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Practical System to Remove Lethal Untracked Orbital Debris

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The environment in low Earth orbit (LEO) is congested with orbital debris threatening the safety of all states, actors, and enterprises who wish to use space. Removing orbital debris is unquestionably one of the top space challenges facing space actors of this generation, one that demands cross-disciplinary solutions to solve this complex systems engineering problem. Based on a review of past and recent approaches to active debris removal, many of the currently proposed technologies and systems focus on removing defunct satellites and other large derelict objects in LEO that are actively cataloged and tracked. While removing the larger space objects is a necessary goal, space sustainability experts agree that the orbital debris ranging from 4 mm to 9 cm poses the greatest risk to operational spacecraft and presents unique challenges for its removal. This paper offers a novel technical approach for the development and near-term deployment of an orbital debris removal system based on existing technology that would be capable of reducing lethal untracked orbital debris in LEO.

I. Introduction

SPACE sustainability has been a critical issue for most developed nations since the Outer Space Treaty was signed in 1967. Telecommunications satellites now comprise more than 60% of all operational satellites in orbit, performing critical functions supporting our way of life, including internet, telephone, data transfer, television, and even financial transactions [1–3]. These space-based assets also perform other important and sometimes critical functions, including navigation and piloting, tracking climate change, environmental monitoring and emergency warning systems, disaster management, Earth science and observation, remote sensing, astronomy and astrophysics, and national security.

An unintended by-product of launching satellites and other objects into space is that millions of pieces of debris have been left in orbit around the Earth. These objects include mission-related objects (e.g., nuts, bolts, pins, shrouds), the debris resulting from deterioration of surfaces (e.g., paint flecks, metals, glasses, composites, plastics), fragments from collisions between derelict spacecraft and other objects, the remains of spacecraft and rocket body breakup events (e.g., due to explosions of batteries or unused fuel), and spacecraft fragments resulting from antisatellite tests. Based on modeling studies, it has been determined that much of the debris currently in orbit will remain there for hundreds and potentially thousands of years, which poses both an immediate threat and future risk to all space actors and activities [4–10]. The congestion of certain orbits, especially those in low Earth orbit (LEO), along with the increasing quantities of space debris and satellites, has further escalated the probability of collisions among both functioning and nonfunctioning space objects and orbital debris [3–5,9,11–18]. Based on humanity's dependence on space-based assets and systems, removing orbital debris from LEO is unquestionably one of the top space challenges of this generation. Solving this challenge will demand nation states, scientists, engineers, industry, and space actors to develop cross-disciplinary solutions to facilitate the design and development of viable systems for removing orbital debris.

II. Origins of Orbital Debris

The sources of orbital debris are primarily human-made, which has been well documented in many studies, papers, presentations, reports, books, documentaries, surveys, and even dramatized in movies [2–5,8–10,12,15,19–22]. Orbital debris information and data have been analyzed and modeled by a number of agencies, organizations, and individuals worldwide, with much of it readily available through public sources. Although there are minor differences in the models and data, orbital debris can be divided into three general categories: 1) micrometeorites and orbital debris (MMOD) objects less than approximately 9 mm; 2) objects greater than 1 cm but less than 10 cm; and 3) objects greater than 10 cm. Obviously, these general categories include a rather wide variety of objects, materials, densities, and quantities within each category. Further, debris compositions, shapes, and velocities for anything smaller than 10 cm are either largely unknown or have been difficult to verify. The data provided in the orbital debris Table 1 summarize the known and predicted orbital debris types, threats, relative risks, and specific issues differentiated by size and orbit.

While objects in the MMOD category comprise the majority of debris in orbit, they are also the least concerning because not only can spacecraft survive collisions with small debris, but also this type of debris can be shielded against. Safeguards employed to protect spacecraft from 3 mm or smaller debris impacts are primarily a type of structural shield composed of reinforced, multilayer insulation (MLI) coverings or "blankets" that provide both passive thermal control and debris protection while in space. Robust materials such as Beta Cloth, Kevlar®, or Nextel® fabrics, and lightweight fiberglass panels are layered in the MMOD shielding to slow and diffuse the energy of small particles before they are able to impact the satellite [9,10,23,24]. As debris continues to proliferate in orbit, MMOD shields have become an essential safety requirement for all spacecraft residing in or passing through LEO.

The second category of orbital debris is primarily composed of human-made objects, including discarded parts from launch and deployment (washers, nuts, bolts, pins, shrouds, etc.), lost equipment from manned missions (books, gloves, thermal blankets, tools, trash bags, even a spatula and a toothbrush), pieces of exploded upper stages, and debris from antisatellite tests and spacecraft breakup events. This class of debris consists of objects approximately the size of a pea (4 mm) to debris approximately the diameter of a baseball (9 cm), and includes more than 1,000,000 of the objects in orbit that are not routinely tracked or cataloged. Impacts with the smaller objects in this class can severely damage a satellite, while a collision with the larger objects in this class have enough kinetic energy to completely destroy a spacecraft [7]. Because MMOD shields are an ineffective mitigation strategy for objects larger than 3 mm, this middle class of "lethal untracked orbital debris" ranging from approximately 4 mm up to 9 cm poses the greatest risk to spacecraft and presents unique challenges to ensuring space sustainability [4,5,7,8]. Further, satellite avoidance

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Table 1 Orbital debris threats, risks and issues differentiated by size and orbit

		Orbital debris size[a]					
		MMOD	Nontrackable	Not actively tracked[b]	Actively tracked and cataloged		
		1–3 mm	4–9 mm	1–9 cm	≥10 cm	>1 m[c]	
	Debris quantities[d]	100,000,000	10,000,000	500,000	19,000	2,000	
	Impact energy LEO (J)[e,f]	70–1,900	1,900–50,000	71,000–8,840,000	>70,700,000	>400,000,000	
	impact energy GEO (J)[e,f]	7–190	190–5,000	7,100–884,000	>7,700,000	>40,000,000	Unique issues
RELATIVE RISK[a,g]	LEO[f]	Very high	High	Moderate	Very low	Very low	LEO has the highest concentration of debris with relative velocities 50 × higher than at GEO.
	MEO	High	Moderate	Moderate	Very low	Very low	Medium Earth orbit
	GSO GEO	High High	Moderate Moderate	Low Low	Very low Very low	Very low Very low	Only objects greater than ~75 cm can be tracked in GEO/GSO with current technology.
	GTO	Low	Low	Very low	Very low	Very low	Spacecraft using GTO have lower risk because they are transitory and do not remain in a fixed orbit.
	HEO	Low	Low	Very low	Very low	Very low	Debris densities at HEOs is relatively low.
	Molniya[h]	Moderate	Moderate	Low	Very low	Very low	The relative risk of a debris collision with spacecraft in a Molniya orbit is significantly less than one in LEO or even GEO most of the time. However, because part of the orbit passes through LEO, there is an increased relative risk.

[a]Generally speaking, larger sizes of orbital debris pose higher levels of damage risk based on mass and kinetic energy, whereas higher quantities of orbital debris pose a greater risk of collision.

[b]Debris in this category has until recently not been actively tracked or cataloged. Recent advancements in ground-based radar (e.g., Space Fence [25]) have opened up the ability to actively track objects as small as ∼1 cm.

[c]Debris in this category includes the very largest of objects such as spent upper stages, derelict spacecraft, and nonfunctioning satellites.

[d]The quantities listed are approximations based on current and past observations, as well as computer modeling. Several worldwide orbital object tracking systems exist that have very high degrees of accuracy for LEO, but less accuracy at higher altitudes.

[e]The estimated kinetic energy (in joules) is based on the average relative velocity of an object impacting another in orbit.

[f]The average relative velocity of debris in LEO is 50× higher than at GEO; thus the kinetic energy of an impact in LEO is 10× higher than an impact in GEO.

[g]Relative risk is an assessment of likelihood of collisions based on a very high–high–moderate–low–very low continuum.

[h]Spacecraft in Molniya orbit have a minor axis that passes through LEO altitudes for several hours each day, which increases relative risk.

GSO = geosynchronous orbit, GTO = geostationary transfer orbit, HEO = highly elliptical orbits.

maneuvers to avoid this type of lethal non-trackable debris have not been feasible.

> *Note:* In March of 2020 the United States Space Force (USSF) declared initial operational capability of the Space Fence radar on the Kwajalein Atoll in the Republic of the Marshall Islands. The Space Fence employs S-band radar arrays capable of detecting debris as small as 1 cm (approximately the size of a marble). However, according to the USSF it will take at least several years to accurately identify, catalog, and track most of the debris in this category [25].

The third category of orbital debris is actively tracked space debris, larger than ∼10 cm (somewhat larger than a baseball). This class of debris also includes much larger objects such as derelict satellites, rocket bodies, spent upper stages, and defunct spacecraft. The Department of Defense, NASA, and other international agencies actively track and catalog space debris in this category, and as a service to satellite operators warnings are transmitted when analysis by the tracking agencies indicates a potential collision with one of these larger objects, allowing satellite operators to implement avoidance maneuvers. This is an effective collision mitigation strategy, but is limited to preventing collisions between operational satellites and the larger tracked objects. Defunct satellites and debris obviously do not have the ability to perform avoidance maneuvers, so collisions between nonoperational objects cannot be avoided, which inevitably leads to collision events and more debris. NASA and other agencies have performed a number of modeling studies of orbits having the highest concentration of debris. These studies tend to agree that the LEO environment could effectively be stabilized by removing as few as five per year of the very large and extremely hazardous objects massing well over 2000 kg and as much as 9000 kg [8,26,27].

Other debris experts believe that a higher risk comes from much smaller but more numerous objects in the 4 mm–9 cm range. In 2013, Nicholas Johnson, NASA chief scientist for orbital debris, stated unequivocally that the greatest risk to space missions comes from untracked debris [28]. A more recent article in *Forbes* echoed this concern [29], as does related articles, posts, and papers from other sources who all agree so much that this class of space junk has been dubbed "lethal untracked debris" [7,30–32]. Avoidance maneuvers and MMOD shields have proven to be effective mitigation strategies for the largest and smallest debris, respectively. However, since objects smaller than 10 cm have not been actively tracked due to technology limitations while objects larger than 3 mm are too large to shield against, this middle class of "lethal untracked debris" ranging from approximately 4 mm up to 9 cm poses the greatest risk to operational spacecraft and presents unique challenges for ensured space sustainability [7,8,26,28–32].

III. Novel Approach to Remove Untracked Orbital Debris

Many technologies for removing space debris have been proposed and, while some show great promise for active removal of derelict satellites and spent upper stages, only a few systems have been proposed to remove untracked orbital debris that pose the greatest risk to operational spacecraft [21,27,33–36]. This observation naturally suggests that development of a system capable of removing this class of debris should be one of the highest priorities to maintain sustainability of space in LEO. Further, the risk of orbital collisions is increasing with the continued deployment of mega-constellations, which in less than two years doubled the number of operational satellites in LEO, and there is some urgency that the system be developed as rapidly as possible.

Proposed here is a novel concept that uses existing, space-ready technology that can be repurposed into a debris removal system capable of being developed and launched in less than five years. The proposed concept uses a deployable perimeter-ring-truss fitted with ballistic materials to create a large orbital debris "net" that, once deployed in a target orbit, would be capable of gathering high-velocity debris. Perimeter-ring-truss mechanisms are typically employed as wide-aperture space antenna systems ranging from 5 to 20 m in diameter (Fig. 1). The AstroMesh® wide-aperture space antenna systems built by Northrop Grumman Astro Aerospace have been flown successfully on commercial and government satellites for 20 years, and have an unprecedented record of on 100% orbit success. According to their company literature: "AstroMesh® is a patented perimeter truss deployable mesh reflector design with over 20 years of space flight heritage. The AstroMesh® family of deployable mesh reflectors have evolved over more than 20 years of continuous development to become the most advanced and reliable reflector technology available. AstroMesh® is the only unfurlable mesh reflector with 100% on-orbit deployment success, with no incidents, no anomalies and no failures" [37–39].

A. Design of the AstroMesh Perimeter-Ring-Truss System

The AstroMesh perimeter-ring-truss consists of a pair of ring-stiffened, geodesic truss domes that, once deployed, form a drum-like structure of exceptional structural efficiency, thermal dimensional stability, and stiffness-to-weight ratios. The deployable perimeter-ring-truss also achieves surprisingly low levels of total mass and stowed volume for these large deployable space structures. The efficient truss and net design of the perimeter-ring-truss also allows for remarkable mass-to-aperture area ratios providing reflector mass-to-area ratios of $0.37\ \mathrm{kg/m^2}$ with diameter increases.

This technology is very mature (technology readiness level (TRL) 9 level) and has successfully flown multiple times in LEO, medium Earth orbit (MEO), and geostationary orbit (GEO) orbits, with many of the AstroMesh reflectors still operational. The perimeter-ring-truss is practical to build using existing materials and technology, and the basic design is the same regardless of aperture size, so an orbital debris system based on this technology would be inherently scalable from approximately 5 m up to 25 m without affecting the fundamental design or functionality. Perimeter-ring-truss systems up to 25 m can be integrated with commercially available spacecraft buses and launched aboard a number of available medium-size launchers, keeping development and launch costs down. The smaller-diameter perimeter-ring-truss systems can even be integrated on smallsats, further reducing deployment costs.

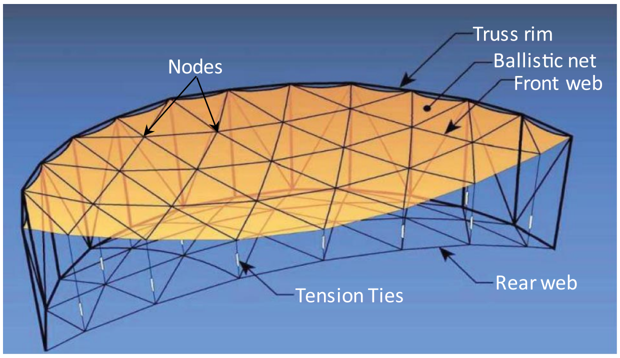

Fig. 2 "Soft good" components of the perimeter-ring-truss system.

The AstroMesh perimeter-ring-truss system, as illustrated in Figs. 2 and 3, is composed of a pair of doubly curved geodesic dome webs that are placed back-to-back in tension across the rims of a deployable graphite-epoxy ring truss. The elliptically shaped deployable ring truss structure is constructed of thin-wall graphite-epoxy tubes with bonded aluminum end fittings. "Longerons" run circumferentially, making up the truss rims, while "battens" connect the front and rear rims and "diagonals" complete each rectangular bay. Each truss bay consists of two longerons, a diagonal, and two battens connected together with aluminum upper and lower truss nodes. Because the entire truss is composed of multiple identical bays, the component commonality and building block assembly reduce production costs significantly. Its structural depth, high structural stability, and the use of standardized truss bay components simplify manufacturing and further reduce production costs.

The front and rear webs are held in tension by spring "tension ties" while the web material is composed of composite or ballistic filaments arranged in a stiff unidirectional matrix forming triangular facets. "Nodes" occur at the intersections of the web matrix, and once the system is in the deployed, fully tensioned state, these nodes become hard points capable of maintaining a minimum uniform tension of $50\ \mathrm{N/m}$ between the mirrored upper and lower web nodes. Once assembled and deployed, the "soft-goods" (i.e., webs, mess, and tension ties) and structural truss (i.e., longerons, diagonals, battons, and truss nodes) make up a quasi-geodesic dome geometry that is remarkably stiff normal to the plane of symmetry between the two webs, creating a highly stable tensioned drum-like structure.

When the truss is stowed, the batten, longeron, and diagonal truss members are packed together and form a narrow, hollow cylinder, with

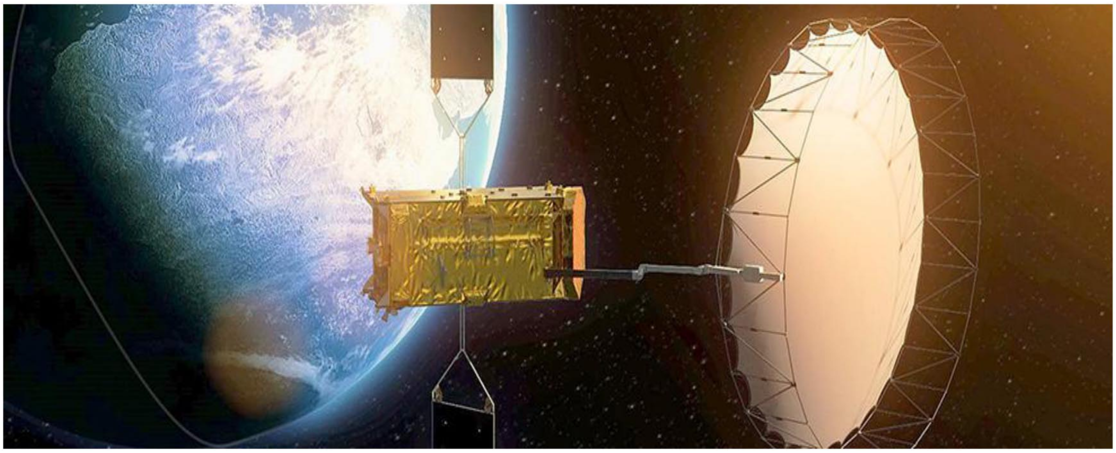

Fig. 1 AstroMesh Deployable Ring Truss antenna system on satellite in LEO.

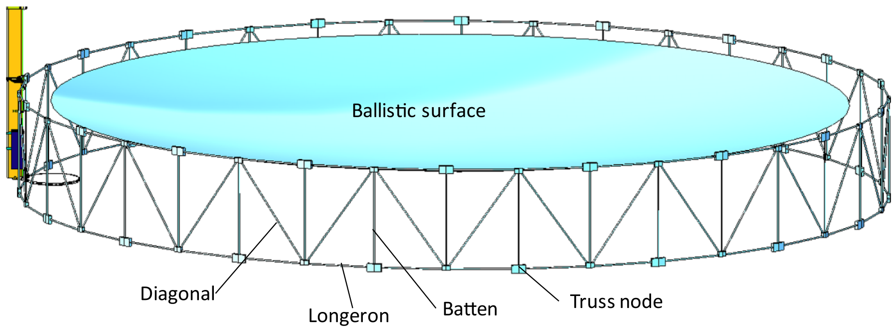

Fig. 3 Structural components of the perimeter-ring-truss system.

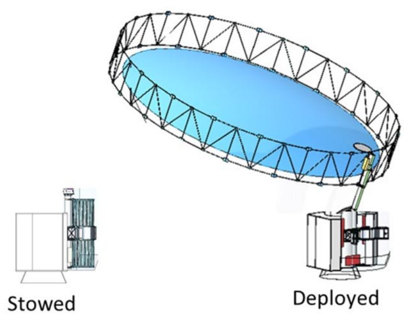

Fig. 4 Stowed and deployed perimeter-ring-truss configurations on notional satellite.

each end preloaded against lightweight composite endcaps that provide debris-shielding for the stowed package. The resulting stowed package is a barrel-like structure that is strapped into lightweight aluminum and composite tie downs during launch and while orbit raising to the final on-orbit destination. The structural stiffness of the truss allows it to be directly mounted from the edge of the ring truss to the satellite, allowing for efficient stowed volume and a stable structure once deployed from the satellite (Fig. 4).

The perimeter-ring-truss system is an inherently robust structure, fully able to deploy in both ground and space environments while maintaining its structural stiffness (ground deployment shown in Fig. 5). While on orbit, the truss maintains abundant stiffness in all directions while remaining kinematically coupled to withstand satellite induced loads even during deployment. Once the tie downs to the spacecraft have been released, the truss system expands naturally due to the release of stowed energy from the tightly packaged bundle of truss members. Deployment continues with a motor-powered phase to full deployment. Perimeter truss kinematics during the deployment phase is controlled by a single robust motor-driven deployment cable that provides synchronous, kinematically unified behavior and low levels of strain in the system. Because the cable enjoys a significant mechanical advantage over perimeter truss kinematics, considerable work-energy is transferred into the truss system at the end of deployment by the cable until the truss latches solidly, thus requiring no further motor cable tension. As a result, the perimeter truss system is unpowered once fully deployed, simplifying on-orbit operations and reducing power loads on the spacecraft.

While satellite antenna applications of the AstroMesh perimeter-ring-truss system employ a radio-frequency (RF)-compatible mesh surface composed of gold-plated molybdenum wire knitted in a tricot configuration, the proposed orbital debris system would replace the mesh with ballistic materials to create a large durable surface that, once deployed in a target orbit, would be capable of gathering high-velocity debris.

B. Design of the AstroMesh Whipple Shield

Existing space-qualified materials such as a Kevlar and Nextel fabrics would be employed in construction of the ballistic surface, with several layers employed in a “Whipple shield” configuration

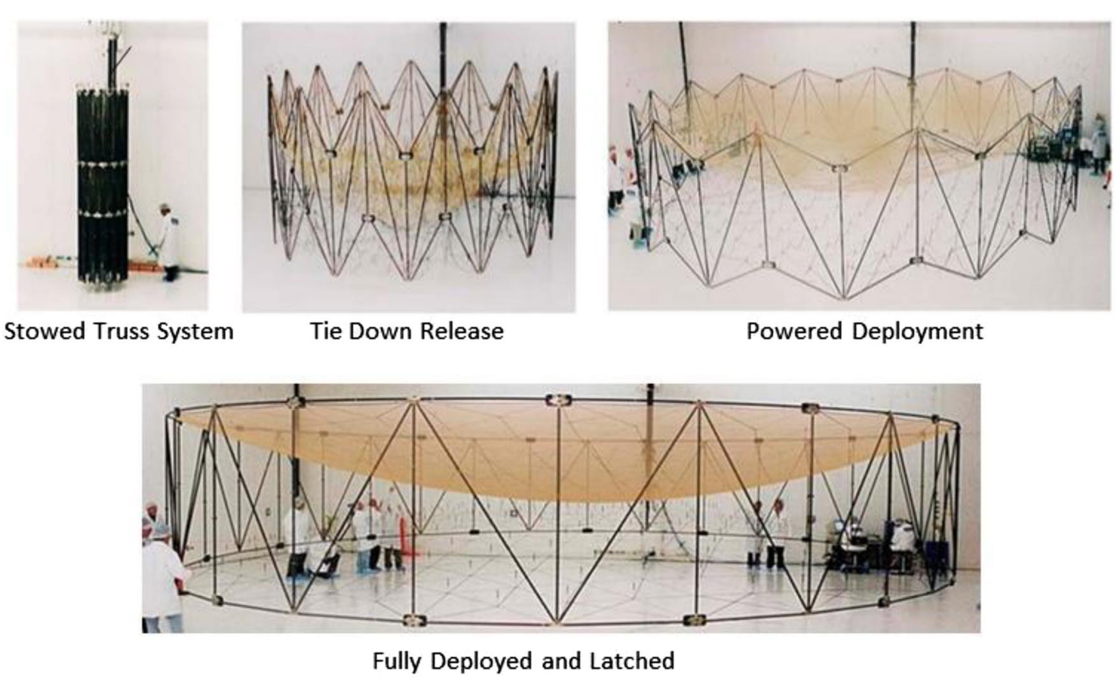

Fig. 5 AstroMesh perimeter-ring-truss system deployment sequence.

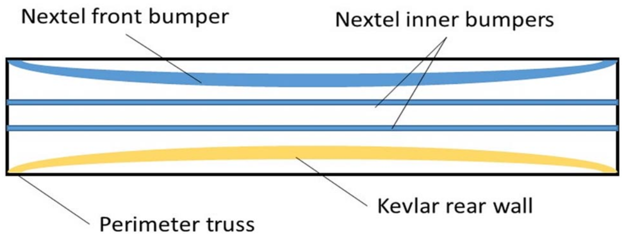

Fig. 6 AstroMesh ballistic Whipple shield configuration.

(Fig. 6). Both Kevlar and Nextel ballistic fabrics are robust, space-qualified materials commonly layered in MMOD shielding to slow and diffuse the energy of small particles before they are able to impact the spacecraft. Variations of Kevlar and Nextel Whipple shields have been used extensively on the International Space Station (ISS), on inflatable modules, and for MMOD shielding on satellites for several decades [10,23,24].

The conceptual design of a Whipple shield for the AstroMesh orbital debris removal (ODR) system was based on NASA's Handbook for Designing MMOD Protection [40], using the following recommended equations [Eqs. (1) and (2)] for preliminary design of the wall thicknesses for the front "bumper" and rear "wall" for a Whipple shield:

$$t_b = c_b m_p/\rho_b = c_b d \rho_p/\rho_b \tag{1}$$

where
t_b = thickness of bumper (first layer)
c_b = coefficient 0.25 when $S/d < 30$, and $c_b = 0.2$ when $S/d \geq 30$
S = overall spacing between outer bumper and rear wall (cm)
d = projectile diameter (cm)
m_p = projectile areal density (g/cm^2)
ρ_b = bumper density (g/cm^3)
ρ_p = projectile density (g/cm^3)

$$t_w = c_w d^{0.5}(\rho_p \rho_b)^{1/6}(M_p)^{1/3}(V_n/S^{0.5})(70/\sigma)^{0.5} \tag{2}$$

where
t_w = thickness of rear wall (last layer)
c_w = coefficient 0.16 cm$^2 \cdot$ s/(g$^{2/3}$ km)
d = projectile diameter (cm)
ρ_p = projectile density (g/cm^3)
ρ_b = bumper density (g/cm^3)
M_p = projectile mass (g)
V_n = normal component of projectile velocity (km/s)
S = overall spacing between outer bumper and rear wall (cm)
σ = rear wall yield stress (ksi)

In addition to the front bumper and rear wall, inner bumpers would be added to further diffuse the kinetic energy of captured debris. The initial design assumed that all bumpers would be constructed of Nextel AF10 fabric, while the rear wall would be constructed of Kevlar fabric. Further design and analysis needs to be performed before a final design for the AstroMesh ODR system Whipple can be accomplished.

While Eqs. (1) and (2) are useful for understanding how Whipple shield wall thickness is derived, in practice the BUMPER code [40] software tool would be used to design and analyze shields for the AstroMesh ODR system. The BUMPER software has been in use since the early 1990s and is the standard tool used by NASA and contractors to perform debris risk assessments on spacecraft. The BUMPER code has been employed on MMOD shielding for most iconic space systems such as the International Space Station, the Space Shuttle, the Russian Mir space station, and both government and commercial satellites and spacecraft [40].

Once the Whipple shield is designed, installation will be somewhat atypical from a standard AstroMesh reflector. The RF mesh is typically stretched beneath the webs into an elliptical surface precisely designed to meet the desired optical properties of the frequencies to be reflected. Because this is not a requirement or even desirable for the ODR system, the front bumper will replace the RF mesh; however, instead of being stretched beneath the webs, the bumper will be loosely installed over the webs, thereby providing a soft, pillow-like surface so that energy from 9 cm and smaller debris impacts will be considerably diffused. This configuration should further serve to minimize impact energy from being transmitted through the system to the spacecraft. Decoupling the front bumper and rear wall from the elastic webs that provide structural stability to the perimeter-ring-truss system will help ensure that if debris larger than 9 cm strikes the ballistic surface it will not impart unacceptable levels of disturbing torques on the spacecraft bus.

C. Potential LEO Targets for the AstroMesh Orbital Debris Removal System

Significant collision events have been well-documented by NASA and other agencies, and as a result several likely debris targets have been identified for the proposed perimeter-truss orbital debris removal system. One target of opportunity would be the Fengyun-1C spacecraft debris field resulting from an antisatellite missile test in January 2007, which accounts for some 20% of the cataloged human-made objects in orbit, much of it being of the 9 cm and smaller type of debris. A second potential target would be the debris field from the collision of the Cosmos 2251 and Iridium 33 satellites in February 2009 [3,41–43].

Operationally, once the host satellite reaches the target orbit the proposed ODR system would be deployed with the ballistic surface being placed directly in the path of the orbital debris cloud. The ballistic surface would act like a baseball catcher's mitt, absorbing the kinetic energy of the targeted orbital debris and trapping the objects between subsequent layers of ballistic fabrics and the rear wall. While not specifically designed to capture other sizes of debris, it is likely that the ballistic surface would also capture objects and debris both smaller and larger than the targeted 4 mm–9 cm space junk. Sensors or cameras mounted on the rim of the truss monitored by ground systems would document effectiveness of the system. After a predetermined period of time on-orbit, the system should have captured sufficient quantities of debris, and the satellite/truss system would be deorbited with the captured space junk, burning up on reentry.

Although further analyses need to be conducted, preliminary debris capture estimates for a 12 m AstroMesh ODR system deployed over a 1-year period would number in the thousands. Because the system is inherently scalable, once a smaller-scale (e.g., 5–9 m) demonstration mission was proven successful, larger AstroMesh ODR systems could be manufactured and deployed to ensure the maximum debris removal yield for each mission. The 5, 9, and 12 m perimeter-ring-truss systems are flight-proven build-to-print designs, so development costs would be limited to the Whipple shields and integration of the ODR spacecraft system.

IV. Insights and Advantages of the AstroMesh Orbital Debris Removal System

The orbital debris removal system proposed in this paper provides a number of advantages over other proposed debris removal concepts presented in papers reviewed by the author. A review of past and recent approaches to both passive and active debris removal determined that the majority of proposed technologies focus on removing the defunct satellites and other intact objects in LEO that are actively cataloged and tracked. While removing the larger—and potentially most damaging—large space objects is necessary, it may not be the most urgent action for reducing the vast quantities of space debris that threaten sustainability and security of space assets, especially in LEO. One insight from this research was that various models and papers on orbital debris in LEO uniformly supported the conclusion that 4 mm–9 cm debris was not regularly tracked, or cataloged. As pointed out in the body of this paper, with the operational capability of the recently completed Space Fence, lack of information on the 1 cm and larger debris may be mitigated in the future. However, according to the USSF and Lockheed Martin, it will likely take years to track and catalog the millions of pieces of debris ranging from 1 to 9 cm. Of note was that the Space Fence is currently unable to track debris smaller than 1 cm, so a gap in data will continue to exist for lethal untracked debris ranging from 4 mm to 1 cm.

Another, perhaps somewhat obvious insight revealed in the research was that MMOD shielding is unable to protect spacecraft from the 4 mm to 9 cm class of debris, which potentially has enough kinetic energy to destroy a spacecraft. As discussed, performing avoidance maneuvers is currently not an option for spacecraft to avoid collisions with debris smaller than approximately 10 cm. A number of papers also agreed that this potentially lethal class of untracked space junk continues to pose the greatest risk to all spacecraft due to its small size, vast quantities in orbit, and potential lethality [7,8,26–32].

In parallel research, the author performed an extensive trade study of orbital debris removal technologies [44]. One of the most significant insights from that research was that to be effective, the ODR system should be designed to capture the targeted class, quantities, and orbit of debris. For instance, while this paper proposes a practical ODR system for removing 4 mm–9 cm debris, this system would be totally unsuited to capture and remove a defunct spacecraft or tumbling upper stage. Several other ODR systems would be better suited for those missions, and in fact a number of technologies have been proposed and are being developed to pursue that type of debris. While this may seem like a logical conclusion, previous research reviewed by the author failed to identify any instance where this insight was asserted. The trade study was also a useful tool to identify the most appropriate ODR system given the debris type, size, and orbit by simply changing the weighting of a number of key factors in the trade space. Because the trade study research went beyond the scope of this current paper, it will be documented in additional papers and presentations in 2021 and 2022 [44].

V. Conclusions

Removing orbital debris from LEO is one of the top space challenges of this generation, one that requires an extraordinary response if we are to solve this extremely complex systems engineering problem. A review of past and recent approaches to both passive and active debris removal determined that the majority of proposed technologies focus on removing the defunct satellites and other intact objects in LEO that already have mitigation measures in place, such as collision avoidance maneuvers. While removing the larger space objects is a reasonable goal, this paper concluded that the most urgent action is to reduce the large quantities of untracked but highly damaging space debris in the 4 mm–9 cm range. Further, because MMOD shielding is unable to protect spacecraft from this class of debris, which has enough kinetic energy to destroy a spacecraft, this potentially lethal class of space junk poses the greatest risk to all spacecraft due to its small size and vast quantities in orbit.

In response to this threat to space sustainability, this paper presented a novel technical solution for the development and deployment of a perimeter-ring-truss-based orbital debris removal system capable of trapping lethal untracked orbital debris in LEO. As discussed in the paper, deployable perimeter-ring-truss systems are recognized throughout the aerospace industry as superior space structures that are both inherently light and stiff and for their unmatched on-orbit deployment success. Compared with other active debris removal concepts, the simplicity and structural efficacy of an orbital debris removal system based on the build-to-print AstroMesh perimeter-ring-truss, coupled with the high TRL and fully space-qualified designs available in various diameters, yields a solution with low development and fabrication costs and a short-term schedule to on-orbit deployment. The proposed orbital debris removal concept also supports a minimum schedule program, with rapid hardware deployment on-orbit to meet the urgent demand of removing orbital debris within years rather than decades.

Additional work must be performed to realize the proposed orbital debris removal concept proposed in this paper. While much of the system is based on off-the-shelf designs, more effort will be required to finalize the Whipple shield concepts proposed in this paper. Results from the ODR technology trade study project, which was briefly introduced in the previous section, should be completed and published. Further, a consensus will be needed from government (NASA, USSF, etc.) and commercial actors on the most valuable targets for removing lethal untracked debris. Funding and support will also be necessary to move forward with further design and development.

While space debris poses an urgent and continuing risk to space sustainability, this paper provided one potential solution for mitigating one of the top space challenges of this decade. The paper discussed various types, quantities, and risks of existing space debris, especially in LEO. It went on to describe a potential technical solution for removing lethal untracked debris based on existing, space-qualified, TRL 9 technology. The paper concluded that this and other proposed ODR systems must be developed and deployed on orbit if we are to achieve the goal of maintaining a safe and secure space environment for the good of all humankind.

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