Chapter 5
New Technological Approaches to Orbital Debris Remediation

Introduction

Efforts to develop active space debris removal projects currently underway were described earlier in Chapter 2. Virtually all of these projects relied on the current state of space technologies. Many of these currently envisioned projects involve sending up a robotic spacecraft that can attach itself to a selected element of orbital debris such as a defunct spacecraft or upper stage rocket launcher and then deorbiting the debris along with the capturing spacecraft. Today, in some instances both the target and the capturing robotic spacecraft are launched as part of the effort to develop an active deorbiting capability and to avoid concerns related to liability claims. There are clear and apparent problems with this approach in that it is extremely expensive, slow and deliberate, and inefficient by almost any index of effectiveness. This chapter explores a number of technical approaches that have been identified as potentially viable that would ultimately be far more effective, achieve de-orbiting more rapidly and effectively, and thus logically cost far less than the one-by-one active de-orbit missions.

These technological approaches can be divided into a number of different categories as follows: (a) Ground based approaches to active debris removal or collision avoidance; (b) Passive de-orbit systems that can be deployed at end of life; (c) New types of active de-orbiting systems that could be mandated to be included that are separate from the regular positioning and orientation capabilities of spacecraft; (d) Innovative active de-orbiting systems that can assist with the removal of many debris elements in a single mission. These might also use different propulsion systems than conventional chemical rocket thrusters; (e) Improved technical means for locating orbital debris for removal by efficient proximity navigation and mating.

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Key Trade-Off Considerations: Innovative Technology vs. Maturity, Reliability and Precision of De-Orbiting System Design

The conventional approach of one-by-one robotic capture of defunct satellites is one that has been demonstrated on a number of occasions and involves minimal risk of de-orbiting the wrong spacecraft. Ground-based systems might be more cost effective, but there are issues of high power particle beam or laser systems being considered space weapons systems and there are also concerns about the accuracy of their targeting systems and potential error. Many of the newer technological approaches discussed in this chapter are likely to be more cost effective, but these are new and largely unproven capabilities. It could take a number of years for these new methods to reach technological maturity. Such new systems need to be proven to be reliable and indeed able to accurately remove debris from orbit. The most secure way to achieve future debris removal might be to mandate active (or passive) removal systems that are separate and complementary to conventional positioning and orienting thruster systems for station-keeping. Such an approach would entail mandating separate and fail safe de-orbiting capabilities. One particularly challenging issue that will perhaps require the greatest amount of new technical capability is the problem of upper stage rocket launchers that transverse the geosynchronous orbital plane and threaten active or defunct satellites at accelerated relative velocity and dangerous relative angles of incidence.

Review of Alternative Technological Approaches

Ground-Based Systems

Ground-based systems can provide important capabilities in addressing orbital debris issues. The first type of capability involves irradiating a debris object that is threatening a collision with another orbiting element in such a way as to slightly change the debris object to avoid impact. This could be a laser-based tracking system or a particle beam projection system that is continuously focused on debris object prior to an impending collision. At orbital speeds even a change of an orbital period by a tiny fraction of second can be sufficient to avoid a collision. There have been innovative suggestions that the officially registered owner of the debris element could have their own operators control the beam projections to alleviate concerns that these systems would be deployed militarily against their own space assets. Such types of ground systems would not constitute active debris removal but simply debris collision avoidance. These temporary measures to avoid major collisions are important steps to undertake until more permanent solutions can be found and undertaken.

Much high powered particle beam weapons or even very high powered laser systems, however, could, in fact, provide active debris removal. It has been proposed that a beamed or directed energy system could be positioned on the International Space Station and from this location it could systematically remove debris from low earth orbit through the use of such a strategically advantageous location. [Lubin and Hughes 2014]

Directed energy systems might well be developed for a range of other capabilities. The logic of developing a super intense beamed energy system could well be used to change the orbit of a potentially hazardous asteroid so it could be captured by the gravity of the sun or perhaps over time entirely break up and disintegrate into harmless pieces of a potentially hazardous asteroid. Such a beamed energy system or super intense laser beam system might also be used for strategic purposes or even to power a spaceship drive system. [Lubin and Hughes 2014]

These ground based systems are clearly most effective to deploy in the case of low earth orbit spacecraft and especially for debris which are orbiting only a few hundred kilometers from the Earth's surface. The ability of ground based systems to address the removal of debris from medium earth orbit, from geosynchronous orbit or defunct upper stage launch vehicles in 12 h transfer orbit is technically challenging and probably not financially viable nor practical under the current terms of the Outer Space Treaty and the Liability Convention. Finally, the use of ground-based systems to create orbital changes for such debris elements, rather than saving the situation, could increase the risk of a collision and not be able to effectuate removal. Currently these ground-based approaches have not been practically demonstrated to be reliable and effective.

Passive De-Orbit Systems

The deployment of passive de-orbit systems at end of life represents the most economical means to ensure the longer-term deorbit of low earth orbit satellites. A number of different concepts have been conceived and tested that at the end of life for a small satellite that could be deployed to create a significant amount of atmospheric drag and thus hasten de-orbit. These concepts include inflatable balloons, inflatable tube membranes (ITMs), suspendable tethers, or solar sails. Essentially these are all rather simple and easily deployable drag systems that are designed to increase the rate at which the de-orbiting process occurs. Such systems are really appropriate and effective for small satellites at relatively low orbits, i.e. under 800 km or so. Such mechanisms can accelerate the rate of de-orbit and allow small LEO satellites to meet the current standard of de-orbit within 25 years. [Rasse]

Satellites that larger in size with deployable solar sails of a larger cross section could use their arrays to assist de-orbit at the end of life. Solar sails have been used to accelerate the de-orbit of the NASA Fastrac satellite. This approach has also been utilized in the CANX-Drag Sail which is a project of the Canadian Government. [Grant Bonin et al.]. This approach of deploying a reasonably large, but very low mass solar sail was also utilized in the case of the European Union Protec 1-2015 program ["Passive Means."]. A large number of university programs in the United States, Europe and other parts of the world have also developed similar capabilities.

These are typically designed for low earth orbit and quite small satellites. When these passive systems are deployed the cross section that creates atmospheric drag can be significantly increased and thus accelerate the de-orbit time and thus make de-orbit two to three times more rapid. There are today some new chemical and electronic thrusters of sufficiently small size and mass that they could be used to assist in the de-orbit of some small satellites or to work in tandem with passive de-orbit systems. The smallest cube satellites, nano-satellites, or so-called femto-satellites will for the most part decay simply due to gravitational effects, especially if they are deployed at 400 km altitude or below.

There are sufficient numbers of these very small satellites now being deployed—and in some cases without formal registration and at altitudes above 400 km. In these instances their deployment can be considered a problem. Solutions to this problem might include flying experiments on the International Space Station and thus not becoming free-flyers. Another option would be to designing "consolidator" satellites that could be the host for a number of small experiments and then deorbit in a controlled burn. In the case of the "host" or "consolidator" satellite they might not only provide thrusters for de-orbit but could also provide a common power supply and perhaps other services common to the small experimental packages that fly in common. National action that provides very clear registration procedures and perhaps imposes fines for not registering small satellites might also be considered. Ultimately there will need to be a review of the 25 year de-orbit rule to see if that is adequate to depopulate low earth orbit at a sufficiently rapid rate. Certainly international agreement to require a 20 year rule for removal of spacecraft from the protected LEO and GEO orbits would be a step forward in seeking to reduce debris in orbit.

It needs to be particularly noted that these passive systems work well for low earth orbit satellites, particularly when Solar Max activities serves to balloon the Earth's atmosphere to higher altitudes but that these systems are not as effective in higher LEO orbits and do not work in any way for medium earth orbit or geosynchronous orbit since they are well above the Earth's atmosphere.

The Prospect of Mandating New Types of Fail Safe End-of-Life De-Orbiting Systems

Another new concept that has been suggested to address the orbital debris removal issue is not so much a new technology, but a new approach to end-of-life processes. This is the proposal that there should be a de-orbit thrusters system that is separate from a spacecraft's regular orientation and station-keeping systems that could also be separately commanded. This capability would, in effect, provide a fail-safe de-orbit system. This idea is not likely to be greeted with enthusiasm by spacecraft owners and operators in that it could involve a separate telemetry and command system, an additional fuel tank, and additional fuel. Conceivably this de-orbit capability could be an ion thrusters system that would make the system lighter in mass.

Nevertheless this sort of fail-safe deorbit system might add 5 % or more to the mass budget for a spacecraft. This would initially be for low earth orbit satellites, but the additional capabilities related to MEO and GEO satellites and there redeployment to graveyard parking orbits might presumably come into play at a future date.

To accomplish this "guaranteed de-orbit" D-Orbit of Italy has developed and is now promoting the future use of a new product which they have designated as a Decommissioning Device (DD). This is a unit which as now designed includes a solid propellant motor and a control/command unit. The advantages of this product would be that it is completely autonomous even if the satellite is defunct, and that it is fully compliant with ESA and NASA safety standards. D-Orbit claims that there would no single point of failure except for the solid fuel motor and that it would be guaranteed to be reliable for more than the lifetime of the satellite and that it would be scalable to adapt to different types of missions. This guaranteed de-orbit system could be designed with a timer set for a period of time well passed the planned operational life to provide additional margin against failure. It could also use a chemical thruster or even an ion thruster either to make this system "cleaner" or to reduce the mass of the fail-safe system. [Antonetti et al.]

As interesting as this proposal is from the perspective of likely limiting the buildup of space debris there are a number of factors to consider. These factors include: (1) this would be a partial solution and as now designed would only be for the de-orbit of low earth orbit satellites. There could, of course, be similar systems designed to raise the orbit of geosynchronous satellites; (2) this type of program would not assist with upper stage rocket motors and other debris elements unless this program was expanded in scope; (3) it would be too large of a system to assist with nanosatellites; (4) it would be a very "expensive" program for commercial satellite operators in terms of a major lost operational capacity and the associated opportunity costs—even if this were just an orbit raising system to deploy to graveyard orbit and used a separate ion thruster; and (5) solid fuel rocket motors although they are quite reliable, are also environmentally more polluting than liquid fuelled rockets. Further the potential future use of electric ion systems, although slower and with less thrust, could be more efficient in terms of reduced overall mass penalties that would be added to the mission and certainly would be less polluting. In short the design of fail-safe systems to raise geosynchronous satellites to super GEO might well find ion-thrusters optimum in terms of imposing the minimum mass penalty.

New Technical Concepts for Active Removal Systems for Orbital Debris

Robotic Capture and De-Orbit

The range of technical approaches that might be used to remove orbital debris are quite diverse and the innovative concepts continue to grow and diversify. The main-line approach which a number of aerospace companies and space agencies are now proceeding involves a basic strategy of sending up a robotic satellite to attach to a debris element and then de-orbiting the composite system. The various projects that are being developed with this type of capability were reviewed in Chapter 2. These developments are on one hand conceived as a way to remove major debris elements from low earth orbit and on the other hand they are seen as a possible mechanism for capturing operational satellites and servicing them by providing new batteries and fuel. The most exotic concept in this regard is the idea that grappling robotic spacecraft with the ability to capture defunct satellites might "harvest" antennas or other re-usable components in space and redeploy them on a new space system. This "harvesting" spacecraft concept is unique in that it is primarily designed to operate at GEO altitudes and thus be able to rendezvous with application satellites in geosynchronous orbit.

The one at a time approach to active debris removal, which is currently the prime approach under development, has the major disadvantage of being extremely expensive, time consuming, and ultimately inefficient. The only exception at this time is the Electro-Dynamic Debris Eliminator which has been provided funding by NASA for prototype development by Space Technology and Research (STAR) Inc. Thus this innovative approach is addressed in both Chapters 2 (existing programs) and Chapter 5 (Future technology).

Spacecraft with Multiple De-Orbit Kits

This proposed approach that provides a variation on the above theme with the intent of being much more efficient and less costly involves a capture spacecraft that was capable of attaching to a number of defunct satellites one after another and attaching to each one a "de-orbit kit". The idea behind the "de-orbit kit" is that there is a concentration of debris in the range of 600 to 2,000 km altitudes that could be addressed by a robotic spacecraft that could attach de-orbit units. One such concept is to equip a robotic spacecraft with a number of "remotely operated semi-self-attaching de-orbiter modules". These units would be deployed via a robotic arm which is fixed to the delivery satellite chassis. Detection of the targeted debris elements would be carried out using a photon camera/sensor attached to kit-deploying satellite and a sanctioned data base provided by the Inter-Agency Space Debris Coordination Committee (IADC), the UN Office of Outer Space Affairs or other appropriate sources such as information provided by the launching country of record.

As proposed by the research team at the Indian Institute of Technology. It would be possible to use different modules for the chaser spacecraft and detachable "de-orbit kits." It is also anticipated that "modules may include the communication system used for communicate between ground based station, satellite system and de-orbit kit." These modules would also need to include some sort of electrical power system (that would most likely be solar cell panel arrays and lithium-ion batteries), an orbital intercept and thrust control system, plus an altitude determination and control system. There would also likely be either a robotic arm or tether linkage system plus a number of "de-orbit kits". It is anticipated that this "kit" would include a GPS system, computer control and communication modules plus a propulsion module, or tether, encompassing net or a deployable passive de-orbit system such as an inflatable balloon or solar sail or inflating foam to create atmospheric drag. [Kaushal et al.].

Tether-Deployed Nets

One of the most common concepts consistently put forward for de-orbiting of debris envisions that a net would be draped over the derelict satellite or upper stage rocket so as to create substantially more atmospheric drag. This is the technique anticipated by the EDDE system described below. This approach has most exotically been described as the RUSTLER system for "Round Up of Space Trash—Low Earth orbit Remediation". Despite the frequency with which there have been references to tether-deployed nets as a de-orbit mechanism this approach has only be simulated on computer models and not actually demonstrated in actual practice. [Hoyt, R.]

Glues, Adhesives, Foams and Mists

A less complicated version of the deployed nets would be to deploy a satellite that would be capable of shooting at close range adhesives, epoxies, foams or mists on to the surface of the debris object. Some have envisioned what might be called very sticky balls or expanding balloon like foams. These balls might be constituted from epoxies, resins or foaming aerogels. Once these adhesives are attached to space debris objects they would expand in volume and in time alter the debris orbits so that they would eventually degrade and presumably burn up in the Earth's atmosphere**.** [Kushner] A variation on this theme would be spaying of mists on the debris spacecraft or defunct rocket stage so that the mists would freeze and create orbital drag. Again although these various ways of shooting or spaying materials onto debris elements have been simulated and modelled they have not actually been tested in space. The concept in all cases is that a remotely controlled dispenser satellite would be designed so that it could be positioned close to derelict space objects. The dispenser satellite then would then shoot glue balls or spray gas mists or expanding foams so as to create new atmospheric drag on the debris element. This would serve to help de-orbit smaller orbital debris. This type of system would, however, be for just low earth orbital debris and smaller debris elements and not for higher orbits and larger space debris. [Kushner]

Terminal Tape or Tether

In addition to tether systems or nets to create drag there have also be proposals to attach to debris what is call a "Terminator Tape". This tape would have an adhesive to cling to the satellite and then it would be deployed just like a gravity gradient antenna to create the maximum gravitational pull. The longer the tape, the greater the gravitational attraction. It would also create some atmospheric drag as well. Again this would be an approach suitable only to low earth orbit satellites [R. Hoyt]

Space Harpoon System

The concept of a space harpoon system as opposed to a robotic grasping system would appear to have several advantages. The proximity of the "chaser" satellite would not need to be nearly as great and thus minimizing the risk of on-orbit collision. Also the "connection" to derelict space objects, whether an upper stage launcher, space craft or other type debris, can be in any shape or size. Finally a harpoon system connection can be connected to a free-flying propulsion system that allows a repetitive process to initiate the de-orbit of multiple satellites rather than a single debris element. There are, of course, alternative de-orbit systems that could be attached to the harpoon tethers such as a passive net system that could create atmospheric drag as opposed to an active propulsion system that could be a chemical rocket system or ion thrusters. Prototype systems have been conceived with a four harpoon deployment mechanisms, but in theory the number of harpoons could be much larger.

Use of an Ion Beam to De-Orbit Debris

Ion beam projection systems represent yet another means to steer debris into a de-orbiting mode. Such an ion beam could be focused on a debris object over a period of time so that it would steer the targeted space debris to a controlled de-orbit. This technique is being studied by the European Space Agency, NASA, and the Japanese Space Agency (JAXA). Some of these studies are focused on high-powered lasers, others on ion beams, and other higher powered particle beams that might be developed as part of a planetary defense system against potentially hazardous asteroids. [Claudio Bombardelli et al.]

There are concerns about the use of such mechanisms in space since they could be seen as anti-satellite weapons and as such may be considered to be contrary to Article 4 of the Outer Space Treaty. One solution to this issue, that has been recently proposed, is that the country that is recorded as the "Launching State" would be given control of the laser or particle beam ionic stream for the de-orbit operation.

Systems Using Electro-Dynamic Systems and the Earth's Magnetic Field as the Propellant

Large-Scale Orbital Debris Cylinder Using Electro-Dynamic Propulsion

Many technical analysts who have considered improved and more cost effective means to remove debris from low earth orbit have come up with the idea of using the Earth's magnetic field as a means to generate electricity so as to drive systems that would conduct the debris removal function. These analysts suggest that using chemical rockets with robotic devices to clamp on large debris elements and bring them down one by one is simply too slow, too inefficient and too costly. A number of these critics of using conventional chemical rocket systems propose that systems that use tethers to generate electricity or perhaps even a large metallic chamber or ring that also trails metallic tethers would be a much more efficient and cost effective approach. Bharat Chaudhary has proposed the idea of deploying in low earth orbit a large Metallic cylindrical orbiter. This concept suggests that debris could simply fly through the cylinder with the result that LEO debris would have its velocity slowed sufficiently that the debris would thereafter tend to de-orbit. This design concept suggests that a stronger electrical field could be generated by attaching both solar cells and tethers to the flying disposal cylinder. It is suggested that resulting reduction in speed would be sufficient so that the debris objects would rather quickly descend towards Earth. Debris slowed in this manner would in reasonably short periods of time burn up on coming in contact with the atmosphere, except in the case of the very largest debris elements**.** Although this is a clever concept, there are many practical questions to be addressed. These include what would be the optimal size of the cylinder? How would one be able to guarantee that there would not be collisions between the cylinder and debris elements and what would be the specific avoidance mechanism? And would the design actually be a cylinder, a circular wire grid or some other more suitable geometry? [B. Chaudhary]

Electro Dynamic Propulsion Systems for Space Debris Removal

There are other concepts that suggest the electrical-generating capability of the Earth to power an orbital debris removal mechanism. The alternative ideas is to create a more targeted system that would provide a "passive vacuuming" of space as discussed above. There are suggestions that one could utilize the Earth's magnetic field to generate electric propulsion to create a new electro-magnetic "space tool" that could search out and remove debris.

At least two quite different variations on this approach would be possible. The least ambitious means would be to have a conventional satellite with chemical propellant that would maneuver in low earth orbit to simply attach tethers to multiple satellites to help de-orbit derelict space objects. This may or may not include an electric ion thrust motor along with the tether to accelerate the de-orbit process. This approach by relying on conventional chemical rockets could likely be designed more quickly and this effort mounted in the not too distant future. [Pearson, Jerome et al.] and also see [Hoyt, R.]

A much more ambitious technological approach would attempt to create a large scale electro-magnetically driven device that would undertake this type of operation for potentially hundreds of orbital debris pieces. This system, as noted in Chapter 2, has been given the name of an Electro Dynamic Debris Eliminator (EDDE). The scale of these systems would be quite large (i.e. kilometers in length), but the mass would be small. This is because it will use tethers to generate electricity so there is no need for chemical propellants. This device would be quite long, although the modules that could be commanded would be compact and few in number and most of the EDDE would be the tethers that connect solar arrays together (Figs. 5.1 and 5.2).

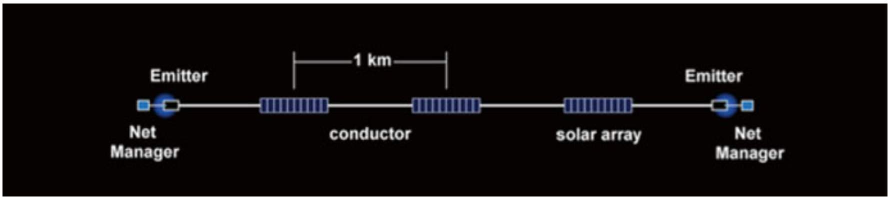

Fig. 5.1 The Schematic design of the overall EDDE system (Graphic courtesy of STAR Inc.)

Fig. 5.2 The EDDE Net manager at end of tether system (Graphic courtesy of STAR Inc.)

The main aspects of the EDDE would be the following: (1) It would be quite low in mass even though it would be about 4 km or so in overall length, and thus relatively easy to launch into low earth orbit in a stowed configuration; (2) In theory it could be maneuverable to virtually all inclinations, including polar orbits, in low earth orbit; (3) The combination of power from solar cells and from the tether flying through the earth's magnetosphere would generate enough electrical power to move the EDDE from location to location without the need for chemical propellants. (4) The deployment of low mass nets onto debris elements would create sufficient atmospheric drag to remove the orbital debris over time with a "net manager" being positioned at each end of the EDDE device; (5) One EDDE spacecraft would be designed with the objective of being able to remove over 100 space debris elements from low earth orbit in about 3 years' time. The developers of this project have ambitiously estimated that 12 EDDE spacecraft over a 7 year period could remove nearly 2,500 space debris objects and leave only smaller debris elements in low earth orbit. (i.e. all debris weighing under just a few kilograms)

This approach sounds very attractive in terms of its not requiring chemical propellants to operate, its ability to remove a very significant debris elements, and its purported ability to remove debris in an environmentally clean way with maximum economic efficiency. Yet major questions still remain. The most important questions are whether this type of technical concept can actually be proved to work as proposed and whether legal, regulatory and liability issues and concerns surmounted. In February 2012 NASA awarded Star Technology and Research (STAR-Tech Inc.) a $1.9 million contract to develop this technology. The legal concerns will be explicitly addressed in a later chapter.

Key Technical Challenges Related to Active Debris Removal

There are several key technical challenges related to active debris removal. These challenges need to be addressed in parallel since these are in many cases complementary capabilities and involve different technologies and system capabilities. One need is the ability to locate and rendezvous or achieve close proximity with debris elements that are derelict in orbit. This means close conjunction without a destructive collision. A second need is to create a de-orbit mechanism that quickly or over time effectuates the de-orbit process for low earth orbit. A third need, which has received the least attention to date is to develop ways to link to debris in higher orbits (i.e. MEO or GEO or highly elliptical transfer orbits) so as to reposition them into a safe parking orbit. The DARPA Raven and Phoenix mission is currently the most relevant project of this type. The development of a capability to provide in-orbit servicing of GEO satellites is closely parallel to the needed capability to rendezvous with a derelict object in GEO orbit and then remove this space debris to a safe parking orbit or in the case of a GEO transfer orbit achieve safe deorbit. A fourth need, that is not so widely agreed, is the extent to which large debris elements need to be brought down in a controlled manner to avoid collision with aircraft or avert potential damage or loss of life on the ground. This is clearly very desirable but difficult to do. Most spacecraft or launch vehicles burn up, but the largest objects can make it through re-entry.

Strategies for Location and Rendezvous of Debris Elements

Although most of the debris elements that constitutes the greatest problem are not a huge distance away from the earth's surface, i.e. typically between 200 km and 1,000 km, the debris is travelling at very high velocities and locating the precise derelict space object and manoeuvring to close proximity without crashing into it at a high relative speed is one of the greatest technical challenges. Some of the steps to help in this regard are simple and straightforward while others require great technical sophistication. In terms of identification there have been suggestions that all space objects should have reflectors applied to them to assist with their location. These identification systems could also have something like a bar code identifier or an RFID. As of yet no internationally agreed procedures for clear identification and ease of rendezvous have yet to be accepted in practice [NASA Office of Space Servicing Office]

There has been a great deal of experience acquired in using optical sensors and docking systems in space. Japan has carried out early experiments in deep space and NASA and participants in the International Space Station have acquired a good deal of experience with docking and capturing spacecraft with the Canada arm. In the past decade the following efforts to accomplish in-orbit activities in space, commonly known as rendezvous and proximity operations (RPO), have been carried out with the results noted below:

The U.S. Air Force XSS-11 mission in 2005 accomplished a close proximity inspection of several satellites with success but did not attempt a docking.

- The NASA DART spacecraft in 2005 attempted an autonomous rendezvous with defunct spacecraft known as MUBLCOM satellite with only partially successful results since there was a slight collision.
- The U.S. Defense Advanced Research Project Agency spacecraft named the Orbital Express demonstrated in 2007 the ability to carry out on-orbit refuelling and servicing of another spacecraft.
- The Swedish Space Corporation PRISMA successfully demonstrated the ability of two microsatellites to fly in close proximity formation.
- The Chinese SJ-12 in 2010 maneuverer close to the SJ-06F spacecraft for reasons thought to be close proximity inspection [Weeden et al.]
- The Raven project in 2016 will aid with the ability to undertake rendezvous and proximity operations.

In addition there are operational low earth orbit satellite constellations such as the Iridium satellite system that is flown as a global network with operators constantly in control of the network. In the early days of operation in the late 1970 when the system was first deployed several "cockpit" errors occurred in terms of network configuration mishaps, but in recent years successful formation has been maintained and no such problems have occurred.

Currently there is a great deal of research work being concentrated on in-orbit servicing by NASA and other space agencies. It is clear that if a servicing spacecraft can be moved into position for on-orbit servicing that the same technology could be used to address active debris removal.

Various Types of De-Orbiting Technology and Systems

The previous parts of this chapter have outlined a wide range of new de-orbiting mechanisms that might be used to assist with the removal of debris from orbit. These techniques can be divided into the following categories: (1) passive elements such as balloons, sails, inflatable vanes, etc. that can be installed on a satellite or spacecraft before launch into low earth orbit and that can be deployed at end of life by command or even a pre-set timer; (2) passive de-orbit systems that can be attached to a spacecraft, upper stage launch vehicle or other debris element on-orbit to hasten its deorbit due to atmospheric draft and perhaps additional gravitational pull (i.e. terminal tape). (These include tethers, nets, glueballs, expanding foams, mists, epoxy materials, etc.) Most of these systems involve the use of chemically-fuelled rockets but some systems have been proposed that could use solar cell and electro-dynamic energy derived from the geo-magnetosphere to provide propulsive power. (3) Active removal propulsion systems that attach to derelict objects and pull them into a new orbit that hastens descent or lifts a geosynchronous spacecraft into a safe super GEO "parking orbit". These can be a captured satellite that brings the debris element down or it can be a more complex spacecraft that attaches a propulsion kit that can actively bring orbital debris down but perhaps less rapidly. Although the tracking and rendezvous requirements are more complicated, these kits could also theoretically be used to elevate a defunct GEO spacecraft to a safe location above the geosynchronous orbit as noted below. (4) Thus the fourth approach, which applies primarily to spacecraft in higher orbits, is the activation of spacecraft propulsion systems and station-keeping thrusters that place a defunct satellite into a "graveyard orbit" where "dead satellites" can remain for millions of years without doing damage to active satellites. MEO orbits are the most difficult to remove since it takes far more power to either bring them down into a de-orbit path or to raise them sufficiently to go super synchronous.

A variation on this theme would be de-orbit units that have separate command and control systems that would be responsible for end-of-life orbital repositioning or de-orbit. Research into all of these capabilities is needed. In the active debris removal arena, the first initiatives may simply be capture and de-orbit systems that work on one piece of debris at a time, but ultimately methods will be developed to bring multiple debris elements down with a single mission. Great emphasis is place on attacking debris in low earth orbit but improved procedures for MEO and GEO debris must be addressed as well.

Finally there is one other concern to consider. This is the problem of upper stage launchers that are designed to boost a geosynchronous satellite into a highly elliptical (or cigar shaped) transfer orbit that does not quickly degrade from its perigee encounter with the Earth's atmosphere. These large scale space objects can cross the Clarke orbit path at relative speeds of many thousands of kilometres and unlike spacecraft in GEO orbit that are traveling with the rotation of the Earth at relatively similar speeds, these upper stage rockets are ascending or descending at dangerous velocities. This particular issue has not been considered in any depth because most vehicles that perform this task do degrade in a matter of weeks because the atmosphere drag at perigee is quite considerable. Unfortunately just one such collision with a large application satellite would generate a large amount of new debris that would be quite dangerous to all satellites in the relatively narrow Clarke orbit. This problem therefore needs careful study.

A variation on this theme would be an active act of terrorism. In this case one might launch a relatively small rocket around the moon with a payload that was simply a container of nails and nuts and bolts. This rocket launch could be orbited around the Moon into achieve a retrograde orbit travelling in the exact opposite direction and speed of geosynchronous satellites and set off an incredibly dangerous chain reaction of debris that could put the entire belts of over 300 operational geosynchronous satellites at risk.

Controlled De-Orbiting Systems that Can Avoid Collisions

The bulk of small satellites that degrade in altitude and eventual de-orbit simply burn up in the atmosphere on re-entry and constitute no harm. There are two concerns about orbital debris that should be addressed in looking to the future. One concern is that new commercial applications are now being developed for the so-called protozone, which is the area above commercial air space (nominally 21 km) and the area below outer space (nominally above 100 km). These applications include high altitude platform systems (HAPS), drone or auto-piloted aircraft freighters, hypersonic transport, space tourism, and dark sky stations. These various vehicles, operating within the protozone could in time be at risk from debris before it is entirely consumed. In addition larger debris elements sub-orbital craft could collide with aircraft or even people or facilities on the ground. There have been serious proposals for independently controlled and fail safe de-orbit systems that could ensure deorbit operations that could be, in essence, auto-piloted down to guarantee that debris could come down in a fully safe manner so as to avoid dangerous collisions. New national space safety provisions such as the provisions of the French Space Operations Act that will come into full effect as of 2020 could well hasten actions to create specific controlled de-orbit capabilities. (Gaudel et al.)

Conclusions

The technology to accomplish effective and cost-efficient removal of orbital debris has still to be accomplished with any degree of competency. There are today a number of quite different approaches to solving this problem. Some are closely linked in positive ways, while others are clearly in competition with alternative systems and technologies. Here are the main strategies currently underway:

(a) Methods and guidelines to prevent the creation of new debris such as the voluntary guidelines developed by IADC and the UN COPUOS.
(b) Improved tracking programs for space situational awareness such as the so-called S-Band radar space fence and the increased sharing of data as to on-orbit earth orbiting vehicles such as the Space Data Association and as recommended by the UNODA Group of Governmental Experts.
(c) Increasing efforts to install passive de-orbit mechanisms on LEO satellites to engender de-orbit at end of life to meet the 25 year de-orbit objective.
(d) Research to develop effective ground-based laser or directed-beam devices that can change the orbits of satellites or space objects so as to avoid collisions or change velocities so as to de-orbit over time.
(e) Development of a variety of space-based on-orbit systems to carry orbit debris down to Earth in a controlled manner, or to create additional atmospheric drag or gravitational pull to de-orbit debris over time.
(f) Development of systems to cope with defunct spacecraft, launchers or other space debris elements in MEO and particularly GEO to move them out of harm's way and into parking orbits as opposed to de-orbiting them.
(g) Explore if on-orbit servicing vehicles, particularly for GEO orbit could serve a dual purpose of debris removal from geosynchronous orbit.
(h) Consider threats to geosynchronous satellites from defunct rockets in transfer orbits or destructive payloads placed in a retrograde Clarke orbit that would endanger all satellites in this narrow but highly useful band.

At this time there are a number of elements that are creating barriers or difficulties to solving the orbital debris problem. These factors include the fact that procedures to avoid the creation of new debris are voluntary and are not backed by specific sanctions or financial incentives or other type rewards. Likewise the current UN Liability Convention does not provide incentives for debris removal and indeed are believed by some to work to discourage launching nations of record to remove debris. There is today no clear-cut international actor in charge of regulating orbital debris removal nor technology designed for active debris removal that has been clearly demonstrated to be effective and cost efficient. There is essentially no reward or incentive to develop such a removal technology or system. Until these conditions change, the solution to the orbital debris problem and its active removal will remain a problem. On top of all of these practical and regulatory problems, there is the additional concern that many of the technologies that could potentially be deployed to remove space debris from orbit, could also be considered to be “space weapons”. Some of the technology could perhaps be seen as being banned under the UN Outer Space Affairs Treaty—especially if it involved technologies that could be equated to being a weapon of mass destruction. Until many of these issues are resolved clearly, the development of active removal procedures will likely lag behind and thus allow the orbital space debris problem to grow. This is another reason why on-orbit servicing will likely lead the way. Finally, the current emphasis is being placed on low earth orbit systems where the greatest problems lie. In the not too distant future, efforts to address orbital debris in medium earth orbit and GEO orbit must become an area of focus as well.

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