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TRIGGERS AND EFFECTS OF AN ACTIVE DEBRIS REMOVAL MARKET

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The continued advancement of active debris removal (ADR) systems may alter how the space industry assesses and accepts levels of risk inherent to system development and operations. Currently, the industry focus relies on debris mitigation techniques and procedures. However, in recent history, an increase in space actors, government and commercial, has revived discussion and development of ADR systems. Several organizations lead the charge in ADR system development and testing, with multiple demos having occurred in the past couple of years, and several more currently planned within the next few years. While these developments are promising for the development of an ADR marketplace, there are several technical, operational, and political challenges that must first be addressed.

Active Debris Removal: Market Readiness
As a whole, ADR is currently advancing through the R&D and Demo phases of development. Separate systems range from the R&D phase to the Market Introduction phase. However, the growth of that marketplace has yet to be seen.

Strengths	Weaknesses
• Growing interest in debris removal or disposal as the number of space actors increases. • Space actors would prefer to decrease the risk to their operational systems. Removing debris and obsolete systems that contribute to debris generation is one option. • Removal of large pieces of debris may be all that is required for space environment sustainability.	• "Tragedy of the Commons" • International liability issues surrounding debris removal, especially small debris unable to be attributed to specific actors. • Technologically challenging, requires additional capability advancements for market development. • Requires significant investment and regulatory advancement for market reality.

Introduction

Space debris has been an important concern of space actors since the release of the 1978 paper *Collision Frequency of Artificial Satellites: The Creation of a Debris Belt* written by Donald J. Kessler and Burton Cour-Palais. Though minimal action has been taken thus far in debris removal, the paper spawned decades of work characterizing the number, types, and orbits of debris in outer space, as well as the creation of voluntary debris mitigation standards that have been endorsed worldwide. Most of today's existing space debris is a result of propellant explosions or deliberate destructive action. The largest known debris creation event is a 2007 Chinese Anti-Satellite (ASAT) test, wherein an SC-19 kinetic kill vehicle deliberately destroyed a Chinese weather satellite.[1] To provide a reference point as to the longevity of space debris, the oldest piece currently in orbit is the U.S. Vanguard 1 satellite. Vanguard 1 was launched in 1958 to a medium-Earth orbit (MEO) where it will remain in orbit for at least the next 200 years until it naturally decays back into the Earth's atmosphere or is intentionally de-orbited before then.[2]

For the purposes of this paper, space debris is defined as obsolete spacecraft (satellites and rockets) or fragments of spacecraft that have broken off satellites and rockets. This includes a range of objects, from miniscule paint chips, screws, etc. to whole satellites or rocket bodies, all rendered unusable or nonoperational. This definition is provided because within the international community there are several slightly differing definitions of space debris, all of which come from *non-legally binding* documents.[3,4]

Thus far, the mechanisms for limiting space debris creation reside primarily with space actors following a list of orbital debris mitigation guidelines.[3,4] From country to country, these vary and are mostly voluntary in nature. Recently, with an increase in government and commercial space actors, the concept of using active debris removal (ADR) systems to sustain the space environment has gained traction. However, there are several technical, operational, and political challenges that must first be addressed. As such, these challenges define the hurdles that must be overcome for an ADR market to grow and sustain itself. For the purposes of this paper, an ADR market refers to the purchase of a service by a customer (government, nongovernment, or commercial) in which an ADR service provider works alongside the customer to actively remove from orbit or move to graveyard orbit a piece of space debris. For an economic market to become a reality for ADR, there are several triggering events and milestones that must occur. This paper identifies some of the most important triggers in maturing and balancing a supply of technological solutions with adequate demand for ADR services within the space economy.

What is Active Debris Removal?

For the purposes of this paper, active debris removal is defined as the removal of obsolete spacecraft (satellites and rockets) or fragments of spacecraft that have broken off satellites and rockets, through an *external* disposal method. Disposal here is defined as safely de-orbiting, maneuvering into graveyard orbits, or complete destruction of the debris. Within the umbrella category of ADR, this paper discusses both the removal of small pieces of debris, as well as the safe de-orbit of whole or mostly whole satellites or rocket bodies.

This broad definition is important as it establishes the extent of ADR operations as not just the removal of small pieces of debris, but the removal of systems that have the potential to generate a large amount of additional debris. Furthermore, the term end-of-life (EOL) services, a subset of ADR operations, will also be used in this paper to describe the safe disposal of obsolete spacecraft and rocket bodies. What is not covered within this umbrella are debris mitigation techniques. Though an import aspect of space traffic management (STM), debris mitigation (i.e., limiting the creation of new debris through operational and technical standards) is not the same as removing current and future pieces of space debris.

First and foremost, the use of extensive space situational awareness (SSA) capabilities is required for tracking, identification, and characterization of the space debris environment. As the population of space objects grows, additional and more enhanced SSA capabilities are required if ADR systems are to be utilized to their optimal potential.

Beyond a strong SSA backbone, most ADR solutions require propulsive systems (chemical or electric) to control the delta-v (change in velocity) of the target debris. Additionally, the use of a rendezvous and proximity operations (RPO) suite of technologies (composed of optical and/or radar systems) and guidance, navigation, and control (GNC) algorithms are essential enablers of ADR solutions. These commonalities provide a broad basis for EOL and ADR technologies to satisfy the debris concerns. As such, a number of ADR and EOL services concepts have been discussed, designed, and demonstrated to some degree.

Concepts for ADR solutions include one or more of the following technologies:

- Ground-based laser
- Space-based laser
- Electrodynamic tethers
- Solar sails
- Harpoons
- Aerogel
- Foam-based drag
- Grappling arms
- System capture and containment

Technologically, the ability to find, track, intercept, and remove small pieces of debris is an incredibly difficult challenge. Current state-of-the-art SSA systems can track many pieces of small debris, but they have their technological limits. Most pieces of debris between 1 cm and 10 cm cannot be tracked with current SSA systems.

However, studies have been performed by the National Aeronautics and Space Administration (NASA), and others, to determine how many pieces of debris must be removed to help curb the growth of more debris. The resultant data shows that the removal of larger pieces of debris is a more efficient method of stemming debris creation and the exponential growth in the density of debris.[5,6,7]

Thus, action beyond this may not be necessary for environmental sustainability. If this is true, once again a demand for ADR would not exist. The outcome of such a progression would be either a sustained market for EOL services or each system that is launched has built-in technology and margins set aside for safe de-orbit or disposal.

Key Market Challenges and Drivers

The key market drivers and challenges of an ADR market are less about the technical aspects of ADR and more political and economic in nature.

Recognizing the Regulatory Commons. In the case of small debris removal, the largest challenge is a "tragedy of the commons" situation. Both everyone and no one is responsible for the orbital environment, so there is little to no market incentive for investment.[8,9] Thus, public support is required.

However, public focus has been on debris mitigation guidelines. These guidelines in effect do not support the creation of an ADR market. Instead, they inhibit it by putting the onus on preventing additional debris instead of removing current debris. If more government action is to be taken, domestically or internationally, the impetus for action must be external in nature, most likely from an accidental collision or hostile action.[10] Otherwise, the technology development required to remove small debris will be underfunded, and the state of small debris removal systems will remain in a research and development (R&D) or demo state.

Orbital debris is a negative externality of space activity, a side effect or consequence of space actors using the domain that affects all actors. As an externality, the level of debris is in some manner proportional to the level of activity or the number of actors within the domain; i.e., as the level of activity and/or number of actors grows, so, too, will the level of debris. As such, it can be compared similarly to pollution on Earth, and even more specifically to the Great Pacific Garbage Patch.

The Great Pacific Garbage Patch is a large area within the Pacific Ocean where garbage, not properly disposed of, has accumulated due to converging ocean currents. Many actors contributed to this garbage patch and will continue to do so even with pollution regulations in place. A key differentiator between the Great Pacific Garbage Patch and orbital debris is that the polluters are more well-known for orbital debris. There is a much smaller number of actors for orbital debris, though that number today is growing. Additionally, for large objects, we generally know who the launching states are. Thus, liability can be effectively be assigned to, and even contractually transitioned between, specific actors.

As the need to address the negative externality of space debris increases, the removal of that debris can be viewed as a positive externality used to curtail the issue, helping all space actors in the process. Compared to the Great Pacific Garbage Patch, the more specific knowledge of who space actors are, and who is or is not liable for specific pieces of debris, provides a foundation from which international cooperation can begin.

***International Cooperation*.** International law states that the liability for space objects rests on the launching state.[11] When the international space regime became law, space debris was not a priority and was not addressed explicitly within the regime. As a result, the language used within these agreements implicitly indicates that debris created in space is still the sole responsibility of the launching state of the object the debris originated from. Depending on the circumstances, such as assets launched by international partnerships, this could also mean several different states, of which primary responsibility is legally unclear if no additional agreements are written between these parties. However, today, agreements are formed to specify who is the responsible launching party in these situations, clarifying these international legal obligations.

For small debris, this provides a unique problem. First, the origin of small pieces of debris may be unknowable. Without attribution, no one can be held legally liable for damages incurred from that piece of debris. Second, if the origin of the debris is known, legally only the launching state can remove the debris from orbit, which also applies to large debris. Thus, unless explicit legal consent is given to another entity to remove the debris, the right of ownership by salvage may not be claimed, even if the intent is just. Thus, because it is more technologically feasible, cost effective, and a more efficient manner of decreasing future debris, the focus for ADR operations has primarily been placed on removing large pieces of space debris and EOL services.

Market Triggers. Sustainable demand for small debris removal services may never materialize. Triggering events for such a market would require domestic and international development. Since small debris exists in a gray area of international politics, no country may be willing to take the risk (technical or political) of de-orbiting small pieces of debris for which it has not been assigned liability. Agreements above and beyond the current international space regime would be required to adjudicate this issue.

Historically, international agreements tend to be more reactive than proactive in nature. Thus, it is highly unlikely that additional agreements to address the liability of small pieces of space debris would be agreed to before the occurrence of a catastrophic triggering event. Examples of a catastrophic triggering event would include use of a highly destructive ASAT, a massive collision, or several large collisions occurring within a single year or separated by a few months. These activities would have to render one or more orbital regimes too dangerous to use or transit through. However, it is difficult to determine what the true magnitude of the end effect might have to be to prompt such action. In either case, such an event, hostile or accidental, is also a national security concern. As many nations rely heavily on space-based capabilities for national security concerns, spanning the DIME (Domestic, Informational, Military, Economic) instruments of power, it would be in their best interest to address such an event to ensure continued operations for all space actors.

If such a triggering event were to occur, the market for cleaning the space environment would need to be funded entirely by government. There is no strict commercial-to-commercial market as is possible with large debris. Thus, the governments of the world would fund the removal of debris in specific orbital regimes as needed to resume operations. Similar in nature to how governments address other forms of pollution, government incentives could take multiple forms. Domestically, each government has tools at its disposal, such as levying taxes (or providing tax breaks), establishing mandatory regulatory procedures, funding public-private partnerships (that range from the R&D and operational stages of the product lifecycle), or providing direct contracts to commercial providers.

Some in the industry believe the onset of a commercially driven proliferated low-Earth orbit (pLEO) and MEO may be another major influence in the further development of the ADR market. Much of the concern raised from a commercially driven pLEO is that the density of space objects will increase the risk of collisions exponentially, eventually to an untenable level. With the risk at such a high level, governments may seek to limit the risk of environmental degradation by enacting laws that require safe removal or disposal of these systems.[12] Legislation such as this will likely apply to new systems, leaving current debris to either be grandfathered in or requiring additional legislation.

Cooperative Versus Uncooperative Targets. For large pieces of debris, the remaining challenge is technical in nature: Is the target uncooperative or cooperative? Before discussing the technical challenges and needs for capturing debris, the difference between an uncooperative and a cooperative target should be defined. There are several definitions for what constitutes and demarcates an uncooperative and cooperative piece of debris. For the purposes of this paper, there will be two aspects used to define the difference. First, the physical state of the debris (i.e., the physical and orbital properties of the debris) is of utmost importance. Here the questions are numerous. How much is known about the physical and orbital characteristics of the debris? What is its general size and shape? How well are the orbital parameters known, and is the debris tumbling (i.e., residual angular momentum forces the debris to rotate around its center of gravity)?

Those first pieces of information are the minimum required to help capture and de-orbit a piece of debris. Beyond that, what can help distinguish between an uncooperative and cooperative piece of debris is knowledge about the extent of purposeful docking support. This information includes intended docking points, markings, or visual guide points on the debris intended to guide de-orbit systems, and the ability to transmit information between the target and the de-orbit system. The level of detailed information known on a piece of debris' physical state and whether the debris has the ability to guide and/or communicate with a de-orbit system defines whether a piece of debris is uncooperative or cooperative.

What is not included in this definition for what includes uncooperative versus cooperative is the consent of ownership to de-orbit or dispose. That is an additional parameter on top of this definition. In order to legally de-orbit or dispose of a piece of debris, there must be consent from those liable for the piece of debris. Otherwise, such activities could be considered hostile in nature. As stated previously, this provides additional hurdles for small pieces of debris where attribution is difficult to know.

With this definition in hand, it is easy to understand that capturing uncooperative debris is challenging, especially if the object is tumbling. The RPO and docking stages to do so require advanced GNC subsystems. Today, the development of these technologies has come to a tipping point of performing under adequate risk levels. This tipping point is a result of the advancement in automated operations. Automated operations require substantial analysis to build the "right playbook" to approach the target debris.[13]

These playbooks are based on multiple factors, including the design of the ADR system, and the size, shape, orbit, and state of the target debris. This knowledge can help inform the algorithms used to integrate the RPO payload and GNC subsystem for RPO and docking operations. While these operations are automated, operationally, humans have not been removed from the loop just yet. Knowing the piece(s) of debris intended to be de-orbited or maneuvered to a graveyard orbit also helps determine what the appropriate mechanism for docking should be. No single mechanism for de-orbit or transit has been proven as the most efficient mechanism available. This may be a result of the lack of testing, but more likely than not it is because of the diversity of debris that exists within the space ecosystem.

Formalizing Procedures. An additional step would be to establish a formal procedure and/or provide economic support to work with operators to perform uncooperative de-orbit or disposal on currently operating or obsolete spacecraft. With the onset of a commercially driven pLEO, the step toward mandatory procedures may occur, especially as countries such as the United States begin to advance more rigid STM systems to account for the orders-of-magnitude increase in space objects.

After launch, the challenge lies in performing the operations as designed. As RPO and de-orbit technologies are relatively new, further demonstration of their capabilities is required to win the confidence of customers. Some current examples of the leaders in these technologies can provide better understanding of where today's capabilities lie and the likely roadmap for incremental development.

Leaders in the Technology

While there is a legitimate distinction to be made between EOL and ADR services, the technologies required for each are so similar that there is cross-pollination between leaders in each.

Below is a list of the primary leaders in the on-orbit servicing (OOS), EOL, and/or ADR space and the systems they have been developing (type, current phase):

- Astroscale (Japan):
  - ELSA-d (EOL, Demo)
  - ADRAS-J (ADR, Demo)
- Space Logistics LLC (owned by Northrop Grumman, United States):
  - MEV-1, MEV-2 (OOS and EOL, Demo and Market Entry)
- University of Surrey and Surrey Satellite Technology Ltd (SSTL, United Kingdom):
  - RemoveDEBRIS (EOL and ADR, Demo)
- ClearSpace (Switzerland):
  - ClearSpace-1 and ADRIOS (EOL, R&D)
- The Aerospace Corporation (United States):
  - Brane Craft (EOL and ADR, R&D)
- Defense Advanced Research Projects Agency (DARPA) with Space Logistics LLC (United States):
  - RSGS (OOS and EOL, R&D)
- NASA with Maxar (United States):
  - OSAM-1 (Formerly Restore-L) (OOS, R&D)

More information on these leaders and others is present in other reports by The Aerospace Corporation.[14] While the aforementioned examples have been making great progress, there is plenty of work to do before ADR services becomes a viable commercial business. Some key technology, regulatory, and business drivers can help define how that market can be established.

Gamechanger Lifecycle: Market and Technology Triggers

Advancement of ADR technologies, especially those in common with OOS technologies, have begun to be demonstrated to a point of acceptable mission risk levels. The market and technology triggers associated with ADR can be broken into four categories across the lifecycle: R&D, Growth, Maturity, and Decline triggers.

R&D and Demo Phase. The R&D and demo triggers refer to the events, technical and/or political in nature, that have led to the conceptualization and demonstration of ADR systems and missions. First, RPO technologies have been in use since Apollo, contributing to some of our early human missions, the Hubble servicing missions, and building and operating the ISS. Since their first development, RPO technologies have continuously increased their level of autonomy for the past five decades. This development has enabled a point of maturation for GNC systems and RPO payloads such that OOS and EOL missions are now possible.

Additionally, advancements in characterizing the space debris environment have helped inform the political and technical nature of ADR development. SSA capabilities detailing the extent of space debris have raised awareness of the space debris issue within the community. The technical advancements in SSA have also helped pave the way for pre-launch identification of target debris for de-orbit or disposal. In this way, debris removal missions can be better planned and operated.

Growth Phase. Growth triggers for ADR identify events that build confidence in the use of ADR or initiate additional investment beyond the R&D stage. Technical triggers here primarily include on-orbit tech demonstrations. As previously described, both government and commercial actors have begun to demonstrate the suite of capabilities available to OOS and ADR operations. The primary political and economic triggers include mandating the use of ADR technologies and/or building stronger guidelines for de-orbit or disposal. However, this is a nested trigger. Without a major debris disaster caused by a collision, intentional or not, the likelihood of stronger debris guidelines is diminished. The only trigger that may force preemptive action is the onset of a commercially driven pLEO. Increasing the orbital population by orders of magnitude may be the one trigger that helps initiate a proactive decision surrounding the aforementioned triggers. An additional growth trigger may be the repurposing of or use of OOS systems in-orbit to perform ADR. Assuming OOS would grow and mature before ADR, as the market is more viable, additional technologies could be "tacked" onto OOS systems. When not pursuing OOS opportunities, these systems could be used to remove pieces of debris in nearby orbits, thus accomplishing two purposes and expanding the business case of such systems.

Maturity Phase. Maturity triggers for ADR signal when ADR has become ubiquitous in space operations. From the political and economic side, this could be events like the creation of an international consortium where governments pay ADR services to remove small debris or the integration of ADR services with space insurance providers. This type of organization could also evolve into or from a public-private partnership. Further down the road, such an organization could become a second Intelsat, transitioning from an organization with government involvement to a purely private company. Technical maturity triggers include the maturation of multiple de-orbit or disposal technologies and the development and standardization of de-orbit CONOPS for multiple orbital regimes, as part of a more expansive STM system. These maturity triggers would signify a shift in the structure of the space industry. With ADR ubiquity, the conception of acceptable risk levels would expand. That lowered risk mentality may alter the number and types of active space actors and orbital systems, as well as lead to an advancement or refinement of liability in space.

Lastly, triggers for decline are meant to show when the necessity of ADR services declines or is no longer required. Decline triggers may include the advancement of onboard capabilities for de-orbit or disposal. It may also include analyses of the debris environment that shows a stable downward or flattening trend that requires minimal ADR operations to continue. Finally, a decline in use of the space domain is an extreme example of a decline trigger for ADR. Figure 1 below shows how these triggers fit into the maturity curve of an ADR and EOL market.

Influence on Space-based Markets

The creation of a debris removal economy would impact several aspects of commercial space. This is especially true given the onset of a commercially driven pLEO. Today, the space industry has an average 10 percent failure rate for launch and deployment.[10] A high failure rate for commercially driven pLEO would result in a much higher number of nonfunctional spacecrafts in orbit in highly populous orbital regimes. As a result, it is likely that debris removal services could pair themselves with the space insurance industry to ensure the timely removal of obsolete or incapacitated satellites.[15,6] This pairing would change the manner in which the space insurance industry is structured, as well as feedback into the structure of satellite development. Today, satellite developers generally attempt to minimize the risk of failure of their systems. While that would still be the case, this feedback of debris removal service availability could result in more space actors taking on additional risk with the development of their satellites. Knowing that a debris removal service is available if the satellite fails, developers are more likely to attempt novel designs and demonstrate new capabilities that may be riskier and/or simpler in design than what is launched today.

Similarly, an established ADR market could increase the level of investment in CubeSats besides use for demonstration purposes. Generally, CubeSats have no form of propulsion and are launched into orbits that follow the voluntary de-orbit guidelines. If a de-orbit service is available for purchase at affordable rates, space actors may see an opportunity in lowering their launch cost by launching CubeSats into an expansive set of orbital regimes and types of operations.

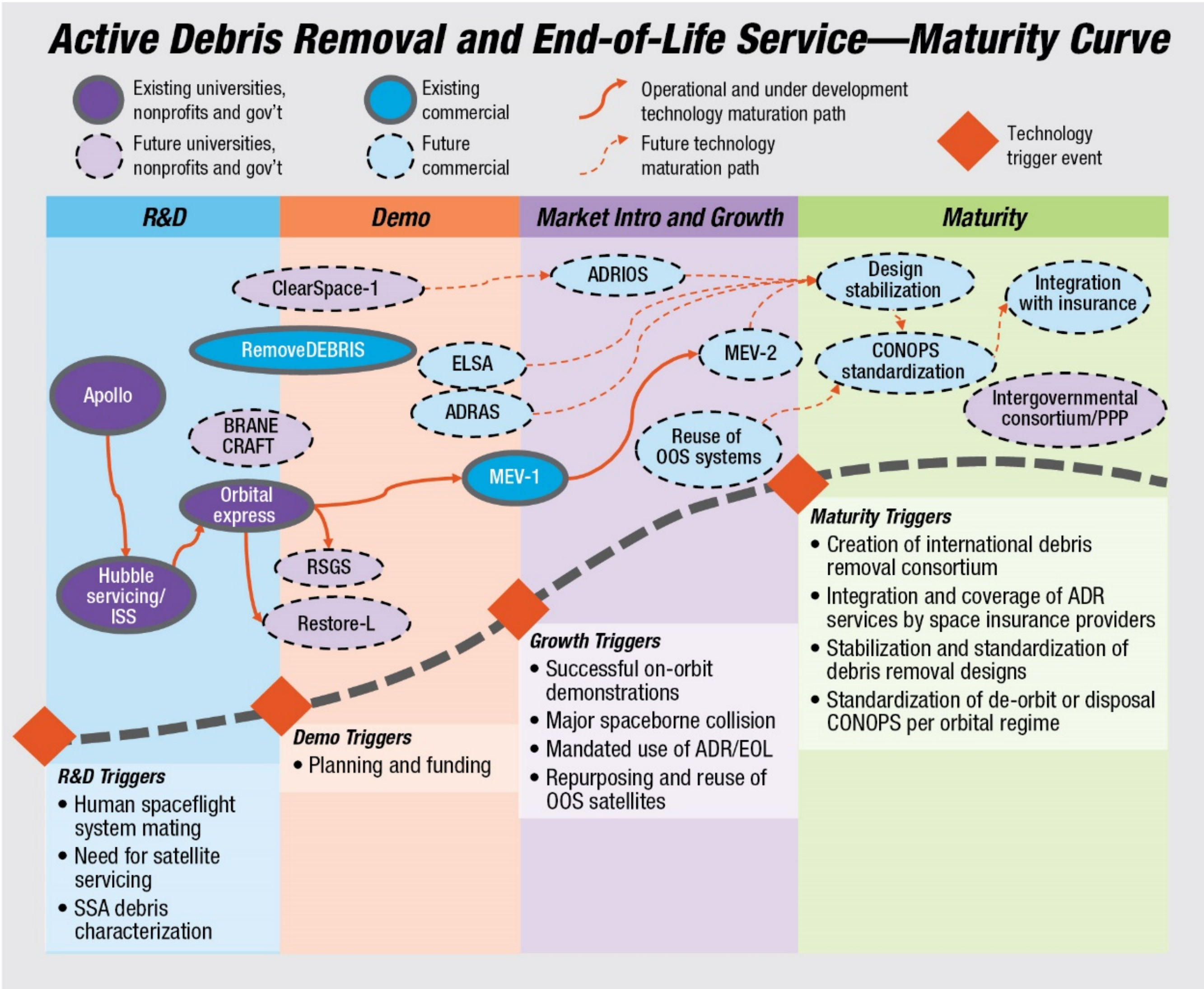

Figure 1: Lifecycle Maturity Curve for Active Debris Removal (ADR) and End-of-Life (EOL) Services. Currently the ADR and EOL market primarily exists within the R&D and Demo phases. Several actors are pushing that into the Market Intro and Growth Phase, but various trigger events must occur to advance the market state of play entirely. Once this market is mature, various events could trigger market decline, including advancement of onboard capabilities for de-orbit or disposal, a stable downward or flattening of the debris environment, or even a decline in use of the space domain.

Conclusion

ADR technologies currently live within the R&D and Demo phases of the economic lifecycle. In order to realize sustainable market demand, and for market solutions to mature beyond the R&D or Demo stages, significant external regulatory support, technical development, and an increase in market certainty is required. This is especially true for small debris removal, where the creation of a sustainable marketplace is much less likely to grow. While the technology to perform RPO has been slowly evolving for decades and becoming more automated over time, ADR technology is approaching a tipping point for realization. However, it requires substantial investment, including proactive government (political and economic) support and commercial (economic) investment. Studies have shown that removal of large pieces of debris substantially slows the growth of the debris population. The market demand for ADR services may be limited to performing such operations unless a more catastrophic triggering event pushes governments toward further investment. As such, the use of ADR systems occupies a niche market, which may be limited to large pieces of debris. However, if certain triggers are met, an extensive ADR economy would have a substantial impact on the space industry.

Acronyms

ADR	Active Debris Removal
ADRAS-J	Active Debris Removal by Astroscale - JAXA
ADRIOS	Active Debris Removal/ In-Orbit Servicing
ASAT	anti-satellite
DARPA	Defense Advanced Research Projects Agency
DIME	Diplomatic, Informational, Military, and Economic
ELSA-d	End-of-Life Service by Astroscale demonstration
EOL	end of life
GNC	guidance, navigation, and control
JAXA	Japan Aerospace Exploration Agency
LEO	low Earth orbit
MEO	medium Earth orbit
MEV	mission extension vehicle
NASA	National Aeronautics and Space Administration
OOS	on-orbit servicing
OSAM	on-orbit servicing, assembly, and manufacturing
RPO	rendezvous and proximity operations
RSGS	robotic servicing of geosynchronous satellites
SSA	space situational awareness
SSTL	Surrey Satellite Technology Ltd
STM	space traffic management

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