70th International Astronautical Congress (IAC), Washington D.C., United States, 21-25 October 2019.

IAC-19-D1.6.9

On-Orbit Servicing Ontology applied to Recommended Standards for Satellites in Earth Orbit

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Abstract

The Consortium for Execution of Rendezvous and Servicing Operations (CONFERS) is an industry-led initiative with initial seed funding provided by the Defense Advanced Research Projects Agency (DARPA) that aims to leverage best practices from government and industry to research, develop, and publish non-binding, consensus-derived technical and operations standards for On-Orbit Servicing (OOS) and Rendezvous and Proximity Operations (RPO). As part of the CONFERS effort, the University of Southern California's (USC) Space Engineering Research Center (SERC) conducted research into existing RPO methodologies and practices and OOS methodologies through literature review and interviews with practitioners. Following the first year of analytical input focused solely on RPO, the second year's activities have focused further into the full extent of attributes for satellite servicing and in-space docking (OOS). USC's focus was to develop a taxonomy of functions and attributes related to all aspects of technical elements and techniques required for past/current/anticipated OOS missions. A taxonomy database was created that allowed various key elements to be broken down into quantifiable data within common categories. Following the taxonomy creation, working with the Space Infrastructure Foundation (SIF) a review of existing standards in space along with other industries were analyzed and compared for possible matches. This standards gap analysis focused primarily from the end of the RPO maneuver to the point of physical contact or action between two spacecraft. These comparisons were then used to recommend where gaps in standards exist and where it might be most beneficial to create new ones, enabling spacecraft of various shapes and sizes to safely execute various OOS operations, and spur the industry between customers and providers. The field of space servicing is a rapidly growing field, with governments and numerous private entities developing robotic systems for mission extension vehicles and satellite repair. With an increased number of servicing missions forthcoming, a system of guidelines and standards on how to effectively and safely design on-orbit servicing activities is a next natural step to enable the expansion of this burgeoning industry.

Keywords: Satellite, Rendezvous, Servicing, Ontology, Safety

Nomenclature

ATTRIBUTE ..... Quantitative metric or characteristic to enable a function to be executed or satisfied

CLIENT .... Satellite or Platform to be Serviced

ELEMENT / MISSION ELEMENT .... An activity within the overall orbital servicing architecture that requires multiple functions

FUNCTION . Activity required to affect a particular OOS element

SERVICER ... Satellite or Platform that provides Service

Acronyms/Abbreviations

AIAA American Institute of Aeronautics and Astronautics

ANSI .... American National Standards Institute

CCSDS Consultative Committee for Space Data Systems

CONFERS .. Consortium for Execution of Rendezvous and Servicing Operations

CVSA .... Commercial Vehicle Safety Alliance

DARPA ... Defense Advanced Research Projects Agency

DOT .... Department of Transportation

ESA .... European Space Agency

ESTEC European Space Research and Technology Centre

EVA .... Extravehicular Activity
FMCSR ...... Federal Motor Carrier Safety Regulations
ISO ...... International Organization for Standardization
JAXA .... Japan Aerospace Exploration Agency
LEO .... Low Earth Orbit
NASA .. National Aeronautics and Space Administration
NHTSA National Highway Traffic Safety Administration
NRL .... Naval Research Lab
OOS .... On Orbit Servicing
RPO .... Rendezvous and Proximity Operations
SERC .... Space Engineering Research Center
USC .... University of Southern California

1 Introduction

Next-generation space activities, where companies and organizations begin to provide services for each others space assets, are real and coming on-line. ”Servicing” in the context of space constitutes a large and robust set of missions, all of which require some sort of interaction between different space objects. In general terms, to the burgeoning commercial space community worldwide these interactions are new; to-date almost all space-to-space interactions have been executed by nation states or commercial companies working for and under nation-state processes and oversight. With the enormous economic and societal potential in new ”servicing” mission sets possible, it makes sense to proliferate processes, standards, practices, procedures, and verification methods to the global commercial space community to encourage mitigation of any risks inherent in this high risk/reward domain of multiple RPO maneuvers and manipulations.

1.1 CONFERS: What is it?

The Consortium for Execution of Rendezvous and Servicing Operations (CONFERS) is an industry-led initiative with initial seed funding provided by the Defense Advanced Research Projects Agency (DARPA) to leverage best practices from government and industry to research, develop, and publish non-binding, consensus-derived technical and operations standards for OOS and RPO [1, 2]. The goal for these standards is to provide the foundation for a new commercial repertoire of robust safe space-based capabilities to encourage and support the future in-space economy. CONFERS is open to participation by private sector stakeholders in the international satellite servicing community. All companies and academic institutions developing, operating, insuring, and purchasing OOS and RPO capabilities are encouraged to join and contribute their experience and expertise.

1.2 USC’s role in CONFERS

As the technical advisors for the CONFERS consortium, USC SERC was given the task to assess the current state-of-the-art, uncover standards or best practices, and recommend possible actions to consider as potential safety standards in RPO and OOS for the CONFERS community to consider. The task was broken out into two single year efforts, with the first year focusing on RPO and second year OOS. Following the first year’s work and results [3, 4], this paper focuses on the results of the OOS work in the second year, with the methods listed below.

1.3 First year efforts – Recap

Over the first year effort the team at the SERC executed a number of investigations that led to further efforts by the CONFERS team as a whole. These included: identifying and seeding a specific RPO/OOS lexicon process, encouragement to develop a ”standard” set of mission element definitions and diagrams, and development of a set of metrics to quantify RPO safety for basic approach and docking missions, similar to those that satellite servicers would undertake. The resultant metrics created scaleable and unitless ratio’s that could apply to any particular ”Client” and ”Servicer” combination through identification of potential contact and external interference. Three unitless metrics were identified to be used both in the design phase of RPO platforms as well as prior to each RPO engagement to give some measure of ”goodness” or ”risk assessment”. These are detailed in a previous publication [3].

1.4 Second year efforts

Following USC’s efforts towards RPO for the first year of the CONFERS program, the second year efforts focused on the larger context of OOS. The second years effort consisted of the following investigations and analysis:

(i) Surveying existing and planned standards that may be applicable to satellite servicing missions;

(ii) Evaluating space domain and analogous industries for seed ideas to inform potential standards;

(iii) De-constructing the initial mission element diagram/architecture into a set of functions and attributes;

(iv) Seed attributes with quantitative values based on engineering practices, processes, standards and other analysis;

(v) Perform detailed Monte-Carlo and decision tree analysis to suss out the most critical attributes for safety related standards to inform CONFERS members to consider.

2 What is Safety?

The question, what does the term "space safety" mean in relation to the "servicing" function, is critical as it sets the stage for an approach to what possible risk areas to identify as a standard or practice, and informed our approach to the analysis.

Historically the context associated with the term "safety" in space refers to the "element" itself. Satellite safety typically looks at risks or attributes that could cause harm to the satellite itself, or the failure of its operation or intended mission to be successful over time. Normally these are from internal attributes interacting with the external environment (i.e. temperature, radiation, sunlight, RF etc.), or just getting to the orbit through launch. More recently additional environmental attributes such as contending with the probability of an unplanned encounter with a physical object in orbit, like another satellite or space debris, has been added to this list.

The historical definition of "satellite safety" contextually broadens into a larger orbital regime as more debris and traffic (i.e. more satellites) are considered. At the moment we are witnessing a large influx of new satellites and constellations planning to be launched into Low Earth Orbit (LEO).

The context of "safety" most analogous to on-orbit servicing typically is associated with "reaching out and touching". Rendezvous and Proximity Operations (RPO) is the art and technique of getting close to and setting up the ability to "touch" another satellite or space object in orbit to affect an action. The entire new market and mission segment of "on orbit servicing" predicates its existence on effective and low-cost actions to get up close and personal with objects on orbit, on a regular basis. The key is that it must do so in a "safe" manner...

To-date RPO has mainly been the sole domain of nation-states and large government agencies (RosCosmos and NASA as examples) which have looked at "safety" relative to docking two objects since the start of manned space activities. By and large this has happened without problems, with a few notable exceptions [5, 6]. However, the context here in looking at "safety" for RPO is the reality that it is transitioning quickly from just a singular sporadic "mission" to regular and higher tempo "market" operations with new companies, universities and organizations around the world. Thus, not only is the operating realm a bit more cluttered relative to how RPO has occurred generally in the past (i.e. more debris, new constellations etc.), but the published and available expertise in RPO (through handbooks or manuals as examples) do not currently exist.

For the domain of "commercial servicing", another unique attribute stems from space activities generally being "out of sight", which translates to the problem of orbital "safety" as being out of mind. While other industries (marine, rail, automotive etc.) may have similar risks for collisions or accidents, the lack of immediate visual knowledge in space means there is, to some extent, a lack of global conscious oversight concerning what the new Servicing industry is doing during RPO.

Thus, "safety" in the context of On-Orbit Servicing (OOS) has two masters; minimizing the risks of generating debris on orbit of any kind, and applying some level of cogent self-regulation to avoid oversight being thrust upon all parties via Governmental regulations.

3 Existing and Analogous Standards

The first major analysis in the 2nd year surveyed existing and planned standards for applicability to satellite servicing and RPO missions. Within the space domain roughly 50 standards were initially identified applicable in some way to RPO and OOS [7].

3.1 Existing Standards in the Space Domain

Table 1 shows an initial look at space standards identified as applicable to RPO or OOS, from various organizations, including the International Organization for Standardiztion (ISO), the American Institute for Aeronautics and Astronautics (AIAA), the American National Standards Institute (ANSI), and the Consultative Committee for Space Data Systems (CCSDS). For reference we have included as many as possible. [8–78].

Table 1: First look for Space Standards that may address RPO and OOS Elements

Standard	**Identifier**
Spacecraft Identification Field Code Assignment Procedures	CCSDS 320.0-M-7
Mitigation of Impacts	ISO 11227:2012
Proton Flux at GEO	ISO 12208:2015
Electromagnetic Compatibility	ISO 14302:2002
	ISO 24637:2009
	ISO 24637:2009
	AIAA S-121A-2017
Launch Vehicle Interface to Spacecraft	ISO 14303:2002
Structural Design	ISO 14622:2000
Launch Vehicle Loading Test	ISO 14953:2000
Exchange of Mathematical Models for Dynamic and Static Analysis	ISO 14954:2005
Pressurized Structures	ISO 14623:2003
	ISO 24638:2008
	ANSI/AIAA S-081B-2018
	ANSI/AIAA S-080A-2018
Compatibility of Materials	ISO 14624
Surface Cleanliness of Fluid Systems	ISO 14952
Contamination and Cleanliness Control	ISO 15388:2012
Stress Analysis	ISO 16454:2007
Simulation	ISO 16781:2013
Connectors for Serviceability	AIAA G-072-1995
Grasping, Berthing, Docking Interfaces	AIAA G-056-1992
On-board Communication	CCSDS 850.0-G-2
Orbit Data Messages	CCSDS 502.0-B-2
Tracking Data Message	CCSDS 503.0-B-1
Attitude Data Messages	CCSDS 504.0-B-1
Cojunction Data Message	CCSDS 508.0-B-1
Exchange of Orbit Information	ISO/TR 11233:2014
	ISO 26900:2012
Telerobotics Lexicon	AIAA S-066-1995
Concept of Operations	ISO 14711:2003
Operability	ISO 14950:2004
Documentation	ISO 23041:2018
Space Debris Mitigation	ISO/TR 18146:2015 ISO/TR 20590:2017
	ISO/CD 20893
	ISO 24113:2011
Ground Testing (General)	ISO 15864:2004
Ground Testing (Fluids)	ISO 15859:2004
Safety of Launch Site Operations	ISO 14620-2:2011
Flight Safety During Launch	ISO 14620-3:2005
Launch Integration Practices	AIAA R-099-2001
Early Operations	ISO 10784-1:2011
Space Solar Panels - ESD testing	ISO 11221:2011
Prevention of Break-Up of Unmanned Vehicles	ISO 16127:2014
	ISO 21347:2005
Avoiding Collisions	ISO/TR 16158:2013
Measuring Residual Fuel	ISO 23339:2010
Disposal of GEO satellites	ISO 26872:2010
Telerobotics	CCSDS 540.0-G-1

Of these, only about one third were found to have quantitative values with a physical attribute or process associated with them, whereas the rest formulated outlines for what analysis to perform to get a quantifiable metric. Non-quantified standards lead to different interpretations of a quantifiable attribute by different entities, resulting in a wide variety of systems that are compliant with the standard, but operate with very different parameters. For example, the ISO standard on *Electromagnetic Compatibility (ISO 14302:2002)* identifies specific frequency ranges and emission energies which, if exceeded, could damage nearby spacecraft [10]. Compare this to another ISO standard on the *Prevention of Break-Up of Unmanned Vehicles (ISO 16127:2014)* which is meant to specify how to safely decommission unmanned spacecraft to prevent creation of debris, but does not specify how to do this. Rather, it uses phrases such as

> ”The risk of potential malfunctions shall be considered within the break-up prevention plan, which

> shall include a contingency plan to mitigate against the risk of the malfunction causing a break-up"

without specifying any criteria to design for or verify against [60]. The goal of CONFERS is to build upon existing standards such as these to identify best practices for the industry to codify qualitative methods and metrics to achieve quantifiable safety goals, for as many physical attributes involved in "servicing" as practical.

3.2 Analogs to Space

Recognizing other vehicle platforms and domains that have faced similar challenges, the team drew upon additional comparisons by looking at standards that might hold analogous functions or attributes from automotive, aviation, and naval industries to space. Quantitative evaluation into some of these terrestrial domains helped to focus the OOS ontology into similar decomposition of actions to functions and attributes.

Although there are no specific standards in the Space domain for RPO and OOS at the moment, there are countless standards in terrestrial industries that provided examples to draw from. These were considered as *analogous standards*, with equivalencies in gross functions, processes or elements to the RPO or OOS domain, providing inspiration for design guidelines and best practices to apply to space-based applications. To pick a specific example, consider the backup sensors on cars; they have specific quantitative standards that specify a required ranging resolution needed to make out hazards while reversing a motor vehicle [79]. Translating that functional example to the Space domain, the *backup sensor* analogy may be extended to sensors used onboard a Servicer used for final range approach during many RPO operations. This function and its attributes may benefit from a set of standards specifying a recommended ranging/distance resolution relative to what may contribute to a risk during rendezvous. This is but one example of a potential functional element on a Servicer that may benefit from some quantitative attributes being assigned and thus considered for standards, better enabling a large number of new entrants in OOS to validate their component selection and approaches to execute RPO operations, safely.

An interesting observation of these analagous industries was an identified interaction between Government regulators and an industry consortium that showed a high degree of quantitative self governance, which may provide inspiration for the satellite servicing community. The Commercial Vehicle Safety Alliance (CVSA) is a multinational commercial consortium that supports and supplements government standards from US and Canada, primarily for commercial over-road transport connection interfaces. In addition to providing inspection services and self-regulation for their industry, the CVSA publishes supplemental guidelines to accompany government standards for vehicle connection safety, as many of these standards are open-ended and have many different potential implementations. To provide a specific example lets look at Section 393.70(d) of supbart F of the Federal Motor Carrier Safety Regulations (FMCSRs):

> §393.70(d) requires that every full trailer must be coupled to the frame, or an extension of the frame, of the motor vehicle which tows it with one or more safety devices to prevent the towed vehicle from breaking loose in the event the tow-bar fails or becomes disconnected. The safety device must be connected to the towed and towing vehicles and to the tow-bar in a manner which prevents the tow-bar from dropping to the ground in the event it fails or becomes disconnected. [80]

Although this standard requires that some form of two-fault tolerant system must be implemented to prevent accidental disconnection of the towed trailer, no specific method of implementing this is providing, leaving this an open-ended problem for an end user. To simplify operations for vehicle operators, the industry based CVSA has issued detailed qualitative guidelines pertaining to §393.70(d) of the Federal Motor Carrier Safety Regulations:

> The Federal Motor Carrier Safety Regulations (FMCSRs) do not specify a minimum number of fasteners. However, the industry recommends that a minimum of ten 5/8 inch bolts be used. If $\frac{1}{2}$ inch bolts are used, the industry recommends at least 14 bolts. [The CVSA] has adopted these industry standards as a part of its vehicle out-of-service criteria [81].

These guidelines do not overrule federal regulations, nor are they strict regulations that all industry members are obliged to abide by; rather they are informational and easy to implement, allowing standardization of parts and tooling for those who volunteer to follow the guidelines for this one function (i.e. towed vehicle safety). The authors highlight this interaction between Government regulators and industry consortium as a positive collaboration where industry actually sets quantitative metrics.

4 Mission Element Taxonomy Creation

As it was identified in the first year that a standard "architectural diagram and definition" did not exist that was accepted globally, the CONFERS members created and approved a mission architecture operational view (OV-1) [82] to help define individual elements to effect a "service" action. Fig. 1 describes a top level set of elements where each executes a specific orbital related action, along the way to a servicing event. Starting with this OV-1, our next step was to de-construct each element into finer functions and attributes, suitable for quantitative metrics to begin to apply.

4.1 Functions & Attributes from Mission Elements

Deconstruction of the OV-1 (see Fig. 1) the team created and identified what are referred to as "function:attribute" pairs for each element. Briefly, "functions" are defined as an activity required to affect a particular phase on OV-1 elements, while "attributes" are defined as the quantitative metric or characteristic required to enable that function. For example, the phase *Depart Parking Orbit* was identified to have the functions *Pre-Service Preparations*, and *Transit Conjunction Analysis*. Then one attribute of *Pre-Service Preparations* can be identified as *Minimum Fuel Remaining at Client Orbit*. This translates to the following: In order to depart the parking orbit, the Servicer must perform pre-service preparations, which in quantitative terms means it must evaluate the amount of propellant the maneuver will take to ensure sufficient propellant will remain at the end of the maneuver to perform the desired servicing operations. (As an analogy, this is similar to the minimum fuel remaining required for planning a flight to one airport by aircraft, to account for weather diversion to another airport).

Fig. 2 shows a sample of the resultant initial taxonomy that links OV-1 elements, functions, and associated attributes to each other. The full taxonomy chart can be found in Appendix A. Multiple references helped to identify what additional functions may be needed for each element [83, 84].

For our analysis, formal definitions of *functions* and *attributes* are as follows:

Function: An activity required to effect a particular OV-1 OOS element. There can be multiple functions required for each element. Functions are defined as actions that are either primary or secondary activities that correspond to a particular event in the OV-1 required for a particular service.

Attribute: The quantitative metric or characteristic to enable a function to be executed or satisfied. There can be multiple attributes assigned to each function.

In many cases, finding attributes are straightforward, and many have measurable value metrics that can be logically assigned, estimated, or calculated. What is not straightforward

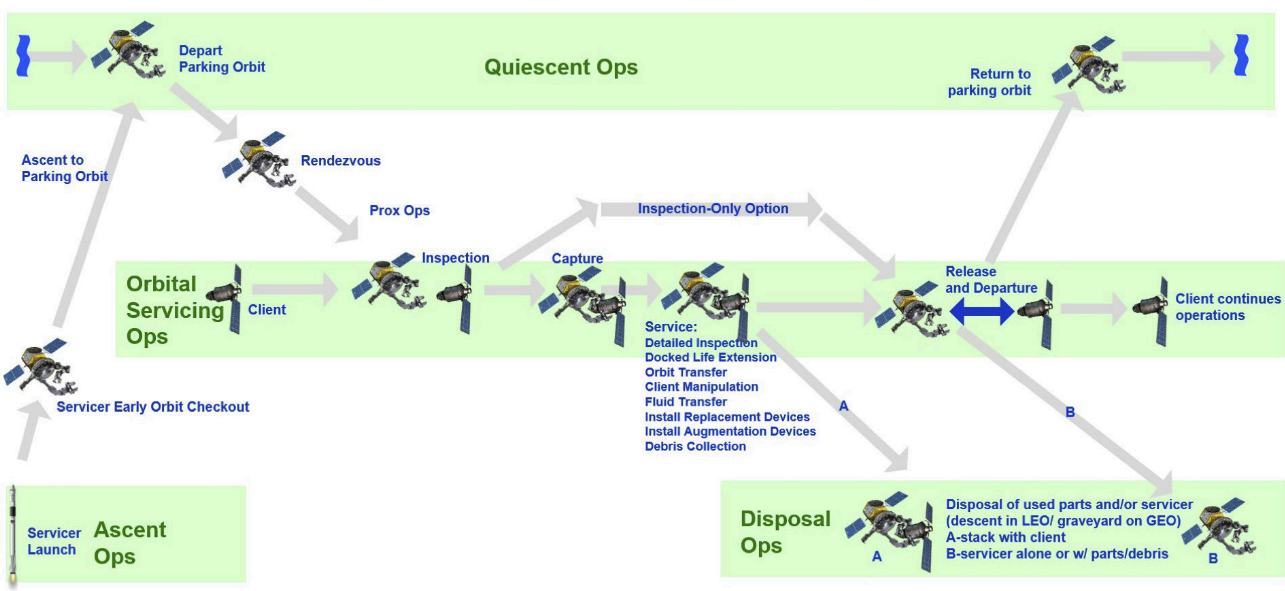


Fig. 1: CONFERS OOS OV-1

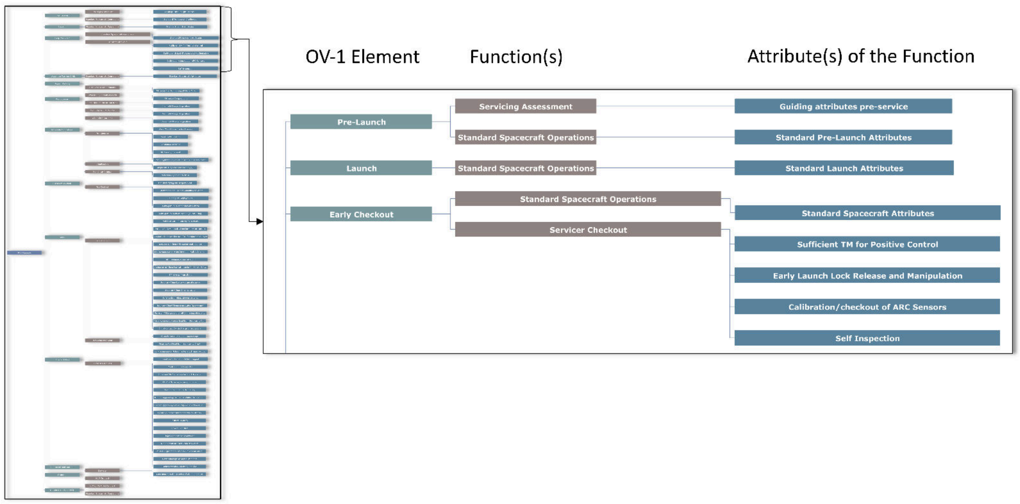


Fig. 2: OOS Taxonomy Tree [Partial]

is identifying attributes that affect *safety* as defined in our original OOS analysis context.

To provide an example of a set of functions and attributes pulled out of a servicing action from the OV-1 diagram, let's look at one function identified for *illumination*. Illumination of the Client is generally required in a servicing action for verification of successful approach and contact. Illumination could include ambient light (Sun), artificial light (provided on site), or alternative wavelength (i.e., infrared). Initial attributes identified that provide a quantitative description of the *illumination* function are:

(i) Amplitude/Brightness (Lumens/m^2)

(ii) Distance between light source and Client object to be illuminated

(iii) Active guidance and control enabled to avoid loss of illumination

For the *brightness* attribute, two common occurrences found in historical analyses are 126 000 Lumens/m^2 for sunlight in Low Earth Orbit (LEO) [85] (Fig. 3) and 860 Lumens/m^2 for standard space shuttle Extravehicular Activity (EVA) suit helmets [86] (Fig. 4). This breakdown would lend itself to the assessment and assignment of a minimum Lumens for "safe" OOS service. In the case of the Astronaut EVA, Hamilton-Sundstrand assessed a 1 meter standoff from an object from an astronaut using his/her vision only required a minimum of 860 Lumens/m^2.

Fig. 3: Sunlight in LEO

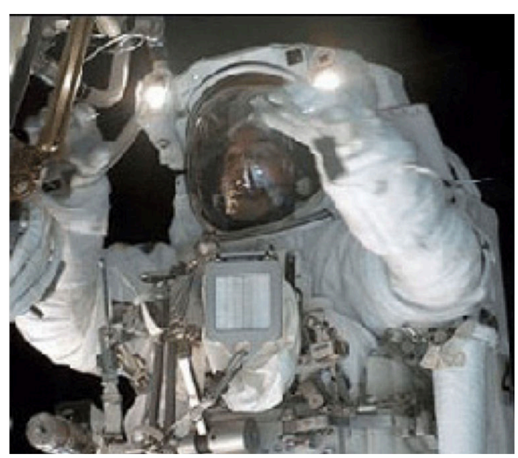


Fig. 4: EVA Headlamp

4.2 Quantitative Assignment of Attributes

After breaking down the OV-1 diagram into Functions and Attributes, quantitative values were proposed and initially assigned for each of the attributes (i.e. the *Illumination* example). This was done by looking for existing space and analogous domain standards, specifically those identified earlier as having quantitative values associated with them. The goal, by applying this method to all the functions and attributes from the OV-1 taxonomy analysis, was to see if a correlation could be found between each OV-1 element and a set of quantitative metrics to numerically assess various aspects of a function for its ”safety”. The process was to take each attribute and through research from a number of sources try to find a metric that may apply.

To exemplify this process, lets continue the previous attribute example where a value of $860\,\text{Lumens}/\text{m}^2$ was assigned for the *brightness*, based upon previous work for astronaut close approach work [86]. We also related this to an analogous standard in the automotive industry, issued by the Department of Transportation’s (DOT) National Highway Traffic Safety Administration (NHTSA), on automobile headlamps [87] Together, the quantitative metric for the *brightness* attribute of the *illumination* function would be proposed as:

> The Amplitude-Brightness required for sufficient human validation of optical images should be at least $860\,\text{Lumens}/\text{m}^2$.

To provide another example lets look at pose estimation in the OV-1 element *Client Preparation*, which we broke down into the function and attribute of *Pre-Contact* and *Orientation of Client and Appropriate Inertial Condition*, respectively. This attribute was given a quantifiable metric based on research done by the Integrated 3D Sensors Suite (I3DS) team funded through the ESA Horizon 2020 initiative [84, 88]. Given this input, a quantitative metric is proposed as:

> The Client must demonstrate and maintain stability in pitch/yaw/roll to <1 deg/second. If consumable ADACS is used, sufficient margin exists that is $>10\%$ required during the entire time of the Servicing operation plus 4 days.

This process was applied to as many of the function/attribute pairs as possible, and the results of this are detailed in Appendix B.

4.3 Future work: Monte-Carlo and Decision Tree Analysis

While an initial set of quantitative metrics were created (Appendix B) what remains is to identify the most relevant attributes for OOS safety. One methodology using a combination of Monte-Carlo analysis and Decision Trees to select the most critical safety attribute was proposed but not pursued in this years analysis. For future work this process could be accomplished by taking the list of Attributes created in the function:attribute analysis and running Monte-Carlo distributed simulations (given a set of bounds) on these attributes to see how this affects OOS mission outcome. Then after performing this analysis for all of the attributes, the data would be fed through a decision tree matrix in order to determine the sensitivity of each attribute, identifying those that have the greatest effect on mission success and thus safety.

These so called *sensitive* attributes might then form the basis of the guidelines and best practices for On-Orbit Servicing (OOS).

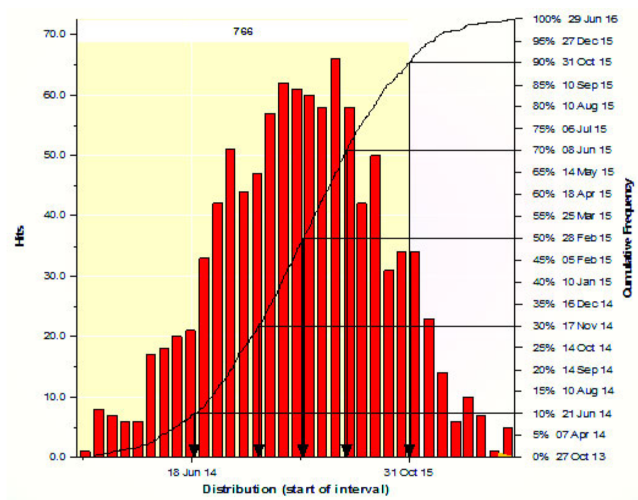


Fig. 5: Monte-Carlo Distribution [Representation Only]

5 First look at interfaces

The SERC also performed preliminary analysis on interface mechanisms used for On-Orbit Servicing as they relate to ”safe” OOS. The goal of this was to create an ontological breakdown of existing interfaces to begin to classify common functions and attributes. Interfaces have multiple requirements and responsibilities that must operate within the various physical elements, and within the environment of space.

Fig. 6 depicts some top level operational and environmental considerations.

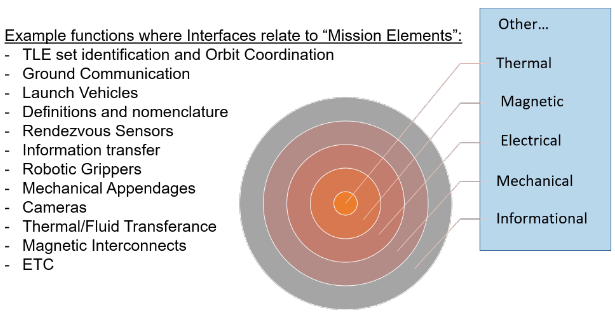


Fig. 6: Interface considerations for "Safe" OOS operations

This started out as a survey of docking interfaces with information published or publicly available on a website (see Appendix C for the full survey results). The approximately 25 interfaces found in the survey covered a wide range of sizes, from CubeSat-class docking interfaces on the lower end to space station human rated interfaces on the upper end, and everything in-between [89–95]. However, this list is not comprehensive, and contains only interfaces with information readily available and searchable on the web; there are likely more interfaces which are proprietary. From this top level survey and the identified considerations, an initial set of attributes and quantitative metrics were identified relative to specific environmental inputs for initial discussion relative to OOS. (Shown below in Table 2).

It was found that the term *interface* is very wide-ranging, and has different meanings to different groups of people. This made it difficult to classify *features* (or properties of) and *requirements* (regulated or mandated attributes of) for interfaces. Traditionally, though there is no consensus on a formal definition, interfaces have been considered as hard contact mechanical devices, such as docking rings or robotic end-effectors. Recently, however, non-traditional approaches haven been tested or implemented, such as the use of electro-adhesion [96], gecko gripping material [97], even spring-loaded harpoons [98]. These advances, though exciting, make classifying interfaces and defining safety properties for them difficult in a traditional sense. Instead of defining a set of best practices for interface design based on existing designs, our OOS interface work was broken down into suggested *requirements* and *features*, for which quantitative values can be defined without restricting the method or design by which the interface achieves this. For example, a feature of the electrical requirements can be the *RF Shielding Robustness*:

> In order to shield the on-board electronics from potential interference of the RF emissions from the Client spacecraft, the electronics must be able to handle an applied electric field of up to 50 V/m for emission frequencies between 2 GHz - 4 GHz or 5.5 GHz - 5.9 GHz, and up to 50 V/m for all other frequencies [72].

	Possible Interface Requirements for Safety	*Quantitative Development Approach*
Mechanical	Initial Contact Impact Force	TBD % less than client contact point yield with a TBD factor of safety
	Grip force	TBD % less than client fixture yield
	Two failure tolerant connection	99% 1st mechanism hold over ± TBD lateral force, 100% 2nd mechanicam hold for TBD hours, or until primary mechanism restored
	Contact sensing	+/- TBD mm in longitudinal, +/- TBD mm in lateral, and +/- TBD radians in rotational
	Two failure contact sensing	99% 1st mechanism hold over ±TBD lateral displacement, 100% 2nd mechanicam hold for TBD hours, or until primary mechanism restored
Electrical	Total Overcurrent Capability	2x nominal current transport over interface, with fuse inline
	Thermal capability	Can handle 3x current transport over interface connection/wiring
	Ripple on Current/Voltage	Less than TBD % on current/voltage
	RF shielding robustness (Electric Field from Client source)	Able to handle up to 50V/m between 2-4GHz or 5.5-5.9GHz, 20V/m all other frequencies
	Two failure power inhibit on contact	99% mechanical contact inhibit for force/shock/etc, 100% secondary electrical inhibit on failure of 1st
	Static discharge capability upon initial physical contact	Handle up to 10kVolts
	Data input protection	Can handle incorrect / malicious data from external system
	Polarity Reversal Capability	method in place to handle reversed polarity on interface between two spacecraft

	Possible Interface Requirements for Safety	*Quantitative Development Approach*
Fluid/Pressure	Max. overpressure	2.5x over rated pressure capacity on fittings and lines
	Automatic overpressure release	Leak before burst, at TBD times rated pressure
	Fluid containment	Capture TBD % of outgass/burnoff at connect/disconnect; Zero release of contaminants within TBD meters of Client optics
	Discharge thrust upon valve failure	Less than TBD Newton
	TBD	
Thermal	Thermal Transfer Limit	If able to transfer thermal from client, interface to handle up to TBD % over designed for W-m2
	Temperature measurement accuracy	+/- 10% of the actual thermal condition contacted
	Thermal Isolation Capability	If thermal is isolated, able to isolate from Client up to TBD times Servicer thermal transfer at interface
	Thermal Radiation Consideration	Minimize thermal radiation towards client spacecraft and/or design to allow thermal radiation incoming from client spacecraft. Possible characterization is max W/m^2 based on Servicer thermal design, or some area factor of safety
Magnetic	EM field external to interface geometry	Less than TBD % EM field beyond interface geometry, or less than TBD Gauss value applied at cm^2 surface
	Induced electrical field or current	Less than TBD micro-T induced onto the Client surface or electrical lines
	Structure Degaussing	Less than TBD Gauss magnetic field internal to structure

Table 2: Interface Survey Attributes

These *requirements* and *features* were created to fit a wide variety of OOS interfaces, primarily to address any aspects of the interfaces themselves that could affect system safety through avenues such as release of mass, inadvertent application of force, electrical discharge, etc. These follow top-level categories such as Mechanical, Electrical, Pressure Systems, Thermal Control, and so on, creating functions that are applicable to all (or a wide range) of the interfaces identified through the survey. Its possible that as the survey expands by adding new systems, or existing systems that do not have information available online, these features and quantitative assessments of them will change.

6 Recognizing Similar Work Globally

While the SERC effort has been performing this RPO and OOS research under the umbrella and funding from CONFERS, other groups worldwide have been pursuing similar avenues of research simultaneously. Most notably, the European Space Agency (ESA) has been doing RPO and OOS research through the European Space Research and Technology Centre (ESTEC) in The Netherlands [99], and the Japanese Aerospace Exploration Agency (JAXA) has been conducting their own independent review of OOS missions to determine standards and best practices [100, 101].

Additionally, within the United States, a group at the National Aeronautics and Space Administration (NASA), specifically at the Goddard Space Flight Center (GSFC), has performed research on On-Orbit Servicing for satellites, part of which was used to support this research [83].

Efforts were made to contact researchers in Russia and China doing similar work, but so far no contact, either to perform joint research with USC on an academic basis, or to join the CONFERS consortium as industry members, has occurred.

In addition to making guidelines and best practices for use by members of the CONFERS consortium, the CONFERS standards group has presented findings at an International Organization for Standardization (ISO) conference in London in June of 2019, where the CONFERS principles and practices were accepted into working draft by the ISO committee for consideration [102].

7 Conclusions

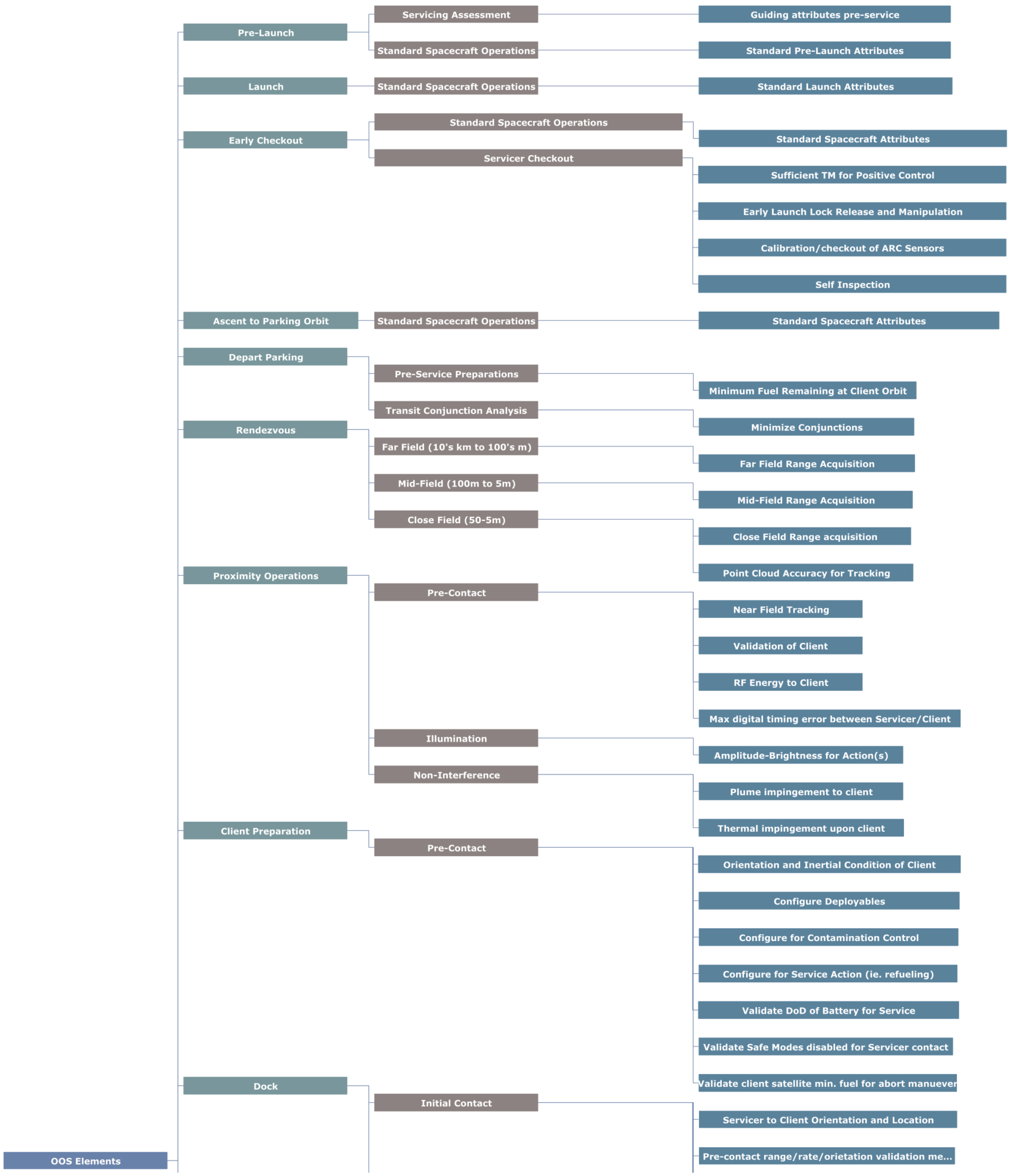
USC's activities during this phase of CONFERS research developed a top level taxonomy to provide a foundation to uncover critical quantitative and qualitative metrics related to all aspects of on-orbit servicing. The notion of ”safety” as it relates to the global commons around Earth and its context to the relatively new field of RPO for pure commercial purposes was proferred. A preliminary look at critical attributes for ”interfaces” of any kind was offered without focusing on any particular flavor or method to achieve the interface function. A suggested path forward to take the very large set of potential attributes and work through a convergence of traditional aerospace simulation with informatics decision tree analysis was offered as a way to find the most ”safety critical” technical activities to pursue as possible standards work in the future.

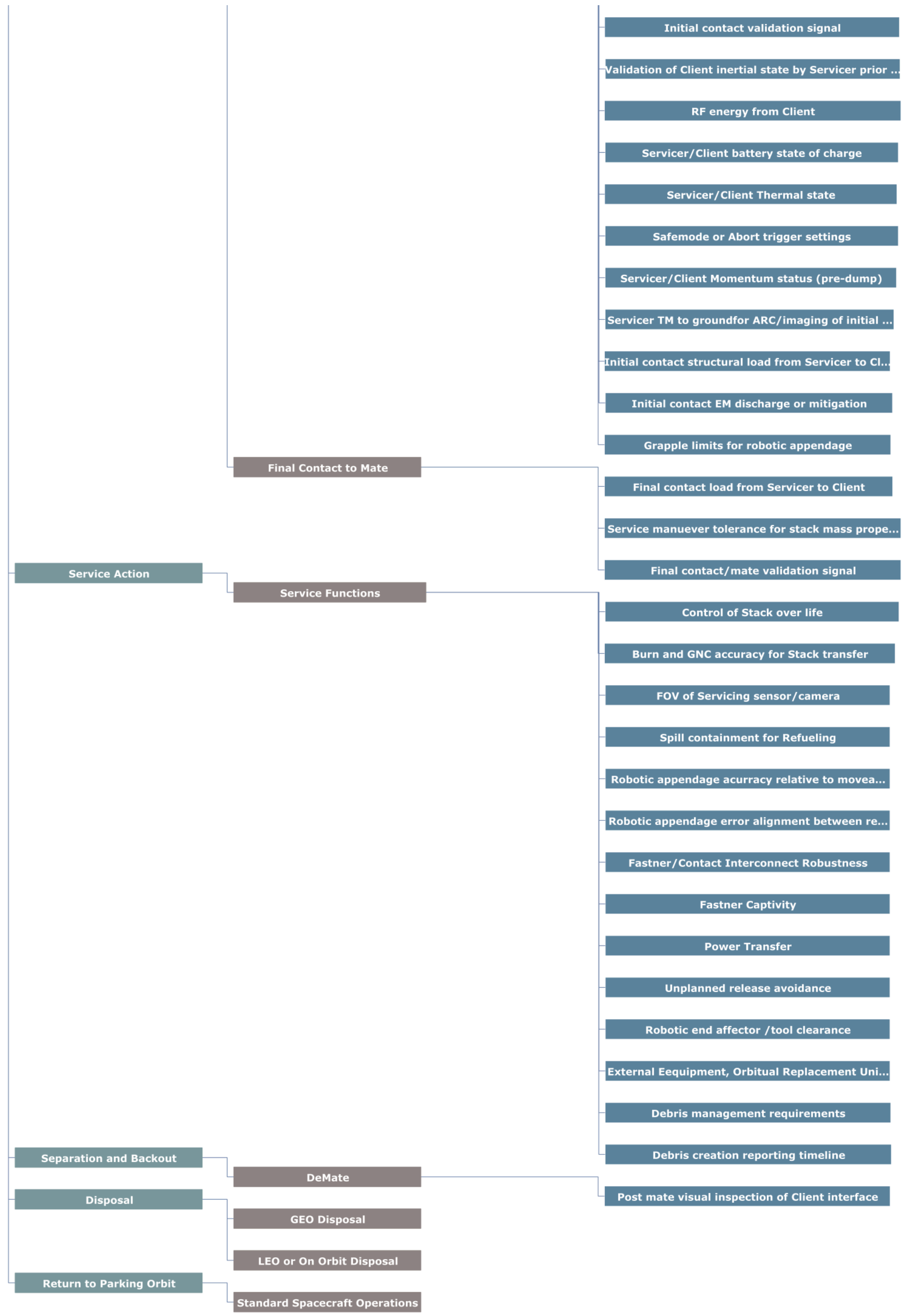
The Space community has a large number of standards already in place that this community can utilize; from data formatting, communications, debris mitigation recommendations, etc. The challenge going forward in the RPO/OOS domain is finding and creating those standards that are critical to maintain the ”safest environment” in Earth orbit for this new community and market to thrive.

Acknowledgements

The authors wish to thank Todd Master and Srimal Choi from DARPA, Erin Fowler from the Naval Research Lab (NRL), Brian Weeden and Ian Christensen from Secure World Foundation, and Frederick Slane, Michael Kearney and Ramon Krosley from the Space Infrastructure Foundation for their support and inspiration on this project.

Appendix A (Taxonomy Tree)




Initial contact validation signal
Validation of Client inertial state by Servicer prior ...
RF energy from Client
Servicer/Client battery state of charge
Servicer/Client Thermal state
Safemode or Abort trigger settings
Servicer/Client Momentum status (pre-dump)
Servicer TM to groundfor ARC/imaging of initial ...
Initial contact structural load from Servicer to Cl...
Initial contact EM discharge or mitigation
Grapple limits for robotic appendage
Final Contact to Mate
Final contact load from Servicer to Client
Service manuever tolerance for stack mass prope...
Service Action
Final contact/mate validation signal
Service Functions
Control of Stack over life
Burn and GNC accuracy for Stack transfer
FOV of Servicing sensor/camera
Spill containment for Refueling
Robotic appendage acurracy relative to movea...
Robotic appendage error alignment between re...
Fastner/Contact Interconnect Robustness
Fastner Captivity
Power Transfer
Unplanned release avoidance
Robotic end affector /tool clearance
External Equipment, Orbitual Replacement Uni...
Debris management requirements
Debris creation reporting timeline
Separation and Backout
DeMate
Post mate visual inspection of Client interface
Disposal
GEO Disposal
LEO or On Orbit Disposal
Return to Parking Orbit
Standard Spacecraft Operations

Appendix B (OOS Topology Worksheet)

Elements	OV-1 Mission Elements or Event Description	Functions associated with Element or Event	Attributes associated with Functions	Proposed Quantitative Value	Reference	Existing Space Standard	Other Domain Standard
A	**Pre-Launch**	a) Servicing Assessment (Client/Servicer) b) Standard spacecraft operations and guidelines	Standard Spacecraft Attributes	There are a number of capabilities that both Servicer and Client should have. Recommend a guideline document be developed that identifies a servicing "hard contact" assessment. While this is currently contractual, this lends itself to a standard guideline that all "servicing" players discuss ahead of time.	NASA Functional Decomposition Document, Appendix D (pg 121)	AIAA R-099-2001	
B	**Launch**	Standard Spacecraft Operations	Standard Spacecraft Attributes			ISO 14622:2000	
C	**Early Orbit Checkout**	Standard Spacecraft Operations	Standard Spacecraft Attributes			ISO 10784-1:2011	
		Servicer Functions Checkout	Sufficient TM for Positive (Robotic) Control	TBD bps from ground to Servicer (Recommend a rate that is 3x what a robotic appendage control system requires, with a bandwidth 2x required of the data at frequency.)			
			Early launch lock release and manipulation	Launch locks for deployable systems (Is there a standard for a launch hold down and release mechanism already or is something that is needed. Would also apply to parasitic tools or free flyers that are used as inspectors to aide the servicer. Whatever launch lock with release mechanism is considered a "safety" item that if fails will release mass.)			
			Calibration of ARC sensors	Values for alignment should be based on the source proposed, either onboard or moon/sun/earth/star etc. Background noise figures should be set as a standard for the calibration object if not onboard.			
			Self Inspection of critical hold down mechanisms prior to manuevering burn that begins the Servicers "operation"	Minimum resolution of image should be defined by the smallest mechanical item on each clamp/hold down such that visual validation can be used to backup an indicator that the object is connected, under minimum lighting conditions (defined as lumens/m2) for artificial or sun.			
D	**Ascent to Parking Orbit**	Standard Spacecraft Operations	Standard Spacecraft Attributes				
E	**Depart Parking Orbit**	Pre-Service Preparations	Minimum Fuel Remaining at Client Orbit	>10% to return to parking orbit or get to the Servicer disposal orbit, whichever is greater. Goal is to always maintain enough fuel to move the Servicer to a safe/stable/EOL orbit, to avoid a "dead" satellite problem.		ISO 23339:2010	
		Transit Conjunction Analysis	Minimum conjunctions	Through either JSpOC or CSPOC (or other) prior to servicer transfer and manuever a documented planned trajectory has been checked for possible conjunctions.			
F	**Rendezvous**	Pre-Contact-FarRange/Field (10's km to 100's m)	Far Range/Field Acquisition	Camera min. FOV, resolution for TBD distance acquisition, minimum tracking for bearing angles is 1 pixel accuracy on "center" of the target. Tracking rate is expected to be > 1Hz.	OG4 document		
				Min. two data points validation that acquisition of object is the Client (FOV and TLE)			
		Pre-Contact-Mid/Near Range/Field 100m to 5 m	Mid/Near Range/Field Acquisition	Line-of-site (LOS) vector from Optical imaging should be +/- TBD degrees			
				Error budget for near field sensors to calculate attitude manuevers onboard to maintain the imaging boresight within 5% of the attitude control onboard Servicer.			
		Pre-Contact-Mid/Near Range/Field 10-50meter client validation	10-50meter client detection based on given Client models	Tracking algorithm on sensors meet minimum of 90% successful detection at 15 degree rotation and 10cm scale.			[HINTERST2012] Hinterstoisser, Stefan, et al. "Model based training, detection and pose estimation of texture-less 3d objects in he avily cluttered scenes ." Asian conference on computer vision. Springer, Berlin, Heidelberg, 2012.
				Expected Accuracy for 3D point cloud model tracking comparisons: 10m, Position RMS 0.01-0.05(m), Angle RMS(deg) 0.01-0.02; 25 m Position RMS(m) 0.1-0.5, Angle RMS(deg) 0.02-0.05; 50m Position RMS 3.5-6.0(m), Angles RMS(deg) 0.5-1.0	InFuse_SPACEAPPS_D5.6_V2.0		
		Pre-Contact-Close Range/Field 5 m to 1 m	Close Range/Field Acquisition	Relative Range and Rate sensors +/- 0.1% and 1%, respectively for meter accuracy and meters/second accuracy.	Appendix E, NASA IDL Payload Element Study		
			Point Cloud Accuracy for tracking determination	For Point cloud tracking success attributes: Descriptor radius (DR) and cluster size(CS) should be resolvable (1-10% of size of object detected); DR and CS should be same order of magnitude; Model point density should be no more than one order of magnitude different from scene point density. All numbers based on client model resolved at full scale (on ground or in orbit).			
G	**Prox Ops Inspection**	Pre-Contact	Near Field tracking	For constant observations near or around the client, maximum errors should be within ±0.1% of range, ±1% of acceleration, and ±5deg of pitch/roll/yaw	SP A, B, D		
			Validation of Client	Confirmation of image taken of satellite should be validated with Client in proprietary setting. If object cannot be confirmed as Client, inspection abort should occur. Safeguard of images and videos must be maintained.			
			RF Energy to Client	Maintain electric field below 20V/m peak (below 50V/m for communication between 2-4GHz or 5.5-5.9GHz)	AIAA S-121A-201X Public Review Draft	AIAA S-121A-2017	
			Onboard Digital timing coordination between Servicer/Client's spacecraft	Any difference in the onboard clock timing between Servicer and Client should be no greater than 0.20 seconds relative to each other.		CCSDS 301.0-B-4	
		Illumination	Amplitude-Brightness required	Amplitude-Brightness required for sufficient human validation of optical images should be at least 860Lum/m^2	Based on NASA EVA Headlamp for an astronaut within 1 meter of the object and ocular observation		DOT HS 811 439 #108, Part 564
		Non-Interference	Plume impingement to Client	Use Metric#3 to keep potential plume impingement levels below critical level, defined by calculation to prevent rotation of client at speeds in excess of the servicer appendage escape speed	CONFERS Plume Impingement Metric (Metric #3)		
			Thermal impingement to Client	Shading of or imparting radiative energy or adding sun reflectance impingement to Client must be less than 25% of the Clients maximum thermal heat rejection or heater values, if the thermal impingement is beyond TBD hours. (Must compute given thermal profile of Client spacecraft and clearly identify the limits to Servicer.)			
H	**Client Preparation**	Pre-Contact	Orientation of Client and appropriate inertial condition	Client must demonstrate and maintain stability in pitch/yaw/roll to <1 deg/second. If consumable ADCS is used, sufficient margin exists that is >10% required during the entire time of the Servicing operation plus 4 days.	OG4_I3DS_D1.2-Use Case		
			Configure deployables (if possible)	Match ground based Client model given to Servicer for specific geometric profile prior to imaging or servicing. Deviations from ground based model should be identified to Servicer prior to Servicing operations. Client should take all measures to maximize or optimise detection features.	OG4_I3DS_D1.2-Use Case		
			Configure for contamination control (if possible)	TBD Values? Servicer shall perform all relative close approach, dock, contact, mate, de-mate and flyaway to minimize thruster plume contamination onto surfaces of the client.		ISO 15388:2012	

Elements	OV-1 Mission Elements or Event Description	Functions associated with Element or Event	Attributes associated with Functions	Proposed Quantitative Value	Reference	Existing Space Standard	Other Domain Standard
			Configure for refueling	Validation of onboard valve settings, propulsion commands disabled, etc. shall be done and communciated to Servicer as positive indication Client is in condition for refueling.			DOT HS 811 439 #106
			Validate battery DoD	DOD > TBD % (Minimum of 3x expected engagement of servicing operation)			
			Validate Client satellite disables safe modes that would counteract Servicer upon contact/dock/mate	Receive positive validation from Client ground support team.			
			Validate client satellite has min. prop fuel for abort	RCS fuel > TBD m/s (use RPO metric back out)		ISO 23339:2010	FAA 121.161
I	**Dock**	Initial Contact	Relative Servicer to Client orientation/location	RPO metrics defined by the sensors onboard Servicer. Min. of no more than 10% offset in any relative axis between servicer/client prior to start of final RPO manuever to first contact.			DOT HS 811 439 #208, #214
			Pre-contact range/rate/orientation measurements	±10cm range, ±5cm transverse, ±0.5deg pitch/yaw, ±1deg roll	SP A, B, D		
			Initial Contact validation signal	Validation signal from hardware contact required to continue, contact sensor accuracy <TBD mm or TBD deg. Ground indication should be both audible and light signature to provide operators dual notification, whether autonomous onboard or manual from ground.			FAA 121.289
			Validation of Client inertial state prior to dock manuever	Client must demonstrate and maintain stability in pitch/yaw/roll to <1 deg/second prior to contact. Servicer validation using passive/active sensors prior to contact will validate if the client is maintaining stability.			
			RF Energy from Client	Maintain electric field below 20V/m peak (below 50V/m for comm between 2-4GHz or 5.5-5.9GHz)	AIAA S-121A-201X Public Review Draft	AIAA S-121A-2017	
			Servicer/Client battery state of charge	+/- % DOD (to account for any loss of SA power)			
			Servicer/Client thermal state	Shading of or imparting radiative energy or adding sun reflectance impingement to Client or from Client to Servicer must be less than 25% of the Client/Servicers maximum thermal heat rejection or heater values, if the thermal impingement is beyond TBD hours. (Possible to use an IR camera for non-contact measurement and validation of thermal states.)			
			Safemode or Abort trigger settings	Servicer and Client operations teams validate software modes are set for safe mode and/or abort prior to contact. (Note this is one of the items that should be in the Servicer/Client contract that each validates what each safe/abort mode does, given possible faults in the servicing operation. Given that Clients may not have taken into account various "servicing" functions, the only real way to validate this is to run simulations on ground prototype systems that have same flight software enabled, and validate expected response.)			
			Servicer/Client Momentum Status	No more than 50 % of total RWA saturation is built up on either Client or Servicer in a positive momentum control service, prior to contact. Validation that nominal planned RWA buildup on Servicer does not exceed TBD % prior to end of Servicing operation and de-mating from Client? (Is it safe or prudent to desaturate with client attached?)			
			Pre-Dock visual observation/inspection of contact point	Min. of TBD images at a resolution to account for smallest contact mechanism or structure planned by Servicer contact mechanism, for pre-contact validation of client contact point robustness.			
			Servicer transmission to ground for ARC/imaging	Downlink rate maintained at TBD bps, latency < TBDms, Dropouts less than TBD/min.			
			Initial contact structure/mechanical load from Servicer to Client	Load limits do not exceed yield strength of intended contact point (or see RPO metric). Max force and torque is TBD (case dependant).	CONFERS Impact Mitigation Metric (Metric #1)		DOT HS 811 439 #208, #214
			Initial contact Electromagnetic discharge mitigation	Servicer able to accept and mitigate up to 10,000 volt differential upon initial contact with any external appendage.	See NRL testing under Phoenix.		
			Grapple Limits for Robotic appendage Servicer to Client	Compliance control within TBD relative position and rate of the robotic appendage that avoids client yield, upon contact.		AIAA G-056-1992	
		Final Contact-to-Mate	Final contact load between Servicer/Client	Comprehensive force < TBD % of yield limit of grapple point.			
			Servicer manuever to est. stack mass properties	Min. imparted torque, max imparted torque. Fidelity of measurement to +/- TBD N-m.			
			Final Contact/Mate validation signal	Validation signal required to continue, contact sensor accuracy TBD mm or TBD deg, two fault tolerant or two methods recommended.			
J	**Service: (Life Extension, Orbit reposition, refueling, self-refueling at depot, Manipulation, ORU add/replace, debris collection, disposal or debris or client)**	Service Actions (formerly Docking Actions)	Servicer control and stability of stack over Servicing operation	TBD values.			FAA 121.163
			Burn and GNC Accuracy for transfer by Servicer	TBD values.			
			FOV of Service camera	Based on camera FOV and positions and service to be performed.	-SSP 30550 Vol 1 Rev c, page 9 - Feb 17, 1995 SPDM Model		
			Spill Containment for Refueling	Primary method to recover any release of transferring consumable that turns to gas should contain 99% of any release. (?) If a cover is a used, nominal contact between client fuel valve wall and cover should be positively maintained during refueling. Internal surface of cover that is used to maintain the coating resulting from outgassing should not touch optics or important objects on Client/Servicer.		ISO 23339:2010	
			Robotic Appendage Accuracy relative to Moveable or non moveable interface for grapple	+/- 5mm in any direction, and +/- 1 degree in any axis	D2.14 OG5		
			Robotic Appendage error alignment between relative pose and orientation of serviced contact/grapple/connection point	TBD in all axes, or 5% difference in measured pose to actual position in X,Y,Z from "tip" and omega in rotation.	?		
			Fastner Contact/Interconnect	Fastner max. torque as measured by robotic end affector of no more than 5.3N-m (3.9ft-lbf), and/or number of turns of fastner based on ground calibration (fastner specific)		AIAA G-072-1995	
			Fastner Captivity	Fastner captivity cavity (TBD cubic cm) or 2 times size of largest fastner times number of fastners proposed to be captive at any one service event.			
			Power Transfer from one object to another after connection	+/- TBD % ripple current on voltage supply side		AIAA G-072-1995	
			Un-planned release of object through robotic appendage manipulation	Robotic appendage operation shall have two methods for connection at all times during object manuevering. One active through the robotic appendage mechanical connection to the object, and one passive (through another means).			

Elements	OV-1 Mission Elements or Event Description	Functions associated with Element or Event	Attributes associated with Functions	Proposed Quantitative Value	Reference	Existing Space Standard	Other Domain Standard
			Robotic End Effector/Tool Clearance	Access envelopes as defined	Para C3.2.2.1; - Section D Para D3.2.2.1; - Section E para E3.2.1.1; - Section G para G3.2.2.1; - Section H para H3.2.2.1; - Section K	AIAA G-056-1992	
			External Requipment, Orbital Replacement Unit, Maintanence Unit replacement	- All external items can be transported while exposed to on orbit space environment for up to 8 hours without active thermal interface to robotic system. - Color of Idependent replacement or moveable object should be either white or black to support differentiation using a B/W optical system. - Keying to avoid inadvertant mis connection shall conform to TBD standard...	-SSP 30550 Vol 1 Rev c, page 7, 3.2.1.9, 3.2.1.13 - SSP 50005 Para 9.5.3.2.i.8.a		
			Debris Collection	- Net or receptable size for capture is equal or greater than 3x the total volume anticipate for an excepted debris mission. - Net or receptable wall size is 2x smaller than the expected maximum size of the debris to collect	Is there any data from Clean Debris		
			Disposal in GEO	Follow International guidelines on graveyard orbit altitude; - Safe mode all consumable attitude control systems, drain all batteries to maximum DoD		ISO 26872:2010	
			Debris Creation Reporting Timeline	Within TBD hours of un-intended debris creation, with time/content and aprozimiate velocity			
K	**Separation and Backout**	DeMate	Client Servicer Intertial control	Pre-release client validates safe mode/inertial hold modes off. Maximum separation torques imparted by Servicer NTE +/- TBD % of detumble rate of Client. Separation velocity minimum TBD m/s, or equivalent to the Metric 3 velocity to avoid any Servicer/Client appendage.			
			Post mate visual inspection of interface	TBD resolution based on smallest object affected (i.e. fuel valve e.g.)			
L	**Disposal of Used parts and/or servicer**	Spacecraft disposal to avoid any debris in operational orbits	See specifics in NASA NPR 8715.6	See specifics in NASA NPR 8715.6	NASA NPR 8715.6	ISO 26872:2010	
M	**Return to Parking Orbit**	Standard Spacecraft Operations	Standard Spacecraft Attributes				
N	**Client Operations Continues/Changes**	Standard Spacecraft Operations	Standard Spacecraft Attributes				

Appendix C (Interface Survey Results)

Name	Developer	Existing?	Flight Tested?	ICD Available?	Gendered?	Human Rated?	Propellant	Power	Data	Docking	Grapple	Transfer Diameter (m)	Comments
Rapidly Attachable Fluid Transfer Interface (RAFTI)	Orbit Fab	Y	N	Y	Y	N	Y	N	Y	Y	N	N/A	Fits on microsats
Androgynous Peripheral Attach System (APAS)-95	Roscosmos / NASA	Y	Y		N	Y	N	Y* [1]	Y*	Y	N	0.8	Essentially same as APAS-89
Common Berthing Mechanism (CBM)	NASA / ESA / Roscosmos / JAXA	Y	Y	Y	N	Y	Y	Y	Y	Y	N	0.8	
CLING	USC SERC	Y	N	N	N	N				Y	N	0.1	Genderless docking system with embedded RPOS
Satellite Grasper Tool (SGT)	Honeybee Robotics	Y			Y							0.1	
Universal Gripper Anchor (UGA)	Honeybee Robotics	Y			N						Y	UNK	
International Berthing and Docking Mechanism (IBDM)	ESA	Y	Y	Y [2]	N	Y	N	Y	Y	Y	N	0.8	IDSS Compatible (International Docking System Standard)
Standard Interface for Robotic Manipulation of Payloads in Future Space Missions (SIROM)	EU/University of StrathClyde	Y	N										Part of Horizon 2020 Standard Technologies
NASA Docking System (NDS)	NASA	Y	Y	Y [3]	N	Y	Y* [4]	Y	Y	Y	N	0.813	IDSS Compatible, uses magnets to assist rotational alignment
Gecko Gripper	Altius Space Machines / JPL	Y	N		N/A	N	N	N	N	Y	Y	N/A	Does not require a connector on the other end, only a durable surface to grasp
MagTag Satellite Servicing Interface	Altius Space Machines	Y			Y								
Magnetic Extendable Capture System	AstroScale												
Astrobee Free Flyer Berth	NASA Ames	Y	Y	Y	Y	Y				Y		~0.1	
Latching End Effector (LEE)	MDA	Y	Y		Y		N	N	Y	Y	Y	N/A	Found on the end of Canadarm2 (SSRMS). Also used by Japanese arm (JEMRMS)
Power and Data Grapple Fixture (PDGF)	Spar Aerospace (Now MDA)	Y	Y		Y	N	N	Y	Y	Y	Y	N/A	Interfaces with Canadarm2. Replaceable on orbit
Flight Releasable Grapple Fixture (FRGF)	Spar Aerospace (Now MDA)	Y	Y		Y	N	N	N	N	N	Y	N/A	Interfaces with Canadarm2
Latchable Grapple Fixture (LGF)	Spar Aerospace (Now MDA)	Y	Y		Y	N	N	N	N	Y	Y	N/A	Interfaces with Canadarm2
Power and Video Grapple Fixture (PVGF)	Spar Aerospace (Now MDA)	Y	Y		Y	N	N	Y	Y	Y	Y	N/A	Interfaces with Canadarm2
Electrical Flight Grapple Fixture (EFGF)	Spar Aerospace (Now MDA)	Y	Y		Y	N	N	Y	Y	N	Y	N/A	Interfaces with Canadarm1
Probe Fixture Assembly (PFA)	MDA	Y	Y		Y	N	N			Y	Y	~0.1	Flew on Orbital Express?
User Defined Adapter (UDA)	NovaWurks	Y	Y	Y	Y	Y	Y	Y					
Tyvak Cubesat Docking Mechanism	Tyvak	Y											For Cubesats
SPHERES Universal Docking Port (UDP)	MIT	Y	Y		N		N	N	N	Y		N/A	
inetlligent Space System Interface (iSSI)	iBOSS	Y	Y	Y	N	N	N	Y	Y	Y	Y	N/A	can also transfer heat load. Data is transferred optically

Yellow box indicates information not publicly available

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