In-Orbit Assembly of Large Spacecraft Using Small Spacecraft and Innovative Technologies

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Abstract

The size of any single spacecraft is ultimately limited by the volume and mass constraints of currently available launchers, even if elaborate deployment techniques are employed. Costs of a single large spacecraft may also be unfeasible for some applications such as space telescopes, due to the increasing cost and complexity of very large monolithic components such as polished mirrors.

The capability to assemble in-orbit will be required to address missions with large infrastructures or large instruments/apertures for the purposes of increased resolution or sensitivity. This can be achieved by launching multiple smaller spacecraft elements with innovative technologies to assemble (or self-assemble) once in space and build a larger much fractionated spacecraft than the individual modules launched.

Up until now, in-orbit assembly has been restricted to the domain of very large and expensive missions such as space stations. However, we are now entering into a new and exciting era of space exploitation, where new mission applications/markets are on the horizon which will require the ability to assemble large spacecraft in orbit. These missions will need to be commercially viable and use both innovative technologies and small/micro satellite approaches, in order to be commercially successful, whilst still being safety compliant. This will enable organisations such as SSTL, to compete in an area previously exclusive to large commercial players. However, in-orbit assembly brings its own challenges in terms of guidance, navigation and control, robotics, sensors, docking mechanisms, system control, data handling, optical alignment and stability, lighting, as well as many other elements including non-technical issues such as regulatory and safety constraints. Nevertheless, small satellites can also be used to demonstrate and de-risk these technologies.

In line with these future mission trends and challenges, and to prepare for future commercial mission demands, SSTL has recently been making strides towards developing its overall capability in “in-orbit assembly in space” using small satellites and low-cost commercial approaches. This includes studies and collaborations with Surrey Space Centre (SSC) to investigate the three main potential approaches for in-orbit assembly, i.e. deployable structures, robotic assembly and modular rendezvous and docking. Furthermore, SSTL is currently developing an innovative small ~20kg nanosatellite (the “Target”) as part of the ELSA-d mission which will include various rendezvous and docking demonstrations. This paper provides an overview and latest results/status of all these exciting recent in-orbit assembly related activities.

Keywords: in-orbit assembly, large telescopes, fractionated architecture, space robotics and autonomous systems.
1. Introduction and Background Rationale

Since the dawn of the space age, the design methodology for spacecraft has been fundamentally constrained by (a) the available primary (or secondary) launcher volume within the fairing and (b) the dynamic environment within the launcher after ignition (i.e. vibration, noise, and shock levels). This imposes significant limitations on the size, volume, and design of spacecraft that can be accommodated within the fairing of a single launch vehicle, the largest of which is currently less than 5m in available diameter. Even planned larger launchers such as Blue Origin’s New Glenn and NASA’s SLS Block 2 will be restricted to 7m and 8.4m respectively in fairing diameter. The structural designs for satellites, especially those that are large and complex such as optical space telescopes, are significantly driven by the necessity to survive the aggressive launch environment for the first 20 minutes or so of the ascent to orbit.

For instruments in the Radio Frequency domain, the challenges imposed by fairing constraints are currently addressed to some extent by antennas that unfold or deploy on-orbit. In the optical and infrared domains, this is a significantly more challenging problem, which has up to now either been addressed by simply having large monolithic mirrors (which are fundamentally limited by the volume and mass lifting capacity of any launch vehicle) or by complex ‘semi-folding’ designs such as the NASA JWST (James Webb Space Telescope), costing some $9 billion. This is currently about the largest practicable telescope that can be origami-folded into the largest available launcher fairing.

There are, of course, additional considerations apart from launch fairing constraints which also affect large space systems. For example, the increasing complexity of manufacturing larger mirrors directly affects the cost associated with optical space telescopes. Generally, the cost of a mirror increases by factors greater than the square of its radius; this makes monolithic observatories such as Hubble less financially attractive to the commercial sector. A similar argument also applies for other monolithic systems such as SAR. More broadly, costs of a launching a single large spacecraft may be unfeasible for some applications.

In summary, regardless of the application, the size of any single spacecraft is ultimately limited by the primary or secondary volume constraints of currently available launchers and costs. Clearly, a radically different approach is needed for larger space systems, e.g., the next generation of telescopes have proposed apertures that are double (or more than) the fairing diameter of existing and future launchers. These future space missions will require some form of in-orbit assembly in order to address missions with larger infrastructures or increasingly larger instruments and instrument apertures for the purposes of improved resolution or sensitivity. We notionally define in-orbit assembly within this paper as requiring connection, movement, separation (and possibly reconnection) of objects. The role of small satellites (or SmallSats) as an effective means to develop and implement such concepts was recently discussed [1,2] given their low-cost and short-lead time. Additionally, small satellites are generally less structurally complex as they tend to be physically compact and have lesser coupling to the launcher environment. The focus of this paper is on the role of small satellites in achieving on-orbit assembly and SSTL’s work towards realizing this mission. Note that, for the purpose of assembly as discussed in this paper, a small satellite is defined to be one that is at or under 1000 kg [2].

Up until now, “In-Orbit Assembly” has been restricted to the domain of very large and expensive institutional missions, e.g. assembly of the International Space Station. However, we are now entering an exciting new era of space exploitation where new mission applications/markets for assembly are on the horizon which will lead to a far more sustainable space economy [3]. This era will be enabled by an ability to assemble large infrastructures in orbit using low-cost innovative technologies (e.g. robotics and autonomous systems) and SmallSats in order to be commercially competitive, whilst still being safety compliant. This will also create a new level playing field for lean aerospace organisations such as SSTL to compete in an area previously exclusive to large institutional players.

For extremely large orbital structures such as large aperture telescopes (either sparse or filled), next-generation communication antennas, and space tourism assets, In-orbit construction is considered a lower cost method than launching carefully stowed and elaborately deployed monolithic structures [4,5], due to the reduced level of structural analysis necessary and the relaxed requirements on the materials used for the structure. In brief, it is much easier to construct a large structure in space when one does not have to also consider how to make it survive launch in one piece and fit within a launch vehicle fairing. It is for this reason that SSTL and SSC consider in-orbit construction the more appropriate future technical route for large in-orbit structures than monolithic deployable structures. The techniques being developed at SSTL and SSC will go a long way to achieve that ultimate end goal. This would involve launching multiple smaller spacecraft elements to assemble (or self-assemble) once in space and build a larger much fractionated spacecraft than the individual modules launched, which could be used for optical,
One can identify several categories of missions suitable for in-orbit assembly with the involvement of small satellites, which could herald a generation of exciting future missions. The following diverse non-exhaustive list contains some examples of such missions which could be assembled in-orbit in the foreseeable future:

- **Observational Payloads:**
  - High Resolution Optical/IR telescopes (see Figure 1-1 and Figure 1-2)
  - Grazing incidence X-Ray telescopes
  - Multiple Optical/IR telescopes for wider swath capability (see Figure 1-3 right)
  - Multiple multi-wavelength instruments for sensor fusion capability (see Figure 1-4)
  - RF/SAR Antennas

- **Modular Platforms** (e.g. optics spacecraft + Propulsion spacecraft, see Figure 1-3 left)

- **Occulting Objects** (e.g. for long baseline coronagraphs [6] or weather manipulation)

- **Solar Concentrators** using very large mirrors

- **Space Power Generation from orbit** (see Figure 1-5)

- **Masts and Booms** to provide general large scale infrastructure (e.g. for Space Tourism)

These missions/applications for in-orbit assembly will have many commonalities with each other (as well as with similar missions involving proximity operations with more than one spacecraft). However they will also have their own unique requirements and constraints. For example, whilst optical/IR telescopes and solar concentrators will require large mirrors, the tolerances on the latter will be much more relaxed. In the case of observational payloads, is anticipated that fully deployable telescopes will be a natural precursor to any in-orbit assembled telescopes. In fact we are already seeing this evolution with SAR and RF telescopes. However it is likely that there is a tipping point where in-orbit assembly becomes more cost effective and less risky than pure mechanical deployment. This topic is further discussed in chapter 6.
2. Technical capabilities required for achieving in-orbit assembly

2.1 Introduction

From our perspective, there are three fundamental capabilities that will enable in-orbit assembling of a larger spacecraft from modular components:

a) **Connectors** that can disconnect and re-connect modules in the space environment

b) **Assembly philosophy** to manoeuvre these modules from their separated initial configuration to their desired final configuration

c) **RDV-related technologies**

These capabilities are explained in further detail below. It is anticipated that these techniques will need to be augmented by deployable and/or inflatable structures (e.g. for trusses, baffles or connecting booms) for certain mission applications, especially for increasingly larger structures. In the longer term it is also expected that 3d printing will become a core capability. Several of the key techniques and technologies for in-orbit assembly are also applicable to other missions that require proximity operations (e.g. proximity sensors), namely In-Orbit Servicing, Active Debris Removal, Inspection, Formation Flying and Asteroid Rendezvous missions. The shared “technology pull” for all these similar missions is advantageous as it means there is a larger market for the core technology needs.

2.2 Connectors

A connector is a physical interface to bring together two or more separate modular elements together. Apart from the implicit mechanical requirements for such a system, they should also have the capability to transfer electric power, data for communications, and appropriate thermal transfer characteristics. There is evidence for the importance of such a system based on at least two ongoing projects. SIROM [12] and the iBOSS system [11,12,13] are two interfaces pushing the envelope on a standardized interface for connecting payloads.

![Image of iBOSS](image-url)

*Figure 2-1: iBOSS – An Intelligent Modular System for On-Orbit Satellite Servicing/Assembly [11,12,13]*

2.3 Assembly Philosophy

Moving modules from the initial to final positions can be approached in four fundamentally different ways, each with their own strengths and weaknesses:

2.3.1 Autonomous free-flyer modules

This approach is one which utilizes a swarm of satellite modules where each of the agents is a fully independent free-flying satellite capable of docking, undocking, and formation flying. The use of such a system is discussed in section 7.3 on the GOAT mission concept [14]. This presents a highly versatile solution, although this approach also has a correspondingly high complexity and risk on account of multiple free-flying elements, each with its own propulsion modules. Additionally, there is significant replication of parts due to the complexity of so many autonomous modules which results in a large cost and mass penalty with this approach.

2.3.2 Self-assembly space robot

This system is where a robotic arm is rigidly attached to a base satellite (see Figure 2-2); however, a degree of mobility of the manipulator can be enabled by placing it on a slider. A standard pick and place method as seen with typical industrial robots is used to move modules into their final locations on the base vehicle (or some appendage). Thus, it is evident that at every stage of the assembly process, the modules that are always rigidly connected to either the spacecraft (inside it when stowed or on it when in its final configuration), or to the manipulator during the pick-and-place operation. We believe that this is indeed the simplest approach to assembly but also less versatile; the working volume of the robot is limited by its span, so assembling a larger task requires a significantly larger robot which introduces a variety of complications. Further, this assembly technique may need to be additionally augmented by deployable systems, especially for larger structure. For example, our studies indicate that this challenge will be encountered in constructing secondary mirrors in large-aperture telescopes [14]; here the separation distance between the primary and secondary mirrors can exceed the span of the robot arm.

![Conceptual representation of a self-assembly mission for telescopes](image-url)

*Figure 2-2: Conceptual representation of a self-assembly mission for telescopes*
2.3.3 Free-flying assembly robots

This type of robot takes features of the philosophies in both sections 2.3.1 and 2.3.2, in that it comprises a robot arm attached to a free-flying base (see Figure 2-3). However, the goal is to perform assembly on another separate agent but not assembling on itself. The reason for this being that a greater degree of mobility can be incorporated allowing easier assembly of really large structures, at least in theory.

Here, the parts may be stowed within the space robot or the secondary spacecraft upon which assembly is to be carried out. Thus, here at least two modular spacecraft have some level of intelligence but the majority of elements are ‘dumb’ i.e. they lack propulsive and compute abilities to relocate themselves. The free-flyer robots are used to ferry these ‘dumb’ modules into their final locations, this approach requires identical technology to those developed in both categories discussed above. It is worth noting that the two free-flying approaches discussed so far place additional requirements on the connectors in order to make them capable of safely docking two independent spacecraft. Also, many of the key GNC techniques and technologies required for free-flying assembly are also applicable to other missions that require proximity operations. SSTL has been developing significant experience in these areas on previous missions and studies as described later in this paper. Such a system is also utilized in the GOAT concept [14] as part of the assembly process.

![Figure 2-3: Conceptual representation of a free-flying assembly mission for telescopes](image)

2.3.4 Climbing assembly robots

This refers to a limbed-robotic system that can move along a spacecraft to different locations to perform assembly on it; unlike free-flying robots, the robotic system does not have any thrust-generating elements of its own as it is technically a separate agent (i.e. not always rigidly attached to the base spacecraft). The mobility of the robot along the vehicle is facilitated via standardized interfaces (such as the SIROM and IBOSS) placed at various points of the spacecraft. This introduces a valuable design homogeneity that simultaneously can solve the problems of mobility, manipulation, and assembly as a standardized interface can permit all of these core robotic and assembly capabilities. An example of a conceptual inchworm robot is illustrated in Figure 2-4, which depicts the multi-stage process of transporting an assembly module to its final configuration.

![Figure 2-4: Inchworm Assembly Robot Concept](image)

The current flight-proven state-of-the-art for such a robotic system is the inchworm robot utilized on the Canadarm [15], which can use either end of its two links to latch to the ISS thus allowing it to walk end-over-end. We envision that for SSTL’s purposes, a much smaller inchworm assembly robot can move itself along with the modules around the spacecraft structure, similar to that seen on the recently proposed BILL-E robot [16]. A crucial advantage here is that the robots (and the modules) are always physically attached to the base vehicle upon which assembly is being performed thus eliminating the complexity and risks introduced by all of the above discussed free-flying systems. Finally, the mobility of the robot via the standardized interface on the base craft suggests that any robot’s working volume is limited only by the availability of attachment points and not their size; in other words, they can work over a volume much larger than their immediate reach (i.e. the span of a two-link arm).

More complex multi-limbed designs that embrace a similar mobile robot philosophy have also been proposed for constructing ultra-large aperture telescopes, e.g. the hexbot used in RAMST [7] for assembling a 100m primary mirror of an optical telescope (see Figure 2-5).
2.5 Summary and Discussion

It is now apparent how assembly is achieved using more than one satellite combined with all three capabilities (e.g. where one spacecraft carries all the necessary parts, and another free flying craft carries out the robotic assembly). Extra mission safety is required to provide collision avoidance capabilities, due to inevitable proximity operations. Figure 2-6 shows the main factors that need to be considered for in-orbit assembly on a large scale, depending on the choices of techniques and technologies.

![Figure 2-6: Factors that need to be considered for in-orbit assembly on a large scale](image)

Specifically, SSTL/SSC internal studies indicate that robotic assembly increases the mass efficiency of the optical telescope systems in the full mission architecture, by limiting the number of intelligent agents which essentially means fewer spacecraft sensors, reduced propulsive agents, avionics, etc. Robotic assembly is achievable using a single spacecraft carrying all the necessary parts within its launch volume (up to a certain limit). This has the advantage of avoiding complexities required for operating two or more spacecraft in close proximity (i.e. collision avoidance technologies). However, if multiple launches are required then each vehicle could perform a single RDV&D (or Berthing) operation attaching itself into a single larger platform for subsequent assembly using any of the methods in the assembly philosophy but preferably with as few proximity operations as possible (making the free-flyer assembly philosophy less preferred).

If a universal androgynous connector such as the SIROM, iBOSS or equivalent is used as a basis for a modular assembly system, then an inchworm robot with this connector for its two end-effectors is an incredibly versatile tool. In this case the satellite bus itself would have universal connectors on it for three different
possibly overlapping reasons; some connectors would hold the stowed parts, others would be used to hold the parts in their final configuration, while others would create a ‘route’ for the inchworm robot to move around the bus. The universal connectors allow the inchworm robot to ‘walk’ across the satellite even when it is carrying one or more modules by utilizing the universal connectors of the modules themselves.

Use of an inchworm robot appears to be a very promising choice for an assembly system, not only because of the flexibility and simplicity it offers, but also of its extensible mobility when one takes into consideration docked spacecraft. If two docked spacecraft have identical connectors systems for component attachment, an inchworm robot could walk between these two vehicles and move parts from one craft to the other. The universal connectors on each end of the robot also have the ability to act as ‘tool changers’ allowing specialist end effectors to be used. These tools would allow this robot to be used for more complex tasks beyond the simple modular assembly thus proving the versatility of its design.

The self-assembly robotic assembly approach is far simpler than the inchworm robot, however, this technique does not scale up well to larger, more complex assembly tasks. It also lacks the flexibility of being used for other secondary tasks beyond assembly making it less versatile. Even so, the merits of such a system exist in that it would be an ideal lower risk technical demonstration mission to give flight heritage to some of the technologies needed for all of the other assembly philosophies.

3. Future Vision for in-orbit assembly

The three fundamental capabilities discussed in Chapter 2 will enable a wide range of other mission concepts and create new market opportunities precluding the development of new flight hardware. As a simple extension, on-orbit maintenance and upgrade missions can be undertaken using the same capabilities. A clear view of the possibilities is critical to ensuring that the technology developed for early orbital assembly missions has the maximum re-use value in the long term.

If an inchworm robotic manipulator and a set of modular solar arrays and antennas were developed using a standardized universal connector, these parts will appeal to a wide range of satellite manufacturers including SSTL. The consequent new market could benefit from a range of low-cost modules based on space proven COTS components in which SSTL already has a great deal of experience.

The size of the many primary payloads launched today is limited by fairing volume as opposed to mass-to-orbit. If a flight-proven modular architecture and assembly system was available, then more compact stacks of components could be launched and assembled on-orbit into larger vehicles. The technology to allow operators to launch larger satellites for the same costs obviously has a significant potential market, even without considering the opportunities for servicing and upgrades that it enables.

If a constellation of ‘assembled on-orbit’ satellites was required, a single large launch could deliver all the components along with a manipulator all mounted on a central dispenser-like structure. The manipulator could then assemble and release each satellite in turn. This approach would share the cost of the manipulator between multiple vehicles. The need for each satellite to carry the manipulator’s mass for its full mission duration is also removed. Once the full constellation has been deployed, the assembly platform could either deorbit itself or remain on-orbit revenue if it could continue to provide a revenue stream beyond its primary assembly mission. For example, an active debris removal mission could be undertaken where the assembly space robot deorbits another non-serviceable spacecraft.

Comprehensive servicing missions become possible when modular satellites are in use. These could not only repair existing systems but also add new payloads to existing buses on orbit. For example, if the modular satellites in a constellation shared a single orbital plane, a servicing mission could RDV&D with each vehicle using minimal delta-V. This mission could replace or add payload or bus elements to the whole constellation using a single small-sat launch.

When a modular satellite reaches the end of its life, a robotic servicing vehicle could RDV and capture it to harvest any salvageable components to build new vehicles or maintain existing ones. This new market for on-orbit spares could be a new revenue stream for satellite operators while also reducing the cost of parts for new and existing vehicles.

Even grander visions are currently being pursued by Made in Space [17], who are currently developing additive manufacturing techniques to ‘print’ (i.e. 3-D printing) spacecraft structural elements on-orbit enabling much larger space systems than currently possible. This logical next step for in-orbit assembly will effectively move the manufacturing of spacecraft into orbit [1]. Eventually raw materials alone will be launched and then design software uploaded to manufacture the required functions on “gossamer” spacecraft, thus completely bypassing the structural
constraints of the launch phase and, possibly, also simplifying the demands on the launcher itself leading to lower launch costs.

In the longer term, the raw materials will be resourced from space itself rather than from the ground, i.e. using “in-situ resource utilisation” techniques either from natural objects (such as Near Earth Asteroids, or the Moon), or man-made objects (i.e. dead spacecraft in LEO or GEO). This would avoid the need to launch materials at all, further reducing mission costs.

However, it should be noted that an assembly system will still be required to attach various active spacecraft components onto these large structures. The opportunity to build and flight-qualify an assembly system before such additive manufacturing is flown will help accelerate this technology, which in itself creates another market opportunity.

Thus, in summary, it is evident that the potential market for in-orbit assembly systems could itself be far bigger than one for large aperture telescopes, even if these observatories are the first in-orbit assembled platforms. For this reason, the general challenge of physically re-configurable spacecraft should be first addressed in early technology demonstration missions as these will likely give rise to markets that will accelerate the ambitious vision for in-orbit assembly described in this section.

4. SSTL’s approach towards developing in-orbit assembly capability with smallsats

In line with these future mission trends and challenges and to prepare for future commercial mission demands, SSTL have recently been making strides towards developing its overall capability in “in-orbit assembly in space” using low-cost commercial approaches. This is a stepwise multi-pronged approach and has initially focused on providing relatively standard platforms within collaborative projects to demonstrate or provide key technologies for in-orbit assembly.

However more recently it has also included studies and collaborations with our colleagues at Surrey Space Centre (SSC) to investigate all of the three main potential approaches which can be used for in-orbit assembly, i.e.

- deployable structures
- modular rendezvous and docking
- robotic assembly

Indeed SSC are already collaborating with CalTech, Jet Propulsion Laboratory (JPL), and Indian Institute of Space Science and Technology (IIST) on the Autonomous Assembly of a Reconfigurable Space Telescope (AAReST) mission [18,19], which will demonstrate some key aspects of low cost in-orbit assembly (including close proximity rendezvous and docking) and reconfiguration of a space telescope based on multiple mirror elements. A launch is expected in 2019.

Figure 4-1: The AAReST Mission Concept

However AAReST is only a very small scale academic mission demonstration using three cubesats (a “Fixed Core NanoSat” plus 2 separable “MirrorSats”), and is only limited to very close ranges (the spacecraft are initially joined together). For this reason SSTL and SSC are now also investigating the missions and technologies, which will be natural follow-ons to the AAReST telescope scenario in order to develop in-orbit assembly capability. This has included a recent NSTP-2 study (described in more detail in section 7.4) to investigate a cooperative two-spacecraft rendezvous and docking mission demonstrator using microsatellites (an active Chaser and a passive Target), as well as a follow on-in-orbit assembled EO telescope in LEO as a larger multi-spacecraft demonstration. These missions would be stepping stones to larger multi-spacecraft demonstrations and mission concepts which have been preliminarily investigated by SSTL, such as persistent surveillance from GEO and very large astronomical telescopes (both with large primary mirrors of 25m or greater), such as the GOAT (Giant Orbiting Astronomical Telescope) concept [14] which is discussed in section 7.3.
5. Platform Provision Developments

One of SSTL’s approaches to in-orbit assembly is to work with organisations who are providing specific solutions, and require low cost platforms on which they can implement specific hardware such as docking equipment, lighting or robotic arms. SSTL already has significant study heritage and some flight heritage in this area via the following studies/missions:

- RemoveDebris
- A proposed servicing mission to GEO
- ELSA-d

5.1 RemoveDebris

RemoveDebris [20] is a low cost recently launched mission which is Europe’s first practical in-orbit demonstration of “capture and disposal” techniques, thus demonstrating the technology needed to apply ADR to existing space objects which do not have a pre-existing ADR capability.

SSC is the prime contractor of the RemoveDebris mission and SSTL provided the main RemoveSat micro-spacecraft (see Figure 5-1).

RemoveDebris will provide in-orbit demonstration of the viability of a series of cost effective technologies that can be used to observe, capture and remove space debris from orbit. Some of these technologies and techniques, namely the Vision Based Navigation (VBN) system, the use of differential GPS, and the implementation of a video camera, are also directly applicable to future in-orbit assembly missions, where close proximity operations is also required.

RemoveDebris was launched in April earlier this year to the ISS. The satellite was then successfully deployed from the ISS in June via the NanoRacks Kaber, into a circular orbit with nominal altitude of 400km. In-orbit commissioning has also now been successfully carried out and the satellite is now ready for the experimental phase of the mission to begin.

Figure 5-1: RemoveSat Platform provided by SSTL

The mission concept consists of a main micro-satellite platform “RemoveSAT” of ~100kg mass that once in orbit will release two 2U cubesats “DSAT’s” which will act as space debris simulators. Four key technologies, to be used at different stages of a typical Active Debris Removal (ADR) mission will be tested:

- A Vision Based Navigation (VBN) system including a 2D-camera & 3D-LIDAR, to observe/quantify the relative dynamics between an uncooperative debris and the retrieving platform
- Two technologies for debris capture: a net and a harpoon
- A de-orbit sail, to increase the satellite platform drag, thus reducing its speed and orbit altitude until it burns up in the Earth’s atmosphere.

One of the cubesats, after low speed ejection from the satellite platform will be observed using the VBN to prove the hardware and performance in term of range, LOS and attitude, whilst the CubeSat also relays attitude data to the satellite platform for validation. The second cubesat, after ejection, will inflate a structure to increase its size to make it comparable to that of larger debris becoming a more size-representative target for the net capture experiment i.e. a net will be launched by the platform to envelope and capture the cubesat.

The DSAT will also carry GPS receivers - differential GPS (DGPS) to augment and assess the measurements from the vision-based navigation (VBN) sensors. It will also allow simulation of non co-operative target behaviour in a controlled and safe way.

The total duration of operations is expected to be around 40 weeks. Throughout the mission, RemoveSAT will communicate using an S-band up and downlink to the SSTL ground station in Guildford, where the centre of operations is also located. The communications link will
be used to transmit commands and receive spacecraft telemetry. The spacecraft telemetry will include the raw VBN and DGPS data, which will be analysed on the ground rather than on-board in real-time. Videos to assess the success of the demonstrations will be relayed back to the ground.

5.2 Proposed servicing mission to GEO

In 2015/16, SSTL did substantial work with an external organisation to develop a platform for a servicing mission to GEO, including a transfer via electric propulsion from GTO. This was to carry a range of Customer Furnished Equipment including Rendezvous and Docking Equipment, Robotic arms, and Electric Propulsion. Unfortunately this work was covered by a Non-Disclosure Agreement (NDA) and has never been published. Although this prospect did not come to fruition, it gave SSTL substantial knowhow in how to approach such mission developments.

5.3 ELSA-d

ELSA-d (see Figure 5-3) [21], is a twin small satellite mission scheduled to launch in 2020, which will demonstrate key rendezvous and docking technologies, and proximity operational concepts in readiness for provision of a commercial deorbit service in 2020 as constellations are starting production and deployment. These technologies and demonstrations are also highly relevant for in-orbit assembly missions.

Figure 5-3: ELSA-d will demonstrate capture and disposal of space debris, Credit: Astroscale

ELSA-d, which stands for End of Life Services by Astroscale-(demonstration) is comprised of a highly manoeuvrable "Chaser" microsatellite and "Target" nanosatellite. Astroscale are designing the mission and manufacturing the "Chaser" in Tokyo using avionics components from SSTL. In addition, SSTL are supplying the "Target" satellite (see Figure 5-4).

Figure 5-4: The ELSA-d Target spacecraft which is being built by SSTL

The mission will validate an innovative capture mechanism, as well as the CONOPS for capturing and removing non-tumbling and tumbling semi-controlled targets from orbit. The Target and the Chaser will be attached for launch and deorbit, but will be deployed while on-orbit in a series of three increasingly complex separation and capture manoeuvres using rendezvous and docking algorithms. A docking plate with optical markers will be attached to the Target, allowing the Chaser to identify and estimate attitude during the docking.

SSTL’s Target satellite incorporates S Band communications, GPS positioning, a 3-axis control system and laser retro-reflector. A variant of the SSTL-42 constellation platform family designed for operational missions in the 5kg-100kg range, it will also fly an HD camera and lighting to record the capture sequences during eclipse. These latter two technologies are potentially key technologies to support future in-orbit assembly operations.

Following successful demonstration, the “Chaser” spacecraft is intended to be mass produced to provide an on-demand service for constellation missions.

The ELSA-d mission is funded through private capital, and the project will address all the necessary regulatory aspects.
6. Deployable Structures Developments

6.1 Overview

The multi-billion dollar Earth observation applications market continues to demand better spatial and temporal resolution; simply put, this means bigger apertures and more satellites.

For the former, this will ultimately demand the need for in-orbit assembly (as already discussed earlier in this paper). However dealing with strict mechanical and alignment tolerances, especially in optical systems is difficult under normal conditions, but when in the context of a RDV&D or robotically assembled system in orbit, this becomes much more complex. This is further compounded by the need for large deployable structures (e.g. trusses, baffles or connecting booms).

A good first step is to have a single low complexity system which deploys a SAR or Optical/IR telescope from a smaller stowed state. As most of a typical Cassegrain-style telescope is empty space for the optical beam path between the primary and secondary mirror, the sensible initial way forward for optical/IR systems is to deploy only the secondary mirror from a smaller stowed state. This allows the payload to be shrunk in order to minimise the volume of the whole spacecraft.

A subsequent step for optical/IR telescopes would be to develop a fully deployable telescope, including also a deployable primary mirror (e.g. a mini-JWST). This has two benefits, firstly it also allows the stowed spacecraft to fit into small volumes and secondly it avoid the need for ever larger monolithic mirrors which have large costs and timescales (for accuracy, mirror polishing, sag avoidance etc) associated, which are not appropriate for low cost missions and rapid implementations, e.g. using small satellites.

Nevertheless there are cost and complexity limitations of single-body deployable structures with increasing physical size. At some stage, a step change is expected where in-orbit assembly will be more cost effective. However this is not immediately obvious yet. A preliminary guess of the “goldilocks” optical/IR telescope mirror diameter ranges for low cost commercial missions is as follows:

- Monolithic primary: up to 0.5-1m
- Deployable primary: 1m-3m
- In-orbit assembly via rendezvous and docking or robotic assembly, and a deployable secondary (Primary: 2m-10m)
- In-orbit assembly via rendezvous and docking and robotic assembly, and a deployable/ robotic assembled connected secondary (Primary: 10m-50m?)
- In-orbit assembly via rendezvous and docking and robotic assembly, and a formation flying secondary! (Primary: >50m?)

In line with these expected increases in instrument apertures, SSTL are collaborating with partners to develop both a deployable SAR spacecraft, and a deployable optical telescope to minimise the distance between the primary and secondary mirror during launch, and then extend out and align in-orbit. This is initially aiming to reduce the launch cost of a large constellation of EO satellites in LEO. However, the development also produces a number of enabling technologies for fully deployable optical/IR telescopes and ultimately in-orbit assembly. The autonomous deployment and control of optomechanical components requires very high accuracy and repeatability which will be valuable experience for a number of in-orbit assembly applications not limited to optical instrumentation. The development and maturing of the automatic alignment techniques and algorithms of optical elements in-orbit is an important enabler to building large optical systems in space, as the alignment of which is currently one of the major technical challenges.

The following sections discuss these two deployable telescope developments in more details.
6.2 Deployable SAR (CarbSAR)

SSTL are developing a small “Carbonite-type” micro-spacecraft with a novel deployable SAR antenna. This “CarbSAR” spacecraft is aimed for a demonstration mission launch by end 2019. It will be able to fit into a small secondary launch volume and will have the following specification: <1m GSD, X-band, 3% duty cycle, 5x5km swath, FMC mode of operation fixed beam.

6.3 Deployable Optical Telescopes

SSTL, alongside SSC and the Dynamic Optics and Photonics Group at the University of Oxford are developing a novel optical telescope with a deployable secondary mirror for a spacecraft (see Figure 6-2) which addresses the market needs for a <1m GSD imager in a small launch volume [28].

This system will allow many identical satellites to be launched into a constellation from a single launch vehicle, providing a low-cost solution to rapid-revisit high resolution imaging requirements. Alternatively, two or three satellites could be launched in a dedicated small satellite launch vehicle, where previously only one would have fit.

SSTL has already demonstrated low-cost 1m GSD imagery from the Carbonite-2 platform, but the deployable telescope solution provides the opportunity to build on this capability by significantly improving revisit time, without the typical increase in cost.

The developments are focused on a telescopic deployable structure (developed by SSC) and a fine alignment system to align the Cassegrain-type telescope in-orbit. A three-concentric barrel deployable structure and mechanisms was selected following a requirements analysis and trade-off study which led to this design.

The dynamic nature of this system exacerbates traditional optical challenges such as alignment and stray light control; solutions to these are being developed and all contribute to a growing experience in deployable optical instruments.

Figure 6-2: Demonstrator Spacecraft Concept with the Deployable Optical telescope
7. Rendezvous & Docking Developments

7.1 Introduction

SSTL have also been involved in or leading the following studies which have involved directly developing particular expertise in RDV&D at SSTL.

7.2 Initial ESA Studies

SSTL’s first foray into studies on RDV&D was to lead the ESA Service Oriented Active Debris Removal (SOADR) mission study [29] and then participate in the ESA e.Deorbit Mission Phase A study [30].

7.2.1 ESA SOADR Study

The SOADR Study involved the following three areas:

- Address the technical feasibility of an Active Debris Removal (ADR) mission, targeting a ‘heavy’ (>4000kg) object in Sun Synchronous Orbit (SSO).
- Define a business model for the implementation of the mission defined as the output of objective 1.
- Define a business plan for future ADR missions, and to define the technology roadmaps needed to achieve sustainable ADR activities.

In order to provide a realistic assessment of the business opportunities, a technical feasibility assessment (inc. a development plan and cost estimate) was performed in order to generate a realistic initial baseline. This performed on removing Envisat from orbit, using an SSTL Chaser spacecraft concept (see Figure 7-1). This included investigating relevant technologies for proximity operations relevant to in-orbit assembly including possible capture systems, a GNC sensor suite of wide and narrow angle cameras (flight proven) and a LIDAR (under development) for relative guidance and navigation, and a GNC system including the necessary software and processing algorithms and development of mission simulators and hardware in the loop.

7.2.2 ESA e.Deorbit Mission Phase A study

The ESA e.Deorbit mission objective is to “Remove a single large ESA-owned Space Debris from the LEO protected zone” with emphasis on the Envisat spacecraft. The mission consists of a satellite (chaser) that is launched by a small or medium launcher, performs a rendezvous with the ESA-owned debris (target), captures and removes the target from the LEO protected zone. An overall driver for all e.Deorbit mission options is to minimise the mission cost.

SSTL played an integral role in the e.Deorbit mission Phase A study, and led one of the three Chaser design case options (see Figure 7-2 and Figure 7-3). This option was where the Chaser should safely capture and stabilise Envisat utilising a robotic manipulator arm as part of a re-orbit mission concept which would ensure the Envisat perigee is >2000km altitude rather than an atmospheric re-entry mission.

Figure 7-2: Physical configuration of the SSTL Chaser in the ESA e.Deorbit Mission Phase A study

The Chaser also required a propulsion system with adequate thrust and rotation/translation capacity to perform the rendezvous, capture and stabilisation of Envisat. In addition a navigation payload capable of guiding the Chaser to correct relative position wrt Envisat was required. The Chaser was also required to ensure there is no re-contact between itself and Envisat after separating from Envisat (i.e. no collision risk).

Figure 7-3: SSTL’s Chaser with manipulator arm deployed and locked onto Envisat adapter ring
7.3 Internal R&D studies into building large telescopes in orbit using small satellites

More recently, SSTL carried out an internally funded study into the broad implications of building large telescopes in orbit using small satellites, in particular for persistent surveillance from GEO. This also included roadmapping activities, to identify the numerous key underpinning systems, capabilities and technologies to be developed. (see Table 7-1).

<table>
<thead>
<tr>
<th>Technology Groups</th>
<th>Some of the Key Technology Focus Areas Needed in this Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission Architecture Trades</td>
<td>Mission Architecture Trades</td>
</tr>
<tr>
<td>System Implications of Assembly and CONOPS</td>
<td>System Implications of Assembly and CONOPS</td>
</tr>
<tr>
<td>Detailed Mission Analysis for Formation Flying and Assembly</td>
<td>Detailed Mission Analysis for Formation Flying and Assembly</td>
</tr>
<tr>
<td>System Implications of Fractionated Spacecraft</td>
<td>System Implications of Fractionated Spacecraft</td>
</tr>
<tr>
<td>DSN for On-Orbit Assembly and Formation Flying</td>
<td>DSN for On-Orbit Assembly and Formation Flying</td>
</tr>
<tr>
<td>Design for servicing and repair</td>
<td>Design for servicing and repair</td>
</tr>
<tr>
<td>Launcher accommodation and multi-dispensers</td>
<td>Launcher accommodation and multi-dispensers</td>
</tr>
<tr>
<td>Docking and Locking Mechanisms</td>
<td>Docking and Locking Mechanisms</td>
</tr>
<tr>
<td>Robotic manipulators and end effectors</td>
<td>Robotic manipulators and end effectors</td>
</tr>
<tr>
<td>Mechanical design of mirror segments (structural and thermal)</td>
<td>Mechanical design of mirror segments (structural and thermal)</td>
</tr>
<tr>
<td>Thermal Control of Segmented Mirrors</td>
<td>Thermal Control of Segmented Mirrors</td>
</tr>
<tr>
<td>Multi-function Structures</td>
<td>Multi-function Structures</td>
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<tr>
<td>Additive Layer Manufacturing</td>
<td>Additive Layer Manufacturing</td>
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<tr>
<td>Large Sun-Shields</td>
<td>Large Sun-Shields</td>
</tr>
<tr>
<td>Deployable Booms and Truss Elements</td>
<td>Deployable Booms and Truss Elements</td>
</tr>
<tr>
<td>Relative Proximity Formation Flying</td>
<td>Relative Proximity Formation Flying</td>
</tr>
<tr>
<td>GNC On-Board Software</td>
<td>GNC On-Board Software</td>
</tr>
<tr>
<td>Optical/IR Cameras for Navigation</td>
<td>Optical/IR Cameras for Navigation</td>
</tr>
<tr>
<td>S DOP Propulsion Architectures</td>
<td>S DOP Propulsion Architectures</td>
</tr>
<tr>
<td>Precision control electric thrusters for fine pointing</td>
<td>Precision control electric thrusters for fine pointing</td>
</tr>
<tr>
<td>System integration of GNC (relative nav) with AOCS (absolute nav)</td>
<td>System integration of GNC (relative nav) with AOCS (absolute nav)</td>
</tr>
<tr>
<td>Refuelling capability</td>
<td>Refuelling capability</td>
</tr>
<tr>
<td>Low Range Proximity Inter-Satellite Communications</td>
<td>Low Range Proximity Inter-Satellite Communications</td>
</tr>
<tr>
<td>Local area wireless mesh network</td>
<td>Local area wireless mesh network</td>
</tr>
<tr>
<td>GNC Processing</td>
<td>GNC Processing</td>
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<tr>
<td>Safety/FIR Process</td>
<td>Safety/FIR Process</td>
</tr>
<tr>
<td>Data handling for Tera-bit class focal plane</td>
<td>Data handling for Tera-bit class focal plane</td>
</tr>
<tr>
<td>Autonomy in on-orbit operations</td>
<td>Autonomy in on-orbit operations</td>
</tr>
<tr>
<td>Decision making software (rationality)</td>
<td>Decision making software (rationality)</td>
</tr>
<tr>
<td>Fractionated Power System for multiple system elements</td>
<td>Fractionated Power System for multiple system elements</td>
</tr>
<tr>
<td>Inter-Satellite Link (long range) for TT&amp;C, safety monitoring</td>
<td>Inter-Satellite Link (long range) for TT&amp;C, safety monitoring</td>
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<tr>
<td>Segmental mirrors design</td>
<td>Segmental mirrors design</td>
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<tr>
<td>Deformable mirrors and mirror actuators</td>
<td>Deformable mirrors and mirror actuators</td>
</tr>
<tr>
<td>Metrology and wavefront sensing</td>
<td>Metrology and wavefront sensing</td>
</tr>
<tr>
<td>Adaptive optics and focal plane control electronics</td>
<td>Adaptive optics and focal plane control electronics</td>
</tr>
<tr>
<td>Lens class lens assemblies</td>
<td>Lens class lens assemblies</td>
</tr>
<tr>
<td>Rad-Hard Large CMOS-Focal Plane Arrays</td>
<td>Rad-Hard Large CMOS-Focal Plane Arrays</td>
</tr>
<tr>
<td>Supervised autonomy</td>
<td>Supervised autonomy</td>
</tr>
<tr>
<td>Tele-operation and tele-presence</td>
<td>Tele-operation and tele-presence</td>
</tr>
<tr>
<td>Image Processing for Fractionated or Sparse Mirror Imagery</td>
<td>Image Processing for Fractionated or Sparse Mirror Imagery</td>
</tr>
<tr>
<td>Mission Operations with inter-satellite link tasking</td>
<td>Mission Operations with inter-satellite link tasking</td>
</tr>
<tr>
<td>Test Bed and Simulators (Hardware in the Loop)</td>
<td>Test Bed and Simulators (Hardware in the Loop)</td>
</tr>
<tr>
<td>Specialised E&amp;E and M&amp;E for docking and assembly ground verification</td>
<td>Specialised E&amp;E and M&amp;E for docking and assembly ground verification</td>
</tr>
<tr>
<td>Design for Manufacture throughout the system</td>
<td>Design for Manufacture throughout the system</td>
</tr>
<tr>
<td>Supply chain management</td>
<td>Supply chain management</td>
</tr>
<tr>
<td>Ground manufacturing and testing facilities</td>
<td>Ground manufacturing and testing facilities</td>
</tr>
<tr>
<td>Engagement with licensing authorities understand risk appetite</td>
<td>Engagement with licensing authorities understand risk appetite</td>
</tr>
<tr>
<td>Debris constraints</td>
<td>Debris constraints</td>
</tr>
<tr>
<td>Understand mission liability and risk profile</td>
<td>Understand mission liability and risk profile</td>
</tr>
<tr>
<td>Financing and long-term investment</td>
<td>Financing and long-term investment</td>
</tr>
</tbody>
</table>

Table 7-1: Key areas needed for implementation of large scale on-orbit assembly

This resulted in a landmark SSTL/SSC paper for the IAC in 2016 [14]. The paper described some of the different aspects of the on-orbit assembly and operation of a very large telescope, assembled on-orbit from a number of discrete separate elements. This was a very early phase assessment, based on projecting what is known now into the future, in order to understand the implications when fractionated systems are scaled-up to large sizes. The reference application in the paper was on an astronomical telescope; however it was effectively a reversed EO telescope, which had been studied for persistent surveillance from GEO.

The notional concept (see Figure 7-4) was a 25m diameter sparse aperture (annular ring) telescope, composed of 36 discrete articulated segmented telescopes of 1.8m diameter. The total focal length was 185m, giving a total field of view 1300 arc sec. The system was envisaged to be formed by individual free-flying mirror segments which dock together to form the primary and secondary mirrors, which are then placed onto a deployable boom and truss structure from central ‘Hub-Sats’. The total mass in orbit was found to be minimised by keeping the individual mirror segment diameter low (~0.1m), however this results in ~14,000 mirror segments being required. Even with this approach the minimum mass in orbit is >100 tonnes.

![Figure 7-4: Conceptual 25m primary diameter modular GOAT telescope [14]](image)

A preliminary investigation into the cost drivers showed that the final system cost will be heavily influenced by the ‘logistics’ of the assembly process (due to the large number of system elements) in particular the number and type of launchers used to put this mass into orbit. Furthermore, certain technologies (such as robotic manipulators) could be a major cost contributors.
7.4 **UKSA NSTP2 study on GNC for future low-cost RDV&D missions**

Building on from the knowhow developed during the SSTL’s participation in the ESA SOADR and e.Deorbit studies, and then the 2016 IAC paper, SSTL recently successfully completed a UK National Space Technology Programme (NSTP-2) study in collaboration with SSC, to develop GNC and sensor architectures for future low cost rendezvous and docking missions (including in-orbit assembly), whilst still being safety compliant. This was intended to provide a natural follow-on to the AAReST mission, using microsatellites rather than cubesats.

A separate dedicated paper [31] (written shortly before the study was complete) provides a much more comprehensive description of the study. This paper provides a shorter overview of the study including the results and conclusions of the study.

The first phase of the study involved the definition of a preliminary reference mission and requirements, a review of regulatory aspects, and a trade-off of sensors and GNC architectures. In parallel a thorough review of regulatory aspects was carried out (particularly as the assumption was that the design would need to be UK-licensing compliant), and it was clear that mission safety and robustness were major drivers of the spacecraft design. For example the safety aspects drive the need for reliable/failure tolerant spacecraft as well as the critical rendezvous approach phase being performed under permanent ground control. Two “co-operative” in-orbit assembly reference missions were defined as part of the study (Figure 7-6), rather than one, in a logical sequential two-step approach:

- A longer term Earth Observation (EO) telescope demonstrator in LEO” using 8 modular microsatellites. This defined the longer term direction of the application and developments.
- A shorter term lower complexity but safety compliant two-spacecraft rendezvous and docking precursor mission demonstrator using microsatellites (a Chaser spacecraft and a Target spacecraft). This was the baseline reference mission and the focus of the study

![Figure 7-6: Baseline Reference mission](image)

The second phase of the study was focused on analysing the following main topics in detail for the baseline reference mission:

- **Mission Analysis**
- **Systems**
- **GNC simulation and modelling**
- **Sensor Breadboarding and Testing**
- **Development planning and Roadmapping for the GNC and Sensors**
- **Update of Mission and GNC Requirements**

In our baseline reference mission, the Chaser was the master spacecraft, and was responsible for carrying the main sensors and performing the rendezvous manoeuvres, including any potential collision avoidance manoeuvres. The Target maintained a stable attitude for the observations and the docking phase.

The baseline rendezvous sensors on the Chaser were: 1) Relative GPS, 2) a small optical camera, and 3) a COTS LIDAR sensor. The Target spacecraft also contributed its GPS measurements across the inter-satellite link and provides visual identifiers (Glyphs and LEDs) for the optical camera on the Chaser.

A fully redundant yet low cost Xenon propulsion system was implemented and capable of 100mN thrust and full 6 DOF control. We also implemented an innovative operations architecture to give 24/7 coverage in critical phases which includes the use of both AddValue’s BGAN system and Polar S-Band downlinks to the KSAT stations at Svalbard and Troll. This avoids needing alignment of long strings of ground stations, which still have limited windows under which ground control is feasible. Finally, small video cameras were included on each spacecraft to provide final approach images (downlinked post docking) for validation and PR purposes.
Although the study was intended to be focused mainly on GNC development aspects (rather than be a full mission-level systems study), a very wide range of systems tasks related to the GNC aspects were investigated and achieved to develop a feasible mission scenario/CONOPS and show feasibility. These included processing architectures, relative GPS/ISL development, propulsion architectures, collision avoidance and mission safety/robustness, communications and high level spacecraft system design. Table 7-2 summarises the preliminary key spacecraft features and parameters for the precursor reference mission design. The overall preliminary mass and worst case power budgets were feasible in line with the assumptions made. Several Chaser and Target “day-in-the-life” scenarios were analysed.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacecraft heritage</td>
<td>Standard SSTL avionics in most areas</td>
</tr>
<tr>
<td></td>
<td>Heritage baseline is the SSTL-42 range with some additional changes</td>
</tr>
<tr>
<td></td>
<td>Structure and payloads are bespoke</td>
</tr>
<tr>
<td>Redundancy/Reliability</td>
<td>Fully Redundant at system level (extra 3rd units in critical areas)</td>
</tr>
<tr>
<td></td>
<td>1 Failure Tolerant to complete the mission</td>
</tr>
<tr>
<td></td>
<td>2 Failure Tolerant to avoid potential rendezvous collisions</td>
</tr>
<tr>
<td>Spacecraft Dimensions</td>
<td>Hexagonal Cylinders:</td>
</tr>
<tr>
<td></td>
<td>Height 1.16m</td>
</tr>
<tr>
<td></td>
<td>Diameter: 0.6m (diameter across flats)</td>
</tr>
<tr>
<td>Max Spacecraft Mass</td>
<td>Dry Mass: 134.9kg (inc. system margin)</td>
</tr>
<tr>
<td></td>
<td>Launch Mass: 146.9kg (inc. 12kg propellant if fully loaded, providing substantial margin)</td>
</tr>
<tr>
<td></td>
<td>c.f. 150kg assumed for mission analysis and design estimates</td>
</tr>
<tr>
<td>Payload</td>
<td>Chaser: Camera, COTS LIDAR, Payload Processors, Video Camera, Docking System</td>
</tr>
<tr>
<td></td>
<td>Target: Glyph/LED panel, Video Camera, Docking System</td>
</tr>
<tr>
<td>Propulsion</td>
<td>Xenon Cold Gas/Resistojet System providing redundant 6 DOF control, and 100mN thrust.</td>
</tr>
<tr>
<td></td>
<td>1sp: 48s (Warm Gas), 30s (Cold Gas)</td>
</tr>
<tr>
<td>AOCs Actuators</td>
<td>Magnetorquers and Thrusters</td>
</tr>
<tr>
<td></td>
<td>Reaction Wheels as backup</td>
</tr>
<tr>
<td>AOCs Sensors</td>
<td>Star-trackers, GPS, Magnetometers, Sun-Sensors, Accelerometers</td>
</tr>
<tr>
<td>Power</td>
<td>Body-Mounted Solar Arrays</td>
</tr>
<tr>
<td></td>
<td>82.8W OAP generated on Chaser, c.f. 79.1W (inc system margin) required</td>
</tr>
<tr>
<td>RF Comms</td>
<td>S-Band TTC to Svalbard and Troll (nominal 10kbps, max 200kbps)</td>
</tr>
<tr>
<td></td>
<td>L-Band TTC using BGAN via I4 (nominal 10kbps, max 250kbps)</td>
</tr>
<tr>
<td></td>
<td>S-Band 2-way Intersatellite Link (ISL), (nominal 10kbps)</td>
</tr>
<tr>
<td>Data Handling</td>
<td>Double Fault Tolerant Core-ISL</td>
</tr>
<tr>
<td>Payload Storage</td>
<td>PIU from RemoveDebris</td>
</tr>
</tbody>
</table>

The Chaser and Target spacecraft configurations are shown in Figure 7-7 with their main external equipments (such as the sensors) which were particularly relevant for the study.

![Figure 7-7: The Chaser and Target spacecraft configurations and main external equipment](image)

All the key tasks and goals of the study were met and, as a result, the following conclusions were made as a result of the study:

- The mission analysis investigated a range of RDV scenarios and has shown that the trajectory of the Chaser spacecraft approach to the target spacecraft can be achieved with a very low ΔV.
- The GNC simulator developed in the study showed excellent positional control and low ΔV use. It is also flexible for use with other types of RDV missions and other sensors/actuators.
- The sensor combination can be used in all lighting conditions (including eclipse).
- The GNC architecture is low-cost but also safety compliant/robust.
- The system design is feasible using microsatellites.
- A Technology Readiness Level (TRL) of ≥4 was achieved for both the sensors and the GNC architecture.

In summary, this study substantially developed SSTL and SSC’s general capability in RDV&D and has provided both parties with the core GNC/sensor capability to be actively involved in future missions in this area, such as demonstration missions in the shorter term and modular telescopes in the longer term.
8. Robotics Developments

8.1 Background

SSC have been carrying out research into space robotics for many years, though it has been mainly the preserve of expensive institutional missions (e.g. planetary rovers). Therefore SSTL’s interest in this field has been very limited - until recently. This is due to the emergence of new commercial low cost missions in the following areas, where Space Robotics may be an enabling technology:

- In-Orbit Assembly (e.g. telescopes/SAR’s)
- In-Orbit Servicing (refuelling, repair/replacement)
- Active Debris Removal (ADR)
- Asteroid mining and (commercial) sample return

As a result, a significant effort this year is being made to bring space robotics in line with our efforts in the other parallel fields of RDV&D and Deployable Structures.

8.2 Robotics Strategy and activities in 2018

In order to develop the space robotics capability at SSTL in 2018 and beyond, we have been pursuing a multi-pronged approach. Firstly, to help SSTL with R&D activities, future proposals and develop future strategy (inc. demo mission definition), a highly experienced SSC space robotics academic and expert, Dr Mini C. Saaj, is now embedded within SSTL as part of a weekly secondment. SSTL also has several active PhD and MSc space robotics projects running under Dr Saaj, and will be co-funding a new PhD to start in October 2018.

Secondly two active R&D projects were initiated at the start of 2018 (with several more planned for 2019) which are strongly related to space robotics:

- On-Orbit Serviceability: A project to review the current knowledge level within SSTL and determining what is required to compete in for on-orbit serviceability with potential to provide the capacity for on-orbit manufacturing
- Developing a robot manipulator arm for a candidate demonstration mission

Finally, we have initiated a robotics study on “in-orbit assembly” which is being funded by our parent company, Airbus DS. This is being carried out by SSC, and steered by SSTL and Airbus DS.

These space robotics activities are described in more detail in the following chapters.

8.3 Secondment of Robotics Academic at SSTL

In order to meet the anticipated future needs for space robotics for applications such as in-orbit assembly, SSTL have recently ramped up its links with SSC in particular with Dr Saaj, who leads the Robotics and Control group at SSC. As part of this increased collaborative push, since January 2018, Dr Saaj has been embedded within SSTL on a long term indefinite secondment for approximately half a day a week. The aim of this secondment is to help SSTL develop its robotics strategy and expertise, including regular working with the engineering team on robotics R&D activities and working towards a potential robotic demonstration mission (including investigating demonstration tasks and deriving mission requirements).

It has or will also involve feeding in inputs from the following ongoing/planned PhD’s and ongoing MSc projects funded by or involving SSTL:

- “A Controlled Floating Space Robot for Capturing a Target In-Orbit”, Algerian KHTT (KnowHow and Technology Transfer) PhD project with SSTL (now in 3rd year) [32]
- “TWINSAT (Small Space Robots for In-orbit Operations)” – PhD with Kick Off in October 2018 and co-funded by SSTL and EPSRC
- Systems Design of a Space Robot for In-Orbit Operation (MSc project)
- Control Design System for a Robotic Spacecraft (MSc project)

The results of these activities will be covered in separate dedicated papers later this year.

8.4 On-Orbit Serviceability R&D Project

This year SSTL is carrying out an internal R&D study to understand the market and business case for On-Orbit Servicing (OOS) and the application of the case to SSTL. The term OOS here covers various activities including mission extension/orbit transfer, repair and refuelling of both cooperative and uncooperative spacecraft whilst the spacecraft is on orbit. Several of these applications overlap with in-orbit assembly, especially in the case of mission extension and orbit transfer (which is virtually equivalent to a modular spacecraft which could be composed of a propulsion element and a platform element). The overall outcome of the study will be used as an advisory to how SSTL may, or may not, be able to enter into the emerging OOS market and will offer recommendations or direction for the company.
8.5 Robotic Manipulator Arm R&D Project

Earlier this year, SSTL kicked off an internal R&D project towards developing a Robotic Manipulator Arm, in collaboration with SSC. This is also to help make an informed assessment of whether we should ultimately “make” or “buy-in” such technology. The first part of this work was to identify potential business cases for such an arm. Two main business cases for the Robotic Manipulator Arm have been identified:

1. In-Orbit Assembly (IOA)
2. Active Debris Removal (ADR)

The strategy has been to firstly define the reference missions (not just a pure demonstration mission) based on these business cases, which would be the first envisaged real mission applications using the robotic arm following a demonstration mission. Following this, a simple precursor mission/spacecraft (i.e. a micro or nanosatellite) has been defined to demonstrate and verify a robotic arm functionality which could scale accordingly to be in line with the reference mission(s).

An SSTL-SSC workshop was also held to define potential demonstrations that could be carried out as part of a preliminary low cost robotic demonstration mission. The consensus was that the most sensible demonstration was to put a robotic arm through a series of pre-defined movements and rates, rather than try to do anything else too complex such as moving mirror segments (with the exception of a connection verification and perhaps the demonstration of pulling levers or pressing buttons). A camera and sensors on the robot arm/hand and on the base spacecraft would be implemented.

For each business case, SSTL and SSC have gathered requirements for a reference mission and the preceding demonstration mission. The requirements for the arm come from the demonstration mission, with the aim to verify robotic arm functionality. The driving requirements are:

- **DOF:** Initially 4, then 5-6 in longer term
- **Mass:** < 5kg
- **Reach:** ~0.5-1m (TBC)
- **Accuracy:** <2mm (TBC) at Effector Tip

![Figure 8-2: SSTL’s preliminary conceptual Robotic Manipulator Arm](image)

The next part of this work to be completed this year consists of developing an EM/Breadboard of a low cost stiff joint/harmonic drive with the following scope:

- Investigate options for procuring low cost harmonic drives (COTS or towards COTS end of the COTS-Space certified spectrum).
- Procure a low cost harmonic drive. Design into Low Cost Stiff Joint with housing and bearings, using grease lubrication.
- Design and build a simple test rig for the drive.
- Complete functional and life testing on the drive.

The harmonic drive development can also be used for a range of other applications such as Solar Array Drive Mechanisms (SADMs), hinges and antenna pointing mechanisms (APMs). Next year it is planned to design and build a 4-axis robotic manipulator arm (with no effector) based on the low cost harmonic drive, and perform/complete simple functional testing. In the longer term higher degrees of freedom for the arm and effector will be developed.
8.6 Study on Robotic Autonomous Systems for On Orbit Services

In late 2017, SSTL, SSC and Airbus DS began collaborating on an 18-month R&D project to study the application of Robotics and Autonomous Systems (RAS) for On Orbit Services. The study is part of an approach by Airbus DS to fund universities (such as the University of Surrey’s SSC) to carry out research for specific Airbus DS business units and/or subsidiaries – in this case SSTL. As the end-user, SSTL provides steering and guidance throughout the project concerning a specific application while also offering additional internal “in-kind” R&D funds. In this way, both SSTL and Airbus DS are effectively customers and key stakeholders. In this triangular initiative, the project is taking advantage of SSC’s expertise in spacecraft engineering and RAS to address the main knowledge gaps at SSTL in robotic on-orbit operations, with a particular focus on on-orbit assembly (OOA).

The activities and results within this study will be covered in separate dedicated papers in the near future.

9. Roadmap and Next Steps

SSTL’s long term roadmap features “In-Orbit Assembly” using small satellites as a key cross-sector and multi-mission technique.

The studies carried out so far by SSTL show that capability in many of the required technologies needed already exists in other institutions and entities around the world, and thus this kind of system is therefore one whereby it would be more beneficial to partner with outside organisations than to embark on new developments ‘from scratch’. This would allow the best elements of different partners to be included. This partnering is something that SSTL has been actively seeking to include as part of its long term roadmapping activities in in-orbit assembly, including “make/buy/partner” decisions in the key technology areas.

Over the next few years SSTL will be actively developing both its internal capabilities and external collaborations in order to achieve these goals. A series of R&D and collaborative projects (with external partners such as SSC) are planned and being developed for implementation in 2019 and beyond.

10. Discussion and Conclusions

This paper has provided a brief overview of in-orbit assembly, a glimpse of what the longer term future might hold, and a summary of the current status of such activities at SSTL, which includes providing platforms, demonstration missions, and in-orbit assembly mission and technology development activities. Most of these are also being carried out in collaboration with SSC, though collaborations with other partners will also be required especially with increasing mission complexity.

Our work so far indicates that the most appropriate in-orbit assembly methodologies will depend upon the application. For example, some moderately sized in-orbit assembly concepts (e.g. modular spacecraft of two or more satellites) may not require any robotics or deployable structures for in orbit assembly, and could be optimally assembled purely by RDV&D. Similarly some moderately sized in-orbit assembly concepts may be better achieved by a single robotics spacecraft with or without deployable structures.

For increasingly larger in-orbit assembly applications, RDV&D alone will become mass (and likely cost) inefficient, due to the use of many fully independent spacecraft, and would need to be augmented by robotics and/or deployable structures. Similarly, due to launcher size restrictions, robotics-based approaches would also need to be eventually augmented by RDV&D (for transporting additional spacecraft elements) and also possibly deployable structures.

All of these parallel activities show that assembling large satellites in space using small satellites and low cost philosophies could be feasible. They also show that small satellites can be used as a key resource for demonstrating the underpinning technologies required for in-orbit assembly.

These activities have developed SSTL and SSC’s capability in in-orbit assembly and provide both parties with the core capability to be actively involved in future missions in this area.
References


