Combatting Space Debris with Autonomous Systems

An AIMS CDT Mini-Project Report by
Amanda Matthes

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Abstract

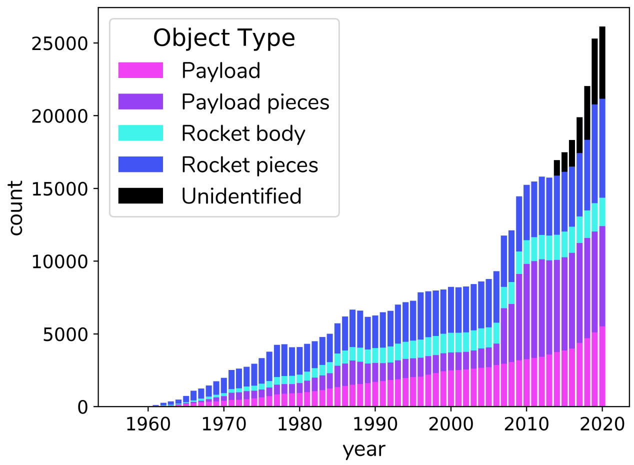

Figure 1: Yearly count of tracked objects in earth's orbit since 1957, broken down by type. Made with data from [1] up to 01 January 2020.

Satellites provide humans across the world with many invaluable services. But as we continue to launch an increasing number of missions, those satellites are more and more likely to be damaged by orbiting objects, mostly space debris. In this report, I will first explain why space debris is a real concern, and then present four key technologies that can help us combat the problem. Those technologies are space surveillance and tracking (SST), collision avoidance, on-orbit servicing and finally, space debris removal. I will show how AIMS expertise will be highly applicable in each case.

Contents

1 Motivation

1.1 Why earth's orbit is valuable

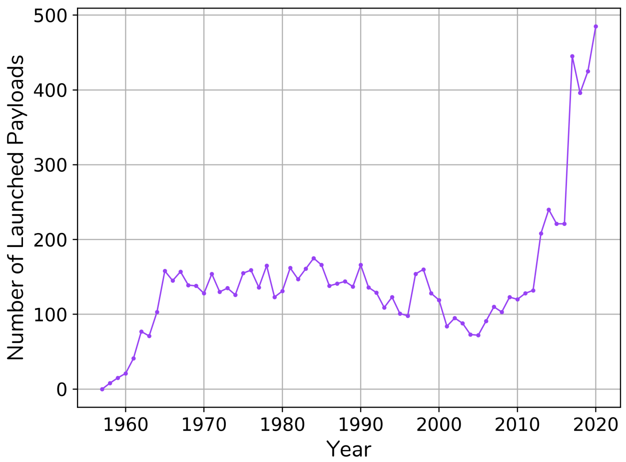

Figure 2: Number of payloads launched every year since the launch of Sputnik 1 in 1957. This graph includes the first 480 Starlink satellites which are a major reason for the recent spike. As of June, this year has already set a new record. Plotted with data from [2] up to 04 June 2020.

Today, we heavily rely on satellites for navigation, communication, weather forecasting, climate and astronomy research, and of course, a permanent human presence in space on the ISS. And the market is not even saturated. Launching into space is still expensive (although less so than in the past [3]), but that has not stopped commercial and government space agencies to drastically exceed historical launch statistics (see figure 2). Recently, launches have been dominated by the introduction of almost 500 Starlink satellites (as of 04 June 2020), with hundreds more planned, to deliver high-speed internet everywhere on the globe [4].

This report examines what humans need to do to continue to have access to existing and future space technologies. But first, we need to understand why change is even necessary.

1.2 Is debris really a threat?

Satellites are fragile and can easily be damaged by asteroids and solar flares. But the risk of such natural impacts is dwarfed by that of artificial space debris [5]. Of the over 9,800 satellites launched since Sputnik, over 5,500 are still in space, but only half of those are still functioning. On top of that, there are over 13,000 pieces of payload and rocket debris (caused by explosions, collisions, anti-satellite weapon tests and degradation) currently being tracked. Additionally, we expect millions of objects that are too small to be tracked (< 10cm) but, given the high relative velocities (≈ 10km/s), could still cause damage to operational satellites [1].

But space is big, so are these really worrisome numbers in this context? To see if the amount of space debris should concern us, we need to look at the flux of debris, rather than its absolute number. That is, how much space debris passes through a chunk of space, or in other words, how likely is an impact on a new mission? NASA provides the software tool ORDEM (Orbital Debris Engineering Model) which estimates the average flux a spacecraft experiences in a given orbit and year, by taking into account not only the distribution of space debris but also its relative velocities [6]. Figure 3 shows the expected cumulative flux in 2020 as a function of debris diameter for three orbits. Firstly, I plotted data for a circular orbit at 865km with zero inclination. This is the height at which China destroyed one of their weather satellites (Fengyun-1C) with an anti-satellite weapon in 2007, introducing over 3,400 tracked pieces of debris (counted with [1]). That region now contains more debris than any other (see figure 4). At this height, ORDEM predicts that over 10 years, a spacecraft with a cross-sectional area of 1m^2 can expect 6000 ± 700 impacts of debris sized 100μm or larger and 7 ± 4 impacts of debris sized 1mm or larger (if the 2020 data is representative of those 10 years). This may sound harmless until we also consider the relative velocities with which these impacts happen. This is shown in figure 5 (for debris larger than 100μm). Most debris impacts occur in the so-called hypervelocity regime, at several km/s. At such high speeds, even millimetre-sized debris can deal damage and produce fragment ejecta as well as some plasma, that can affect electronic components [7].

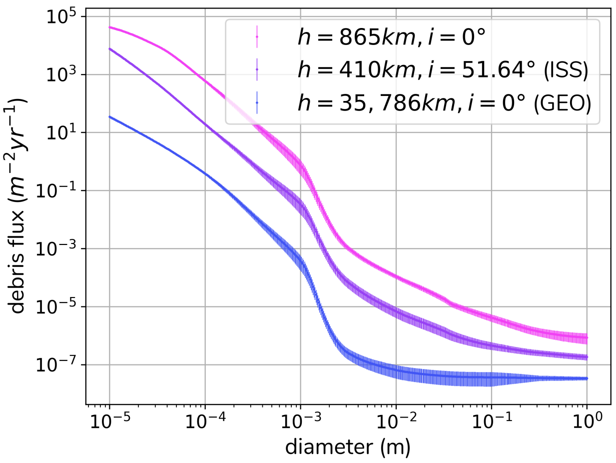

Figure 3: Cumulative debris flux in 2020 at 840km, compared to flux at the ISS orbit and earth's geostationary orbit (GEO), made with data from ORDEM 3.1. Flux is calculated along a spacecraft's orbit and with respect to cross-sectional area.

Figure 6 is a photograph of one of the larger returned pieces of the Hubble Space Telescope after impact craters were cored out for analysis. This was one of the datasets used to validate ORDEM's flux predictions [8]. Figure 7 shows what an impact crater on a solar array looks like. This piece was also retrieved from the Hubble Space Telescope.

Humans on earth are not at risk of being hit by space debris, as most of it does not survive re-entry. Humans in space, on the other hand, are more exposed. The ISS orbits at only around

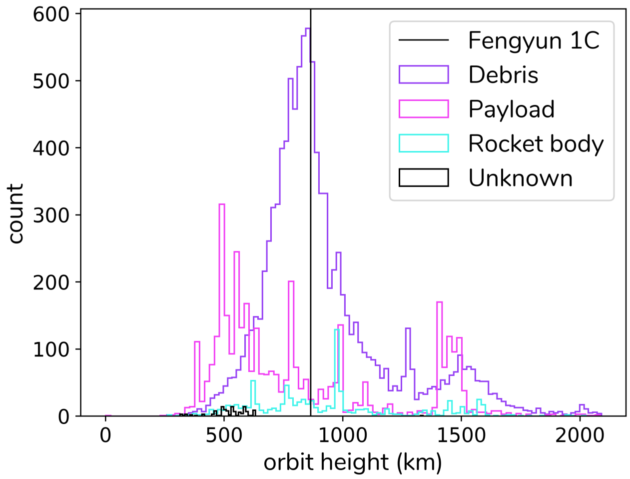

Figure 4: Distribution of objects in low earth orbit (LEO), the most crowded of earth's orbits, as of 31 May 2020. Plotted with data from [2].

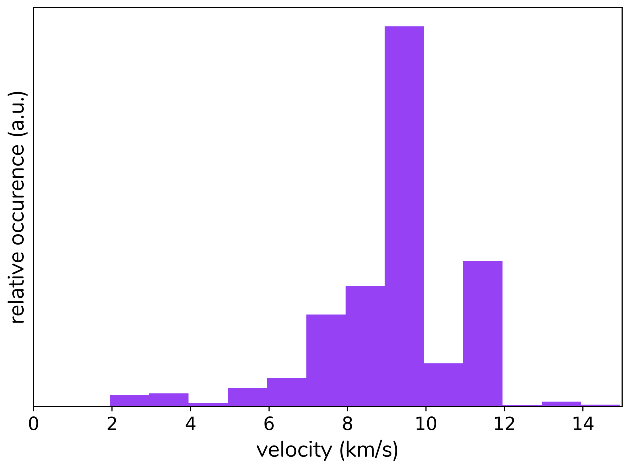

Figure 5: Velocity distribution of debris larger than 100μm that a spacecraft in an uninclined, circular orbit at 865km would experience along its orbit in 2020. The average velocity is 9 ± 2km/s. Made with data from ORDEM 3.1.

410km and figures 3 and 4 show that this orbit is much less busy. However, the ISS is a lot larger than other satellites and provides a bigger cross-section for incoming debris. The station can manoeuvre out of the way of larger ($>$ 10cm) pieces, but smaller ones are harder to track and avoid. They have damaged solar panels, airlock shields, windows and handrails which has caused cuts in EVA gloves during spacewalks [11]. So far, the ISS hasn't expe-

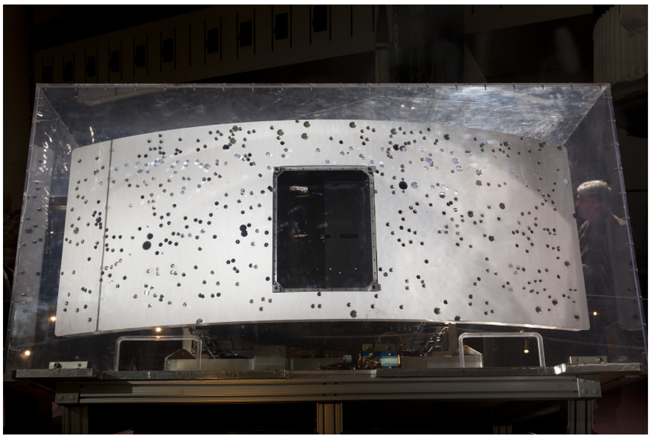

Figure 6: 215cm × 92cm radiator of Hubble's Wide Field Planetary Camera 2 (WFPC2) after impact craters were cored out for analysis. It was returned after 16 years in space. Credit: [9]

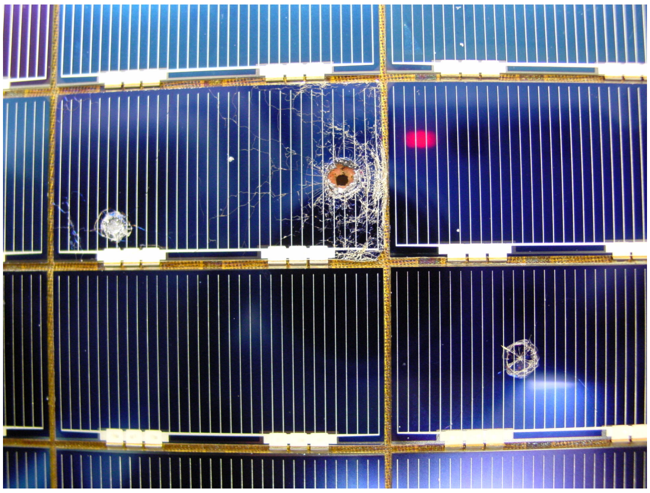

Figure 7: A piece of one of the returned solar arrays from the Hubble Space Telescope. Most impact craters have diameters between micrometres and millimetres. Credit: [10]

rienced any major failures as a result of debris. But as the number of objects in space grows, the damage will pile up and more repairs and shielding will become necessary.

It is now clear that space debris poses a real threat that needs to be confronted. The following sections explore how we can do this without having to restrict satellite launches, at least in the near future. In particular, this report covers finding, tracking, evading, preventing and finally removing debris, with a focus on how autonomous systems can be useful for that.

2 Space surveillance and tracking (SST)

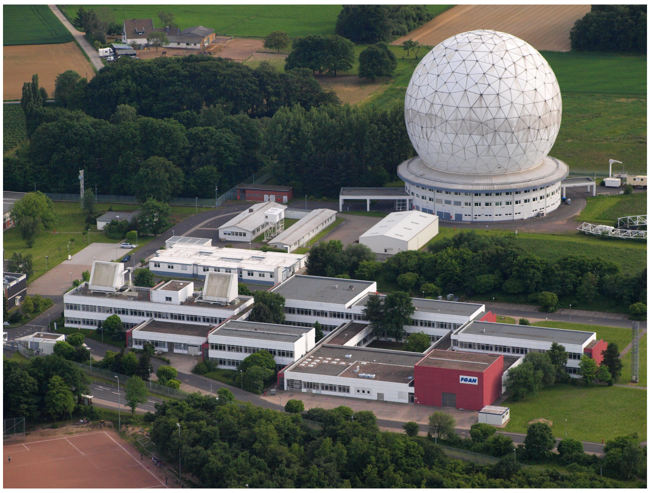

Figure 8: The space observation radar TIRA (Tracking and Imaging Radar) in Germany. It is protected by the world's largest radome [12]. Credit: [13]

A good space surveillance and tracking (SST) system regularly produces a catalogue of objects in near-earth space with their orbital parameters and ideally additional information like mass, size and origin. Accurate SST is necessary to predict collisions and, if possible, take action (see section 3), and to make informed decisions about shielding for future missions.

2.1 Data sources

Space can be surveilled using radar, laser-ranging or optical telescopes, on earth or in space. Figure 8 is a photo of one such radar facility. Ground-based systems are not as restricted by mass or power but have to deal with weather, atmospheric variability and light pollution. Different methods are effective for different debris sizes and orbits. There is no one-size-fits-all system. Moreover, surveilling the entire sky requires multiple systems across the globe. This means that raw surveillance data consists of a mix of images, taken from different locations, with different technologies, and at different times. The next step is to turn this data into a catalogue of objects.

2.2 Data evaluation

The raw images first need to be searched for objects. Then those need to be correlated with known existing objects. A good surveillance system also needs to be able to deal with new objects, as new debris is constantly created.

This problem is ideally suited for machine learning techniques, as the datasets are large and there is lots of old labelled data. And there is plenty of interest for better data exploitation, as demonstrated by the recent call for funding proposals by the UK Space Agency, with grants of up to £250, 000 [14]. Examples of previous work include: using convolutional neural networks for satellite detection [15], using particle filters for state estimation and then managing uncertainty by autonomously scheduling new observations of poorly tracked objects [16], and using ontology-based Bayesian networks to model object behaviour [17].

2.3 Existing space object catalogues and their uses

The 18th Space Control Squadron publishes the US catalogue on space-track.org [2] (excluding classified missions). Many other catalogues can be found online (e.g. [1],[18], [19] and [20]) but they are mostly just annotated copies of the one on space-track.org, except for the Russian Vimpel catalogue [21].

A reliable catalogue can be used to predict collisions and re-entries, and can aid mission designers in picking less crowded orbits and in choosing appropriate shielding. In the future, as collision avoidance becomes more crucial with more satellites, it would be ideal to have several high-quality independent catalogues that can be checked against each other.

3 Collision avoidance

When tracking data reveals that a functioning satellite is about to collide with another object in space, it is often able to manoeuvre out of the way. This not only saves the satellite in question but also avoids the generation of more debris. 19% of the tracked payload related objects in orbit today are pieces of Iridium 33 and Cosmos-2251, the two satellites that collided in 2009 (calculated with [1] on 10 June 2020). Together with preventing the use of anti-satellite weapons, avoiding collisions is the most important way of preventing new space debris.

NASA sends out collision risk alerts to satellite operators whenever they see a risk of collision [22]. The operators then have a few days to manually adjust the orbit. In low earth orbit (LEO, altitudes below 2, 000km), a satellite will have to perform about one to three collision avoidance manoeuvre per year to lower its collision risk by 90% [23].

Scanning through tracking data for close encounters is already being done autonomously to some degree. But most notifications are false alarms and analysts still have to manually decide which alerts need to be taken seriously [23]. Once it is decided that the risk of collision is too high, experts have to decide how to adjust the satellite's orbit. They not only have to avoid the close encounter without creating a new one but also have to preserve precious fuel. With space traffic increasing (see figure 1), this will only become more labour intensive. There is a need and opportunity to automate much of this process.

It has been estimated that debris impact avoidance manoeuvres currently cost global satellite operators €14 million each year [24]. This is not just a problem for the far future.
SpaceX claims that their Starlink satellites are already capable of autonomous collision avoidance manoeuvres, using tracking data from the US Air Force [4] but do not provide any technical details. No-one else is so far implementing anything similar.

4 On-orbit servicing

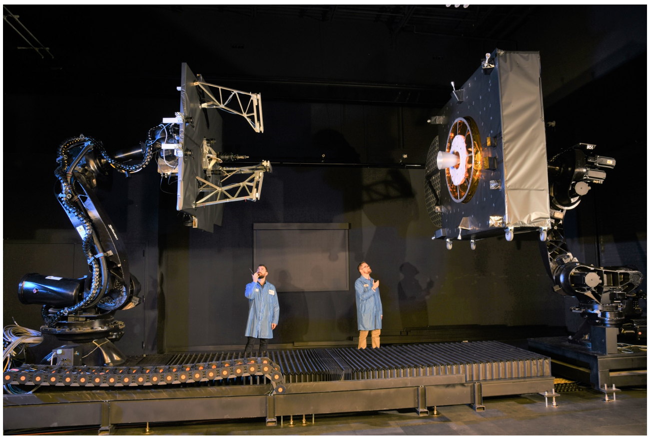

Figure 9: Proximity tests at Northrop Grumman. Credit: [25]

Even without external damage from artificial or natural causes, satellites can experience failures. Sometimes a satellite can still be functional but run out of fuel. With a boost, it could continue its service for many more years. But without it, it has to move to a graveyard orbit (if it can). Maybe a solar array is malfunctioning, and a satellite that is otherwise perfectly functional runs out of power. The goal of on-orbit servicing is to repair existing satellites to avoid having to send a replacement. This reduces the number of dead payloads in orbit that would otherwise provide big targets for collisions.
The most famous servicing missions are the ones to the Hubble Space Telescope. On five occasions, astronauts visited the telescope for repairs, replacements, enhancements and orbit-adjustments [26]. Apart from Hubble, only space stations and few selected satellites have been serviced on orbit [27]. But all of those missions have put human lives at risk. Some companies, like Northrop Grumman [25], Airbus [28] and Astroscale [29] are now interested in using robots to perform simple servicing tasks to provide commercial services to operators with satellites in need.
The MEV-1 (Mission Extension Vehicle) mission by Northrop Grumman first demonstrated that this is possible [25]. MEV-1 was launched in October 2019 and successfully docked with the geostationary communications satellite Intelsat 901 in February 2020. It then used its own thrusters to put the client satellite that had run out of fuel back into orbit, where it will stay for now. Intelsat is paying around $13 million per year for this service [30] which they expect to work in their favour [31]. This means that unlike with some space-debris mitigation measures, there could be a short-term economic incentive to invest in on-orbit servicing. If appropriately designed, servicing a satellite can be cheaper than launching a new system. However, with launch costs dropping, it is possible that servicing missions will, in the future, only be economical for expensive satellites, like the Hubble Space Telescope. Nevertheless, the market is there, albeit very young. On-orbit servicing requires precise robotics for safe docking and repairs. The ISS already has several highly capable robot arms, but this application would be different, in that the base cannot be assumed to be fixed. Movements of the arm will cause the whole system to move. Autonomous servicing vehicles also need to have excellent computer vision to interact with the target.

5 Space debris removal

Even if we stopped all launches today, much of the existing debris, even in low orbits, would not re-enter for decades. Vanguard 1, for example, was launched in 1958 as the fourth satellite ever. It has a perigee altitude of less than 700km but remains in orbit to this day, as the oldest man-made object in space [1]. Not only do existing debris objects endanger satellites, but collisions among them will also continue to produce more and more uncontrolled pieces. This is known as Kessler syndrome (named after Donald Kessler who wrote about the phenomenon) and tells us that intervening in the debris problem earlier will generally be cheaper. Many ideas for debris removal have been suggested but no usable system exists yet.

5.1 Proximity-based proposals

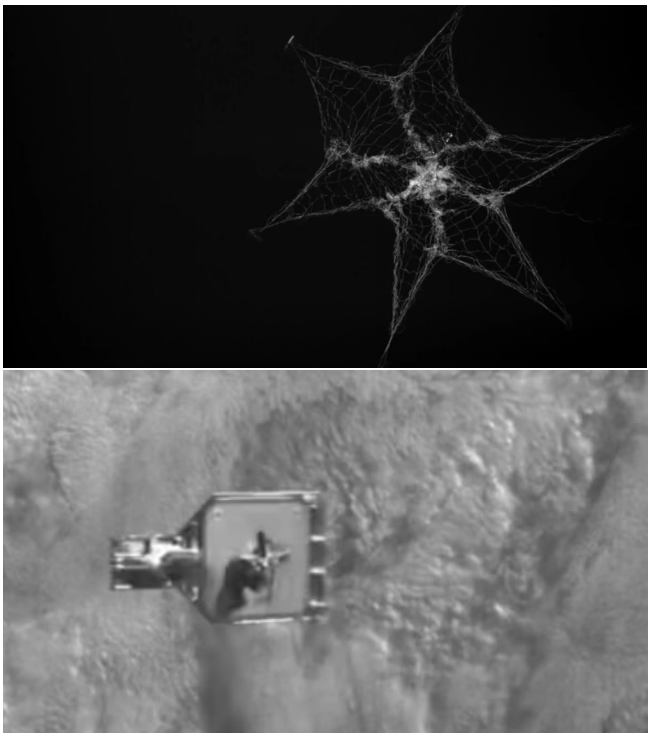

Figure 10: Photos of the RemoveDEBRIS net and harpoon demonstration captured from the mothercraft. The mission used a CubeSat as a target for the net. Credit: [32]

One commonly proposed way is to capture the target satellite with a so-called chaser that can then use its own propulsion system to deorbit the composite. In the general case, the target will not be cooperative and tumbling. Proposed capturing methods include nets, harpoons and robot arms. In 2018, the RemoveDEBRIS mission for the first time demonstrated the use of a net and a harpoon to capture objects in space [32] (see figure 10). The mission also demonstrated camera and LiDAR image processing capabilities, by comparing their tracking and pose estimations to actual flight data. Here, much work is still needed. Performance was sometimes good but not reliably so, especially when dealing with the earth in the background. Dependable computer vision will be critical for a safe rendezvous in space and there is lots of room for future work.

Other suggestions that involve close approaches include: attaching a long electrodynamic tether (EDT) to the target that uses earth's magnetic field to lower its orbit, using an ion-beam to push the target into re-entry, and increasing the targets natural atmospheric drag (using expanding foam or a sail) to speed up orbit decay. EDTs only work for non-tumbling debris in low orbits ($< 1,500$km) and require tethers several kilometres long [33]. Ion-beam shepherds are strong enough to move the largest rockets in orbit and avoid touching the target but still need to be fairly close ($\approx$ 10m to 20m) and require fuel for the beam [34]. Drag methods also only work in low orbits (where atmospheric drag is significant) and can actually increase total collision probability [35, p. 33]. This is because, even though the time spent in orbit is shorter, the target now has a higher cross-section which makes collisions more likely. It is therefore clear that capturing the target and actively dragging it into re-entry will be preferred over these alternative proposals, at least in the general case. But should one of these less conventional methods end up being more desirable for a certain application, they would still require excellent computer vision to work.

All methods discussed so far would only be able to remove one large piece of debris at a time. They could still be helpful since large objects are likely to shed more smaller pieces over time. However, as shown in the introduction, most impacts are caused by small debris pieces, and there are many of those. These methods also require lots of fuel and always risk causing more debris when in close proximity of the potentially out-of-control target.

5.2 Lasers

Lasers are a promising alternative that could deorbit trackable debris of any size, by transferring momentum via pulsed ablation of the surface [36] [37]. They can be used at a distance and avoid risky close encounters that could generate more debris. A removal system would consist of both a laser and a separate sensor for target acquisition. It could be placed on earth or in space [38]. Ground-based systems need to have advanced adaptive optics to correct for atmospheric effects but are much less restricted by size and power. Lasers are now strong enough to move even the largest pieces of debris, but also accurate enough to target debris down to 1cm. Ideally, there would be several lasers at different locations to achieve good coverage of the sky. Such a laser system network could autonomously collect tracking data, select suitable targets by considering the harm a piece of debris poses and the time it would take to deorbit it. It would have to schedule laser targeting times, as targets are only visible during short time windows and many targets will require several passes. The system would also have to ensure that no collisions are caused when lowering an object's orbit, and it would have to deal with some uncertainty in the available data on object orbits. Developing such a laser network system clearly requires experts in all aspects of autonomous intelligent system design.

6 Conclusion

Satellites are currently threatened by increased human space activities that have put large numbers of objects into orbit, most of which are uncontrolled debris. The problem of making space activities sustainable presents many opportunities to apply technological advances in autonomous intelligent systems. In particular, I pointed out the demand for better space surveillance and tracking, the need for autonomous collision avoidance, the brand new market of on-orbit servicing and the uncertain next steps in space debris removal. Some of these fields are more mature than others, but all of them offer lots of room for novel ideas.

APPENDIX

A Responsible research innovation considerations

This appendix explores ethical, legal and societal concerns regarding the technologies discussed above, as part of Responsible Research and Innovation (RRI) discussions.

Collision avoidance and on-orbit servicing benefit all parties involved when they work as intended. Caution must be taken to avoid damaging other satellites and creating more debris in the process. Providers of these services will need appropriate insurance. More interesting are the ethical implications of developing space surveillance and debris removal methods.

A.1 Space surveillance and tracking (SST)

A reliable SST system is an important tool to keep space activities sustainable, but it can have other implications. Government space agencies occasionally launch classified missions for which they do not disclose a satellite's purpose or orbit. Such satellites are mostly used for reconnaissance, signals intelligence and communications [39] and their movement patterns are often indicative of their purpose. This means that space surveillance can potentially reveal sensitive data. Currently, the US is the major source for both SST data and for collision alerts. So even though the public US space object catalogue (which serves as the major SST catalogue source) excludes all classified missions [2], collision alerts will still take classified objects into account. If academia were to start collaborating on a new SST system independent of government agencies, it would have to consider the implications of possibly revealing information about classified satellites. This is already a concern as classified satellites can be spotted by amateur astronomers [40] and close inspection can often reveal a satellite's purpose, but systematic surveillance with full sky coverage would make this a more pressing problem.

A.2 Space debris removal

Any space debris removal system can be misused as an anti-satellite weapon. This can be particularly apparent with long-range solutions, like lasers. Attacking a nation's satellites is an effective way to disrupt internal communications, signals intelligence and reconnaissance capabilities. It is therefore important that this technology is researched and developed publicly and collaboratively if we want to avoid any suspicion of malicious intent or monopoly on potentially powerful weapons.

It is also unclear who should be responsible for space debris removal. It is in everybody's interest, but all existing proposals are expensive. Should there be a tax on launching that is used to fund clean-up efforts? What entity would be responsible for this? Or should everyone be responsible for cleaning up their own satellites by paying commercial contractors? What if there is a collision that causes hundreds of debris pieces? These are all open questions and their answers will heavily depend on which removal methods become reality. A laser system would likely require funding at the government agency level and international collaboration to place sensors and lasers at strategical locations. But for single capture-and-deorbit missions, we could imagine several commercial actors offering such services. It could then become mandatory for new missions to organise their own removal, once necessary. But can operators of past missions be expected to pay for leftover debris? This further poses the question: What counts as space debris? Could operators avoid paying clean-up fees (if those are introduced) by claiming that an old inoperative satellite is still providing some value?

These questions will inform what systems get funded and more importantly used. They make it clear that space debris removal is not just a technological challenge, but also a political and legal one. Experts in those fields have already started examining what existing legislation has to say about these issues and where it lacks [41], but further work is needed and it will require global attention from commercial and government space agencies.

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