A Mission Architecture and Systems Level Design of Navigation, Robotics and Grappling Hardware for an On-Orbit Servicing Spacecraft

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ABSTRACT

On-orbit servicing (OOS) includes a range of servicing types that increase the lifetime of a satellite and its performance, as well as ensuring that it does not contribute to the growing issue of space debris. The avoidance of satellites becoming derelict is particularly important given the rise of 'mega-constellations'. With the first cases of it in the 1970s, OOS has been achieved many times using crewed missions and robots controlled from the ground or by astronauts, for example during repairs and upgrades to the Hubble Space Telescope (HST) and on the International Space Station (ISS). This has allowed various space agencies and other organisations to mature processes and tools for several OOS mission types.

The Northrop Grumman Mission Extension Vehicle-1's (MEV-1) success servicing Intelsat 901 in early 2020 demonstrated that OOS is now viable from a commercial as well as technical standpoint. However, due to low technology maturity, autonomous rendezvous and proximity operations (RPO) and servicing remain challenging, despite autonomous rendezvous and docking with space stations having been demonstrated many times.

This report will investigate the current state of the art in OOS and which technologies require further development to enable widespread adoption of OOS. A mission architecture to support OOS of satellites in the highest populated orbits will be described. Using this architecture, the report will focus on the selection of hardware required for guidance, navigation and control (GNC), for relative navigation towards and docking with the target satellite and of robotics to service the target. The report will use the design of the OneWeb satellites as a baseline for the target spacecraft but will also show how the servicing spacecraft's services could be applied to a range of orbits and target spacecraft.

Keywords: technology readiness; mega-constellations; guidance, navigation and control; proximity operations

ACRONYMS AND ABBREVIATIONS

ADR	Active Debris Removal
CDF	Concurrent Design Facility
CMG	Control Momentum Gyroscope
COTS	Commercial Off the Shelf
DOF	Degrees of Freedom
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
EOL	End of Life
ESA	European Space Agency
ETS-VII	Engineering Test Satellite No. 7
GNC	Guidance, Navigation and Control
GNSS	Global Navigation Satellite System
HST	Hubble Space Telescope
IRP	Individual Research Project
ISS	International Space Station
LEO	Low Earth Orbit
LIDAR	Light Detection and Ranging
MEV	Mission Extension Vehicle
MW	Momentum Wheel
OOA	On-Orbit Assembly
OOM	On-Orbit Manufacture
OOS	On-Orbit Servicing
RNS	Relative Navigation System
RPO	Rendezvous and Proximity Operations
RW	Reaction Wheel
SSN	Space Surveillance Network
TDRSS	Tracking and Data Relay Satellite System
TID	Total Ionising Dose
TMR	Triple Modular Redundancy
TOF	Time of Flight
TONS	TDRSS On-board Navigation System
TRL	Technology Readiness Level

INTRODUCTION

This paper describes work undertaken for the author's MSc Individual Research Project (IRP) at Cranfield University. The project studied mission architectures and technologies for guidance, navigation and control (GNC), relative navigation, grappling and robotics within the context of on-orbit servicing (OOS).

Background

With OOS not currently widely available, spacecraft designers must ensure that it can complete its mission with only the hardware in place at launch. This necessitates high technology readiness level (TRL) components and/or fault tolerant design. Qualification to raise TRL is high cost, with fault tolerance techniques adding mass and complexity. Qualification also leads to the "time-to-market gap problem" with long component development times [1].

With hardware being fixed at launch, heritage and environmental concerns mean it is often very outdated relative to ground-based components. Failures can still occur that cause permanently degraded performance unless ground controllers can find a workaround.

Eventually, a spacecraft's propellant will become depleted. Components may have several years of lifetime remaining, but the mission is forced to end as the spacecraft can no longer manoeuvre.

Satellite disposal once it has reached end of life (EOL) also needs to be considered to comply with the IADC 25-year disposal guideline [2]. The failure of the de-orbit system would put the spacecraft at risk of collision with other resident space objects (RSOs).

The size of large structures such as communications reflectors is currently constrained by the launch vehicle fairing. Current technology is approaching fairing limits - for example, the James Webb Space Telescope uses complex mechanisms to deploy its components [3]. Despite redundancy, the greater number of mechanisms increases the likelihood that a critical failure will occur, prematurely ending the mission.

Aim

This paper seeks to determine how OOS can be used to tackle the problems previously described. A review of previous and current OOS developments will be presented to build understanding of current OOS limitations.

A systems engineering approach will then be used to define an OOS mission architecture, using current technology where possible to provide OOS to a commercially relevant target satellite. Using this approach will also allow the points it raises to be considered by future spacecraft designers.

Technology areas that this paper will focus on will be absolute and relative navigation, grappling hardware and robotics, as these are all key to the successful implementation of an OOS mission.

LITERATURE REVIEW

OOS Types

OOS can be split into five distinct operation types as described below. This paper will particularly focus on operations applicable to orbit maintenance and hardware replacement/refuelling. Active debris removal is out of scope due to the likely tumbling target that complicates docking and makes relative navigation significantly more challenging [4].

1) **Active Debris Removal (ADR)** – removal of objects to avoid collisions and Kessler Syndrome [5].
2) **Orbit maintenance** – keeping the target in an operational orbit or moving it as required.
3) **Hardware replacement/refuelling** – replacing broken or old components to extend lifetime or upgrade functionality. Refuelling extends lifetime.
4) **On-orbit assembly (OOA) of large structures** – enables spacecraft to be assembled that have greater capability than could be launched in a single launch vehicle.
5) **On-orbit manufacture (OOM) of high value components -** uses space environment to produce components that would be impossible to manufacture on Earth. Out of scope for this paper as it would use a single spacecraft.

OOS Applications and Benefits

Hardware replacement would mean spacecraft systems could be designed for significantly shorter lifetimes, as they could be replaced once failed. This would lower the need to tolerate the harsh space environment, meaning more commercial off the shelf (COTS) components could be used, lowering cost and speeding up development. Even if normal lifetime components were used, replacement would allow the satellite to continue operations in the event of an otherwise potentially crippling failure. By replacing hardware, spacecraft capability could also be improved throughout the mission, giving more useful data at less cost than launching an entire satellite.

Orbit maintenance or refuelling would mean the spacecraft lifetime becomes limited by its systems rather than its remaining fuel, as is often currently the case [6, p. 41].

OOA would allow large structures to be built in orbit that would have significantly greater capability than could be launched in a single launch. This would be particularly useful for space observatories [7].

Previous Uses of OOS

Before beginning development of a new OOS mission, it is important to understand previous implementations and the current state of the art, so these can be built upon moving forward.

Early examples of OOS include crewed missions to repair Skylab and the SolarMax, Palapa B2,Westar 6 and Intelsat VI satellites [8] [9, p. 116] [10]. The Hubble Space Telescope has also made extensive use of crewed OOS with five servicing missions repairing and upgrading it [9, p. 25].

Japan's Engineering Test Satellite No. 7 (ETS-VII) was the first spacecraft to perform autonomous rendezvous and docking during its 1997 mission [11], using LIDAR and GPS to achieve this. It included a robot arm that was used to take pictures of the target satellite and for a variety of experiments.

Current State of the Art

OOS missions and mission concepts have been developed by a range of space sector organisations. These include ESA's e.Deorbit [4], the University of Surrey's RemoveDEBRIS [12] and DARPA's Orbital Express [13].

Servicing of geosynchronous satellites is an area currently under significant investigation, with DARPA's Robotic Servicing of Geosynchronous Satellites programme [14] and Airbus's O.CUBED Services [15] and Astroscale's Space Drone [16] all targeting this application. In February 2020, Northrop Grumman's Mission Extension Vehicle (MEV) 1 completed the first docking of two commercial satellites when it docked to Intelsat 901 in GEO (Figure 1) [17]. MEV-1 is now acting as a propulsion system for IS-901, while MEV-2 is en-route to its target satellite, IS-1002 [18].

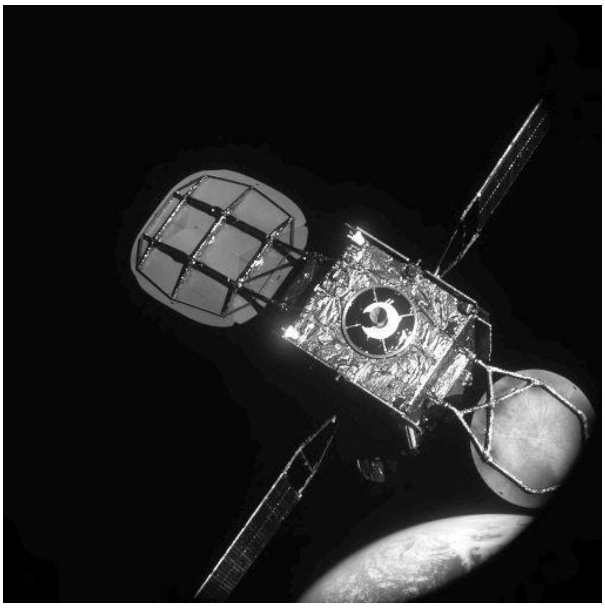

Figure 1: IS-901 seen from MEV-1 [17]

Astroscale's End of Life Services by Astroscale demonstrator (ELSA-d) mission will demonstrate navigation and capture techniques in 2020 [19], with a variant of the mission, ELSA-OW, under development to service the OneWeb constellation [20].

NASA's On-orbit Servicing, Assembly and Manufacturing 1 (OSAM-1) mission is currently targeting a 2023 launch [21] and will demonstrate servicing of the Landsat 7 spacecraft and technologies relevant to OOS [22] including several robot arms and relative navigation systems [23].

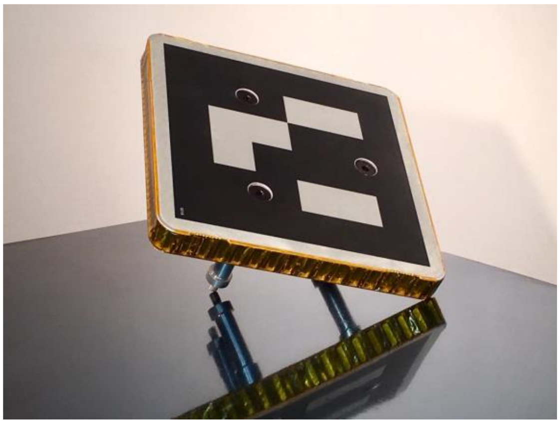

Figure 2: Altius Space Machines' DogTag grappling fixture [24]

MISSION ANALYSIS AND DESIGN

Background

A mission architecture was defined to enable later hardware selection. The servicer would be launched to a parking orbit, complete commissioning then rendezvous and dock with its target. Servicing such as refuelling, hardware replacement or orbit maintenance would be carried out before the servicer moved on to the next target.

A satellite of the OneWeb constellation (Figure 3) was baselined as a target due to its large and growing size and the fitting of each satellite with an Altius Space Machines DogTag grappling fixture (Figure 2) which would facilitate docking [25]. The constellation will also be representative of other 'mega-constellations' current under development such as SpaceX's Starlink and Amazon's Kuiper.

Figure 3: OneWeb satellite [26]

Orbit Selection

While the OneWeb satellites are in 1200 km altitude orbits [27], the target orbit was selected based on which orbit was found to be most populated. This used a satellite database from the Union of Concerned Scientists [28], with graphs generated from it shown in Figure 4 and Figure 5. The analysis found that the most populated region was low Earth orbit (LEO), particularly a Sun-synchronous orbit (SSO) at around 510 km altitude and 97.4 ° inclination. This was therefore selected for the mission architecture.

Servicer Sizing

As a first approximation, the servicer spacecraft's volume was estimated as 1 m^3, which was supported by visual inspection of images of the ELSA-d spacecraft. The servicer was modelled as a cube to simplify dynamics calculations.

The servicer's mass was determined by estimating the mass of each subsystem and adding margins as per the ESA concurrent design facility (CDF) study guidelines [29]. The total dry mass was 237.60 kg.

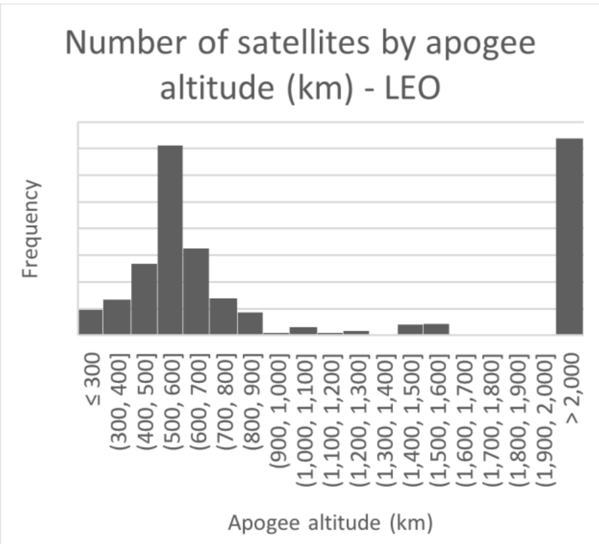

Figure 4: Satellite distribution by apogee altitude

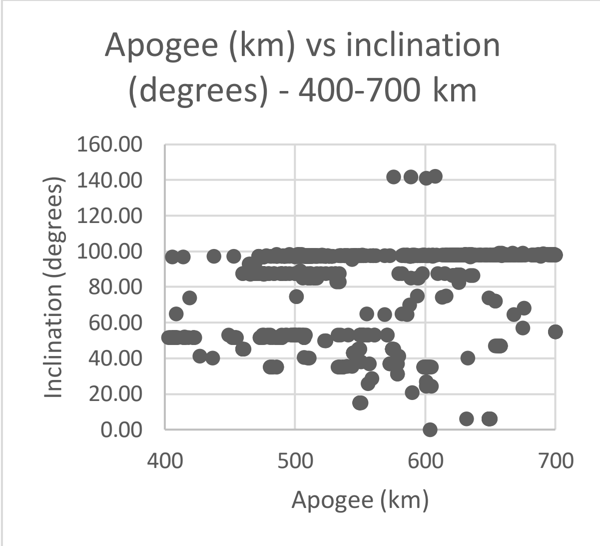

Figure 5: LEO satellite apogee vs inclination

Once the dry mass had been calculated, the required fuel was found by assuming the servicer would complete a series of noncoplanar phasing manoeuvres during its mission. These would take it between a 600 km parking orbit and a 520 km target orbit, with an inclination change of 0.3 °. It was calculated using an algorithm from Vallado [30, pp. 368-369] that this would require a one-way Δv of 190 m/s. Two return trips were assumed, and with fuel for docking a total of 903.1 m/s was required. Using the rocket equation then gave a fuel mass of 84.68 kg, which with margin added gave a total wet mass of 323.97 kg. The spacecraft mass budget is shown in Table 1.

Table 1: Servicer mass budget

System	Component	Mass (kg)
Bus	Structure	30.00
	Margin	6.00
GNC	GNC sensors	20.00
	Margin	4.00
	Reaction wheels	5.00
	Margin	1.00
Payload	Robotics	75.00
	Margin	15.00
	Payload margin	18.00
Propulsion	Thrusters	10.00
	Margin	2.00
	Tanks	10.00
	Margin	2.00
	Fuel	120.67
Totals	Dry mass	198.00
	Margin	39.60
	Total dry	**237.60**
	Total wet	**323.97**

REQUIREMENTS DEFINITION

The key spacecraft requirements related to mass and volume, with a wet mass of no more than 400 kg and no dimension greater than 1.5 m. Another driving requirement was for the spacecraft to be capable of fully autonomous operations, which would enable the servicer to perform more tasks between receiving operator commands [6, p. 71]. A minimum mission lifetime requirement of 10 years was also formalised and was based on MEV-1 servicing IS-901 for five years before moving to its next client [17].

Other requirements were defined alongside these in a requirements specification [31], with those pertaining to specific systems discussed in their relevant sections below.

GUIDANCE, NAVIGATION AND CONTROL (GNC) SYSTEM

GNC Architecture

The GNC system performs absolute navigation for the servicer. It will work independently of the Relative Navigation System (RNS) described later and will be part of the spacecraft's autonomous control. The GNC will use three-axis control, with the default attitude pointing the solar panels towards the Sun for battery charging.

GNC Requirements

The main requirements for the GNC were for orbit and attitude determination accuracy (50-100 m and 0.05-0.25 °, respectively, depending on operational mode), pointing accuracy (0.05-0.25 ° depending on mode), stability margins (based on the ESA CDF guidelines [29]) and slew rate (1 °/s while not docked to the target).

Control Loop

A single-input, single-output control loop design was selected as the low slew rate meant spacecraft axis cross-coupling effects could be ignored. A proportional-integral-derivate controller would potentially be most appropriate for the GNC (and RNS), although detailed control loop design was beyond the project's scope.

Sensors

Orbit determination methods that were considered for the GNC were global navigation satellite systems (GNSS, including GPS), the space surveillance network (SSN), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), the Tracking and Data Relay Satellite System (TDRSS) and the TDRSS On-board Navigation System (TONS) based on TDRSS.

A solution was sought that would allow the GNC to operate independently of the ground. Only TONS, DORIS and GNSS could achieve this. DORIS had the highest accuracy, on the order of a few centimetres [32, p. 596], but this level of accuracy was not required. A GNSS-based system would have the simplest equipment of the three options with a mass of around 1.1 kg and power draw of 7 W [33], and would provide acceptable accuracy, so was selected.

For attitude determination, sensor options included, Sun sensors, Earth horizon sensors, star trackers, gyroscopes, accelerometers, magnetometers and GPS receivers. A high accuracy sensor was required to meet the attitude determination accuracy requirement of 0.05 ° and a star tracker and gyroscope system was devised. The star tracker would be used to periodically provide a highly accurate attitude determination that could then be updated over time using the lower power gyroscopes until their drift necessitated calibration by the star tracker.

The lower power and mass requirement for a GPS system made it a good backup option, especially considering it had already been selected for attitude determination. The baseline between the GPS receivers should be as long as possible to maximise accuracy, meaning they should be placed on opposite corners on the spacecraft.

Plant

The plant models the spacecraft dynamics and external torques such as solar radiation pressure and atmospheric drag so they can be account for in the control loop. Attitude and orbit perturbations were not modelled, but the spacecraft inertia matrix was calculated precisely, as this would influence the servicer's dynamics.

The inertia matrix for the servicer alone was found to be $\begin{bmatrix} 53.99 & 0 & 0 \\ 0 & 53.99 & 0 \\ 0 & 0 & 53.99 \end{bmatrix} \text{kg m}^2$, or $\begin{bmatrix} 82.23 & 0 & 0 \\ 0 & 296.34 & 0 \\ 0 & 0 & 300.92 \end{bmatrix} \text{kg m}^2$ while docked, assuming a full fuel tank. The position of the centre of mass was found for the servicer alone and while docked to the target, with it laying near the docking interface. As propellant is consumed the centre of mass would shift towards the target.

Actuators

GNC actuators had to be selected for attitude and orbit control, with full six degrees of freedom (6DOF) control required. The translation actuators would also be used by the RNS while docking. Several options – reaction wheels (RWs), control moment gyroscopes (CMGs) and momentum wheels (MWs) – could achieve rotation, but only thrusters could be used for translation during orbital manoeuvres and docking.

Eight thrusters were found to be the minimum for 6DOF control [34], with ELSA-d using eight corner-mounted thrusters plus four for translation [35]. This 12-thruster layout was chosen as a baseline and is shown in Figure 6.

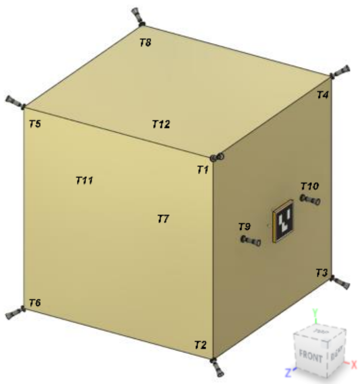

Figure 6: Spacecraft basic physical model with thruster positions labelled

The thrusters were angled so that each produced a torque as well as a thrust. The total torque and thrust could be found using a custom spreadsheet model that determined the values based on the thrust of an individual thruster and its pointing as found using a direction cosine matrix.

Calculations found that the minimum linear acceleration for impulsive orbital manoeuvres was 0.356 m/s^2. The Moog DST-12 thruster was selected, with a maximum thrust of 22 N and an I_{sp} of 302 s [36]. These give a maximum linear acceleration of 0.371 m/s^2.

For attitude control, magnetorquers would not provide sufficient torque. RWs were selected as the primary attitude actuator due to their simplicity over CMGs, lower power draw and several COTS models with flight heritage being available [37] [38, p. 2]. The thrusters could also be used for attitude control, particularly when the servicer is docked to the target, but to avoid excess fuel burn they would normally only be used for orbital manoeuvres or to desaturate the reaction wheels.

RELATIVE NAVIGATION SYSTEM (RNS)

The RNS is used to perform navigation relative to the target satellite and is switched to from the GNC once the target is within sensor range. It remains active until docking has been achieved.

RNS Requirements

The main requirements on the RNS are to provide the following accuracies in target range, range rate, pose and pose rate respectively to the servicer's OBC: 1 cm, 1 cm/s, 1 °, 1 °/s. The handover between GNC and RNS will occur at a baselined range of 80 km to match the handover point in Astroscale's ADRAS-J mission [39]. The onboard computer (OBC) will switch from using orbit state vector and attitude information from the GNC to using target range, range rate, pose and pose rate data from the RNS.

RNS Concept and Component Selection

The DogTag grappling fixture (Figure 2) found on the OneWeb-like target satellite includes an optical fiducial marker that can be tracked by a monocular optical camera at up to 5 m range [40, p. 1]. This forms the innermost layer of the RNS.

From 5 m to 250 m range, a Light Detection and Ranging (LIDAR) sensor will be used, giving a constant range accuracy [41]. A selection of LIDAR options is shown in Table 2. From these, the Canadian Space Agency LARS sensor was selected due to its high accuracy and mixture of triangulation and time of flight (TOF) modes. Triangulation mode enables sub-millimetre accuracy below 1 m range and 2 cm at 10 mm, with a constant 3 cm accuracy in the long-range TOF mode [42, p. 278].

Beyond the 10 km range of the LARS, no target pose information will be required, only range and range rate. For this, a long focal length camera is ideal due to its low power consumption and simplicity relative to a LIDAR system. For example, the narrow field of view variant of Neptec's VisCam could be used for this [43]. The range limit of this sensor is not known, but for comparison Astroscale's ADRAS-J will use a visible camera from 80 km range [39]. This is baselined as the outer limit of the RNS. The RNS architecture is summarised in Figure 7.

Table 2: Existing LIDAR examples [41, p. 58]

System (developer)	Operational mode	Technology & measurement principle	Operational range (m)	Documented range accuracy
LARS (CSA)	Cooperative	Scanning CW Triangulation Pulsed TOF	0.5-10 10-10,000	Sub-mm 3 cm
LCS (Neptec)	Cooperative Non-cooperative	Scanning CW Triangulation	1-10	0.1 mm – 5mm (1σ)
LAMP (JPL)	Cooperative Non-cooperative	Scanning Pulsed TOF	<5,000	10 cm (bias) 2.6 cm (3σ)
RVS (Jena-Optronik)	Cooperative	Scanning Pulsed TOF	<2500	0.01 m – 0.5 m (bias) 0.01 m - 0.1 m (3σ)
RVS-3000 (Jena-Optronik)	Cooperative Non-cooperative	Scanning Pulsed TOF	1-500 1-100	*N/F*
TRIDAR (Neptec)	Non-cooperative	Scanning CW Triangulation Pulsed TOF	0.5-2,000	*N/F*
LDRI (SNL)	Non-cooperative	Scannerless CW AM	<45	0.25 cm
DragonEye (ASC Inc.)	Non-cooperative	Scannerless Pulsed TOF	<1,500	10 cm (bias) 15 cm (3σ)
GoldenEye (ASC Inc.)	Non-cooperative	Scannerless Pulsed TOF	<3,000	10 cm (bias) 15 cm (3σ)
VNS (Ball Aerospace)	Cooperative (potentially non-cooperative)	Scannerless Pulsed TOF	<5,000	10 – 20 cm (3σ at 10 m)

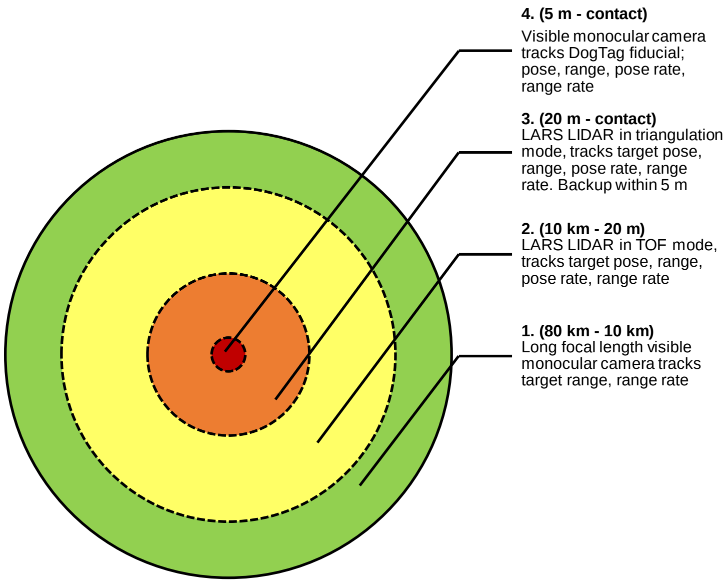

Figure 7: Proposed RNS architecture

Safety

To ensure maximum possible safety during rendezvous and proximity operations, the servicer will employ techniques such as a walking safety ellipse and evacuation points, similar to those used on Astroscale's missions [35] [39] [44, p. 5]. Approach trajectories would also be tightly defined and could use the r-bar method formerly used by the Space Shuttle to approach the International Space Station and Hubble Space Telescope in a passively safe way [45] [46, p. 533].

GRAPPLING AND ROBOTICS

Grappling Fixture

Under the proposed mission concept, a grappling fixture would be used as an interface between the servicing and target and would be attached directly to the side of the servicer. With the OneWeb satellite being baselined as a target, the target can be assumed to carry an Altius Space Machines DogTag grappling fixture (Figure 2). This is normally captured using an electropermanent magnet (EPM) grappling head on the servicer, although mechanical and other forms of grappling are also available [40]. Altius' MagTag fixture, which also uses EPMs [47], could also be used to capture hardware modules on the target for replacement.

For other targets no grappling fixture can be assumed, but alternatives to the DogTag that could be implemented to enable servicing include the iBOSS iSSI [48] or Obruta Space Systems Puck [49].

Alternatively, a probe system like that found on Northrop Grumman's MEV [50] could be used to capture the engine bell of a satellite without a dedicated grappling fixture.

Servicing Arm

A robot arm would be used for dexterous servicing operations such as replacement of failed hardware modules or attaching a refuelling hose. Arm options include the Next Generation Canadarm (NGC) Small [51] (Figure 8), the SPIDER arm used on OSAM-1 [52] and the DARPA FREND arm on which SPIDER is based [53] [54]. All of these would be appropriate options for a servicer spacecraft, but the FREND arm has undergone significant testing and is at around technology readiness level 6 [53]. The author recommends that the servicer be baselined to include an arm based on the FREND design, but which could also factor in lessons learned from NGC Small and SPIDER once the latter has been used on orbit for the OSAM-1 mission.

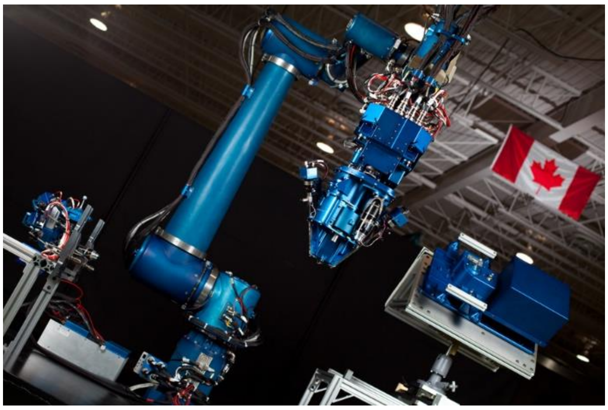

Figure 8: Next Generation Small Canadarm [55]

Tooling and Sensing

Tooling for OOS is currently an area of technology immaturity. Generic tools such as grippers have been used in space for some time and specialist tools have been developed and tested for operations such as unscrewing fuelling caps. However, there is currently no standard tool set or tool specification for tools designed to work with a variety of target spacecraft. NASA's series of Robotic Refuelling Missions has demonstrated tooling and procedures for propellant transfer [56]. With no tool standards currently available though, commercialisation in this area remains challenging.

Regarding sensing, the FREND arm has demonstrated autonomous grappling [57]. Optical cameras are commonly used on robotic arms to give operators live views of the arm's surroundings. For example, the Canadarm3 arm under development for the Lunar Gateway will include six colour cameras at 4K resolution, with "one 360-degree camera on each side of the elbow, one on each boom on swivel mounts and the other two on the "hands"" [58].

AREAS FOR FUTURE DEVELOPMENT

Future work will include areas such as performing a detailed trade-off of chemical versus electric propulsion for orbital manoeuvring. This will require the Δv requirements for orbit transfers using each system to be accurately modelled and understood. If a chemical propulsion system is kept, fuel sloshing and its effect on dynamics will need to be understood and mitigated.

When calculating the servicer Δv requirement, it was assumed that two services would need to be completed for the mission to be economically viable. This will need to be tested using detailed cost-benefit analysis and business modelling.

Illumination during proximity operations will have a significant effect on the RNS, so simulation of this will be required so acceptable illumination parameters can be defined for mission operations.

Areas of further systems engineering development include the need to specify maximum misalignment between the grappling interfaces during capture.

GNS and RNS control loop design will need to be studied in more detail but can make use of current best practices and techniques to ensure an efficient and effective solution is found.

Finally, radiation modelling will be required to determine the total dose received, its effect on the servicer's components and any failures it may cause.

CONCLUSION

This paper has outlined current space industry issues that could be improved using on-orbit servicing and described current OOS endeavours. It has defined a mission architecture using a OneWeb-like satellite as a target, then shown how current technology is in most cases already sufficiently developed to be immediately implemented in an OOS mission. Areas requiring further development have been highlighted, with this paper showing that commercial OOS missions for applications such as hardware replacement are within reach.

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