus component manufacturers are similar to satellite manufactures from a stakeholder analysis perspective. They view OOS/R as a possible threat to their main business. The ability to repair bus components on orbit, could lead to reduction in demand for those components. They would most likely provide negative support for OOS/R. Their interest is high because the success of the OOS/R market could have large effects on bus component manufacturers' bottom line, and may signal a need for a change in business models or even a pivot to manufacture different products. Bus component manufacturers are not typically large companies, and lack the ability to influence the market. Their power is low, and they belong in the "Keep Informed" quadrant.

The launch community is agnostic about the new OOS/R market, as it does not seem that it would affect their business heavily in either direction. Their support is neutral. It is possible that increased on-orbit life could reduce launch demand, but it is also possible that an increased need of on-orbit servicers could increase launch demand. The two possibilities could cancel each other out leaving launch demand at today's level. For this reason, the interest level for the launch community varies from low to high. Given that they have no direct influence on the OOS/R market, their power is low. The launch community will most likely sway between the "Monitor and Keep Informed" quadrants.

Potential customers (commercial and Government) support the idea of OOS/R. Customers remain open to all possible solutions or capabilities that would increase their profits and mission durations. Their interest is currently high since market trends over the last several years have shown a reduced demand for satellite communications, and the Government budget has been historically decreasing over the last decade. OOS/R continues to be a topic of conversation for customers as a possible cost saving measure. A customer's individual power, however, will vary. Small commercial customers may not generate the revenue or be able to provide enough capital to influence the OOS/R market. Larger commercial customers and the Government could provide large amounts of funds to stimulate the OOS/R market and drive change. For these reasons, potential customers belong in both the "Manage Closely" and "Keep Informed" quadrants.

In review, the majority of the stakeholders are positive in their support of the OOS/R industry, which will help the industry grow. All stakeholders have a high interest in OOS/R, but their power and influence is dependent on the stakeholder. Generally, this many stakeholders would be challenging to manage. However, only two management strategies are required to reduce the stakeholder management complexity. They are "Manage Closely" and "Keep Informed".

On-Orbit Failures

"Spacecraft reliability has been steadily improving. Failures, when they do occur, also tend to be less significant. This trend is due to improvements in spacecraft components and subsystems and to the fact that the space environment has been characterized with greater accuracy" (Failure in Spacecraft Systems, 1996). Therefore, while reliability is improving, failures do still occur, and typically, there is a predictable frequency to those failures occurring (Parker, 2015). Identifying which bus components/consumables fail the most will determine which bus components/consumables will provide the most benefit from on-orbit service or repair. Anomalies or situations that reduce the life span of the satellite are considered a failure. With this definition, running out of propellant is included as a failure, but losing a primary reaction wheel is not a failure if the redundant reaction wheel is operational. Collection of failure data was through interviews with subject matter experts. Appendix A contains a summary of the data. Appendix B contains the raw data and questionnaires. The top five bus components/consumables that failed or were consumed most often on-orbit and could provide the largest benefit from OOS/R are:

1. Batteries
2. Solar Arrays
3. Propellant
4. Reaction Wheels
5. Power Distribution Components

The service or repair of bus components/consumables can happen in several ways. Some techniques are more difficult and have higher risk than others have. The most promising techniques for OOS/R (ordered from least to most difficult) are:

- Resupply – provide a fuel that has been exhausted
- External Attach – attach a stand-alone pod, small or large, to the external structure of the satellite to provide additional functionality, or, if plugged into the satellite bus, over riding original functionality from the satellite
- External Swap – remove an external component and replace it with a form, fit, and function replacement
- External Repair – physical restoration of an external component at the piece part level
- Internal Swap – remove an internal component and replacing it with a form, fit, and function replacement
- Internal Repair – physical restoration of an internal component at the piece part level

Of those listed, which techniques are viable options on-orbit? Gaining internal access to a satellite (even when designed for that purpose) for repair requires too many steps, complex robotic arms, and potential debris generation. Therefore, internal swap and internal repair are not viable techniques for OOS/R. External repair is also risky and difficult. While access is not an issue, the current robotics technology is not mature enough to conduct precision surgery on-orbit without generating debris. At this time, external repair is also not worth the risk for

OOS/R. Resupply, external attach, and external swap are simpler solutions with less risk when considering present technology.

Service or repair can take advantage of one or more of the three viable, low risk OOS/R techniques. Batteries are good candidates for service and repair with either external attach, or external swap since they are typically external to the satellite. Solar arrays can utilize similar OOS/R techniques. A lack of propellant could be resolved with either resupply or external attach. Reaction wheels and power distribution components are usually internal to the satellite. To replace their functionality, an external pod could be utilized. An external pod is installed external to the satellite, and needs to be plugged into the satellite TT&C and data bus in order to physically take over function and control from the primary components. These pairings of bus components with the potential techniques to repair them on-orbit will drive the proposed design changes.

Proposed Architecture

Creation of the current overall space architecture did not have OOS/R in mind. That is not surprising since OOS/R is an emergent technology. However, today the technology exists, which drives the need to update the overall space architecture to account for OOS/R. An OOS/R architecture should provide more than a standard on-orbit servicer. A larger OOS/R architecture with the key support functions would enhance the business case for both the commercial industry and the Government.

LEO and GEO have basic differences in space systems and architectures, with different OOS/R capabilities and constraints. Proposed changes will provide a full array of OOS/R capabilities, including ground command and control functions.

GEO Architecture

The proposed GEO architecture in Figure 3 includes an on-orbit servicer, on-orbit depot, on-orbit warehouse, and on-orbit gas tank. Ground operations and launch are also depicted which are vital components of the overall OOS/R architecture. The on-orbit depot requires the on-orbit servicer to tow satellites to the on-orbit depot for OOS/R instead of conducting the OOS/R in the orbit of the customer satellite. There are a few advantages and disadvantages to this approach.

If the OOS/R has a high risk of debris generation, conducting the OOS/R in the on-orbit depot would help contain any generated debris, and thus reduce the risk to neighboring satellites. An on-orbit depot would be itself a larger satellite, or possibly even a space station, similar to the International Space Station (ISS), but without the need to sustain human life. The on-orbit depot would have a much larger suite of tools to conduct OOS/R. Standardizing on-orbit servicers would provide basic OOS/R functions, however on-orbit depots would be more specialized. Service or repair at an on-orbit depot could allow for more than one satellite at a time. The size and capability of the on-orbit depot would determine the number of satellites. A potential
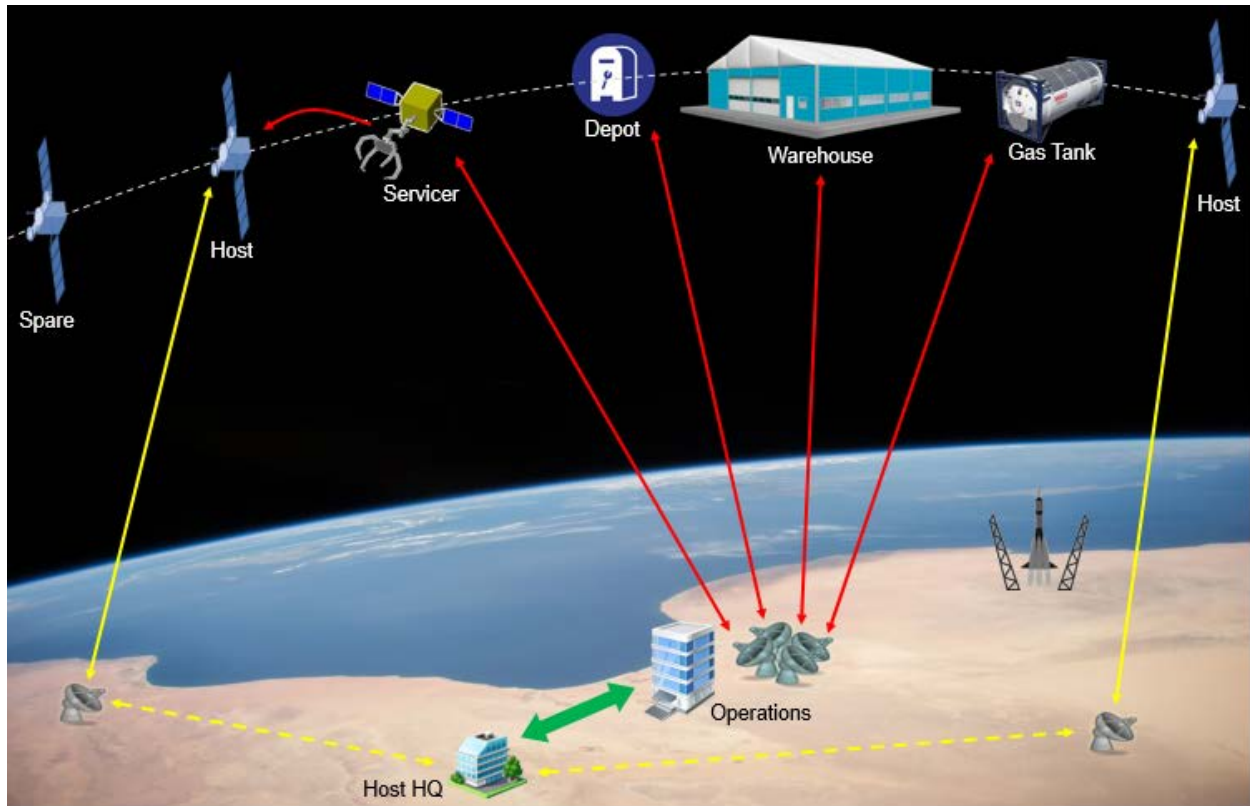
Figure 3 – Proposed GEO Architecture

CONOPS could include having the on-orbit servicer bring the customer satellites to the on-orbit depot where the actual OOS/R takes place, and after repair tow the satellite back to its original orbit (or a new orbit if desired). Coupling an on-orbit depot with an on-orbit warehouse would increase the efficiency of OOS/R.

An on-orbit warehouse is a large space station that houses a large number of plug-and-play units for satellites, built by several satellite manufacturers, including the OOS/R servicer. A lot of servicing time can be saved with having plug-and-play replacement units already on-orbit. Launching replacement units from the ground could take weeks, months, or years depending on the launch manifest, available space, and availability of the replacement unit. The on-orbit servicer could retrieve the required unit from the warehouse and bring it to the customer satellite for OOS/R. However, attaching a small propulsion pod to the replacement unit in the on-orbit warehouse to bring the replacement unit to the on-orbit depot could be more economical if they are close together. Lastly, re-supplying the on-orbit warehouse with new replacement units from the ground needs to occur on a routine basis.

One of the disadvantages of this architecture is that it requires significant propellant for the on-orbit servicer, which would drive a need for it to be a resupplied with additional propellant. A possible solution to this problem would be to have an on-orbit gas tank. This solution could also be applied to customer satellites with low fuel. A large on-orbit gas tank could easily transfer

propellant to other satellites. Propellant transfer can be done in several ways. Customer satellites could maneuver, rendezvous, and dock with the on-orbit gas tank and complete the transfer on their own. The on-orbit servicer could act as a mobile gas truck and fill-up with propellant from the on-orbit gas tank and bring it to customer satellites in need. Alternatively, the on-orbit gas tank could move around the GEO belt bringing the propellant to the customer satellites. Moving commercial satellites for refueling while they are on contract to provide a service to their customers is a poor business practice, because it would likely cause a disruption in service and negatively affect revenue. Therefore, the latter two CONOPS are preferred. There are situations where each would be appropriate, depending on how many on-orbit gas tanks there were on-orbit in GEO. Like the on-orbit warehouse, the on-orbit gas tank would require resupply missions in order to keep it full. Launching another on-orbit gas tank when the current one in use becomes empty (single use only) is another solution. The start-up company, Orbit Fab, is developing an on-orbit gas tank in collaboration with NASA, and launched their first testbed to the ISS in early 2019 (Foust, 2018).

In order to provide OOS/R capabilities to all of the satellites in GEO there would need to be more than one on-orbit servicer, depot, warehouse, and gas tank. There are over 540 active satellites in GEO today ("UCS Satellite Database", 2018). It would theoretically be possible to service or repair each satellite in GEO serially, since they are relatively close to one another and in the same equatorial plane, minimizing the amount of propellant required to maneuver from one to the next. However, on-orbit anomalies do not happen in a predictable manner that would allow for serial OOS/R, driving the need for several on-orbit OOS/R assets. Making the assumption that each satellite requires OOS/R once every three years, and take on average, five days to conduct the OOS/R mission, there would need to be at least five sets of on-orbit servicers, depots, warehouses, and gas tanks (with an orbital speed of .5º/day) in GEO. The assumption that each satellite is serviced or repaired exactly once every three years is unrealistic. It is more realistic that there will be cyclical increases and decreases in OOS/R demand. Increasing the orbital speed or adding a sixth set of OOS/R capabilities would be a more likely solution to meet the need and constraints. It is important to note that those six sets of on-orbit servicers, depots, warehouses, and gas tanks all need communication with the ground, and so the ground architecture is important.

Depicted in Figure 3 is a single command and control center with its associated antennas for communicating with the on-orbit assets. However, the ground architecture would need more than just one antenna location. If there were six sets of OOS/R capability in GEO, than there would need to be six different antenna locations distributed throughout the world. This would enable continuous communication with the on-orbit assets as they moved around in GEO. Only one command and control center would be required, as it could conduct all of the global operations from one location. There is no need for a command and control center to be co-located with each or any of the ground antennas. In case a failure causes the primary command and control center to be non-operational, such as a power outage or cyber-attack, a backup command and control center is also recommended. The command and control center will need fiber connections to the six distributed antennas throughout the globe, as well as a line of

communication with the customer. When conducting OOS/R, the customer needs to be directly involved to provide oversight and liability coverage.

Launch is included in the architecture as a necessary but independent function. Launch is required to get the OOS/R capability into orbit. The OOS/R companies will work with launch service providers to launch their assets into orbit.

LEO Architecture

The proposed LEO architecture in Figure 4 includes the on-orbit servicer. Excluded are the on-orbit depot, on-orbit warehouse and an on-orbit gas tank. The main reason for this is that LEO satellites are generally not in the same orbital plane, so the ability of the on-orbit servicer to go from one satellite to the next conducting OOS/R is more difficult with the increase in required propellant. Economically, it would not be feasible to tug satellites to an on-orbit depot, warehouse, or gas tank. The on-orbit servicer would need to be either very large with a large fuel tank, or be refueled regularly to provide a tug capability in LEO. Either solution has trouble creating a positive business case.
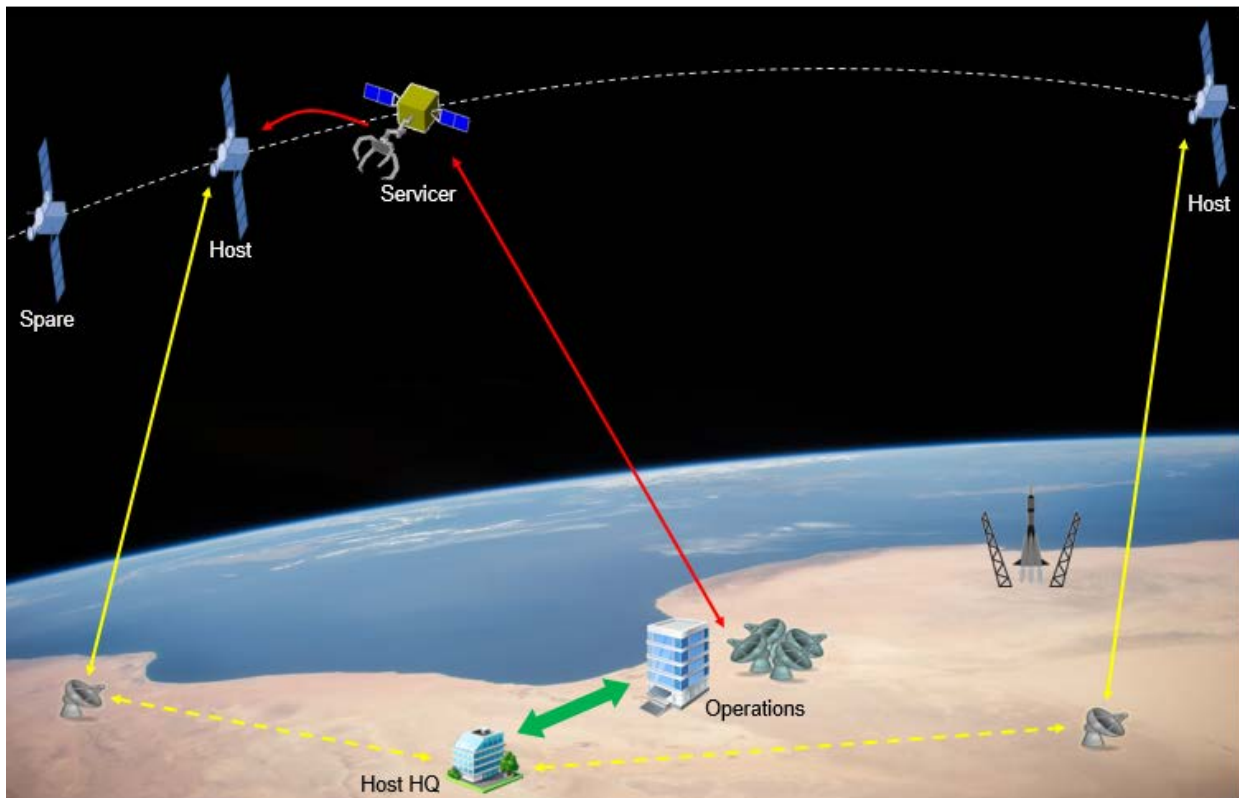

Figure 4 – Proposed LEO Architecture

It may be more economical in LEO to build small, cheap satellites, and when they encounter a life-ending anomaly, they are de-orbited and replaced with another small, cheap satellite. The reduction in launch cost to LEO is making "throw-away" satellites more feasible. There may be situations where OOS/R for a LEO satellite is the preferred solution, especially from a government perspective where the satellites are extremely expensive and mission loss is unacceptable. An OOS/R capability in LEO would have a limited lifespan depending on the amount of propellant. The on-orbit servicer could go to GEO after serving as many customers as possible in LEO. Once in GEO, the on-orbit servicer is refueled and either added to the GEO architecture, or sent back to LEO to serve additional customers.

The ground architecture for LEO OOS/R capability would be very similar to the GEO ground architecture. Use the same six antennas locations around the globe, but use fast tracking antennas instead of the typically used slow tracking antennas for GEO applications. Depending on the coverage, one or two more antenna locations may be necessary to ensure global coverage. The Air Force Satellite Control Network (AFSCN) maintains total coverage with eight ground antenna locations, and so a similar setup would meet the global coverage requirement. Utilization of primary and backup command and control centers complete the LEO ground architecture. Making several satellite design changes to take advantage of these two architectures would provide a lot of OOS/R capability for potential customers.

Proposed Design Changes

OOS/R utilizing the architectures described above may not be possible without satellite design changes. OOS/R would be more effective with satellites designed to accommodate OOS/R capabilities. The first step is for industry to adopt common and standard interfaces for, not only satellite design, but also for on-orbit servicer interfaces. "The lack of clear, widely accepted technical and safety standards for on-orbit activities involving commercial satellites remains a major obstacle to the expansion of the industry" (Erwin, 2017). While "there is no rule-making body for the new and mostly unknown activity of in-orbit services" (Erwin, 2017), the Consortium for Execution of Rendezvous and Servicing Operations (CONFERS) is attempting to fill that void. CONFERS is sponsored by DARPA, and aims to leverage best practices from Government and industry to research, develop, and publish non-binding, consensus-derived technical and operations standards. "Once the consortium members agree on a set of standards, the next step is to work with existing bodies such as the International Organization for Standardization and the Consultative Committee for Space Data Systems" (Erwin, 2017). After industry adopts common and standard interfaces, the full spectrum of OOS/R benefits are obtainable. Additional design changes at the overall satellite level and to the flight software are required. In addition, the five bus components/consumables that fail the most on-orbit (mentioned above) warrant design changes to enable OOS/R capabilities.

Satellite Level

The satellite needs to be designed for disassembly. Current satellite design does not allow for disassembly of satellite connectors and interfaces which makes OOS/R challenging. For example, the use of special space epoxy ensures that two-piece parts never come apart. With OOS/R, engineers need to find a new way to accomplish what the epoxy provides for connectors and interfaces while simultaneously designing them to allow easy disassembly on-orbit.

The disassembly should not generate debris. Debris, large or small, creates a hazard and additional risk for the host satellite, on-orbit servicer, and all other satellites in that particular orbit. For example, any epoxy used should not crack or break off when connectors or interfaces are disconnected, which is common during integration and testing in the factory. If servicing and repairing a satellite causes debris generation and OOS/R becomes popular then OOS/R can cause more harm than good, and not be suitable for the space environment. It may be possible to develop local debris "catchers". At the time of this paper, this capability is in early development. Several companies, such as Surrey Satellite Technology, are pursuing orbital debris "catchers", which could be applied to a satellite debris catching capability.

The removal or lifting of blankets and replacing them may occur when swapping out units or components, which could require updated blanket designs. Not all blankets on a satellite will require this design change, but an external component that is planned to be serviced or repaired which utilizes blankets will require this design change. For example, blankets can cover solar array deployment mechanisms. Removal or peel back of blankets is necessary to disassemble the connectors and interfaces. After installation of a new solar array, the connectors will need to be re-mated and blankets reinstalled.

To retrieve valuable telemetry data for diagnostic purposes the on-orbit servicer requires the satellite design to have an external TT&C and data bus interface to plug into. With such an interface, the on-orbit servicer could directly update the satellite's flight software, and external pods could be plugged into the satellite to allow the satellite's flight software to take command and control of the external pod. For example, an external battery pod needs to be plugged into the satellite so it can consume and recharge the external battery pod. Unfortunately, the ability for the on-orbit servicer to plug into the satellite presents some proprietary, cyber-security, and liability concerns. Satellite owners may not be willing to allow a third party on-orbit servicer to plug into their satellite, since satellites can receive TT&C and update flight software from the ground. However, it is possible that the command antenna or electronics on the satellite are no longer functional, and the only way to collect diagnostic TT&C data and update flight software may be through a physical connection with the on-orbit servicer. Mitigation of proprietary and liability issues needs to occur to enable physical connection between the on-orbit servicer and its host satellite.

Finally, satellites should have standard docking interfaces. Docking the on-orbit servicer to the host satellite is required for OOS/R and/or attaching external pods. Providing a standard docking interface would allow an on-orbit servicer from any company to provide service or repair. A fixed docking interface allows the on-orbit servicer to determine the exact location of every piece

part, nut and bolt, etc., based on the relative distance and location from the interface. This allows the robotic arm to conduct OOS/R without harming or damaging the host satellite. Cameras on the on-orbit servicer provide a visual aid, and the customer satellite's engineering documentation can be used in location calculations for autonomous operations. A robotic arm that misses its target by a couple of millimeters could damage the host satellite and/or generate debris.

Using external pods requires a structural interface and possibly a TT&C and data bus connection to attach to the host satellite. Satellite mission and design life would determine the number of structural interfaces and bus connections needed for external pods. The recommended common standard is four external pods with one structural interface and bus connection in each quadrant of the satellite. These structural interfaces and bus connections should be plug-n-play, because there could be a need to remove and replace a non-functioning external pod with a new external pod that may or may not come from the same manufacturer.

These design changes at the satellite level would require eight new requirements:

- De-mateable connectors on the exterior of the satellite.
- Detachable external units with standard plug-n-play interfaces.
- Detachable/re-attachable external blankets.
- No generation of debris during on-orbit servicing/repair.
- A standard docking interface.
- A standard data bus interface external to the satellite to allow the on-orbit servicer the ability to plug-in and receive the host satellite's TT&C, run diagnostic tests, and inject flight software updates.
- Five standard data bus interfaces external to the satellite to allow for four on-orbit externally attached units and the on-orbit servicer to plug-in.
- Four standard attach points for four on-orbit externally attached units.

Flight Software

Minimal design changes are required on flight software. One area that will need to be re-written is proper on-orbit flight due to center of mass changes. The flight software should recognize on-orbit servicer docking, unit swapping, external pod/unit attachment or removal, and provide adequate attitude and control for the satellite. These design changes would generate three new flight software requirements:

- Flight software will allow four on-orbit externally attached units to supersede the unit being replaced.
- Ensure proper attitude and control when another spacecraft is docked to the satellite in-orbit.
- Ensure proper attitude and control when units are attached to or detached from the satellite in-orbit.

Batteries and Solar Arrays

Batteries and solar arrays will require similar design changes since they are both external to the satellite. Not all of the design changes are physical changes, some will be CONOPS changes. Battery and solar array capacity and efficiency decrease over time. Currently, the design life of the satellite takes into account the capacity and efficiency decay of the solar arrays and batteries. This results in larger batteries and solar arrays than required to conduct the satellite's mission. OOS/R capability will decrease the required size of the batteries and solar arrays because the design life would be for a shorter period than mission life. For example, if battery and solar array capacity is reduced by one third, then the satellite's CONOPS would include the on-orbit swap of the batteries and solar arrays at least twice within the satellite design life. A benefit of swapping batteries and solar arrays on-orbit is the reduction of the overall satellite mass and thus, launch costs.

If batteries and solar arrays were replaced on-orbit, a robotic arm would need to attach to the old and new units, creating a need for a standard structural interface where the robotic arm can grab. To properly align the robotic arm to a standard structural interface, so it can remove the faulty hardware and replace it with a new one, a standard guidance and coordinate system is required. This could be a simple visual aid or target sticker placed at a known location on the old and new units. The visual target reduces the risk of unintended damage to the customer satellite by decreasing the possibility of accidental contact between the on-orbit servicer and the customer satellite.

A plug-n-play standard interface is required for batteries and solar arrays and need to maintain the form, fit, and function of the original component. This enables the on-orbit servicer to replace hardware with a simple swap. It is like changing a tire on your car. The new tires can be from a different manufacturer but as long as the bolt pattern (i.e. the interface) is the same, it works. The ability to swap plug-n-play batteries and solar arrays with third party units should be similar to changing a tire, and is essential to the larger OOS/R architecture. The on-orbit warehouse will be full of satellite components, and those components need to be universal and plug-n-play; otherwise, there is no benefit.

These design changes for batteries and solar arrays would require four new requirements for each component:

- Batteries
  - Standard plug-n-play interfaces.
  - Standard grasping surface interface to allow for removal by robotic arms on-orbit.
  - Optically visual target(s) for precise location by a robotic arm on-orbit.
  - Sixteen integrated, but standalone, plug-n-play sections where each individual section could be entirely replaced on-orbit.
- Solar arrays
  - Standard plug-n-play interfaces.
  - Standard grasping interface to allow for removal by robotic arms on-orbit.
  - Optically visual target(s) for precise location by robotic arm on-orbit.

- Sixteen integrated, but standalone, plug-n-play sections where each individual section can be entirely replaced on-orbit.

Propellant

Today, it is possible to resupply satellites on-orbit with propellant. NASA has demonstrated resupply on-orbit, with no design changes to the satellite (Rainey, 2014). "Satellites are decommissioned when they run out of fuel whether or not they are still capable of functioning properly" (Barnhart, 2014). Therefore, resupply would provide the benefit of extending satellite life. While the on-orbit resupply demonstration did not require design changes, it would be prudent to exercise a few design changes to make the on-orbit resupply process standardized and reduce risk. A beneficial design change is a standard resupply interface for propellant. Without a standard resupply interface, OOS/R will lack much needed flexibility to provide a benefit to a multitude of different satellites. In addition, there should be a standard propellant that every satellite uses which allows one on-orbit servicer to resupply multiple satellites. These standards reduces the timeline to receive additional propellant because the customer satellite does not have to wait for a specific resupply mission due to on-orbit servicer flexibility and competition, which would help drive down costs for OOS/R services.

Design changes should include smaller propellant tanks. Taking a different approach to a satellite's CONOPS to conduct resupply missions results in a satellite not needing a full design life's capacity of propellant. Less propellant would reduce the mass of satellites and in turn, launch costs. Resupply frequency would depend on the satellite's design life, and the cost benefit trade-off between the cost to resupply on-orbit and the savings from a smaller satellite and cheaper launch costs. In today's market, the concept of resupply is the most significant business case driver for the OOS/R market.

These design changes would generate one new propellant requirement:

- Satellites have a standard fill and drain valve to allow for on-orbit re-fueling.

Reaction Wheels and Power Distribution Components

The current design of reaction wheels and power distribution components places them internal to the satellite. Any proposed design changes for reaction wheels would also apply to power distribution components. If there is a plan to conduct OOS/R for anomalous reaction wheels and power distribution components, then it may be feasible to eliminate redundancy of these units, depending on overall satellite reliability requirements. To ensure informed decisions, completing a trade-off analysis regarding eliminating all or some redundancy is recommended. Reducing redundancy would reduce the satellite's mass, and slightly reduce the complexity of the satellite build, test, and flight software, which would decrease overall costs and schedule.

Mounting the reaction wheels and power distribution components externally on the satellite, or mounted internally with easy access structural panels is necessary to swap old and new units. It

is possible for on-orbit servicers to pull back blankets and unscrew panels with their robotic arms, but that process carries high risk to the customer satellite. The option of externally mounting reaction wheels and power distribution components to the satellite is the lower risk option.

A standardized plug-n-play design is another change required to enable the on-orbit servicer to swap reaction wheels and power distribution components. All piece parts of the units must be contained within a single housing, which would allow a robotic arm to pick-up the old unit and replace it with a form, fit, and function replacement. Firmly grabbing the unit with the robotic arm requires a standard structural interface on reaction wheels and power distribution components, just as in the batteries and solar arrays. It also requires a standard guidance and coordinate system externally visible on the units.

Relocating reaction wheels and power distribution components to the outside is a challenge. It could add cost to design and build the satellite, which may not be worth the benefit of OOS/R. Attaching pods that house the reaction wheel or power distribution components to the satellite and plugged into an external TT&C data and bus interface is an alternative. This would allow satellite manufacturers to leave the current designs unchanged, but still create an opportunity for reaction wheels and power distribution components to be serviced or repaired on-orbit.

These design changes would generate five requirements for each reaction wheel and power distribution component:

- Reaction Wheels
  - External installation on the satellite.
  - Standard plug-n-play interfaces.
  - Standard grasping surface interface to allow for removal by robotic arms on-orbit.
  - Optically visual target(s) for precise location by a robotic arm on-orbit.
  - A single standalone plug-n-play component to allow for complete removal and replacement on-orbit.
- Power Distribution Components
  - External installation on the satellite.
  - Standard plug-n-play interfaces.
  - Standard grasping surface interface to allow for removal by robotic arms on-orbit.
  - Optically visual target(s) for precise location by a robotic arm on-orbit.
  - A single standalone plug-n-play component to allow for complete removal and replacement on-orbit.

System Level	# of Requirements
Space Vehicle	8
Flight Software	3
Batteries	4
Solar Arrays	4
Propulsion	1
Reaction Wheels	5
Power Distribution Units	5
TOTAL	**30**

Table 1 – New Requirements Breakdown

All of these design changes at a system, sub-system, or component level would increase the feasibility of OOS/R. Satellite designers and manufacturers need to implement all or some of the proposed design changes for the OOS/R market to succeed. The identification of these thirty new requirements (Table 1) would initially add cost and schedule to satellite development and production. However, there are several opportunities for life cycle cost savings with reductions in mass, propellant, redundancy, and launch. These satellite design changes drive changes to the test strategy as well.

Ground Test Strategy

Changing the satellite design requires the ground test strategy to change in order to verify and validate the new design. New tests will be required, and new opportunities are created to reduce the scope of current testing.

Testing is required on all of the OOS/R processes. Verification and validation is essential for resupply, external attach, and external swap between the on-orbit servicer and the customer satellite. Both the hardware and software must be tested. Mitigation of OOS/R risks requires a thorough test plan. The recommended test plan includes physical test, modeling and simulation, and demonstration.

A high degree of confidence in rendezvous and docking is required, as even a small mistake could lead to disastrous consequences. The test procedures need to test both the hardware and software. The rendezvous process can be verified and validated through modeling and

simulation, and physical docking through physical test, modeling and simulation, and demonstration. The physical docking of two satellites creates a self-compatibility risk that can be mitigated through test.

Conducting Electro-Magnetic Interference (EMI)/Electro-Magnetic Compatibility (EMC) testing between the on-orbit servicer and customer satellite is required to ensure that electro-magnetic energy will cause no harm to either satellite. Minimizing the risk of unintentional generation and propagation of electro-magnetic energy is important while the two satellites are docked together. The current industry standard for EMI/EMC testing will suffice. If the on-orbit servicer or customer satellite are not available (i.e. already on-orbit) modeling and simulation could be used to verify and validate EMI/EMC.

Testing each satellite is required until the OOS/R market becomes mature with viable competition and accepted standards. After the industry embraces OOS/R and it becomes widely used, each satellite redesign will require testing just once. Testing just the first production satellite is required when a satellite manufacturer is producing dozens of the same satellite. Unique designs or one of-a-kind designs still require testing for each unique design component.

Reduction of some satellite testing can occur if the satellite manufacturer knows in advance that the satellite will receive on-orbit servicing. Planned OOS/R reduces qualification, run-time, and burn-in testing, which results in a reduction of lifecycle cost and a satellite's integration and test schedule. Planned OOS/R could also eliminate requirements for redundancy, which would decrease overall unit testing. The reduction in test will be different for each satellite depending on the satellite's reliability requirement. Some satellite manufacturers, or their customers, may be risk averse and proceed with the testing status quo. However, pre-planning OOS/R during satellite manufacture of the five bus components/consumables reduces the consequences of component/consumable failure, and creates an argument for reduced testing, especially among customers who are more open to trade this risk for a cost and schedule savings. While this opportunity for reduced testing is compelling, the main testing methodology should remain the same.

In today's satellite industry, testing occurs at several different stages from piece parts all the way to full-up satellite testing. This methodology should not change. Testing should continue to occur at the piece part, component, unit, sub-system, and system levels, and in this order. This process ensures that issues are caught at the lowest level possible where it is easier and cheaper to resolve the issue. Utilizing OOS/R does not change this methodology. The scope of testing at each of these levels can be reduced, as previously described, but the overall testing methodology should continue as it does today.

These ground test strategy changes will require three new requirements:

- Verification and validation of on-orbit service/repair process through analysis, demonstration and test before launch.
- Verification and validation of rendezvous and docking process through analysis, demonstration and test before launch.
- Completion of EMI/EMC testing between satellite and on-orbit servicer before launch.

Risk

Utilizing and conducting OOS/R creates new risks for the customer satellite. The technology is mature, but the CONOPS is not. Since the OOS/R market is in its infancy, experience is lacking, leading to learning opportunities created from mishaps or near mishaps. There have been eight OOS/R risks identified for the customer satellite. Mitigating each risk reduces either the likelihood or consequence of the risk. Worst-case scenarios, to be conservative, are assessed for each risk. Figure 5 shows a comparison of these risks in a risk matrix where green represents low risks, yellow represents medium risks, and red represents high risks.

The first risk is "do-no-harm". The do-no-harm risk can be defined as -- if the on-orbit servicer unintentionally damages the satellite, then there could be catastrophic mission failure for the satellite. This risk encompasses the possibility that the on-orbit servicer causes more harm than good. Included in this risk, are the risks of rendezvous, docking, and the actual OOS/R with the on-orbit servicer's robotic arm. There are benefits to OOS/R, but if an accident occurs, the consequences outweigh the benefits. Categorization of a do-no-harm consequence could vary greatly depending on the possible damage, but if mission loss is the worst case then it is a level five. Taking every precaution to ensure this risk does not materialize, because there is awareness of this risk, makes the likelihood of this risk low. This risk is a CONOPS or process risk, not a technology risk. Assessment of the likelihood is a level two and categorizes the do-no-harm risk as a medium risk.

The second risk is "debris generation". The debris generation risk can be defined as -- if the OOS/R process creates debris, it increases debris impact risk to all other satellites in that particular orbit. Excessive amounts of debris could be catastrophic to an orbit and its inhabitants. Even small debris can cause havoc because it is traveling several thousand kilometers per hour. The generation of additional debris increases the probability of debris colliding with any satellite within the debris' orbit path. Generation of zero debris during OOS/R operations is important to the OOS/R market becoming successful and conventional. Categorization of the worst-case scenario, mission loss, is a level five. Evaluation of the likelihood of debris generation is a level two as the technology is mature and OOS/R companies are taking steps to mitigate this risk. As with the first risk, debris generation is a medium risk.

The next risk is "on-orbit servicer reliability", and is defined as -- if the on-orbit servicer reliability is low, then its ability to provide on-demand OOS/R is diminished. One of the primary benefits of OOS/R is the on-demand nature. If a satellite experiences an anomaly, and an on-orbit servicer is already on-orbit, then it can help resolve that anomaly immediately. If that service is not available, then the on-demand benefit is not there. Most customers would not be willing to pay for a service that is not available when needed. Any delay in the anomaly resolution with a return to operational mission status, would hurt a commercial satellite company's revenue. Assessment of this consequence is a level two, because the worst-case scenario is a delay in resolution of the anomaly (assuming it is fixable). The anomaly would eventually be resolved, just not as swiftly as possible. Specific contract language between satellite and OOS/R companies on the on-orbit servicer reliability would make the probability of the worst-case scenario low. Consequently, OOS/R companies are currently designing their on-
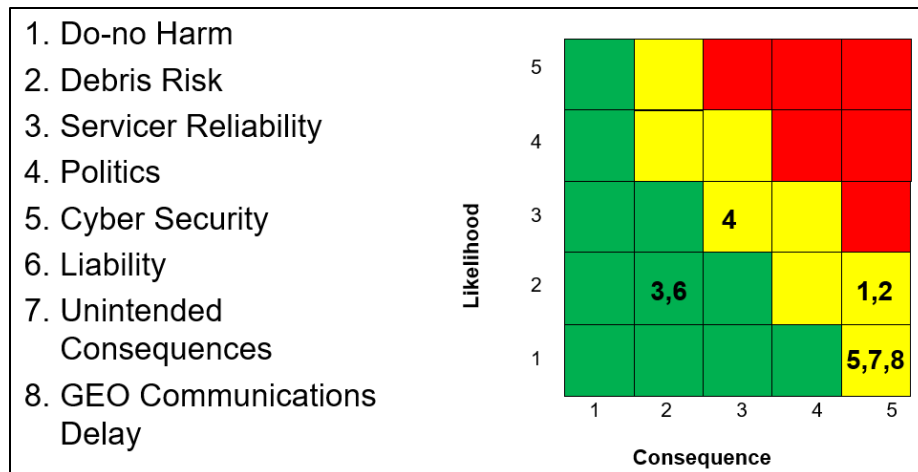
1. Do-no Harm
2. Debris Risk
3. Servicer Reliability
4. Politics
5. Cyber Security
6. Liability
7. Unintended Consequences
8. GEO Communications Delay

Figure 5 – Risk Matrix

orbit servicers with the same reliability and quality standards of today's satellites, if not higher. It is possible that within a few years this risk could be retired as OOS/R companies prove their on-orbit reliability to the space community. Categorization of this likelihood is a level two. Assessment of the overall risk for the on-orbit servicer reliability is low.

"Politics" is the next risk, and can be defined as -- if a country is not comfortable with an on-orbit servicer coming within a certain range of their satellite, then there could be political retaliation against the on-orbit servicer's country of origin. An on-orbit servicer has one or more robotic arms. Theoretically, one could use of the robotic arms for nefarious purposes, such as, intentionally damaging a satellite. Given that the OOS/R capability is a new concept for the space community, it is currently unknown how satellite owners would react when an on-orbit servicer comes within their vicinity as the on-orbit servicer travels by to service another satellite. For example, if a United States-owned OOS/R company needed to maneuver past a Chinese military satellite, how would China respond? Would China quietly stand-by, with the hope that the on-orbit servicer does not make an aggressive co-orbital maneuver in their satellites' direction? Would China take proactive actions in response? Necessity dictates a level of trust between the two parties, as well as, a CONOPS for dealing with these situations when the trust fails. This CONOPS will take shape over the next decade as OOS/R moves forward. Since, these situations have yet to occur in space, it is unknown how different satellite owners across the globe would respond due to the uncertainty. Assessment of both the consequence and likelihood is a level three and categorization of the overall risk is medium.

The fifth risk is "cyber security", which can be defined as -- if there are open and available interfaces on a satellite, then there is the potential for unauthorized cyber intrusions through those interfaces. As described above, one of the proposed design changes are external interface ports for the TT&C and data buses. Theoretically, any satellite with this capability can plug into an external interface on another satellite. This creates the possibility of a satellite rendezvousing with another satellite just to plug into the external interface port. The consequence of a cyber-

intrusion could be severe, and could cause a litany of issues. Worst-case scenario is loss of mission, and the consequence rating is a level five. The likelihood of this occurring is very low, because the threatened satellite would know another satellite is approaching. There is nowhere to hide in space, and so, no surprises. A satellite could be designed with a kill switch to the external interface port(s) (but an on/off switch may not be enough to prevent a cyber-intrusion), where the threatened satellite could turn off access to the interface port(s) when approached by an unknown satellite. Assessment of this risk is a level one for likelihood and categorization of the overall risk for cyber security is medium.

The next risk is "liability." This risk can be defined as -- if fault cannot be determined during an incident involving an on-orbit servicer and its host, then there could be a lengthy legal battle with no prior precedence. This is a business risk, as "defining preconditions to declare failure is difficult in the space insurance industry" (Barnhart, 2013). With the other risks mentioned, such as do-no-harm and debris, it is unknown how liability would be determined if those risks were realized. Holding an OOS/R company liable for any issues created during the OOS/R process could be difficult to determine. Satellites are thousands of miles away from Earth. Gaining an understanding of exactly what happened and when, and what the surrounding circumstances were, is not easy, even with video cameras and software event logs. On the surface, the consequence of such a scenario is monetary, but what this risk really creates is an unwillingness from potential customers to utilize OOS/R capabilities because of the 'unknown' element. This unwillingness could hurt the OOS/R market early on, but the current momentum of the OOS/R market suggests that may not be the case. Estimation of these consequences is a level two. For the most part, it is possible to mitigate this risk with a written agreement in the contract between the OOS/R company and their customers that handles this specific situation, along with several other liability situations that could occur. Likelihood of this risk is a level two. Overall assessment is low on the liability risk.

The seventh risk is "unintended consequences," and can be defined as -- if there are unintended consequences after an on-orbit repair/servicing, then additional analysis, investigation, on-orbit repair/servicing, and/or flight software updates may be required. Making a configuration change to resolve an on-orbit anomaly, hardware or software, creates a possibility that unforeseen, negative consequences could arise from anomaly resolution. While most unintended consequences are typically minor, it is possible to have a catastrophic failure resulting in mission loss. Therefore, the consequence of this risk is at level five. The configuration changes made to resolve on-orbit anomalies are typically determined with incomplete data. Supplemental ground testing can support the incomplete data. The anomaly resolution can be prototyped on the ground before being implemented on-orbit. Estimation of this likelihood is a level one as this anomaly resolution process reduces the probability of unintended consequences. Categorization of this risk is medium.

The last risk, "GEO communications delay", can be defined as -- due to latencies of up to 240 milliseconds for communications to reach GEO there could be unintentional damage to the satellite or the on-orbit servicer if the OOS/R requires a human-in-the-loop interaction. Most OOS/R operations will be autonomous; a few operations will require semi-autonomous

operations and a 240-millisecond delay can cause issues. If there were a need to intervene the OOS/R operation with a human-in-the-loop, there would be a 240-millisecond lag time before an emergency stop command would reach the satellite. For example, immediately stopping a moving robotic arm with a 240-millisecond communication delay can result in damage to the satellite because the robotic arm will continue to move for 240 milliseconds, and the worst case could be mission loss. Therefore, the consequence is assessed to be level five. Currently, OOS/R companies are working to make the autonomous and semiautonomous operations as simple and risk-free as possible, with several ways to stop an operation if needed. Designing the robotic arm to shut itself down if an outside force exceeds a certain threshold is one example to reduce risk. In addition, slowing down the speed of the robotic arm would help mitigate this risk. This risk is not just a software problem; it is also a CONOPS problem. Categorization of the likelihood is level one, as measures should be in place to reduce the probability of these situations. Assessment of the GEO communications delay risk is medium.

Equally weighing all eight risks in importance and averaged together, the overall risk for OOS/R is medium with the average consequence a level four and the average likelihood a level two. There is no doubt that there is risk in OOS/R operations, but the industry is working to mitigate all of these risks to create a high degree of confidence in OOS/R.

Potential Unethical Behavior

OOS/R is a new capability, and new capabilities create new and uncharted ethical problems. The industry will need to decide how to deal with these ethical problems as the industry grows and matures. As in any business, one tries to safeguard product and processes from malicious intent. Fail-safes, contracts, and insurance are measures used to mitigate the effects that result from malicious actions. The new OOS/R market is no different, as both on-orbit servicer companies and customer satellite companies will need to protect themselves from malicious intent. An OOS/R company could take advantage of several unethical situations to generate additional profit. Discussed below are five such unethical situations.

The OOS/R company provides a service that creates positive value for their customers. It is possible that the OOS/R service provided could be less than adequate and only resolves the anomaly temporarily. The customer is forced to pay for OOS/R services again to hopefully resolve the anomaly the second time around or accept the current less-than-adequate situation. An OOS/R company could deliberately provide poor OOS/R services to create the need for follow-up service to generate additional sales. It would be difficult to prove if this was deliberate, just as proving fault and liability is difficult (as discussed above in the Risk section). Of course, if an OOS/R company were to do this repeatedly, it would gain an unfavorable reputation by failing to deliver successful OOS/R capabilities, and future business would be lost. Safeguarding the malicious intent of creating a cycle of follow-up services is possible.

An OOS/R company could deliberately generate debris with the intention to cause harm to other satellites within the same orbit to generate additional customers. Similar to above, this action is difficult to prove as deliberately malicious. An OOS/R company that continually generates

debris would most likely lose business over time as their reputation for quality diminishes. Emphasis on disassembly and repair design of the satellite with zero debris generation solves the ethical problem. Liability would not be on the satellite manufacturer but on the OOS/R company.

Several of the large satellite manufacturers (Northrup Grumman, Boeing, etc.) are currently considering the possibility of developing OOS/R capabilities, if not already doing so. It is conceivable a customer buys their satellite and OOS/R services from the same company. In this arrangement, it is possible the manufacturer to build low quality satellites that increase the need for OOS/R once on-orbit. The satellite owner/customer would bear the burden of extra costs for the additional OOS/R, over and beyond initial expectations. In this unethical example, the satellite/OOS/R company is creating a self-realizing situation at the expense of their customer, thus increasing their profits. However, special contractual clauses that require a specific level of reliability would help mitigate this unethical behavior.

On-orbit servicers have the capability to tow a satellite away from a possible collision. Scheduling for OOS/R requires enough advance notice to bring the on-orbit servicer to the satellite for towing it to safety. The amount of time needed would be dependent on how far away the on-orbit servicer is from the customer satellite. An OOS/R company could maliciously create this scenario for their own benefit. While highly unethical, the OOS/R company could position themselves to tug a threatened satellite out of the way by creating a possible collision scenario. This is similar to when, in a work environment, a co-worker creates a problem they already have the solution for just so they get all the credit. Taking it a step further, there is the possibility that the OOS/R company demands an unusually high price to tug the threatened satellite to safety. The high price could be analogous to a ransom, which is highly unethical.

Since the OOS/R market is young, there is minimal competition. While several companies are investing and producing OOS/R capability, most of those companies are addressing the market with different technological solutions of accomplishing the same goal, so there is very little direct competition. Currently, only two companies are on contract to perform OOS/R services in the next couple of years. This creates a pseudo-monopoly within the market, and with a monopoly comes the unethical practice of price gouging or ransom. If a potential customer satellite needs an emergency service or repair, a single OOS/R company could demand a very high price, and hold that satellite hostage for ransom. With no viable competition, it forces the satellite owner to pay the high price, or deal with the negative consequences of losing a satellite. While this unethical scenario is unlikely under normal business circumstances, it may look different from a political perspective. If Russia was the only entity that had an OOS/R capability in LEO, and a U.S government satellite required OOS/R services, it is highly plausible that Russia could play games with the U.S. and hold the government satellite hostage for a high price or other, non-related, political demands.

All of these potential unethical behaviors are unlikely, but the space industry needs to embrace these ethical challenges in the near future. What looks unethical to one party may look like good business practices to another. Cultural differences and politics in business are becoming more

important, as space is now a global industry. All of this discussion about OOS/R ethics may be moot if the prospective business cases for OOS/R are not profitable.

Business Case

The business case for the OOS/R market is not clear, and it is difficult to quantify with a lack of available data. Due to proprietary issues, study participants were unwilling to share cost and revenue data. Therefore, discussion will be a generalized business case. In years past, the business case for OOS/R was not positive. This is the main reason that OOS/R capabilities have remained on the shelf even though the technology has been viable for at least a decade. For example, resupply has been previously considered, but "nobody has been willing to invest in such a system in part out of concerns about liability in the event that a planned in-orbit rendezvous damages the satellite selected for servicing" (Benedict, 2013), except for Intelsat General Corp, who will be the first customer of OOS/R. Cheaper launch costs and a decreasing revenue per satellite for commercial companies are the leading contributors in the changing OOS/R market place according to a panel of experts at a Washington Space Business Roundtable discussion (Russell, 2018).

The OOS/R market is currently valued at over $3 billion dollars over the next decade (Erwin, 2018). Sharing this substantial amount of revenue among a small market is causing numerous companies to explore the possibilities of OOS/R to get a share of that $3 billion dollars.

Generating a business case for the commercial sector is easier to quantify than for the government sector. The government does not base their decisions on revenue or return on investment like the commercial sector, which makes it difficult to quantify the government sector's decision-making criteria to pursue OOS/R. Therefore, this paper will solely look at the business case in the commercial sector of the OOS/R market. There are two generalized business cases to review -- the business case for LEO and the business case for GEO.

The business case for LEO is not positive. OOS/R is more difficult and more costly to conduct in LEO. As the OOS/R market grows and expands, it is possible that a business case for LEO satellites could become viable, specifically for re-location and de-orbiting services.

> "The market [is] not quite advanced as GEO and has a much different business case for how services will be used… A key difference is that LEO satellites have a shorter life span. Their relatively low manufacturing and launch cost is another major reason. [So,] life extension might not be a priority for LEO operators" (Erwin, 2018).

The re-location of a LEO satellite into a new orbit would allow that satellite to cover a different part of the globe. It could replace a satellite no longer available, or it could be utilized for a new customer in a different geographical location. De-orbiting services would allow a LEO satellite to expend all propellant on the mission. Satellites are currently required to retain enough propellant to de-orbit when their life is over. Therefore, a de-orbiting service could modestly extend the life of a LEO satellite. However, these cases do not provide a sufficient return on investment to be a viable business case for OOS/R, at least not today.

The business case for GEO is slightly positive in two distinct scenarios. The first scenario where the business case closes is a beginning-of-life anomaly. Experiencing mission loss right after orbit insertion is catastrophic. The ability to save the satellite with OOS/R would most likely be worth the additional investment. Studies have shown that about 19% of all beginning-of-life anomalies are catastrophic (1996), and that at least one GEO satellite per year will experience a beginning-of-life anomaly, which establishes a viable customer base (Benedict, 2013). Satellites in GEO "could be $200M-$400M …, [and] the breakeven for recouping this investment takes many years and failure early in life has a very detrimental impact on a company's projected revenues" (Benedict, 2013). It would be a vast capital expense to procure another satellite immediately. In addition, a commercial company would like to avoid lost revenue due to a failed satellite. The lost revenue while waiting for a new satellite to be built and launched may cost the commercial company more than a possible OOS/R solution.

The second scenario is for an extension of life. A satellite that is beyond its design life that is still functional but runs out of propellant is a lost opportunity. By resupplying the satellite with propellant, the satellite gains additional life at the cost of the OOS/R mission. The business case for this scenario is barely positive. Figure 6 below shows an example business case for the GEO extension-of-life scenario. Either scenario "would provide considerable value to the satellite owner operator, the spacecraft manufacturer, and the insurance company, [and] it is probably more likely that a new satellite will suffer from a launch failure than a 'heritage' spacecraft will suddenly fail during several years of life extension" (Benedict, 2013).

- EOL extension "benefit" comes from the delay in spending capital for a new SV
- Assuming $300M for a new SV
- Assuming equal annual revenue between on-orbit SV and new SV
- Average COF (Cost of Funds) for a satellite operator is about 6%
- Average transponder produces $2M annual revenue, so an SV with 48 transponders, would create $96M annual revenue
- Assuming cost of EOL extension service is ~$15M/year

		Return	**>**	**Investment**
Cost of a new SV X COF -	New SV Revenue Increase	>	EOL Cost
$300M X 6%/yr -	0	>	$15M/yr
		$18M/yr	>	$15M/yr

* Simplified version, many other variables involved

Figure 6 – GEO Extension of Life Business Case Example

"About 153 GEO satellites, mostly commercial, would be target customers" (Erwin, 2018), and while these two scenarios show positive business cases, there are still a few reasons to not embrace OOS/R:

1. "Owner operators and the USG would rather build new satellites with the latest technology and additional capabilities than depend on extending the life of older spacecraft.
2. In today's world of shrinking budgets with funding for expensive satellite programs in the crosshairs for cancellation, the arrival of an option (life extension) which could provide justification for space asset budget reduction or delay is seen as a threat, not as a benefit.
3. Owner/operators think servicing places space assets into "harm's way" and creates risk of accidental collision and creation of orbital debris.
4. Owner/operators are not confident that servicing can be conducted without causing attitude transients or other problems which would cause satellite services to be disrupted" (Benedict, 2013).

Conclusion

OOS/R technology is viable and available today. If OOS/R can take hold in the market, it has the potential to change the space industry dramatically. Currently, industry tosses "away … spacecraft simply because repairs or refueling [have not been] possible" (Cantieri, 2017). "Servicing spacecraft can repair, reposition, and refuel satellites using robotic arms" (Cantieri, 2017), most of which has already been demonstrated in space. There is a need to learn how to better take advantage of on-orbit servicing and repair to keep space based capabilities on-orbit longer (which increases their return on investment) as "satellites provide essential strategic and economic value" (Parker, 2015). Satellites need re-engineering and redesigning, while instituting a new architecture that encapsulates OOS/R in order to take full advantage of this new technology.

The architecture at LEO would mostly be identical to the architecture at GEO minus the additional OOS/R components – on-orbit depot, on-orbit warehouse, and on-orbit gas tank. These architectures enhance the OOS/R mission, while minimizing risk. Maintaining/improving the ground architecture is just as important as the on-orbit architecture to ensure constant communication during OOS/R operations. Targeting certain bus components/consumables when designing satellites for OOS/R is also required.

The highest failure rates among bus components/consumables are batteries, solar arrays, propellant, reaction wheels, and power distribution components. Addressing these components/consumables would reduce the majority of on-orbit failures and the probability of catastrophic mission loss. Several different OOS/R methods are available to address these high failure components/consumables, such as resupply, external attach, and external swap. Batteries, solar arrays, reaction wheels, and power distribution components could all benefit from external attach, and external swap. Replenishing propellant with resupply or external attach would

extend the life of the satellite. "Because there … [are limited] options to service satellites in operation today, designers typically include design margin and redundancy" (Barnhart, 2012), and are not thinking about OOS/R when they design their satellites. When OOS/R becomes a reality and more than an idea, it will force designers to change their satellite design to enable OOS/R to keep pace with the industry.

Some major satellite design changes would include common standard interfaces, designing for disassembly, external bus interfaces, plug-in-play swappable units, standard structural interfaces for interaction with robotic arms, with reduced redundancy, reduced capacity, and reduced testing. "Hubble's ability to remain on the forefront of science for more than a quarter century is due in large part to its modularity" (Redd, 2015), which is inspiring today's industry leaders in OOS/R and driving the proposed design changes above.

OOS/R becomes a mainstay in the space industry once the business case increases the return on investment. Building a business case for beginning of life anomalies or life extension in GEO is a challenge, but the business case is positive, and provides a small return on investment (Benedict, 2013). The LEO business case is far from practical, but "servicing satellites in low-Earth orbit could one day become a viable market" (Erwin, 2018). "Satellite owner operators are a conservative community and unwilling to take any chances with space assets" (Benedict, 2013), but they are beginning to come around.

CONFERS is gaining traction, evidenced by its first meeting in May 2018 (Erwin, 2018). "SES, which operates more than 50 geosynchronous satellites and 12 mid-Earth orbit satellites, has signed an agreement to be the first commercial customer to use" (Erwin, 2017) Space Systems Loral's (SSL) on-orbit servicer called Space Infrastructure Services in 2021. Before that, Intelsat General Corp. will be the first commercial satellite to be the benefactor of OOS/R from Orbital ATK's Mission Extension Vehicle (MEV), which is a simple on-orbit servicer conducting life extension, in early 2019 (2018). The MEV is 80% compatible with all of the GEO satellites (Sharkey, 2018), so hopefully more companies will join the emerging OOS/R market (business opportunity), soon. Once accepted, OOS/R will forever change the space industry. A culture shift in the space industry is brewing.

Appendix A – Interview Summary

1. Do you think that it will be feasible, technologically, to conduct on-orbit repair on a routine basis?

    a. Yes, it is technologically feasible
    b. It's a business challenge
        i. Industry will start with servicing and move towards repair/replace as the industry begins to adopt common standards and interfaces

2. Do you think that there is a business case for on-orbit repair? Or what factors would you consider whether or not the repair/service?

    a. The business case will initially be determined on a case-by-case basis because the current benefits are limited
        i. It would greatly depend on the SV mission and the risk involved in servicing/repair/replace (how will you do it?)
    b. The business case for servicing, currently makes more sense than repair/replace
        i. As the industry adopts common standards and interfaces, the business case becomes better
    c. There are competing business cases, such as the cheap SV, throw away model (SpaceX & OneWeb)

3. Who will be the larger customer – government or commercial?

    a. The commercial industry would have a larger demand, but unless the business case closes, commercial industry will be unwilling to participate as a servicing/repair/replace customer (economic decision)
    b. The Government does not have the demand, nor the willingness to take large risks, but given the massive expense of some of their SVs, the Government may actually be willing to participate as a servicing/repair/replace customer
    c. Both seems willing to accept SV refueling as a low-cost method to provide additional SV life

4. In your experience, what bus components fail the most?

    a. Batteries – qty-8
    b. S/A – qty-6
    c. Reaction wheels – qty-6
    d. Fuel – qty-5
    e. Power supply components – qty-5
    f. Gimbals – qty-5
    g. Computers – qty-4

5. Do you think those components could be repaired on-orbit?

    a. Repair
        i. More difficult and not available with today's technology, but in the future it could be possible if SVs are designed differently
        ii. SVs are currently designed to bury certain components deep inside the SV, and trying to pull those components to the outside of the SV, would cause a lot of challenges
    b. Replace
        i. More achievable to swap out whole parts assuming that the interfaces are standard or common
        ii. Possible to replace a unit without actually removing it by installing a new unit externally to the SV and "plugging" it in the SV bus via a common interface
    c. Servicing
        i. Providing a re-supply of any consumable is achievable with today's technology (e.g. fuel, lubricants, cryogenics, etc)
        ii. Provide external plugs and interfaces for external modules to be attached as replacement units
    d. It might make the most sense to design SVs to be upgradable so allow for tech refresh and replacement units

6. How might you change the satellite design in order for those components to be repaired routinely?

    a. Developing common industry standards and interfaces for:
        i. Rendezvous
        ii. Docking
        iii. External bus connection
        iv. Refueling of all consumables
        v. Access panels
    b. Designing connectors that can mate and unmate
    c. Developing components that can be completely plug-n-play as a single unit (possibly rack mounted):
        i. Batteries
        ii. Solar arrays
        iii. Fuel tanks
        iv. Computers
        v. Gimbals
        vi. Access panels
    d. Reduce redundancy, battery capacity, S/A capacity, and fuel capacity, thus reducing the size and complexity of SVs
    e. Completely re-design SVs to have the components most likely to fail towards the outside of the SV for easier access

7. Would constellation architectures need to be changed in order to benefit from on-orbit repair?

    a. Industry is moving from monolithic SVs to smaller SVs in lower orbits that could easily be replenished or serviced/repaired/replace
    b. The architecture needs to have the ability to take SVs offline for servicing/repair/place and still meet mission requirements (spares or overlapping coverage)
    c. A sole repair bot could be included as part of the constellation (vice third party)
    d. The architecture could take advantage of an on-orbit depot where SVs could fly or be taken to in order to receive servicing/repair/replace

8. What interface or other standards do you think would be needed for on-orbit repair to become mainstream?

    a. Key interfaces:
        i. Refueling port
        ii. S/A
        iii. Battery
        iv. Electrical bus
        v. Data bus
        vi. TT&C data stream
        vii. Access panels
        viii. Docking
        ix. Mechanical
        x. Connectors
        xi. Blankets

9. Would any ground testing need to be changed, added, or eliminated?

    a. Added:
        i. All necessary HW/SW tests to V/V the service/repair/replace process
        ii. All necessary test to V/V rendezvous and docking
        iii. One-time EMI testing between the SV and repair bot
        iv. One-time self-compatibility between the SV and repair bot
        v. Digital twin concept
    b. Reduced:
        i. Possible lot testing if SVs are produced in mass
        ii. The amount of qualification test
        iii. The amount of burn-in test
        iv. The amount of run-time
        v. V&V test for components that are planned to be repaired/replaced
    c. Eliminated:
        i. If units are no longer redundant, than testing for those units are cut in half

    d. Need to Keep the Same
        i. Test phases – component -> part -> payload

10. What additional risks do you foresee with routine on-orbit repair?

    a. Do-no harm
    b. Debris risk
    c. Reliability of the repair bot
    d. Political risk
    e. Cybersecurity risk
    f. Liability risk
    g. Unintended consequences

Appendix B – Raw Interview Data

Interview Questions – Joe Anderson, Orbital ATK

1. Do you think that it will be feasible, technologically, to conduct on-orbit repair on a routine basis?
    a. Yes
2. Do you think that there is a business case for on-orbit repair? Or what factors would you consider whether or not the repair/service?
    a. Yes, but wouldn't go into factor specifics
3. Who will be the larger customer – government or commercial?
    a. Commercial
    b. Gov't SV are much more expensive and much more risk averse
4. In your experience, what bus components fail the most?
    a. Didn't ask this question
5. Do you think those components could be repaired on-orbit?
    a. Wants to avoid the swapping of parts; focusing on added components and plugging them into the SV
    b. Batteries
    c. Solar Arrays
    d. T&C
    e. Transmit and receive apertures
    f. Easier in GEO to repair multiple SV because they are in the same plane
6. How might you change the satellite design in order for those components to be repaired routinely?
    a. Need a standard power and data transfer interface between the SV and the repair bot, like a USB port for a SV
    b. S/W needs to be updated to allow for new components to be added whenever
7. Would constellation architectures need to be changed in order to benefit from on-orbit repair?
    a. Doesn't see any changes in constellations
8. What interface or other standards do you think would be needed for on-orbit repair to become mainstream?
    a. See interfaces and standards as a chicken and egg scenario and it will be very difficult
    b. Willing to let innovation take its course and it will hopefully create a de-facto industry standard
9. Would any ground testing need to be changed, added, or eliminated?
    a. No other ground testing is needed for the SV
    b. There is some additional analysis to ensure compatibility between the repair bot and the SV
10. What additional risks do you foresee with routine on-orbit repair?
    a. Do no harm

- MEV – rendezvous and dock with an SV at GEO; docked life extension for fuel; disable all of the SVs propulsion and ADCNS systems; launch spring 2019 and dock with Intelsat in the summer
- MEP – an electric propulsion system that requires the MRV to install it to the SV
- MRV – can carry 10 MEPs and will install them to SVs
- CIRAS project with NASA

Interview Questions – Dave Barnhart, CONFERS

1. Do you think that it will be feasible, technologically, to conduct on-orbit repair on a routine basis?
   a. Yes
   b. Its more of a business challenge
2. Do you think that there is a business case for on-orbit repair? Or what factors would you consider whether or not the repair/service?
   a. Yes, but its limited or niche
   b. The best business case is re-fueling
   c. Repair and replace will come eventually as standards progress
3. Who will be the larger customer – government or commercial?
   a. The current customer is commercial
   b. Not sure on which will be larger in the future
4. In your experience, what bus components fail the most?
   a. Power systems (paper)
      i. S/As, batteries, and power supply components
5. Do you think those components could be repaired on-orbit?
   a. Not today
   b. By addressing how those components are connected will allow it in the future
6. How might you change the satellite design in order for those components to be repaired routinely?
   a. Change the morphology from monolithic to something else
      i. Cellular – inspired by biology (not cost efficient right now)
      ii. Modular
7. Would constellation architectures need to be changed in order to benefit from on-orbit repair?
   a. Yes, have the ability to take one SV off-line for repair/servicing and not lose coverage
   b. The low cost throw away concept from SpaceX and OneWeb is the biggest competitor of on-orbit repair
8. What interface or other standards do you think would be needed for on-orbit repair to become mainstream?
   a. The fuel interfaces
   b. Storable power system interfaces
   c. S/A interfaces
   d. The electrical bus to connect the repair bot to the host
   e. CnDH system (command and data handling)
   f. The concept of plug-n-play that doesn't require a change to the flight software

9. Would any ground testing need to be changed, added, or eliminated?
   a. If you are launching from the ground, there isn't much you can change
   b. Functional validation test that the software is working correctly
   c. If you get away from monolithic systems and go towards smaller and more SVs, than you could possible switch to lot testing
   d. Qual time could be reduced or burn-in testing, run time testing
10. What additional risks do you foresee with routine on-orbit repair?
   a. The biggest risk is do-no harm

- He has a paper on bus failures he can send me
- What if the repair bot could disassemble SVs on-orbit for spare parts for other SVs?
- Made In Space wants to do 3D printing in space to build SVs on-orbit, but its not enough just yet
- What about a spare parts depot on-orbit?
- Airline companies will forward deploy spare parts to other countries so they reduce the time off-line because it will negatively affect revenue

Interview Questions – Srimal Choi, DARPA

1. Do you think that it will be feasible, technologically, to conduct on-orbit repair on a routine basis?
   a. Yes
2. Do you think that there is a business case for on-orbit repair? Or what factors would you consider whether or not the repair/service?
   a. Yes, but it depends on the type of repair
3. Who will be the larger customer – government or commercial?
   a. Commercial
4. In your experience, what bus components fail the most?
   a. Mechanisms – solar arrays deployments, booms
5. Do you think those components could be repaired on-orbit?
   a. Yes
   b. Use a robotic arm to finish the deployment
6. How might you change the satellite design in order for those components to be repaired routinely?
   a. Standard interfaces that does not allow debris
   b. Changes to CONOPS
   c. Plug-n-play components
   d. Standard docking mechanism
   e. The repair bot needs to "see" the SV
7. Would constellation architectures need to be changed in order to benefit from on-orbit repair?
   a. If you have a large constellation, you might want your own repair bot; otherwise a 3rd party application would be a better fit
8. What interface or other standards do you think would be needed for on-orbit repair to become mainstream?

a. Hopefully, CONFERS will become the industry standard
9. Would any ground testing need to be changed, added, or eliminated?
    a. No, still need to do a complete ground test
    b. Could eliminate redundancy an redundant test
10. What additional risks do you foresee with routine on-orbit repair?
    a. Debris generation
    b. Collision avoidance

- CONFERS is currently working to develop best practices for on-orbit repair/servicing, and a common lexicon across industry

Interview Questions – Dal Lee, Boeing

1. Do you think that it will be feasible, technologically, to conduct on-orbit repair on a routine basis?
    a. Yes, fly up a secondary bus and have a remote plug-in
2. Do you think that there is a business case for on-orbit repair? Or what factors would you consider whether or not the repair/service?
    a. Case by case dependent
3. Who will be the larger customer – government or commercial?
    a. Commercial has the numbers, but the government may have the most pressing need
4. In your experience, what bus components fail the most?
    a. Thruster failures – burn through
    b. Power supplies and other electronics that are affected by single event upsets
    c. Computers
5. Do you think those components could be repaired on-orbit?
    a. Repair would be difficult
    b. Replacement is more achievable
    c. Or a pass-by, with an external unit attached after-the-fact
6. How might you change the satellite design in order for those components to be repaired routinely?
    a. Interfaces are key
    b. Docking solution
    c. Ability to connect to the bus to run a BIT from the repair bot to help with diagnosis
7. Would constellation architectures need to be changed in order to benefit from on-orbit repair?
    a. Predicts that the industry is going to move away from giant SV systems and going to smaller satellites in lower orbits and it would be feasible to either provide spare SVs or repair bots within the constellation
    b. Could either be one company delivering the constellation and the repair bot, or a third bot – it all depends on the interfaces
8. What interface or other standards do you think would be needed for on-orbit repair to become mainstream?
    a. The data bus interface

b. Digital processing interface (SerDes)
c. Be 100V compliant and be able to slave down to whatever is required
9. Would any ground testing need to be changed, added, or eliminated?
    a. The attitude control system can handle the change in mass properties when the repair bot is docked
    b. EMI testing between the repair bot and the host
    c. Self-compatibility between the repair and the host
10. What additional risks do you foresee with routine on-orbit repair?
    a. Bad things can happen in GEO so the repair bot need an abort button if the repair bot has an anomaly
    b. The host needs to ensure that it doesn't damage the repair bot

Interview Questions – Josh Davis, Aerospace

1. Do you think that it will be feasible, technologically, to conduct on-orbit repair on a routine basis?
    a. Yes, based on the success of the Orbital Express
2. Do you think that there is a business case for on-orbit repair? Or what factors would you consider whether or not the repair/service?
    a. There is a business case to be made
    b. It will be cheaper to repair/upgrade on-orbit than building new from scratch
3. Who will be the larger customer – government or commercial?
    a. Commercial because they are 10 times larger than the Gov't
    b. But the SEV for the Gov't is opening the door to on-orbit servicing for resiliency purposes
4. In your experience, what bus components fail the most?
    a. Batteries
    b. Electronics
    c. Moving parts
5. Do you think those components could be repaired on-orbit?
    a. Yes, but it depends on the failure
    b. Will initially be modular in nature, not physical repair
6. How might you change the satellite design in order for those components to be repaired routinely?
    a. Develop a modular SV with a single string
    b. Standard connection ports
    c. Cheaper and simpler to host a payload on a standard platform (bus)
7. Would constellation architectures need to be changed in order to benefit from on-orbit repair?
    a. Do things that make sense at the enterprise level, not at the stove pipe level
    b. Logistics will become more important
        i. Getting mass where it needs to be, when it needs to be there
8. What interface or other standards do you think would be needed for on-orbit repair to become mainstream?
    a. Fuel ports – NASA has a new standard which also makes re-fueling on the ground easier too

b. Grapple structures for docking purposes
        c. Modular interfaces for power, data, and thermal
9. Would any ground testing need to be changed, added, or eliminated?
        a. You can relax the testing campaign
        b. Maybe everything doesn't need to be as rigorously tested
10. What additional risks do you foresee with routine on-orbit repair?
        a. Debris generation
                i. Go out to the graveyard orbit to do the servicing, and then come back to the mission orbit

<u>Interview Questions – Ken Lee, Intelsat General</u>

1. Do you think that it will be feasible, technologically, to conduct on-orbit repair on a routine basis?
        a. Yes, technically it's not that challenging
2. Do you think that there is a business case for on-orbit repair? Or what factors would you consider whether or not the repair/service?
        a. Yes, but need to think about it from a tech re-fresh in addition to repair and servicing
        b. Need a hook into being repaired
        c. Factors
                i. Operate over 50 satellites
                ii. In some cases they have SV that generate a lot of revenue, so it makes sense to extend the life of the SV to continue the revenue stream
                iii. Need an assurance of a high degree of success
                iv. Orbital's technical solution is conservative so its lower risk and a higher chance of success
                v. Buying time to include more capability at a lower price when buying the replacement SV
3. Who will be the larger customer – government or commercial?
        a. Commercial because they have so many more satellites
4. In your experience, what bus components fail the most?
        a. Fuel
        b. Available power – batteries and S/As
                i. Degrades over time due to physics
        c. Gyros
5. Do you think those components could be repaired on-orbit?
        a. Yes, have a universal plug and you can attach an external battery pack on-orbit
        b. Doesn't think S/As could be replaced/repaired on-orbit
6. How might you change the satellite design in order for those components to be repaired routinely?
        a. Interfaces are key and need to be plug-n-play
        b. Standardize interfaces b/c everyone has different interfaces and connections
        c. Depends on your goal when you design the SV
        d. Intelsat wants common interfaces (motives)

7. Would constellation architectures need to be changed in order to benefit from on-orbit repair?
   a. Want to have a means of eliminating a "rouge" satellite (loses the ability to command)
      i. Concern for new ideas from OneWeb and SpaceX
8. What interface or other standards do you think would be needed for on-orbit repair to become mainstream?
   a. Intelsat desires to keep their SVs on-orbit for as long as possible
   b. Fuel transfer interfaces and standards
9. Would any ground testing need to be changed, added, or eliminated?
   a. System trade issue
   b. Typically do a lot of testing because its so expensive and we can't touch it after the fact
10. What additional risks do you foresee with routine on-orbit repair?
    a. A lot of risk if the repair/servicing is not done properly
    b. Very nervous about an explosion in GEO orbit
       i. Debris field could take out the entire GEO orbit

- Next year, 2Q2019, Intelsat will have the first ever GEO rendezvous

Interview Questions – Ken Cureton, University of Southern California

1. Do you think that it will be feasible, technologically, to conduct on-orbit repair on a routine basis?
   a. Yes, with on-orbit servicing being easier
2. Do you think that there is a business case for on-orbit repair? Or what factors would you consider whether or not the repair/service?
   a. Yes, SpaceX and Boeing are pursuing on-orbit/servicing
   b. LEO would be cheaper based on fuel costs
3. Who will be the larger customer – government or commercial?
   a. Initially, the gov't
   b. Commercial has been trending towards smaller, disposable SVs
4. In your experience, what bus components fail the most?
   a. Batteries
   b. Solar cells
   c. Anything that has a life span due to chemical properties or items that are affected by radiation
   d. Any consumable will limit the life of the SV
5. Do you think those components could be repaired on-orbit?
   a. Batteries, yes
6. How might you change the satellite design in order for those components to be repaired routinely?
   a. Instead of refueling a cryo tank, it might be easier to replace an entire tank
      i. Optical infrared sensors utilize cryo cooling

b. Most of the components that would need servicing are on the inside of the SV due to launch environment and radiation, and it would be hard to pull those components to the outside of the SV

c. Need access panels or the components need to be on the outside of the SV

d. A lot of DoD/Gov't SVs are not allowed to be accessed remotely

7. Would constellation architectures need to be changed in order to benefit from on-orbit repair?

a. A servicing station at each orbit, where a SV brings the broken SV to the servicing station for repair

8. What interface or other standards do you think would be needed for on-orbit repair to become mainstream?

a. For electrical systems

b. Need a bus that allows the repair bot to plug in

c. Something that would allow plugging into the T&C stream

d. Plug and play nature for LRUs

9. Would any ground testing need to be changed, added, or eliminated?

a. The fundamental maintenance procedures would change

10. What additional risks (politics) do you foresee with routine on-orbit repair?

a. If you are completely dependent on servicing and can't, it would probably be less expensive in the long run to have extra capacity or spares

b. Adding cost risk by increasing the complexity of the repair process

c. Adding schedule risk by increasing ground testing of the repair process

d. Who is the doing the servicing? Russian repairing a US satellite, there might be some hair on fire

e. Cybersecurity risk

- Conduct an AoA:
    o Disposable system
    o On-orbit/in-orbit repair/servicing
    o On-orbit repair at a repair station
- Think about multi-national servicing issues and risk. Commercial would be more willing to allow multi-national.
- Make the assumption that I'm only dealing with unmanned repair systems
- Am I making the assumption that the issue is already known, or will the repair bot need to diagnose as well?
- Use a repair bot to "unhack" a SV

Interview Questions – Rosalind Lewis, Aerospace

1. Do you think that it will be feasible, technologically, to conduct on-orbit repair on a routine basis?

a. Yes. All the necessary pieces have been accomplished on-orbit

2. Do you think that there is a business case for on-orbit repair? Or what factors would you consider whether or not the repair/service?

a. It depends. For low cost LEO birds, just launch a new one

3. Who will be the larger customer – government or commercial?

       a. It depends on the business case
4. In your experience, what bus components fail the most?
       a. Mechanical components
5. Do you think those components could be repaired on-orbit?
       a. If they are designed to be
6. How might you change the satellite design in order for those components to be repaired routinely?
       a. Coatings would be difficult
       b. Make it swappable
7. Would constellation architectures need to be changed in order to benefit from on-orbit repair?
       a. Need better sensing and diagnosis
8. What interface or other standards do you think would be needed for on-orbit repair to become mainstream?
       a. Commodity items
       b. Accessibility interfaces
9. Would any ground testing need to be changed, added, or eliminated?
       a. There will be some opportunities to reduce some testing
10. What additional risks do you foresee with routine on-orbit repair?
       a. Do more harm than good
       b. Unintended consequences
       c. On-orbit repair would increase the risk profile of the SV

Interview Questions – Matt Murdough, Tecolote Research

1. Do you think that it will be feasible, technologically, to conduct on-orbit repair on a routine basis?
       a. Yes
2. Do you think that there is a business case for on-orbit repair? Or what factors would you consider whether or not the repair/service?
       a. Yes for refueling and batteries
       b. Strap-on replacement parts
       c. No/hard for reaction wheels, star trackers, things with lots of connectors or needs calibration
3. Who will be the larger customer – government or commercial?
       a. Commercial needs/demand is growing faster than tech refresh so no advantage to fix it
       b. Gov't because the cost is so much higher and because our tech needs are not as great (can use old tech for our missions)
4. In your experience, what bus components fail the most?
       a. Reaction wheels
       b. Batteries
       c. Fuel
       d. Star trackers
       e. Thermal control
       f. PDU/PCU

   g. Motors and gimbals
 5. Do you think those components could be repaired on-orbit?
   a. Some parts are buried in the middle of the SV for rad hard purposes, so you could pull those parts to the edges of the SV if you rad hard the parts to a greater degree
 6. How might you change the satellite design in order for those components to be repaired routinely?
   a. Design a refueling port
   b. Add a fuel pump to get past blow-down pressure
   c. Need less batteries and your depth of discharge CONOPS could change
   d. No redundancy for replaceable items
 7. Would constellation architectures need to be changed in order to benefit from on-orbit repair?
   a. No
 8. What interface or other standards do you think would be needed for on-orbit repair to become mainstream?
   a. More common interfaces across the space industry
 9. Would any ground testing need to be changed, added, or eliminated?
   a. Less testing in general
     i. Don't need to test each battery cell
   b. The risk doesn't change with eliminating testing steps
     i. Part
     ii. Subcomponent
     iii. Payload
 10. What additional risks do you foresee with routine on-orbit repair?
   a. Debris generation
   b. EMI damage from the repair bot to the host (solved by DARPA)
   c. In the repair bot available? (assuming YES)

- Space class S parts for quality cost 10x more
- Ask Aerospace about the database; maybe email the website about a student releasable version

Interview Questions – Ron Uchimiya, Space Systems/Loral

 1. Do you think that it will be feasible, technologically, to conduct on-orbit repair on a routine basis?
   a. Yes, but very incremental
   b. The industry needs to move together to be successful
 2. Do you think that there is a business case for on-orbit repair? Or what factors would you consider whether or not the repair/service?
   a. Will need a poster child success
   b. Closed loop robotic arm programming is challenging
   c. NASA and DoD are funding the tech dev so there must be a business case
 3. Who will be the larger customer – government or commercial?
   a. Military would be open to being refueled

4. In your experience, what bus components fail the most?
    a. Can't answer – most of his experience is with antenna development
5. Do you think those components could be repaired on-orbit?
    a. Whole sale swap out
6. How might you change the satellite design in order for those components to be repaired routinely?
    a. Need to develop automotive type standards
7. Would constellation architectures need to be changed in order to benefit from on-orbit repair?
    a. Can't answer
8. What interface or other standards do you think would be needed for on-orbit repair to become mainstream?
    a. Need to be like launch locks
9. Would any ground testing need to be changed, added, or eliminated?
    a. An increase in testing for the repair process
10. What additional risks do you foresee with routine on-orbit repair?
    a. Liability issues
    b. Agreements between repair bot company and the customer
11. Who would you recommend that I speak to?
    a. Ted White (Claire also knows him too)
    b. Someone from NASA

- Build replacement parts on-orbit with 3D printing.
- Darpa/SLL project called Restore

Interview Questions – Col Timothy Sejba, Air Force

1. Do you think that it will be feasible, technologically, to conduct on-orbit repair on a routine basis?
    a. Yes, can see future missions that require a larger satellite and refueling would be fundamental to reduce mass and launch costs
    b. Depends on getting to a commonality between buses and payloads
    c. Servicing will be the driver early on
    d. Repair will be dependent on changing the architecture based on SV replacement every 2-5 years
2. Do you think that there is a business case for on-orbit repair? Or what factors would you consider whether or not the repair/service?
    a. Sees benefit, but does not see a business case
    b. Not sure if repairing on-orbit is cheaper than designing a new SV with upgraded tech
3. Who will be the larger customer – government or commercial?
    a. Needs a large market across both gov't and commercial
    b. Believes the higher demand would be on the commercial side because of how many SVs they have
4. In your experience, what bus components fail the most?
    a. Batteries

      b. Solar cells

      c. Reaction wheels

5. Do you think those components could be repaired on-orbit?
      a. If we fundamentally changed the way we designed our SVs
      b. Designed for access

6. How might you change the satellite design in order for those components to be repaired routinely?
      a. In order to make it affordable we need to reduce the size of SVs in order to launch 2 SVs instead of one, and then take advantage of on-orbit refueling
      b. The expendable items usually have some sort of issue and those items need to be easily repaired or replaced (solar arrays, batteries, fuel)

7. Would constellation architectures need to be changed in order to benefit from on-orbit repair?
      a. Need an architecture that can handle a down SV while its waiting to be repaired

8. What interface or other standards do you think would be needed for on-orbit repair to become mainstream?
      a. Power standards, there are different bus sizes which is driven by the payload

9. Would any ground testing need to be changed, added, or eliminated?
      a. Doesn't think you could change or eliminate any test

10. What additional risks do you foresee with routine on-orbit repair?
      a. The risk of not getting repaired when needed – anomaly, launch failure of the repair bot
      b. Put your redundancies where you can buy down the risk of the repair bot

11. Who else do you think I should talk to?
      a. Russ Teehan
      b. Has some folks internally to AD
      c. Fred Kennedy - DARPA

- DARPA F7 project? 5 years ago?
- Moving into a more hostile space environment, so while there is benefits to repair, does that create additional vulnerabilities for our adversaries to take advantage of? (RISK)

Interview Questions – Jerry Sellers, Teaching Science and Technology, Inc.

1. Do you think that it will be feasible, technologically, to conduct on-orbit repair on a routine basis?
      a. Yes

2. Do you think that there is a business case for on-orbit repair? Or what factors would you consider whether or not the repair/service?
      a. Yes, there could be a business case
          i. Skeptical at first, but now believes it could make sense economically
          ii. Life extension makes sense for very expensive satellites
      b. Economics
      c. Schedule
      d. Insurance, warranty – how will that change the landscape?

3. Who will be the larger customer – government or commercial?

a. Gov't because of how expensive they are (political decision)

b. But the commercial will be more likely to take the risk (economic decision)

4. In your experience, what bus components fail the most?
   a. Fuel
   b. Moving parts
   c. Reaction wheels
   d. S/A assemblies
   e. Batteries

5. Do you think those components could be repaired on-orbit?
   a. Yes, assuming the satellite is designed to be repairable
   b. Doesn't think Hubble could have been repaired by a robot
   c. Should it be routine maintenance?

6. How might you change the satellite design in order for those components to be repaired routinely?
   a. Need to look at the entire system architecture
   b. Interfaces are key
   c. Connectors are designed to mate and never un-mate
   d. How do you get access?
   e. Rack mounted? Like airplane design (but they're not repaired by robots)
   f. Thermal control may be thrown out of whack by putting parts on the outside of the satellite
   g. Rapid technology change could complicate industry standards
      i. The standards need to be flexible to change as technology changes

7. Would constellation architectures need to be changed in order to benefit from on-orbit repair?
   a. Reducing system level reliability while still meeting constellation reliability
   b. A repair bot as part of the constellation
   c. Could make the case for not having an on-orbit spare

8. What interface or other standards do you think would be needed for on-orbit repair to become mainstream?
   a. Connectors – plug-n-play
   b. Standard to open up the satellite
   c. How do you handle thermal blankets and coatings on the exterior of the satellite? Is there a standard for that?
   d. The mechanical interface with the satellite and the repair bot

9. Would any ground testing need to be changed, added, or eliminated?
   a. Mating between the satellite and the repair bot
   b. Don't really think you could eliminate any ground testing
   c. Reducing testing of the same test over and over is a risk trade-off
      i. Need very high confidence in your repair bot before you reduce or eliminate any testing

10. What additional risks do you foresee with routine on-orbit repair?
    a. Chicken and egg scenario with on-orbit repair and designing satellites to be repairable
    b. Mitigate the risk with insurance but that industry will change along with the space industry

Interview Questions – Umesh Ketkar, Loyola Marymount University

1. Do you think that it will be feasible, technologically, to conduct on-orbit repair on a routine basis?
   a. Yes, but not sure about the utility
2. Do you think that there is a business case for on-orbit repair? Or what factors would you consider whether or not the repair/service?
   a. Skeptical because launch is half the cost, so why launch something to repair it
3. Who will be the larger customer – government or commercial?
   a. Commercial due to revenue
   b. But the gov't side might be more viable for the more expensive systems
4. In your experience, what bus components fail the most?
   a. Primary CPU
   b. PDU/PCU
   c. High power devices or transforming devices from hi to low or vice versa
   d. Batteries
   e. Mechanical devices like gimbals
   f. Not reaction wheels but CMGs do fail more often
5. Do you think those components could be repaired on-orbit?
   a. Yes, batteries are usually on the outside of the SV (batteries are really heavy so you could reduce mass)
   b. You could swap out reaction wheels or CMGs, if the fault was lubricant, you could inject more lubricant
   c. LEO would be harder GEO because you have match orbital velocity
6. How might you change the satellite design in order for those components to be repaired routinely?
   a. Need standard plug and play connectors
   b. Need panels that can be opened
   c. Or not have panels at all (GEO or ISS orbit) or the units are on the outside of the panels
   d. If we can design for tech refresh, it might increase the business case
7. Would constellation architectures need to be changed in order to benefit from on-orbit repair?
   a. You can fly a lot more single string constellation
   b. Less redundancy of units
   c. Have on-orbit spares until the repair bot gets your satellite
   d. Third party repair bot
8. What interface or other standards do you think would be needed for on-orbit repair to become mainstream?
   a. T&C units need to be standard
   b. Standard plug-n-play connectors
9. Would any ground testing need to be changed, added, or eliminated?
   a. Test all the repair functions
   b. Test could be dramatically shortened if there is less redundancy
10. What additional risks do you foresee with routine on-orbit repair?

a. How long is the life of the repair bot?
　　　b. How reliable is the repair bot?
　　　c. Can the repair bot be repaired?
　　　d. One GEO bird lasted 27 years

- Can I do a back of the napkin business case analysis?

Interview Questions – Marilee Wheaton, Aerospace

1. Do you think that it will be feasible, technologically, to conduct on-orbit repair on a routine basis?
　　　a. Yes
2. Do you think that there is a business case for on-orbit repair? Or what factors would you consider whether or not the repair/service?
　　　a. Yes, but it depends on what happens with the small sat industry because industry is currently trending towards throw away SVs
3. Who will be the larger customer – government or commercial?
　　　a. Commercial because of their revenue stream
　　　b. Government because a mission might be so important
　　　c. Business case dependent for each
4. In your experience, what bus components fail the most?
　　　a. Reaction wheels
　　　b. Plans to get me some data
5. Do you think those components could be repaired on-orbit?
　　　a. Reaction wheels would be hard to get to because they are in the middle of the SV, but they could be placed on the external of the SV or at least towards the outside of the SV
　　　b. Solar arrays – yes with a swap
6. How might you change the satellite design in order for those components to be repaired routinely?
　　　a. S/W needs to put the SV in safe mode first that protects the SV while its being serviced
7. Would constellation architectures need to be changed in order to benefit from on-orbit repair?
　　　a. Changes to mission planning and CONOPS to ensure the mission continues while a SV is being serviced
8. What interface or other standards do you think would be needed for on-orbit repair to become mainstream?
　　　a. Modular bus
9. Would any ground testing need to be changed, added, or eliminated?
　　　a. Digital twin concept of the SV (like a model)
10. What additional risks do you foresee with routine on-orbit repair?
　　　a. What if the repair takes longer than planned? How does that affect mission?
11. Who else do you think I should talk to?
　　　a. Joseph Aguilar – Director of Vehicle Design – 310-336-2479

- We've been doing on-orbit repair/servicing for a long time if you think about software

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