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Initial safety posture investigations for earth regime rendezvous and proximity operations

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ABSTRACT

Next-generation space activities, where companies and organizations begin to provide services for each others space assets, are real and coming on-line. The Consortium for Execution of Rendezvous and Servicing Operations (CONFERS) is an industry-led initiative meant to help enable new companies and industries in pursuit of on-orbit servicing (OOS) through metrics and standard developments. The University of Southern California's (USC) Space Engineering Research Center (SERC) is chartered to examine past and present activities related to this new domain and uncover elements that might benefit from the application of standards or practices for the industry as a whole. This paper will 1) review and update USC's initial technical rendezvous metrics, and 2) introduce OOS functional evaluations and an initial ontology for consideration.

1. Introduction

Space presents a unique challenge; not just from its accessibility and complex dynamics but its disassociation from immediate human impact to physical activities in the orbital domain. Yet, disruption from the loss of capabilities of current or future assets in space would impact societies around the globe. A 2017 study commissioned by the UKs Innovation and Space Agencies and Royal Institute of Navigation indicated that loss of global navigation services within the United Kingdom over only 5 days would be greater than 5.2 billion [1].

With large potential economic impact at stake it makes sense to pursue processes, standards, practices, procedures, and verification methods to mitigate potential failures in the space domain. Unlike other industries that introduce risk to platforms or personnel, those who manufacture and operate spacecraft do not live in space. Thus alternative incentives may be useful when developing guidelines and standards that not only encourages adherence, but can be accepted as responsible and reasonable actions by new-space market parties in *on orbit servicing.* There are multiple exemplars and inspirations to draw from where domain industry members created their own guidelines and standards to maintain economic, mission, and personnel safety. A few are discussed here for context before introducing unique ones to consider in the space domain.

An early analogy is found in the nuclear industry; it has often been identified as a domain that holds great benefit yet commensurate risk associated with its use and operation. Indeed there is a World Nuclear Association in recognition that nuclear activities are not just local in impact but global in reach [2]. Multiple national and international consortium or organizations exist that encompass the operators and system integrators of nuclear reactors, hardware and fuel companies who have successfully come together to manage the unique terrestrial-based safety challenges [3,4]. While standards are practical for companies economic and sound business viability, the industry leaders, workers and their families all have something else in common with the population they serve; they typically reside within proximity of a potential consequence of a failure of their industry. The incentive therefore is not just economic or social, but personal. Incentive to cooperate and work toward the highest degree of safety in their industry then has a unique personal motivator to support standards in safe nuclear operations.

The auto industry faces a somewhat similar albeit alternative challenge; the sheer number of individuals driving cars whose drivers span local and global (i.e. thousands of miles from the industrial factories and leadership) in reach. Automobiles have the added panache of styling, thus it becomes individualistic in its appeal to a very wide number of people which encourages and enables modifications where possible to the vehicles, after they leave the factory, which is different from the

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Nomenclature

SERVICER	Satellite or Platform that provides Service
CLIENT	Satellite or Platform to be Serviced

Acronyms/Abbreviations

ADACS	Attitude Determination and Control System
GNC	Guidance Navigation and Control
ISS	International Space Station
OOS	On Orbit Servicing
RPO	Rendezvous and Proximity Operations
USC	University of Southern California
SERC	Space Engineering Research Center
RSGS	Robotic Servicing of Geosynchronous Satellites
CONFERS	Consortium for Execution of Rendezvous and Servicing Operations
LOR	Lunar Orbit Rendezvous
DARPA	Defense Advanced Research Projects Agency
NRL	Naval Research Laboratory
SWF	Secure World Foundation
SIF	Space Infrastructure Foundation
NHTSB	National Highway Traffic Safety Board
NASTF	National Automotive Service Task Force
ECD	Effective Capture Distance
MCO	Maximum Capture Offset
SSL	Space Systems Loral
SPHERES	Synchronized Position Hold Engage and Reorient Experimental Satellite
OEM	Original Equipment Manufacturer

nuclear industry. From a safety standpoint both the very large number of individuals (in 2016 there were about 225 million licensed drivers in the United States with 268.8 million vehicles registered [5,6]) and the unique attribute that humans can and will find failures or faults in systems through ingenious and sometimes catastrophic ways, provides a unique driver for the auto industry to work hard to find qualitative and quantitative standards of operations to infuse in their vehicles. Its also possible that the number of companies, brands, models and makes, and components made from all over the world and integrated globally, with the again the sheer number of platforms and drivers was a stronger motivator for in-country regulations to be established. An example within the US the National Highway Traffic Safety Board (NHTSB), have rolled up and published standards that take into account everything from the beam strength of headlights to the operation of windshield wipers [7]. Each standard centers around either a function or an attribute of technology that is inherent in an automobile, with relevance to driver operations, which in turn recognizes its relevance to overall safety.

Now enter the domain of space. Space does not have the motivator of platform builders and families living in the domain they build for, nor are there thousands or millions of people operating and driving satellites. Technology and capabilities however have now created a new market segment where old, new, small and large companies and organizations can now exercise actions that to-date 1) have been restricted within the sole domain of a few large government organizations to-date, 2) those actions have consequences if done incorrectly, and 3) whose affects would be global.

The positive news is technology growth and advancement has enabled over the past two decades missions flown that demonstrate the precepts of this new market segment and operations. Demonstrations included re-usability of space systems through the advent of servicing to extend or prolong a space platform's life [8], inspection of a rocket body [9] and proving re-fueling [10] on-orbit is viable. One project even looked at re-purposing retired satellites to create completely new space elements [11–13]. Today there are multiple missions planned and under way by combinations of public, private and public/private entities to create true business in space that follows the successful models of servicing, maintenance and re-use that Earth bound platforms have long enjoyed (i.e. RSGS, Space Logistics, Effective Space, Astroscale, etc) [14,15].

Balancing the risk that events on orbit could create hazards that globally affect the value of space assets and potentially disrupt economic, navigation, or communications, with the very real need for progress and expansion into a vibrant service culture on-orbit, is a significant goal of the new-space industry. Thus, finding an accepted incentive to leverage and motivate existing and new players in the On-Orbit Servicing (OOS) realm, and encouraging the highest level of safeguards in platforms and actions taken around the Earth is one of the current challenges that the Consortium for Execution of Rendezvous and Servicing Operations (CONFERS) is addressing.

2. Safety metrics and posture

To begin to identify types of quantitative metrics that may be explored to define safety in the context of new entrants in space operations and services, USC pursued two distinct analysis thrust areas. These were separated by the nominative action that all Servicer vehicles may engage in; first the act of getting close to another object on orbit (referred to as Rendezvous and Proximity Operations or RPO), second is interacting in some way with that object (ie. maintain, repair, move, extend life, refuel etc). The collective actions are referred to as on orbit servicing (OOS). Each is seperately addressed below.

2.1. RPO Metrics background

As part of the first year initiative for the CONFERS project, The technical team at USC surveyed all previous published rendezvous and proximity operations past missions in both public and private sector settings (manned and unmanned), and created a database of flight identified methodologies, with the goal of finding commonalities between the missions to create safe guidelines for future RPO operations [16]. Upon analysis of the database, no obvious common attributes in RPO were uncovered, which prompted the creation of a set of scale-able metrics that would focus on the risk aspect of the rendezvous safety, or more correctly avoidance of characteristics that would lead to collision between two objects. Evaluation of initial characteristics of a planned rendezvous yielded a safety posture that focused on two major areas, contact actions and remote influence/interference.

In the context of the proposed metrics, each is defined herein.

Contact actions represent specific actions that one space vehicle or platform will make with another space vehicle or platform. In the domain of servicing the expectation is that a *Servicer* (i.e., a vehicle that intends to provide a service) rendezvous with a *Client* (i.e. a vehicle that is in need of service) and will make contact. Contact in this case would be specific to the service action proposed, e.g. connecting a refueling hose, grabbing a spot on the Client for stabilization, connecting to a damaged part of the Client, etc. A contact action can be planned (i.e. a planned docking or robotic grapple to a client), or unplanned (contacting a point on the Client that is un-intended through potential malfunction or error.)

Remote Influence or Interference refers to a Servicer affecting a Clients condition, without making contact with the Client. Some examples might include a Servicer's propulsion system impinging upon a Clients spacecraft at a distance, thus causing a rotation, or a Servicers telemetry system interfering with nominal onboard electronics of a Client causing potential control problems, etc.

Given the large number of variables in any space-to-space rendezvous (orbits, inclination, sun angle, communication contact etc), metrics, rather than guidelines, were chosen as they allowed flexibility in design and usage, and avoid forcing a space mission to work within restricted parameters that may not be achievable in many specific orbital parameters.

Three metrics were proposed: maximum velocity of contact, attitude control, and plume impingement [16]. They were all created as scaleless algorithms that take as inputs physical characteristics and orbital parameters of a Client and Servicer spacecraft, resulting in a value between 0 and 1 if deemed low risk, or greater than 1 if higher risk. These metrics are summarized below. These metrics are applicable not only to docking operations, but to all forms of RPO, including non-contact survey or inspection missions.

2.1.1. Metric 1: contact velocity

The first metric was identified based on a proposed common practice whereby a Servicer should maintain a velocity relative to the Client upon its final propulsive maneuver before contact, such that in the event no braking or stop or slowing maneuver is made prior to first contact, the resultant contact will not cause catastrophic degradation or separable debris to either space platform. The velocity is to be determined by the Servicer through use of a calculable metric, allowing for flexibility in design, operations and interface with a Client vehicle.

The *Contact Velocity* metric was derived with the goal to minimize any damage by limiting the speed at which an inadvertent collision might occur. The scenario in this case is that the final burn fails to halt the Servicer's approach to the Client, and the Servicer contacts the Client with its pre-stop velocity. It is important to note the assumptions made for this scenario:

1. Contact is assumed to occur on a local structure intended for docking or grapple/contact (i.e., bus structure, docking ring, but not a solar panel e.g.)
2. Trajectory and approach are nominal, only velocity is off.
3. Impulse time of the contact is assumed to be 5ms (taken from high speed automotive collision data as a starting point relative to potential assessable deformation on the Client [17]).

The metric value is the ratio of the projected velocity over the maximum permissible velocity.

$$CV_{metric} = \frac{v_{projected}}{v_{max}} \tag{1}$$

The projected velocity of contact is assumed to already be known; it is equivalent to the delta-V of the final burn to approach, where the final braking burn that would cease a forward movement is unsuccessful and this velocity is not canceled out. The maximum velocity is determined based on the material and structural properties of the spacecraft such that the structure does not yield with any impact (and more importantly create debris). The specific approach assumes the vector of the contact is in line with the Client, at any starting distance along either R or V-bar.

2.1.2. Metric 2: remote influence

The second metric was identified based on a proposed common practice whereby a Servicer should maintain a distance and orientation of its impingement devices (i.e. propulsive thrusters etc) such that it does not impart an unplanned torque and/or rotation upon a Client during the final approach to contact. To enable a Servicer to avoid imparting torque remotely through its own propulsive devices on the Client, a metric was designed that calculates a risk of potential unplanned contact by an external Client appendage contacting a Servicer's appendage under rotation, through the use of the Servicer/Client geometry.

The *Remote Influence* metric was derived from the most likely Servicer remote influence, its plume potentially impinging on the Client satellite during approach, causing a rotation from induced torque. The metric was assumed to occur at the worst location on the Client that would impart the highest induced torque (i.e. the solar array that has a very high lever arm to the Client). The following assumptions were made:

1. The torque acts on only one axis.
2. The satellite and solar arrays acts as a rigid body (i.e. there is no flexing when the plume impinges).
3. Plume impacts normal to the surface and acts over a short enough time-period to neglect the rotation of the impingement vector (impingement vector is always normal to the surface).
4. The Client's Attitude Determination And Control System (ADACS) is turned off

The metric value is the ratio of the projected angular velocity from plume impingement to the maximum permissible angular velocity due to plume impingement. The maximum permissible angular velocity is computed based on the geometry of the Client and the retreat time of the Servicer, such that the Servicer can retreat faster than an appendage of the Client rotates towards it (e.g., a solar array). (Retreat could mean physical movement of the Servicer, or rotation of the Servicer to avoid appendage contact etc.)

$$RI_{metric} = \frac{\omega_{proj}}{\omega_{max}} \tag{2}$$

For the metric creation the plume was assumed to impinge perfectly orthogonal to the solar panel for the duration of the burn, with full transfer of the torque into rotational motion, as worst case. Plume effects on optics or external sensitive objects like solar cells or electronics were not considered.

2.1.3. Metric 3: control accuracy

The third metric was from assumed common practice where the Servicer maintains pointing stability and control upon its final approach with intent to connect with a Client, such that the worst-case error offset distance between Servicer and Client never exceeds the Effective Capture Distance (ECD) of the Servicers connection/connecting system. (The ECD relates to the reach of a connecting device, i.e. a robotic arm, net, tether appendage etc., that the Servicer intendeds to connect to the Client with.) *Capture* refers to the act of any docking mechanism, robotic appendage, or deployed system from the Servicer whose intent and capability is to contact/connect to a predetermined location on the Client. The goal of this metric is to prevent the Servicer from being unable to operate its connecting system to the Client, thus preventing a missed capture.

The *Control Accuracy* metric is derived from a range of a Servicer's robotic appendage to a Client. The final approach needs to place the Servicer within range of the capture mechanism, which requires a certain capability of the ADACS and its associated sensor inputs. If the maximum capture offset (MCO) is less than the effective capture distance the metric value is less than 1 and the maneuver is considered with minimal risk. The ECD is a physical distance defined from the Servicer's hardware that is able to contact the Client, and the MCO is the potential error between the known position and the relative position between Servicer and Client.

The assumptions for this metric are:

1. Ranging accuracy is perfect, only angular accuracy has some induced error
2. The error assumes compound offsets from sensors and actuators.
3. The braking burn has the correct magnitude, however the direction is offset by the angular accuracy.
4. Both Client and Servicer will either be in the correct orientation for capture at the end of the burn, or have the attitude control authority to reach the correct orientation.

The output of the metric is the ratio of the Maximum Capture Offset (MCO) to the Effective Capture Distance (ECD).

$$CA_{metric} = \frac{MCO}{ECD} \tag{3}$$

2.2. Initial OOS safety posture

For the second year activities the USC team is creating an ontology that is based on the mission elements of proposed servicing architecture.

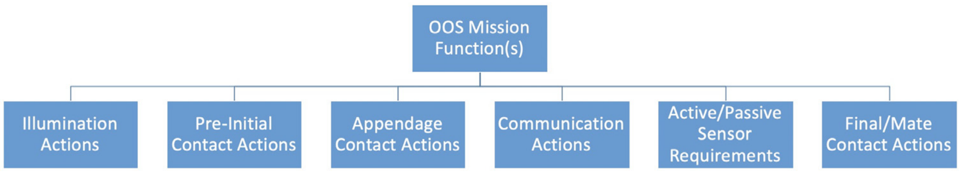

Fig. 1. Preliminary OOS Function Ontology.

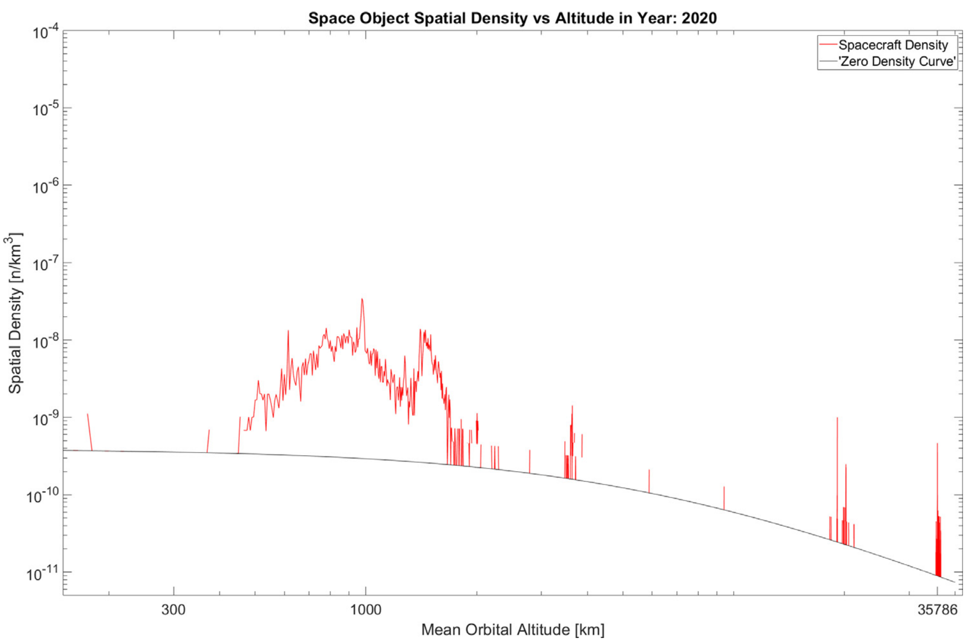

Fig. 2. Current Spatial Density in Orbit.

Each mission element represents an action or set of actions that are defined within a nominal RPO and OOS activity (i.e. rendezvous, contact, dock, service action, etc), and each has multiple functions with corresponding attributes that are quantitative in nature. An initial schema that identifies quantitative values for possible evaluation for standards is being compiled. Fig. 1 shows the very preliminary ontology tree under development. The goal is to create as comprehensive a list of functions as possible that encompass any type of action on-orbit that encompasses OOS, both planned as of today and hopefully new ones in the future.

2.2.1. *Initial look at predicted spatial density of orbits that may affect RPO/OOS test operations*

Most of the upcoming space servicing companies are proposing their first operations to be outside the high value and heavy spatial density orbits, for good reason. Minimizing risk to high value orbits (those that hold much of the global or regional communication or navigation infrastructure) until multiple successful servicing activities have occurred, is a prudent safety posture. Yet alongside this new dawn of multiple vehicles moving between multiple orbits for servicing, an unprecedented surge in new constellations with not just hundreds but thousands of new satellites are in progress. To get a sense of how this may affect upcoming OOS operations, a look at current/projected spatial density is used to get a sense of potential numbers of satellites at various orbits.

Fig. 2 shows the current spatial density plot vs mean orbital altitude for all satellites (and trackable debris) today. Fig. 3 then shows a projection over time of some of the proposed constellations currently identified.

Fig. 2 was created using Celestrak's public SatCat Database of two-line elements (TLEs) [18]. The spatial density was computed by solving for the volume of 5km shells of altitude and summing any objects found in those shells. The range that was computed was from 150km to 42000km in altitude. One interesting feature is the black curve labeled the *Zero Density Curve*. This curve denotes the spatial density of the 5km shells regardless of any objects residing inside them. Since fractional satellites are not possible on this plot, the region below this curve is representative of zero density - an empty shell. As expected, the altitudes with the highest densities of space objects are between 450km and roughly 1200km in altitude, and at Geostationary Orbits around 36000km in altitude. It is unsurprising that the density below 300km is lower due to increased space object rate of decay caused by atmospheric drag.

Fig. 3 shows what the spatial density in orbit might look like approximately 12 years in the future from 2020. Two sources of satellite accumulations were used to create this figure. First, the average number of satellites launched into a specific altitude for the last 3 years was calculated. This number was then assumed to be a linear rate of increase in satellites for a specific altitude and added into the future satellite catalogue each year. The second source involved incorporating planned future constellations. The primary constellations used were: OneWeb, Boeing, SpaceX, Space and Sky Global, Amazon, Telesat, and AstroCast [19–21]. The total number of currently projected satellites to be launched in these constellations number over 57,000, and fall into essentially two mean orbital altitudes: 600km and 1200km. The impact of those constellations on those two altitudes can be easily seen by the large blue spikes in density.

As part of a additional operational safety posture for OOS the team is evaluating what the increase in spatial density due to constellations may mean for transit of servicing vehicles, orbital regimes for demonstration operations, altitudes or zones that offer higher traffic and thus potential for more conjunction alerts, etc. It is expected that OOS vehicles will be traversing orbits at a higher rate than most normal satellites, thus both minimization of conjunction risk and increasing efficiency of onboard maneuvering or consumables would help economic viability of service operations.

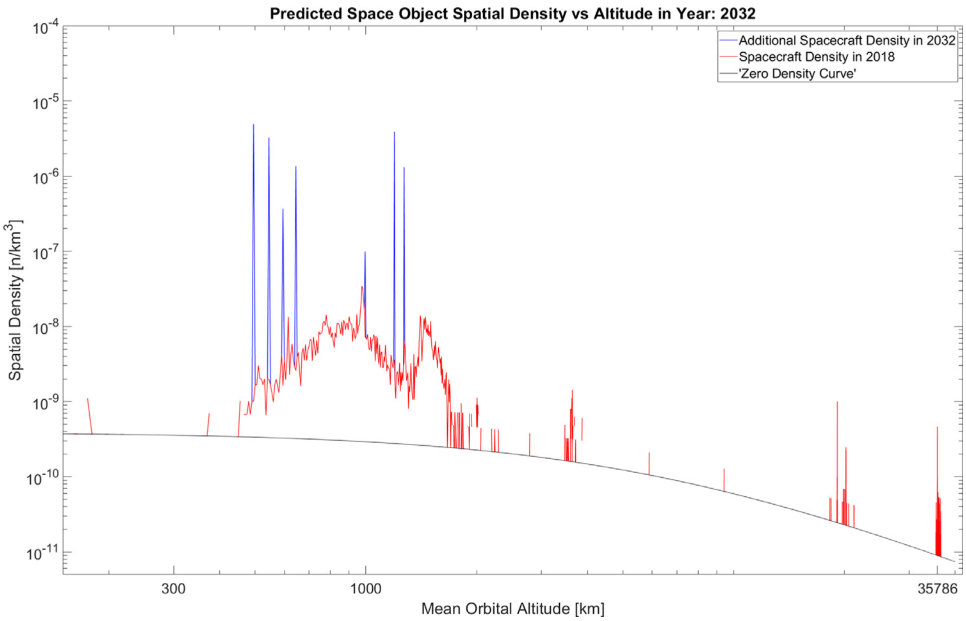

Fig. 3. Predicted Future Spatial Density in Orbit.

Table 1
Metric Application to Survey of Past and Proposed RPO Missions - Summary Results.

Mission Details				Metrics		
Name	Primary Organization	Target	Date	Contact Velocity	Remote Influence	Control Accuracy
STS-41C	NASA	Solar Max	4/9/84	0.1523	0.154	0.245
Dragon	SpaceX	ISS	5/22/12	0.0295	0.00585	0.0198
Apollo 11 (LEM)	NASA	CSM	7/21/69	0.8119	0	6.45
MEV-1	Northrop Grumman	Intelsat-901	2020	0.3221		
RESTORE-L	SSL	Landsat-7	2022	0.2909		
O.CUBED	Airbus	TBD (GEO)	2023	0.393		

3. RPO metrics comparison to past and proposed systems

In the first years analysis the derived RPO specific metrics were applied to the data from the initial survey of all published rendezvous operations, and the results were vetted based on real-life mission results. Table 1 below shows a small subset of the principle groups of RPO events that had the most data to support the metrics evaluation. As a further check on the development of the metrics for validity to current/future systems Table 1 also includes approximate values for upcoming missions using estimated values obtained from open publications and press releases [22–24]. For the contemporary missions the metrics were derived with the assumption of a final approach velocity of no more than 1m/s. Note that for the contemporary missions, only the contact velocity metric was computed, as there was not enough publicly available data two compute the other two metrics.

The values are all less than one for each of the resultant metrics, which indicates that the methodologies the platforms used were/are considered *low risk*, positively validated from past missions. The exception to the past results was the Apollo 11 Lunar Orbit Rendezvous (LOR) event showing a Control Accuracy value much greater than 1, indicating high risk. This LOR value was surmised to be high due to a combination of factors; the rendezvous was performed under manual control thus a human in the loop was providing GNC which is hard to quantify, and the docking capsule guidance equipment fidelity may have been lower-accuracy due to the electronics equipment available at the time which would drive the metric number higher [25].

4. First look at cross-domain analogous standards for OOS

As presented in Section 2.2, part of the second year initiative for the CONFERS team is surveying existing and planned standards that may be applicable to satellite servicing and RPO missions. Within the space domain roughly 50 standards were initially identified applicable in some way to RPO and OOS [26]. Recognizing other vehicle platforms and domains the team drew 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.

As an early example of the analogous decomposition process, looking at an automotive industry typically all sensors/actuators that affect a drivers ability to operate are evaluated and have quantitative values on a companies hardware implementation and acceptance. 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 [7]. Translating that functional example to the Space domain, the *reversing sensor* analogy can be extended to sensors used onboard a servicer used for final 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 low risk rendezvous. This is but one example of potential functional element on a servicer that may benefit from some quantitative attributes being assigned and thus considered for standards, better enabling large number of new entrants in OOS to validate their component selection and approaches to execute RPO operations, safely.

5. Discussion

Within the automotive industry there is direct recognition that companies themselves can create/adopt standards for economic benefit and increased safety [27,28]. Additionally given its global scope and platforms that are readily available and operated everyday, there is also a very rich and vibrant after-market service industry. The notion that information from platform manufacturers about how to service their vehicles directly enables expansion to independent owner/operators and service technicians/providers. A commercial consortium, the National Automotive Service Task Force (NASTF) Board of Directors recognized that individual Motor Vehicle Manufacturers *must* adopt Automotive Service Information Standards to enable this very market of servicing [29]. The concept not just of physical interfaces to service but information about how to service has been one key element to a vibrant auto-service industry.

The comparison to space servicing, with a goal to create the same vibrant after market business opportunities on orbit, finds a similar analogy in development of interfaces. How a Servicer satellite connects to another satellite, through physical/virtual means becomes critical both in terms of safety (identified in early metrics) and in market and economic industry viability. This connection is typically done via an interface. To-date there has been no incentive for platform manufacturers in the space domain (except for manned missions to the ISS), unlike the auto industry, to outfit their satellites with physical connection/interface devices or openly publish information on how to service their satellites on orbit. The capability did not exist, thus the impetus was not there. Today a major effort under CONFERS is to identify the need for this new capability to be created on upcoming satellites and thus help guide standards/interfaces/protocols that balance the need for safe OOS and RPO with economic viability to encourage this unique original equipment manufacturer (OEM) service industry. Some initial example interfaces considered as synonomous with the capability intent to connect to other satellites might include the SPHERES Docking Adaptor [30], a proposed small satellite docking adaptor [31], and an example of a robotic gripper for capture and servicing [32]. As part of the ontology decomposition functions and attributes inherent in satellite to satellite interfaces are being identified for consideration.

6. Conclusions

The emerging markets of on orbit servicing are exciting and a positive expansion of technological capability in orbit. There are companies, organizations and groups all working toward realizing this new service implementation. Safety in the orbital domain consists not just of the platforms or the localized affect between Servicer or Client action, but encompasses the consideration of satellite assets globally. CONFERS is an industry led consortium taking steps to identify, create and support various methodologies, including through practices, standards, guidelines and metrics to increase and recommend safe OOS operations. Terrestrial platforms and industries provide analogies in methods to decompose OOS elements into various quantitative functions and attributes, that may lend themselves to development of standards/metrics or validation/verification methodologies. USC and the CONFERS technical team is working through ontology definitions and analysis to identify possible candidates for consideration of future standards.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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