7 On-Orbit Servicing, Active Debris Removal and Repurposing of Defunct Spacecraft

Introduction

There are many aspects of the NewSpace industries that tend to capture headlines. The idea of mining asteroids or new rocket systems that can be reused by landing them at precisely defined spots give rise to exciting television and helps to fire the human imagination. Two booster rockets landing together in synch produce great visuals that are immediately grasped even by small children. Not all of the NewSpace developments, like in-orbit refueling of a satellite, produce great theater.

The area of on-orbit servicing will appear to some to be the equivalent of taking a satellite into a service station for an oil change. At first glance on-orbit servicing might seem quite unexciting.

However, the truth is that this technology could revolutionize the economics of Space 2.0 industries. If we could cut the cost of space enterprises in a major way it could greatly expand the number of things we could do in space and make them profitable.

Some of the things that the new on-orbit servicing space companies are contemplating are straight out of *Star Wars*. We might learn ways to turn old spacecraft into shiny new satellites with many new capabilities. If we could recycle old satellites into new it might make a range of new space applications possible and also help clean up a lot of space junk in the bargain.

Today many of these activities are in the shadows. These shadows are created in part because a number of the activities are being led and funded by the Defense Advanced Research Projects Agency (DARPA) under their so-called Phoenix project. This thus tends to put such activities under the secrecy umbrella of national defense. Another shadow of sorts comes from the news media as a result of not covering activities that seem more mundane. The refueling of a rocket thrust system in space is just not as 'sexy' as a giant new big Falcon rocket boosting Elon Musk's Tesla sports car into space.

Yet these new on-orbit services may prove central to much of what happens in Earth orbit in years to come. Also, it

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is interesting to note that organizations such as the DARPA are working with a range of start-up companies such as Altius Space Machines, NovaWurks and other lesser known names to invent this new technology [1].

New on-orbit servicing technology may prove key to removing space junk from orbit, manufacturing and processing of materials in space, building solar power satellites, recycling of defunct components and units in space by making new satellites out of old ones, and much more. The bottom line is that new technology developed by DARPA, NASA, other space agencies such as ESA, DLR, JAXA, the Chinese National Space Administration, and ROSCOSMOS, together with NewSpace industries, are now upping the ante on what can be done in space.

We are now seeing a raft of new ideas and capabilities as well as a redefining of the capabilities, dexterity, degree of autonomous artificial intelligence, as well as the cost efficiency of robotic systems in space. Progress in this area represents an unusual blend of sophisticated and high-cost space programs funded by civil and defense-related space agencies like NASA, ESA, DLR, JAXA and DARPA on one hand and Silicon Valley-like innovators from the Space 2.0 firms on the other. The key is not how big or well-established are the space innovators, but those who are able to come up with outside-the-box innovation.

What are today still largely governmental or defense-agency projects are increasingly giving rise to new commercial ventures in this area. Already there are three commercial ventures who are offering such on-orbit services as lifetime extension for commercial satellites, active space debris removal, or transfer of satellites from one orbit to another. These organizations are the U. S.-based ViviSat, the Canadian firm MacDonald Dettwiler Associates, who have developed a lifetime extension vehicle, and Cone-Express, which is a Netherlands-based firm that has designed their craft to uniquely fit into space available on the Ariane launch vehicle [2].

Sufficient progress has been made in this area so that efforts are now underway to create a new process for defining what might be called satellite servicing standards. This is not what might be called following a 'normal' international standards-making consultative process under the auspices of an international organization or association. Instead DARPA released a request for proposal for the Consortium for Execution of Rendezvous and Servicing Operations (CONFERS) Program in 2016, and on October 3, 2017, it selected a team consisting of the Secure World Foundation (SWF), the University of Southern California's Space Engineering Research Center (SERC), the Space Infrastructure Foundation (SIF), as well as Advanced Technology International (ATI) to serve as team leaders for this consortium [3].

Emerging New Capabilities in On-Orbit Serving Around the World

There are actually a wide range of new technologies and space-based capabilities that are under development at this time. These are systems to assist with or accomplish: (i) on-orbit servicing, refueling and component replacement; (ii) the capture and then repositioning of spacecraft to desired orbital positions; (iii) many different types of systems to assist with the active removal of space debris: and (iv) the development of robotic devices and artificially intelligent programs that are associated with refueling, installation of new components, sensors, antennas, and replacement batteries.

There are even more ambitious efforts to develop technologies, systems and artificial intelligence capabilities to convert or ‘cannibalize’ defunct satellites or orbital debris in order to make them into new usable spacecraft systems. Finally there are efforts, in many cases by the so-called space-mining companies, to develop new capabilities in terms both technology and new types of processing systems designed to allow space processing and space manufacturing, as well as to develop quality and materials standards for 3D or additive manufacturing in space.

The leader of many of these efforts is DARPA. DARPA has been engaged in R & D efforts in this area for over a decade. Projects have included: the Orbital Express mission in cooperation with NASA, the Spacecraft for the Unmanned Modification of Orbits (SUMO), and the Front End Robotic Enabling Near-Term Demonstration (FREND) mission. In its current on-orbit servicing vehicle project now underway, DARPA has involved a consortium of partners in an attempt to obtain greater commercial input on how to use the vehicle. This consortium consists of the Secure World Foundation, the University of Southern California’s Space Engineering Research Center, the Space Infrastructure Foundation, as well as Advanced Technology International.

DARPA has established a revised set a mission objectives for its new test mission for on-orbit servicing that is scheduled for 2020 or 2021. These include working with an upgrading of an operational rather than a decommissioned satellite. They have also developed the ability to create a detailed 3D image of the satellite to facilitate a precision coupling with the satellite before using the FREND robotic arms grappling system to undertake system upgrades. Fig. 7.1 shows the FREND robotic arms grappling a large aperture communications antenna that is being transferred from a defunct satellite, to demonstrate how it might be repurposed in space.

Finally DARPA has broadened the scope to undertake the project with a commercial consortium as a partner. This is so as to allow the future development of a commercial on-orbit servicing organization that could work on governmental and commercial satellites and also seek to create international standards for on-orbit servicing. To date, a number of aerospace companies such as Airbus, MacDonald Dettwiler and Associates (MDA), Boeing, and Lockheed Martin have expressed interest in working with CONFERS in such a standards-developing effort [4].

As of November 2018 the members in in the CONFERS consortium had grown to 23, and on November 8, 2018, the first CONFERS conference was held in Washington, D. C., with a number of aerospace industries and governmental officials presenting their views on the future of the on-orbit servicing industry [5].

In addition, DARPA is pursuing a program known as Satlets, with new objectives as well. This is now considered a spin-off of the Phoenix on-orbit serving activities. Satlets are designed to

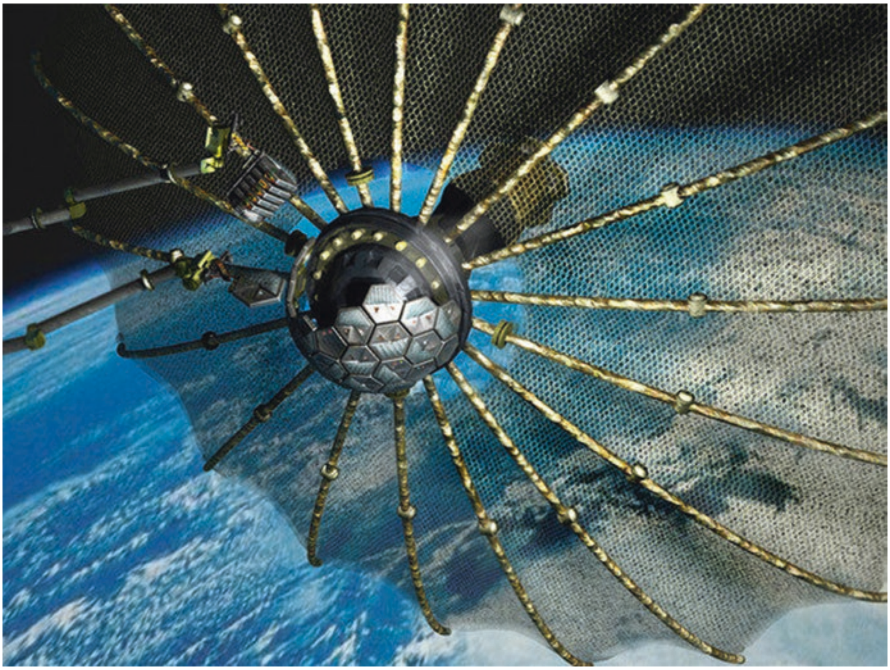

Fig. 7.1 Two FREND robotic arms simulating the manipulation of a satellite antenna in space. (Graphic courtesy of DARPA.)

be combined with components 'harvested' from defunct satellites. The current generation of Satlets are two-unit cubesat modules, each with a total mass of 7.5 kilograms. In their current incarnations these are known as eXCITE small satellites, or HI-Sats. Each satlet thus contains its own systems for propulsion, power, attitude control and memory. Space technology startup Novawurks is building the spacecraft using its Hyper-Integrated Satlet, or HI-Sat, product. This project can be scaled up from one module to hundreds of these Hi-Sats working as a constellation [6].

In addition to these independent development projects DARPA has worked with NASA on a number of efforts to develop robotic systems capable of demonstrating the ability to capture and couple with satellites and then carry out refueling and component replacement. This started with collaboration on the Orbital Express system in 2007 and then a collaborative test of the so-called Dextre system. (See Fig. 7.2).

Canada's Dextre robotic space helper was fabricated by MacDonald Dettwiler and Associates (MDA). This project was financed by the Canadian Space Agency. The Dextre system, also known as the Special Purpose Dexterous Manipulator, was specifically designed to work with and support NASA's Robotic Refueling Mission (RRM) experiment that was carried out on-board the International Space Station (ISS) in March 2012. This system is shown below in Fig. 7.3.

Fig. 7.2 Simulating the mating of the chaser Astro repair satellite about to capture the Next satellite. (Graphic courtesy of DARPA.)

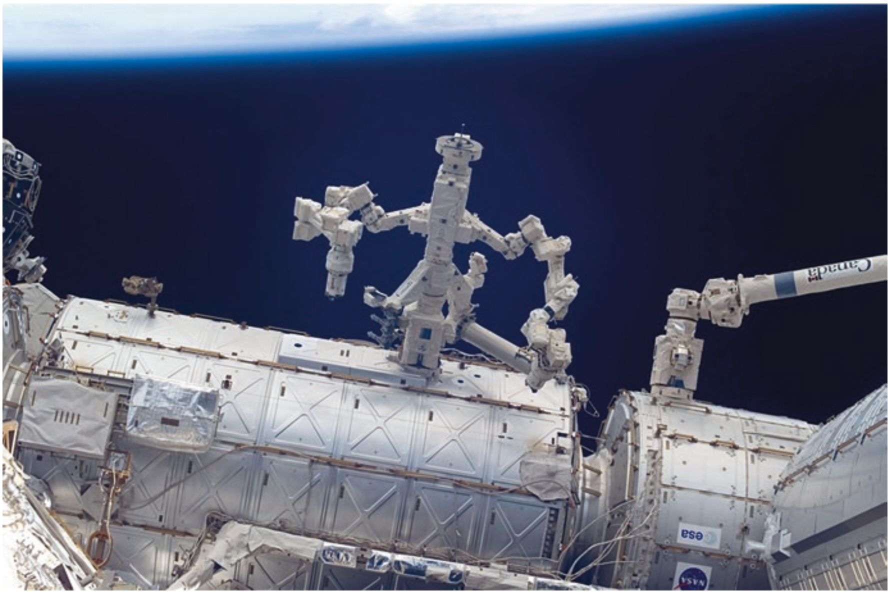

Fig. 7.3 Dextre robotic system shown on the ISS. (Graphic courtesy of NASA.)

The Dextre system, however, can be used in space for other purposes that include external maintenance activities for the ISS, support for astronaut extravehicular activities – especially to carry out equipment maintenance and fine motion actions related to calibrations – retrofitting of equipment, or in performing tests or experiments. These capabilities could even be used in the future to support space processing and manufacturing [7].

Dextre is one of the reasons why MDA is considered one of the leading commercial firms to develop commercially based services in the area of active debris removal, repositioning of satellites to new orbits, and in-space processing and manufacturing.

The Dextre system was designed as the “hands” for the Space Station Remote Manipulator System (SSRMS). Thus Dextre is able to give the ISS robotic Mobile Servicing System (MSS) the ability to perform fine dexterous tasks. The satellite was launched to the ISS on STS-123 in March 2008 and is controlled entirely from the ground. The hope is that this type of proven capability can be useful for a wide range of future space operations that include on-orbit servicing, on-orbit refueling and perhaps ultimately space processing and manufacturing operations. This type of capability, of course, can also be of use in active debris removal operations as well.

Coping with Space Debris

The issue of space debris has only grown in importance in the past two decades. This problem was greatly increased in 2007 by the Chinese launching of a missile to purposely hit a defunct weather satellite. The explosion created over 2,000 new debris elements over 10 centimeters in size. This was followed by the 2009 accidental collision of a defunct Russian Cosmos satellite with an Iridium mobile communications satellite that also created over 2,000 new debris elements (Fig. 7.4).

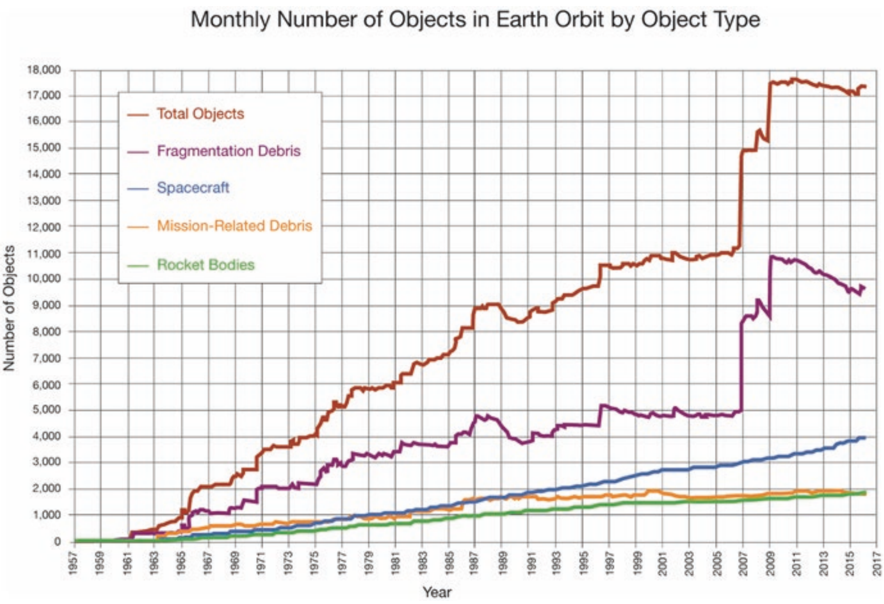

Fig. 7.4 Chart showing the steady rise in space debris and sharp increases in 2007 and 2009. (Graphic courtesy of NASA.)

There is urgent interest in seeking to remove the largest defunct satellites in low Earth orbit, such as Envirsat, which is over 10,000 kilograms in size. In addition, the United States has just issued a new Space Directive-3 that is aimed at providing for improved space situational awareness and improved procedures for space traffic management. Scott Pace, Executive Secretary of the National Space Council, has described this process as follows: “The reforms, which will be enacted over the coming months and years, will be specific to the United States rather than negotiated through the United Nations.” Pace has explained that “the space council opted for a bottom-up process in the name of expediency rather than trying to create an international treaty. By setting a proper example, the United States intends to establish norms that Europe, China, Russia, and others working in space will follow” [8].

Engaging in Active Debris Removal

There remain a number of issues to be resolved as to the regulatory environment that would allow governmental or private entities to engage in active debris removal. Some believe that an amendment is needed to the Liability Agreement that places responsibility for space objects with the registered launching state rather than with the actual owner and operator of a spacecraft. Currently it is only the launching state that is held responsible for all generated space debris. The key point is whether liability for space objects might be transferred from one entity to another and if “absolute liability” might be transferred from one entity to another for debris striking Earth.

Some of the latest significant developments are in the areas of licensing of satellite launches, updating of space oversight processes, and space traffic management. These subjects have all been addressed in the U. S. Space Policy Directives issued by the United States in April and June of 2018. (See Appendix D at the end this book for the full text of these directives.)

The main thrust of these latest U. S. space policy directives has been to say in effect that there would be a national effort to increase the speed of licensing of satellite systems, particularly large-scale constellations, on one hand, but also to improve the accuracy of space situational awareness and upgrade procedures in space traffic management by the United States on the other hand. The hope is that other spacefaring nations would follow suit.

While the regulatory and global space governance aspects of this sensitive matter continue to be considered in international forums such as the U. N. Committee on the Peaceful Uses of Outer Space (COPUOS) and in its Working Group on the Long-Term Sustainability of Outer Space Activities (LTSOSA), actual efforts to improve both space situational awareness and space traffic management processes continue.

There are now a number of commercial entities that are tracking space policies around the world, and the U. S. Space Policy Directive 3 directs the U. S. Space Command to take these sources of information into account in addition to using the additional resources of the new S-band radar addressed earlier in this chapter [9].

In addition there are a number of Earth-based laser and directed energy systems that might be employed to redirect the orbits of space objects that are in danger of potentially colliding with other space objects that would create more space debris. These types of systems are probably the most cost-effective way to avoid space object collisions in the shorter term, but there is a wide consensus that this is not likely to provide a long-term solution. Either governments or commercial operators must find that. There have even been suggestions that a form of space insurance process might be devised to implement a commercial-type approach to the space debris problem over the longer term [10, 11].

Meanwhile there are a number of efforts that are going forward to develop the actual technology that might be able to address the orbital debris effort. Many of these efforts involve such ideas as having passive systems deploy at the end of life that have little cost. This might be something such as balloon systems to create atmospheric drag in order to bring low Earth orbit satellites down faster. There are other ideas that would involve sending up satellites that could spray out epoxy materials or harpoon a defunct satellite with netting materials. Again the idea would be to create atmospheric drag to bring down a satellite so it would burn up in the atmosphere. There are now dozens of "active" deorbit technologies, as well as less costly passive systems, based on increased atmospheric drag, now under consideration. The current plans to launch many thousands of new satellites now make these new plans to de-orbit existing satellites much more urgent.

The following, however, represent some of the current programs that are seeking to develop and operate systems that could carry out active debris removal. A number of these efforts represent commercial initiatives [12].

ConeXpress Orbital Life Extension Vehicle (Sometimes Called ConeX or CX-OLEV)

This initiative of Dutch Space of Leiden is based in the Netherlands, but it is closely associated with ESA and Arianespace. The initial concept that gave rise to ConeX was to use what is called "the standard Ariane 5 conical payload adapter" as the main feature of its design. This project is seeking to create a propulsive unit that would fit in as a flattened cone-shaped mechanism uniquely designed to fit as an integral part of the Ariane 5 launch vehicle. It would have to be readapted to the Ariane 6.

The estimated cost of a ConeX mission has been projected to be about 35 million Euros. The system could be used to lift a spacecraft outward from LEO to GEO in a spiral orbit, or to deorbit a defunct space object. The ConeX would be powered by an electrical propulsion system that derives from the design developed by ESA for the Smart-1 lunar mission. Currently there are no active customers to use such a device for either rescuing a spacecraft that failed to reach GEO orbit or for actively removing a defunct satellite in a dangerous orbit. (See Fig. 7.5.)

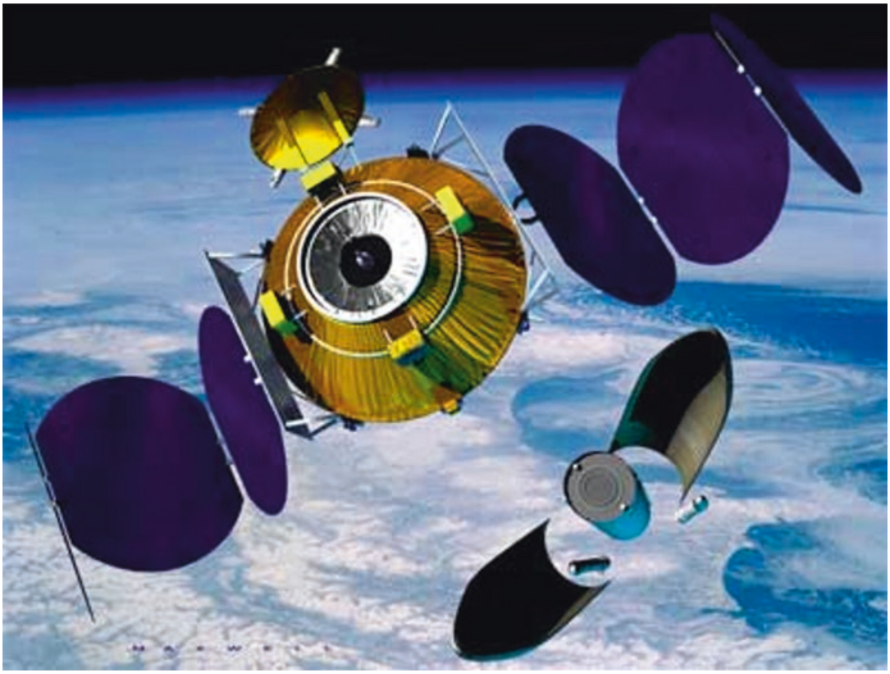

Fig. 7.5 Artist's impression of ConeXpress Orbital Life Extension Vehicle operating in space. (Graphic courtesy of ESA.)

MacDonald Dettwiler and Associates and Space Infrastructure Servicing

McDonald Dettwiler and Associates (MDA) has long been a leader in developing space robotic systems. They have also been one of the first commercial firms to develop systems that could be used as free flying on-orbit servicing vehicles due to their work for NASA and DARPA. They have developed what they call a Space Infrastructure Servicing vehicle. This SES vehicle is a multi-functional unit designed for on-orbit servicing, refueling or retrofit, for repositioning a satellite in the 'wrong' orbit, or as a means for active debris removal. In early 2011 MDA had arranged with INTELSAT to undertake a servicing mission, but the final contractual arrangements were never concluded, and the agreement was thus canceled in 2012. MDA and its subsidiary SSL is currently seeking to find specific commercial or governmental customers to actually commission in-orbit missions. It has since altered its approach to organize its on-orbit servicing offerings into a partnership that includes MDA, Draper Laboratories, SSL, DARPA and the Naval Research Laboratories [13].

The Satellite Infrastructure Services (SIS) website indicates that SIS will be able to offer on-orbit services on a contractual basis within the next two years. Its promotional offering, for this type of on-orbit service, states the following: "Space Infrastructure Services, SIS, offers the world's first on-demand

Fig. 7.6 The Vivasat MEV shown as mated with a satellite for servicing purposes. (Graphic courtesy of Vivasat.)

robotic service spacecraft available for missions in 2021 and beyond. These can be pre-scheduled or as an emergency call-up servicing – like roadside assistance in space. Services are insured and payment is not due until successful service completion, and your satellite continues to operate during most SIS on-orbit robotic servicing procedures. Our servicer is compatible with government and commercial spacecraft – even those not designed to be serviced in space." These services could of course be used for active space debris removal, but the economic costs that would likely be above $40 million suggest that these services would be for lifetime extension or orbital rescue of a quite expensive spacecraft [14].

Vivisat and Its Mission Extension Vehicle

Vivisat, which is U. S.-based, has developed what it calls its Mission Extension Vehicle (MEV). Vivasat was organized as a direct competitor to SIS. This MEV on-orbit service has been presented as a means for refueling and repairing satellites, but it could also be used for repositioning of spacecraft or to undertake active debris removal. It is advertised as being very flexible, in that the MEV was designed to mate with virtually all of the roughly 500 geosynchronous application satellites currently in orbit or now scheduled for launch. The SIS vehicle has now also been redesigned so that it can capture and mate with spacecraft not designed for on-orbit servicing. (See Vivasat Mission Extension Vehicle in Fig. 7.6.)

The truth is that there has not been any truly demonstrated commercial market for on-orbit servicing of satellites or for active debris removal. The significant amount of effort and resources that the DARPA has devoted to this type of effort through its Phoenix and other programs could change the attitude toward on-orbit servicing going forward.

X-37B OTV – NASA, U. S. Air Force and DARPA

Some have indicated that other initiatives, such as the U. S. Air Force X37B OTV, might be used for reclaiming and re-deploying space resources in a cost-effective manner as a reusable vehicle. The X-37B orbital test vehicle has been developed as an experimental, reusable spaceplane. It is somewhat like a small shuttle and is unmanned and completely robotic. This is now a classified project after this project was turned over to the U. S. Air Force from NASA. It is thus only speculation to suggest that such a vehicle might be used as a mechanism for repairing or refueling malfunctioning satellites, or for returning classified spacecraft back to Earth.

Sierra Nevada Dreamchaser Spaceplane

Yet another alternative for a vehicle that might be used for on-orbit servicing or to deploy systems to initiative de-orbit of large defunct objects in low Earth orbit is the Sierra Nevada Space Plane that has now been dropped from the competition for a means to fly astronauts to the International Space Station and provide a return capability.

The Remove Debris Small Satellite

On June 20, 2018, the Remove Debris proof of concept small satellite was launched by Nanorocks from the Kaber launch facility on the ISS. This small satellite with a mass of some 100 kilograms was constructed by Surrey Space Technology, Ltd. after some five years of development [15].

This experimental small satellite is designed to test the feasibility of various concepts that have been proposed for lower cost ways to create passive systems that might accelerate the deorbit defunct space object. The small satellite consists of the following component parts: (i) two cubesats; (ii) a net and a harpoon; (iii) a laser ranging instrument; and (iv) a "dragsail" designed to unfurl behind the main satellite. The idea is to test these various components to create significant drag to help space junk develop aerodynamic resistance to Earth's atmosphere and thus decay. This is only a test project of techniques, but if these tests are deemed successful it could form the basis of other actual projects to use the techniques in the future with actual debris objects [16]. (See Fig. 7.7.)

German DLR DEOS Mission

Another effort to demonstrate active debris removal is the so-called DEOS mission that is being carried out by the German space agency DLR. This project, which has a target satellite and a chaser satellite that will capture the target satellite and demonstrate its removal from orbit, is, in many ways, akin to the DARPA/NASA Orbital Express mission completed in 2007. It has precise sensors that will ensure that the capture in orbit is successful and that the mating is accomplished without damaging to the chasing or target satellite.

CleanSpace One – EPFL

A miniature version of the Orbital Express and the DEOS mission is the experimental test known as CleanSpace One. This mission is being carried out by a team of organizations in Switzerland. The project, which is using

Fig. 7.7 The Remove Debris small satellite being readied for release by the Nanoracks Kaber launch system via the JAXA Kibo airlock on the ISS. (Graphic courtesy of NASA and Nanoracks.)

only cubesat technology, is being led by the École Polytechnique Fédérale de Lausanne (EPFL) and The Swiss Space Centre – a division of EPFL. Another partner was the Swiss Space Systems (S-3) that has now declared bankruptcy, and this may delay the project.

EDDE – Electro-Dynamic Debris Eliminator

Currently there are three mainline strategies to diminish orbital space debris. These three concepts are: (i) the use of land-based energy transmission systems that could over time help divert orbits of objects projected to collide; (ii) the use of passive systems to speed deorbit due to the creation of aerodynamic drag; and (iii) active debris elimination by systems that could drag debris down swiftly. There is, however, yet one other concept of particular interest. This is the proposed deployment of a space system that could be sustained in space by using Earth's magnetic field to create an electronic propulsive force to deploy a device of 'passive nets' to create atmospheric drag to deorbit debris. NASA in 2012 awarded a $1.9 million development contract to the Star Technology and Research (STAR) Company. This system, as shown below in Fig. 7.8, is known as the Electro-Dynamic Debris Eliminator (EDDE) [17].

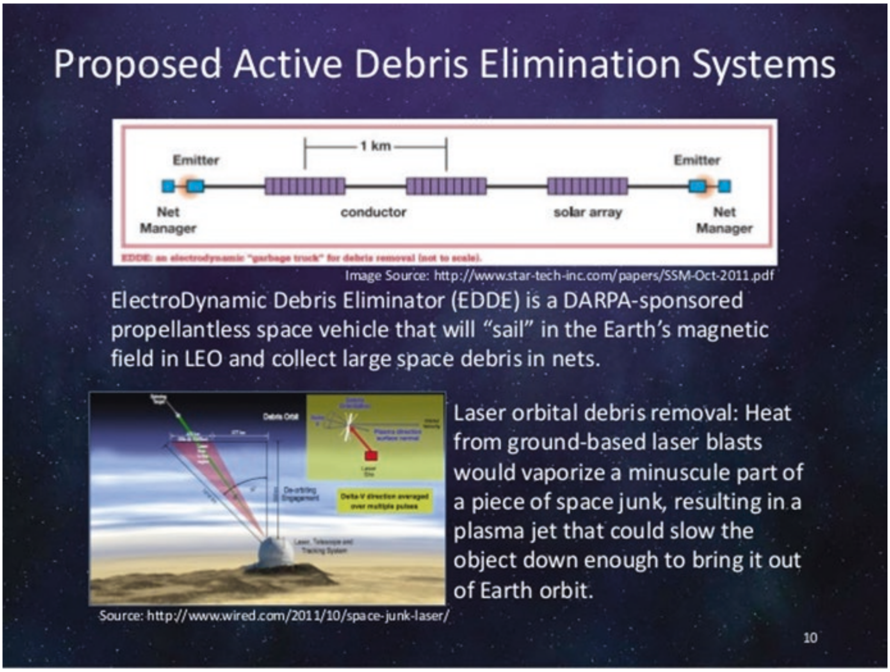

Fig. 7.8 Conceptual designs for active debris removal such as an Electro-Dynamic Debris Eliminator (EDDE) or Laser Heat System from the ground.

Conclusions

Some of the biggest changes and innovations that seem to be coming in the field of satellite applications are now being driven by DARPA. This applies to such activities as the development of spaceplane systems and various aspects of the so-called "Phoenix" projects that include sophisticated robotic capabilities in space, refurbishment and retrofit of satellites in orbit, the possible cannibalization of defunct satellites to redeploy parts from these satellites into a new system, and new ideas about satlet units for many flexible new uses. There are also new capabilities originating here related to better space situational awareness, space traffic management, active debris removal, and improved command and control capabilities related to space operations. It does not seem to be an exaggeration to say that all of these technical and process innovations will likely lead to new commercial opportunities that will follow from the DARPA-driven efforts to truly transform the field of space applications and to advance the cause of new Space 2.0 industry innovation.

There are changes that are driven by Space Directive 2 and Space Directive 3 that are seeking to improve space situational awareness processes and improved use of private capabilities to track space debris, space objects and satellites in orbit. These directives are aimed at increasing capabilities to carry out space traffic management and shifting regulatory oversight responsibilities to the new Office of Space Commercialization in the Commerce department.

The bottom line is that two major trends are coming together. One trend is concern about orbital space debris, the need for improved space situational awareness, and finding better ways to engage in space traffic management and reduce debris objectives. The other trend is the development of new space technologies and the burgeoning of new more cost effective capabilities that are coming from the world of Space 2.0 and new ways of doing things in space. These two trends are spurring innovations in the world of on-orbit servicing and in new ways to cope with orbital debris. Research from the world of defense and space agencies and innovation from the world of Space 2.0 are coming together to create new capabilities and new opportunities.

Meanwhile the volume of space debris continues to grow. The latest studies from ESA project a major collision occurring approximately once every five years. Low Earth orbit and Sun-synchronous polar orbits are of particular concern. Today tracking systems are monitoring and charting the orbits of approximately 22,000 objects in low to medium Earth orbit that are at least 10 centimeters or larger (or about the size of a softball). Perhaps of even greater concern is that there are now some 700,000 objects 1 centimeter or larger in size that are creating a worrisome and constant avalanche of space debris that increasingly blankets low Earth orbit at a time when many thousands of satellites in LEO constellations are proposed to be launched within the next few years. Clearly this is both of concern and an opportunity to innovate in the field of on-orbit servicing and debris-removal activities.

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