Institution: University of Surrey

Unit of Assessment: 12 Engineering

Title of case study: Cleaning-up Space: Advancing active space debris removal and satellite de-orbiting technologies

Period when the underpinning research was undertaken: 2012 - 2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Professor Guglielmo Aglietti	Professor of Space Engineering	31/12/2012 – present
Professor Craig Underwood	Lecturer, Reader and Professor of Spacecraft Engineering	01/01/1986 – 07/10/2019
	Emeritus Professor of Spacecraft Engineering	08/10/2019 – present
Dr Andrew Viquerat	Senior Lecturer	20/08/2012 – present
Dr Jason Forshaw	Research Fellow (II)	21/10/2013 – 24/11/2017

Period when the claimed impact occurred: 2013 - 2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact (indicative maximum 100 words)

Research and innovation from the Surrey Space Centre is driving the development of Active Debris Removal (ADR) solutions necessary to clean-up Space. The InflateSail mission demonstrated for the first time the successful de-orbiting of a satellite using European inflatable and drag-sail technologies leading to the first commercial use of de-orbiting drag-sails. The RemoveDebris mission was the world's first in-orbit demonstration of net capture and harpoon capture technologies, establishing their viability and raising their technology readiness level (TRL). Knowledge gained has informed ongoing industry innovation and directly influenced industry standards and policies. Media coverage has contributed to the international attention on space debris mitigation increasing public awareness of space debris as a global concern and understanding of ADR technologies.

2. Underpinning research (indicative maximum 500 words)

The amount of space debris in orbit is increasing exponentially as satellite technology is increasingly relied upon and mega-constellations are launched. Satellites in Earth's orbit face the constant risk of collision with fragments of debris. It is now routine for spacecraft operators to manoeuvre their missions away from potential collision paths, e.g., the European Space Agency (ESA) reports performing, on average, two collision avoidance manoeuvres per year per mission flown.

The urgent need for space debris mitigation measures has international agreement. The Inter-Agency Space Debris Coordination committee (IADC) published mitigation guidelines (2007) recommending that satellites re-enter Earth's atmosphere within 25 years of mission completion. The United Nations Office for Outer Space Affairs (UNOOSA) published similar space debris mitigation guidelines in 2010. ESA has recently produced a range of CleanSpace roadmaps, two of which focus on (a) space debris mitigation and (b) technologies for space debris remediation.

The Surrey Space Centre (SSC, University of Surrey) – directed by Underwood, then Aglietti – has pioneered innovation in Active Debris Removal (ADR) since the mid-1990s.

2.1 Space Debris Mitigation: De-orbiting Sails

For Low Earth Orbit (LEO) missions (below about 750km altitude) the residual atmosphere encountered in orbit offers a potentially simple and relatively low-cost method of post-mission disposal (PMD) using deployable drag augmentation devices (e.g., drag-sails). A de-orbiting drag-sail significantly reduces the ballistic coefficient of the orbiting object by increasing the cross-sectional area it presents to the free-stream as it moves at hypervelocity along its orbital trajectory, with the result of dramatically increasing the rate at which the spacecraft loses altitude and re-enters Earth's atmosphere.

SSC has been very active over the past decade in developing the technologies needed for enhanced-drag ADR, and through the InflateSail (QB50-UK06) CubeSat mission **[R1]**, has demonstrated the first successful disposal of a European satellite using this technique.

The InflateSail CubeSat, designed and built at SSC for Von Karman Institute, Belgium was an in-orbit technology demonstrator for the EU Q5050 programme (with InflateSail's ADR payload developed through the DEPLOYTECH project) **[R1]**. The 3.2kg CubeSat was equipped with a 1m long inflatable mast and a $10m^2$ deployable drag-sail. Launched on 23 June 2017, this in-orbit demonstrator automatically activated its payload, inflating its metre-long metal-polymer laminate tubular mast, and then activated a stepper motor to extend four lightweight bi-stable rigid composite booms from the end of the mast to draw out the 3.1m x 3.1m square, 12µm thick polyethylene naphthalate drag-sail (see Figure 1a). The sail deployment mechanism was derived from earlier work at SSC (including **[R2]** and **[R3]**). The mast/sail ADR system proved itself to be effective, and InflateSail dropped from 505km to re-entry (250km) in just less than 72 days.

2.2 Technologies for Active Space Debris Remediation: the RemoveDebris Mission

The RemoveDebris mission **[R4, R5, R6]** (project managed by SSC) was a "first in space" demonstration of low-cost ADR technologies, including the use of a net (Airbus DS Germany), a harpoon (Airbus DS UK) and vision-based navigation (VBN) (CSEM, Switzerland / INRIA / Airbus DS France). This mission was based around a 100kg microsatellite platform (provided by SSTL) that ejected a CubeSat nanosatellite as an 'artificial debris' target primarily based on the QB50 avionics **[R2]** developed and provided by SSC. The microsatellite platform also hosted a de-orbiting drag-sail (developed and provided by SSC, see 2.1) for orbital lifetime reduction. The platform was released in-orbit by the International Space Station robotic arm on 4 April 2018.

Three primary experiments were performed sequentially during the 6-month operational mission **[**See **R5, R6]**: (i) *Net Demonstration*: The net succeeded in capturing the target (CubeSat DS-1), establishing this technology as a candidate for large space debris capture (see Figure 1b); (ii) *Harpoon Target Assembly Demonstration*: The harpoon fired as planned and successfully 'captured' the deployable target, achieving a firing speed of 18 m/s (See Figure 1c). This technology was also proven as viable for large space debris capture; and (iii) *Vision-based Navigation (VBN) Demonstration*: This demonstration assessed sensor robustness (camera and LiDAR) using actual flight data (of CubeSat DS-2) in real conditions and assessed algorithm performance, and in doing so, raised the TRL of this technology from 2 to 7.

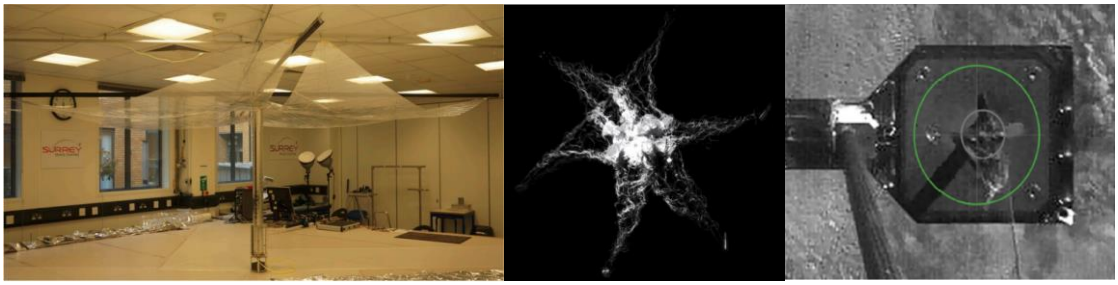

Figure 1 *(a) InflateSail inflatable mast and drag sail deployment test; (b) RemoveDebris demonstration: Net opening pulled by the 6 throw masses; (c) RemoveDebris demonstration: Harpoon imbedded in the target.*

3. References to the research (indicative maximum of six references)

[R1] Underwood C, Viquerat A, Aglietti G et al (2019) InflateSail de-orbit flight demonstration results and follow-on drag-sail applications. *Acta Astronautica* Volume 162, Pages 344-358. DOI: 10.1016/j.actaastro.2019.05.054

[R2] Fernandez JM, Visagie L, Schenk M, Stohlman OR**, Aglietti GS**, Lappas VJ, Erb S (2014) Design and development of a gossamer sail system for deorbiting in low earth orbit. *Acta Astronautica* Volume 103, Pages 204–225. DOI: 10.1016/j.actaastro.2014.06.018

[R3] A. Hoskin, **A. Viquerat**, **G. S. Aglietti** (2017) Tip force during blossoming of coiled deployable booms. *International Journal of Solids and Structures*, Volumes 118–119. DOI: 10.1016/j.ijsolstr.2017.04.023

[R4] Forshaw, J.L., Aglietti, G.S., Navarathinam, N., Kadhem, H., Salmon, T., Pisseloup, A., Joffre, E., Chabot, T., Retat, I., Axthelm, R. and Barraclough, S. (2016) RemoveDEBRIS: An in-orbit active debris removal demonstration mission. *Acta Astronautica*, *127*, pp.448-463. DOI: 10.1016/j.actaastro.2016.06.018

[R5] Forshaw, J.L., Aglietti, G.S., Fellowes, S., Salmon, T., Retat, I., Hall, A., Chabot, T., Pisseloup, A., Tye, D., Bernal, C. and Chaumette, F. (2020) The active space debris removal mission RemoveDebris. Part 1: from concept to launch. *Acta Astronautica*, *168*, pp.293-309. DOI: 10.1016/j.actaastro.2019.09.002

[R6] Aglietti, G.S., Taylor, B., Fellowes, S., Salmon, T., Retat, I., Hall, A., Chabot, T., Pisseloup, A., Cox, C., Mafficini, A. and Vinkoff, N. (2020) The active space debris removal mission RemoveDebris. Part 2: in orbit operations. *Acta Astronautica*, *168*, pp.310-322. DOI: 10.1016/j.actaastro.2019.09.001

Funding:

- Underwood, C. (P.I). DEPLOYTECH "Large Deployable Technologies for Space." European Commission SP7 – SPACE Grant No: 284474 (1 January 2012 – 31 December 2014). Funding awarded to Surrey: €585,120.56.
- Underwood, C. (P.I). QB50 "An international network of 50 CubeSats for multi-point, in-situ measurements in the lower thermosphere and re-entry research." European Commission FP7-SPACE Grant No: 284427 (1 November 2011 – 31 December 2017). Funding awarded to SSC: €600,000.
- Agiletti, G.S. (P.I). RemoveDebris "A Low Cost Active Debris Removal Demonstration Mission." European Commission FP7-SPACE Grant No: 607099 (1 October 2013 – 31 March 2019). Funding awarded to SSC: €2,662,767.20.

4. Details of the impact (indicative maximum 750 words)

Commercial adoption of technology

Following the success of the InflateSail mission and lessons learnt from the RemoveDebris mission, the first commercial use of de-orbiting drag-sails was in *Spaceflight*'s SSO-A ride-share mission (launched 3 December 2018). This mission launched 64 spacecraft (from 34 different organisations in 17 countries) from two large deployment platforms (Upper and Lower Free Flyers). In a commercial sale worth £185,000, SSC provided *Spaceflight* with two custom de-orbiting sail systems **[S1]** - based on that used in the InflateSail mission **[R1]** and previous SSC research **[R2, R3]**. These sail systems were fitted to the two Free Flyer platforms to facilitate responsible PMD.

Mission Director at Spaceflight said: "*The de-orbit sails provided [by SSC] helped us responsibly de-orbit our spacecraft deployers after completing the record-setting SSO-A mission. Spaceflight is committed to being a responsible steward of the space environment and Surrey Space Centre is a key partner in helping us put our words into action*." **[S2]**

Data from SSC show that both Free Flyers are de-orbiting on schedule. The Lower platform should de-orbit within ~5 years, and the Upper platform in less than 14 years, far less than the 25-years requirement. Importantly, the use of de-orbiting drag-sails in the SSO-A mission demonstrates the potential of this technology to operators and removed a total of 1.2 tonnes of space debris in the process **[S2]**.

Advancing innovation in Active Debris Removal

Operators require access to standard cost-effective PMD technologies to achieve compliance with mitigation guidelines. Research by the SSC has been crucial in driving technological and platform development forward towards the full commercialisation of practical, cost-effective and reliable ADR systems for LEO spacecraft.

The InflateSail mission demonstrated for the first time the de-orbiting of a spacecraft using European inflatable and drag-sail technologies and the first successful disposal of a European satellite using this technique **[R1, S3].**

The ultimate purpose of the RemoveDebris mission demonstrations was to pave the way for industrial/commercial development and exploitation. The RemoveDebris mission was the world's first ADR mission to successfully demonstrate in-orbit, cost-effective technologies, including the first demonstrations of net capture and harpoon capture, alongside elements of the whole sequence of operations, such as the vision-based navigation, essential to mission success. Importantly, the overall success of these demonstrations established these technologies as viable candidates for large space debris capture, and significantly increased this technology's maturity **[R6, S3, S4]**. Furthermore, the use of CubeSats as artificial debris targets represents a novel methodology for in-orbit testing that avoids any legal issues associated with targeting, capturing or de-orbiting debris that is legally owned by other entities.

Knowledge gained from SSC research and innovation has informed ongoing industry innovation. For example, {*Text removed for publication*}.

Influencing the Space Industry

SSC have a significant presence at all the world's major space debris conferences, and the team was involved with the definition of new standards and defining policy for the future. Aglietti was invited to join the UK delegation to the United Nations Committee on the Peaceful Uses of Outer Space at the UN General Assembly in Vienna (Feb 2019) **[S8]** and to give an invited talk "On orbit operations: friend or foe" at the United Nations Institute for Disarmament Research, 2019 Space Security Conference, Geneva, 28 and 29 May 2019 **[S9]**. Aglietti's team also contributed to the Inter-Agency Space Debris Coordination Committee and the Space Mission Planning Advisory Group, The Secure World Foundation, UK Space Agency, European Space Agency and CNES (French space agency) working groups and workshops.

RemoveDebris has received significant industry recognition in being awarded the 2019 Sir Arthur C Clarke Award (Space Achievement – Industry/Project Team) and the Aviation Week Network 63rd Annual Laureate Award 2020 (Technology & Innovation).

Public Understanding of Space Debris Mitigation Technologies

The RemoveDebris mission received global media coverage, leading to increased public awareness of space debris as a global concern, which increasingly threatens our continued use of near-Earth space, and the development of mitigation technologies.

Key parts of the RemoveDebris mission were televised by national and international news organisations with a combined total of 3.5 billion viewers. The media campaign has reached a diverse range of audiences with significant items on international news (Sky News, CNN, BBC) children's TV (e.g., BBC *Newsround*) and topical shows such as the *Daily Show* (USA) and the *One Show* (BBC1, UK). The University of Surrey's YouTube channel received circa 500,000 views of RemoveDebris content, and the mission was described in numerous press articles (*Wall Street*

Journal, The Times, Financial Times) **[S10]**. Several international documentaries and TV shows also featured the RemoveDebris mission (including Iran, Sweden, Germany, China).

The RemoveDebris mission part-funded the Royal Society's "Cleaning up space junk" exhibit at the Royal Society Summer Science Exhibition (2016). This is the Royal Society's most prestigious public engagement event evolved from "Conversatziones" that has been held annually since 1778 to showcase global state-of-the-art science **[S11]**.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[S1] Taylor, B., Fellows, S., Dyer, B., Viquerat, A. and Aglietti, G.S. (2020). *A modular drag-deorbiting sail for large satellites in low Earth orbit*. In AIAA Scitech 2020 Forum (p.2166). DOI: 10.2514/6.2020-2166

[S2] Spaceflight Industries – SS0-A update http://spaceflight.com/sso-a-mission-update-upper-and-lower-free-flyers-deorbiting-as-planned/

[S3] NASA (2020). State of the Art Report of Small Spacecraft. 14.0 Deorbit Systems. Available from: https://www.nasa.gov/smallsat-institute/sst-soa-2020/passive-deorbit-systems

[S4] *Example of media coverage from RemoveDebris mission highlighting technology firsts*: Parnell, B-A. (2018). RemoveDEBRIS: UK Satellite Is The First To Clean Up Space Junk. *Forbes* [Online]. 19 September 2018, 08:06 EDT. Available from: https://www.forbes.com/sites/bridaineparnell/2018/09/19/removedebris-uk-satellite-is-the-first-to-clean-up-space-junk/?sh=53deb3155940

[S5] Email from {*Text removed for publication*}

[S6] Email from {*Text removed for publication*}

[S7] SSTL and ASTROSCALE team up for Orbital Debris Removal Missions. Available from: https://www.sstl.co.uk/media-hub/latest-news/2017/sstl-and-astroscale-team-up-for-orbital-debris-rem

Pool, R (2021). Space debris: the scrapheap in the sky. *Engineering and Technology (E&T)* [Online]. 17 March 2021. Available from: https://eandt.theiet.org/content/articles/2021/03/space-debris-the-scrapheap-in-the-sky/?utm_source=Adestra&utm_campaign=E%26T%20Digital%20Edition%20-%20April%202021%20%28UK%29&utm_medium=E%26T%20Magazine&utm_content=E%26T%20Digital%20Edition&utm_term=147223

[S8] UK Delegation at United Nations Committee https://www.unoosa.org/res/oosadoc/data/documents/2019/aac_105c_12019inf/aac_105c_12019inf48_0_html/AC105_C1_2019_INF_48EFS.pdf

[S9] Invited Talk at United Nations Institute for Disarmament Research https://unidir.org/publication/unidir-space-security-conference-2019

[S10] Hodges, J., Njolinjo, D., Duke, R. (February 2019). '*RemoveDEBRIS Dissemination Report'*. Created to capture all the dissemination events related to the RemoveDebris mission funded by the European Commission under FP7 grant No: 607099. (pdf). Remove Debris tests were captured by video cameras of the microsatellite platform and can be viewed on the University of Surrey's YouTube Channel i.e., https://www.youtube.com/watch?v=jCxRAa_VE9I

[S11] Royal Society Summer Science Exhibition 2016 https://royalsociety.org/science-events-and-lectures/2016/summer-science-exhibition/exhibits/cleaning-up-space-junk/