Orbital Debris Skimmer (Skimmer for short)

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Innovations

- Up to 50 meter-per-second (mps) de-orbit DV of small 2-4 cm orbital debris objects is 99% electrically powered, which saves fuel, extends the mission to many, many objects.
- Kevlar capture bag allows energic capture up to 1 mps, vs the common <0.01 mps capture, which saves fuel.
- Kevlar capture bag also embeds mm scale objects between the bag's layers, sweeping up an unlimited number of these mm sized objects these up in normal ops.
- 3U packaging for easy rideshare placement.
- Unique elements are packed into 1U, allowing the other 2U to be COTS sourced.
- The unique hybrid water thruster from Pale Blue allows safe long term storage so the cubesat can be added to empty slots in rideshares, possibly greatly reducing launch costs.
- Unique hybrid water thruster from Pale Blue also allows the high ISP (2000s) Ion engine to low thrust, long duration tasks, while allowing the same water reservoir to feed the 1mN resistojet for last minute capture adjustments.
- COTS Startracker in center U can also track debris.
- With fuel conservation, and Kevlar capture, the 3U cubesat is designed to perform many small orbital debris object captures and de-orbit missions over a multi-year lifetime.

Overview

Many concepts for orbital debris removal have been suggested, from direct capture with a robotic arm, to the use of nets, harpoons, plasma jets and lasers. Given the variety of orbital debris targets, from large upper stages to dead satellites, to stray bolts and finally to post collision fragments of many shapes and sizes, there is no single concept that can address them all. The Skimmer concept is meant to address smaller objects, no larger than 10 cm across.

When removing these smaller objects, the mechanism of removal needs to be highly reusable, perhaps removing 24-300 of these objects before it needs to de-orbit itself. While solar power is nearly unlimited, maneuver fuel is not. Any solution for small objects needs to minimize the fuel used to remove an object. Skimmer can use the orbital momentum of the orbital debris object itself, in conjunction with a crossbow inspired ejector that is completely solar powered, allowing fuel use to be reduced by 95% compared to a solution that was simply capture and move to a lower altitude. In this way Skimmer can essentially skip across a set of similar orbits (which often occurs after orbital collision) cross-bowing the object into a new lower energy orbit (that should deorbit in 100-1000 days) while providing Skimmer a bit of DV to move to the next object capture (thanks to conservation of momentum). Figure 1 depicts how the classic crossbow can be redesigned to apply DV to an orbital debris object without the use of fuel.

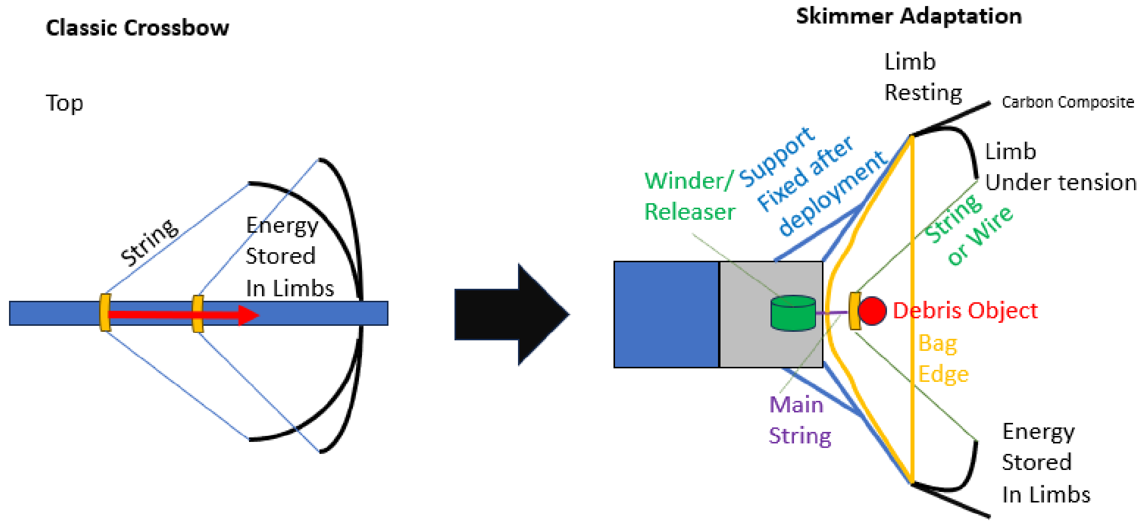

Figure 1. Translating a crossbow into an orbital debris removing cubesat

The Talisman Mantis Elite Crossbow can launch a 460 grain (26 gram) arrow at up to 200 meters-per-second (mps). This seems like the highest velocity available, but a search of Google returns a number of low-cost crossbows that exceed 300 feet-per-second (fps) so we will 100 mps as a conservative value of how fast a crossbow type mechanism can launch a 25 gram object. This is pushing off a static launcher, so the arrow gets all the momentum transfer, but with the Skimmer, you have 4-5 kg average mass to push off of, so much of that force goes into the velocity of what is launched vs the launcher itself. The exact amount is governed by conservation of momentum:

$$M_{object} \times V_{object} + M_{skimmer} \times V_{skimmer} = 0$$

100 mps is DV applied to quickly drop a space craft like Cargo Dragon down to a de-orbit altitude form the ISS. Some studies have suggested that 11 mps can lead to de-orbiting in special cases[1]. We will use a launch velocity and angle that creates the expectation of a 100 day deorbit of a 25 gram object from 500km. As a starting point, we will assume a 50 mps exit velocity in the optimal deorbit direction can be achieved for a 25g object which will provide most of the DV for the Skimmer to rendezvous with the next target.

[1] https://conference.sdo.esoc.esa.int/proceedings/sdc7/paper/1008/SDC7-paper1008.pdf

Figure 2 expands on this by showing the outcomes from slightly more massive orbital debris objects.

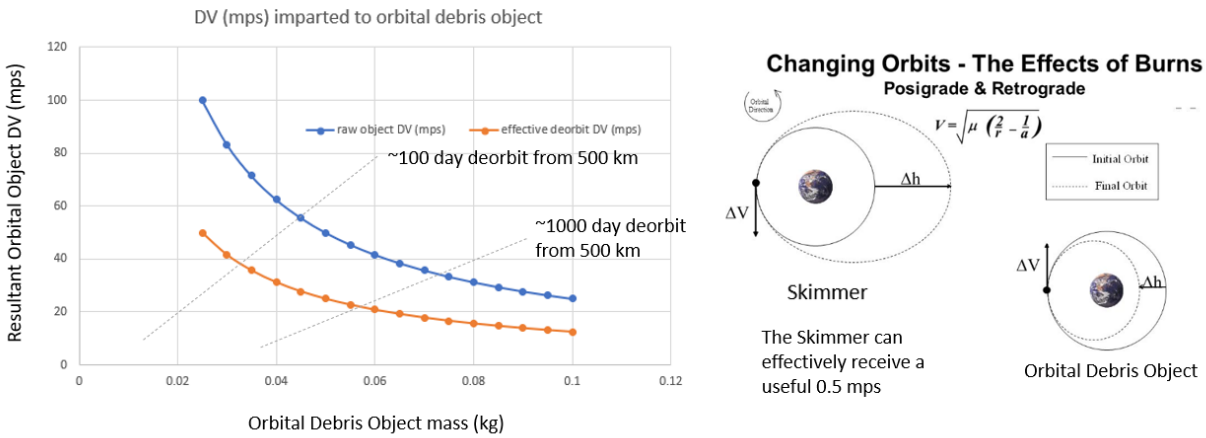

Figure 2. Expected deorbit time after DV, which can happen 24 – 300 times in a Skimmer lifetime[2]

The deobit DV of the orbital debris objects (which is the opposite direction of its orbit) will result in a small orbit boosting DV to the Skimmer, effectively 0.5 mps, that can move the Skimmer toward the next target. The water thruster will be needed to finalize the next crossing rendezvous. Please note these rendezvous operations occur over long periods of time, allowing for small DVs to lead to many productive rendezvous.

Another way to minimize fuel use is to reduce how precise the rendezvous must be. Rendezvous chases to 0.01 mps (needed for grabbing with a robotic arm) can be fuel expensive. With Skimmer most captures will be off center ones under 1 mps. This is well within kelvar capabilities, but off-center captures can lead to significant tumbling, so a magnetorquer will be used to slowly detumble the Skimmer with no or minimal fuel use. With the addition of small reaction wheels, the Skimmer will return to an attitude that is optimized for a combination of object de-orbit and Skimmer boost launch of the orbital debris object.

[2] Depending on clustering of orbital object targets, with a "cloud" offering many more opportunities

Skimmer Design

Skimmer's reference design is a 3U cubesat. A U is a 10cm cube. From front (which is the debris object facing side) to back, the first U is the capture and crossbow cube, the center U is the control, power, comms and other essential functionality U, and the 3rd U is a water-based thruster. A water thruster provides high thrust with a non-toxic "fuel" that can easily be used as low-cost capacity fillers on rideshare missions. Skimmer is designed to be approximately 4 kg of dry mass total. Skimmer uses a Kevlar 60 cm x 60 cm catcher that collapses on catch, designed to allow a 1 mps relative velocity catch of a 25g object.

The concept can be scaled up to a 12 U cubesat that can handle 200 gram 10 cm wide objects using a 1m x 1m capture area, but in this proposal we will discuss only the 3U Skimmer reference design.

The reference design for Skimmer is based on a 3U package that is easy to deploy with various rideshare missions. The approach is to use as much COTS hardware as possible. Good solutions are now available for thrust and the general satellite operations as 1U connectable modules (see figure 3). Only 1U of the 3U needs to be created specifically for the mission, namely the capture bag and crossbow like ejector and closure components (see figure 4).

Skimmer Components

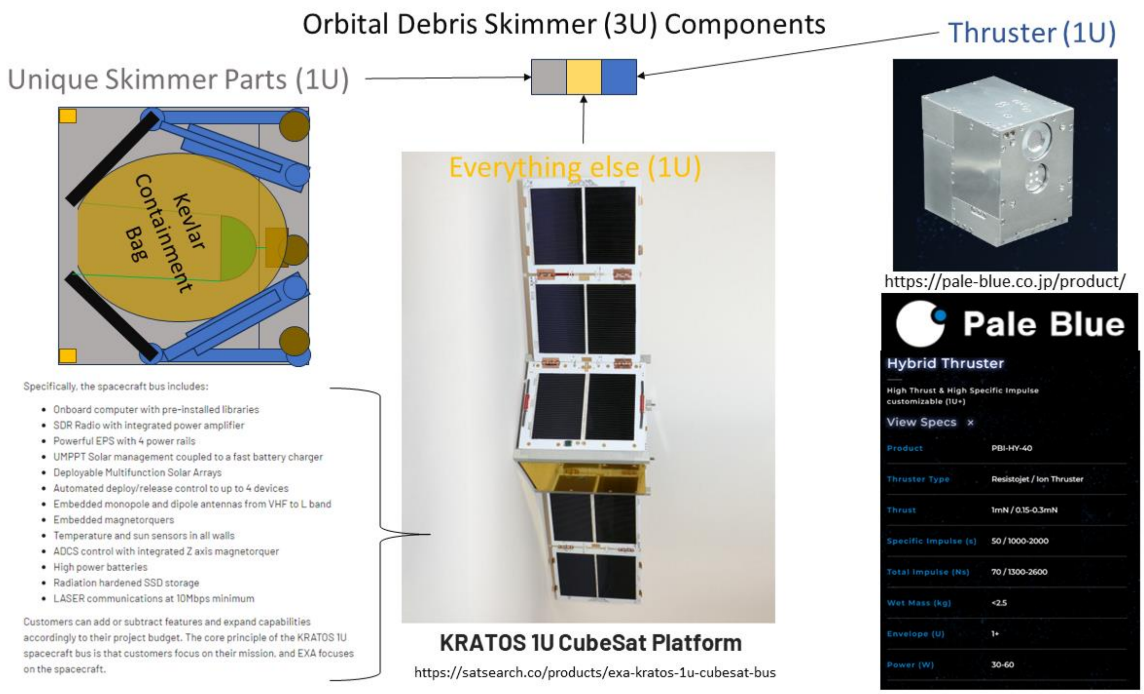

Figure 3. Major Skimmer Components

Front U (The unique orbital debris remediation parts)

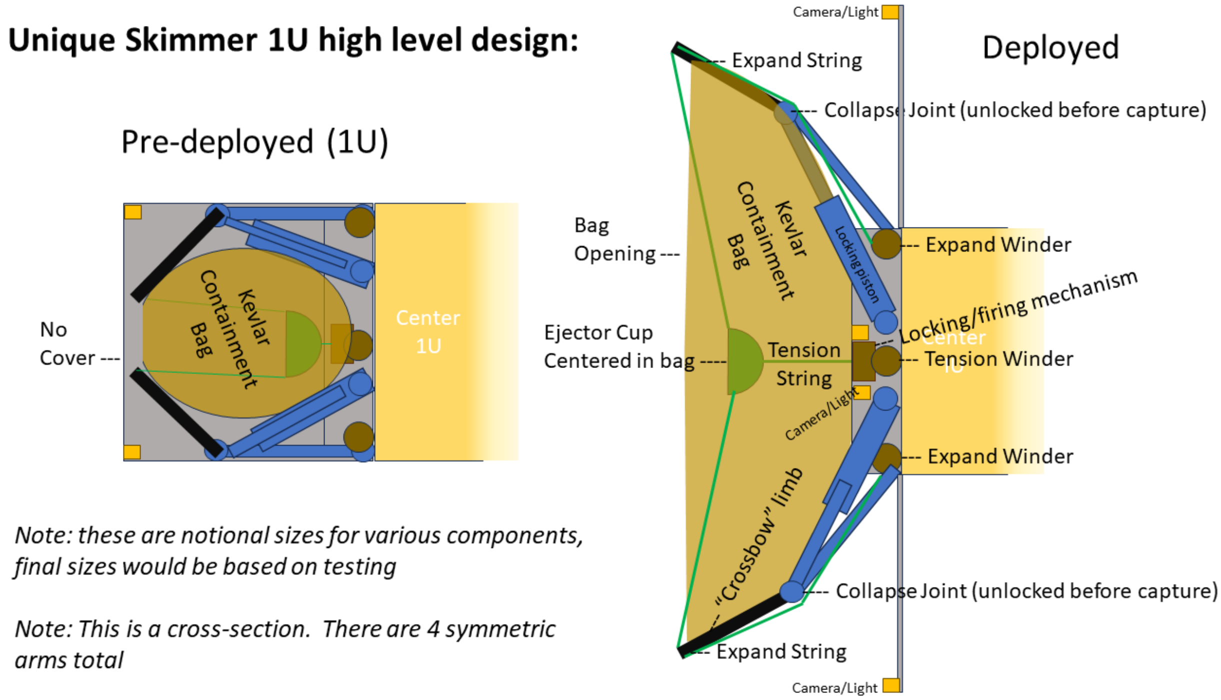

Figure 4. Unique Skimmer 1U high level design

"Crossbow" Ejector Limbs

The materials and mass are estimated from a carbon composite crossbow which is a type of crossbow that uses carbon fiber as the main material for the limbs, which are the flexible parts that store and release energy when shooting. Carbon fiber is a very strong and lightweight material that can improve the performance and durability of crossbows. Carbon fiber has a long history of use in space, including robot arms.

The weight of the limbs of a carbon composite crossbow depends on several factors, such as the length, width, thickness, shape, and design of the limbs, as well as the type and amount of carbon fiber used.

High performance crossbow limbs can be found at less than 0.4 kg a pair. Given that the Skimmer design can be optimized for the mission, the needed limbs will be shorter and thinner, resulting in a total mass estimate for the ejector limbs to be around 0.2 kg. With Kevlar bag and other components this U should be less than 0.8 kg.

The Kevlar capture bag

While the value of Kevlar vests in stopping bullets with up to 100 mps velocities is well known[3] the 1-2 mps impact on the Kevlar capture bag won't require nearly the layers of a bullet proof vest. It is expected that a few layers will be sufficient with a total mass of 0.2 kg. The selection of the right type and Kevlar and the specific bag design is important. Some preliminary testing will suggest the best design that both captures a 2-4 cm wide object intact and also allows smaller mm sized particles to get

[3] https://www.sciencedirect.com/science/article/pii/S2214914718301727

stuck between the top and bottom layers of the bag. These embedded mm sizes orbital debris objects will be de-orbited with the rest of the cubesat at its end of life. Kevlar has a long history of use in space operations.

Although packaged at 1U, the final size of capture bag opening will be at least 30 cm wide and may be wider based on testing an overall system optimization.

The Center U (Common Support Functionality)

All cubesats need a core set of functionalities, such as power, computing, comms and pointing. It is best to purchase a good solution that has been tested and then integrate it with the 2 other U. The KARTOS 1U solution highlighted is a good refence solution. Ultimately it might be replaced with another 1U solution, but KARTOS 1U does represent a flight proven solution at an affordable list price of around $40K. The extended solar panels may be folded (or segments deleted) in a way that they are fully behind the Kevlar bag so that a near miss does not lead to a solar panel impact.

Back U (The thruster)

Pale Blue's Hybrid Thruster is a good candidate to provide this functionality. It draws from one water tank to provide the type of thrust/ISP needed at any time. The Crossing Rendezvous will need high resistojet thrust just before object capture. Otherwise, the Ion Thruster will provide high ISP but lower thrust for orbit changes and the positioning of the orbital debris object before ejection. Given the average wet mass of the cubesat is about 4 kg, this should provide about 650 m/s for orbital adjustments.

$$\Delta v = \frac{I}{m}$$

Given that $I = 2600\,\mathrm{Ns}$ and $m = 4\,\mathrm{kg}$

$$\Delta v = \frac{2600\,\mathrm{Ns}}{4\,\mathrm{kg}}$$

$$\Delta v = 650\,\mathrm{m/s}$$

Figure 5

We should reserve 50 mps for final deorbit, leaving 600 m/s to work with.

Note that the Hybrid thruster has an extendable water tank option. This allows a 4U design with a 2U Hybrid Thruster to do potentially 4-6x the work since the ion and resistojet masses are the same, but now have much more water to work with.

Also, factor in that the orbital debris ejection process with create a small DV as well.

In a cloud of debris situation, where we allow for a 1 mps capture velocity, we might have fuel for 300 object captures (factoring in the orbital debris object ejection DV).

Skimmer CONOPS

The following is a high level summary of the Concept of Operations for the use of Skimmer, from planning to productive orbital debris object deorbiting to final Skimmer end-of-life disposal.
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CONOPS: Operational Modes

- Initial Deployment
- Initial unfold and check out
- Crossing Rendezvous mode (same place, but with up to 1 mps difference in relative velocity)
- Capture mode (milli-sec bag collapse with 98% closure)
- De-tumble mode (use of reactions wheels, magnetorquers)
- Debris inspection, positioning, deorbit/boost prep
- Deorbit/boost/De-tumble mode
- Deorbit mode

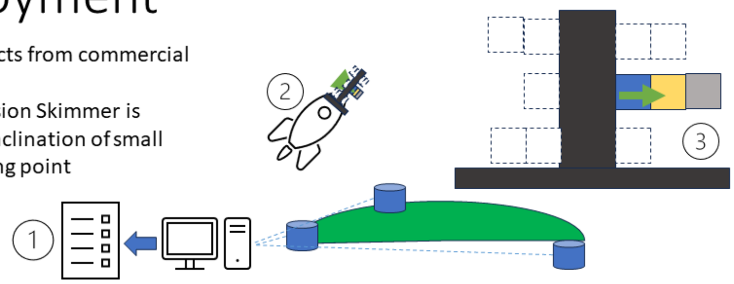
2 times a month*

When Mission Fuel Expended

* There is potential that within a debris cloud caused by an orbital breakup, operations could be increased by a factor of 10x, as long as the objects remained within the max tracking distance of the Skimmer sensor

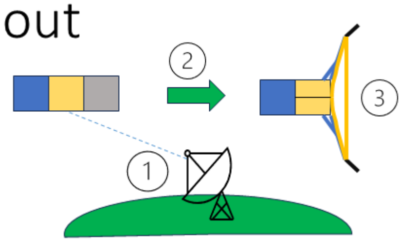
CONOPS: Initial Deployment

1) Develop a listing of best orbital debris objects from commercial and government sources and their orbits.
2) Perhaps on a cubesat type "rideshare" mission Skimmer is launched into an orbit within 1 degree of inclination of small orbital debris objects. SSO is popular starting point
3) Skimmer is deployed into LEO



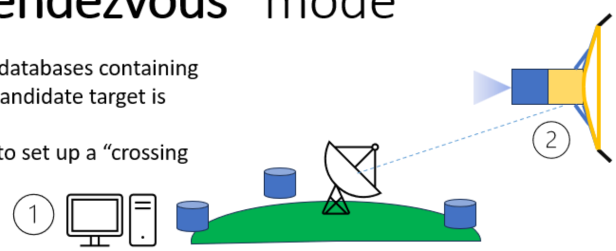
CONOPS: Initial unfold and check out

1) Establish Comms with Skimmer
2) Test subsystems
3) Deploy capture bag



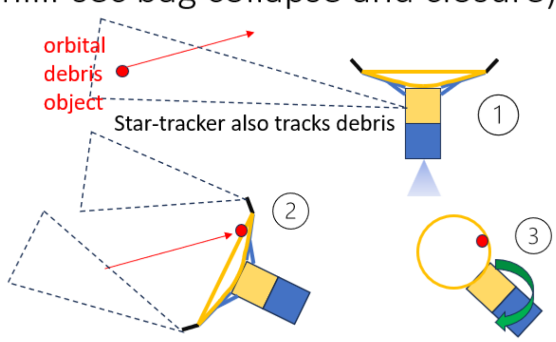
CONOPS: "Crossing Rendezvous" mode

1) Based on exact orbit of Skimmer, and using databases containing the orbits of small orbital debris objects, a candidate target is selected based on the most update data
2) Skimmer performs a "burn" of the thruster to set up a "crossing rendezvous" with the target



CONOPS: Capture mode (milli-sec bag collapse and closure)

1) When within 10 km of expected crossing rendezvous Skimmer begins to scan for the object with both visible and IR sensors. Thruster fires to create a close rendezvous
2) Reaction wheels spin the Skimmer so that the orbital debris object impacts the Kevlar bag, which is flexible and absorbs the energy
3) The bag collapses keeping the orbital debris object and any small particles that may have broken off it inside. But with the off-center impact, the Skimmer will start to tumble

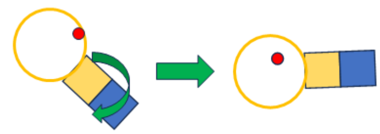


Crossing rendezvous will require occasional human checks based on latest data.

Capture will be automated.

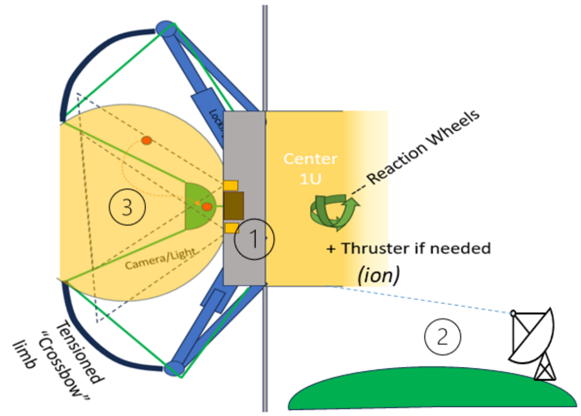
CONOPS: De-tumble mode (use of reactions wheels, magnetorquers)

1) It is likely Skimmer is tumbling, so gradual use of reaction wheels and magnetorquers should bring the system to rest after a week or two.



CONOPS: Debris inspection, positioning, deorbit/boost prep

1) After de-tumble cameras examine the state of the orbital debris object
2) Ground operators determine the best next steps
3) The orbital debris object needs to be moved into the ejector cup through the use of reaction wheels and thruster if needed

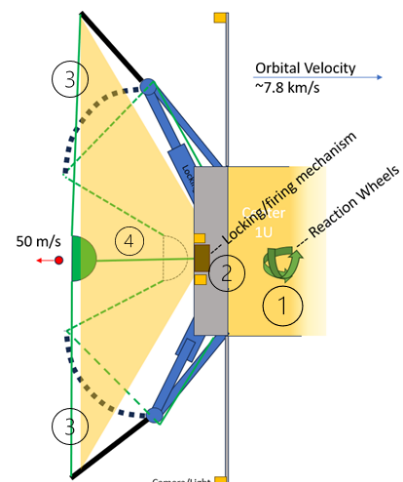


De-tumble will be automated.

Debris inspection and positioning will be human in the loop process that will need to be performed during a good comms window.

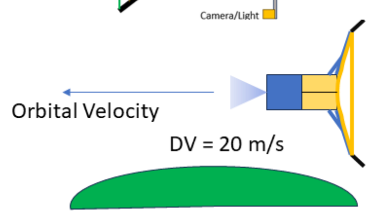
CONOPS: Deorbit/boost/detumble

1) Reaction Wheels orient Skimmer into an optimal direction to achieve orbital debris object deorbit at 50 m/s and to slightly boost Skimmer toward the next target (note that 50 m/s will allow the exact ejection angle to have a safety factor of maybe +/- 10 deg from optimal)
2) The locking/firing mechanism fires (unlocks)
3) The "crossbow limbs" fling the cup outward as they release the energy from being in tension and return to a resting state
4) The cup is stopped at the end of the string, and will be rewound over time, with the expand string unwound enough to maximize bag capture area
5) Given the object ejection is not tightly controlled, some small detumbling steps may be needed



CONOPS: Deorbit

1) When mission fuel burn times indicate there is just enough fuel to re-enter (20% safety margin) Skimmer will thrust in a optimal set of burns to re-enter in 100 days.



Costing

In the near term, costing is expected to follow the industry standard of $50K per U deployed over a production run of 10, so $150K each. 2 of the 3 U are created by companies with track records of success with cubesats which should reduce cost and technical risk. The most expensive part of development will be the R&D and testing for the unique Skimmer 1U cube.

In the longer time frame, new delivery systems like Starship may reduce the launch cost part of the solution, and longer manufacturing runs, allow then entire Skimmer to be create and operate at $50K per satellite including operations for 5 years if 100 have been deployed. In the short run, a $150K system could mitigate 24 2-4 cm sized objects per year if greatly separated or up to 300 total if clustered in a cloud, and many more millimeter objects.

Mass production and lower launch costs could bring the cost down to $50K per Skimmer. It is suggested that 100 Skimmers be built and placed for $5M and a team of 3-5 staff operate them a $1M per year. For a total cost of $6M to mitigate up to 30,000 2-4 cm objects, or $200/object. If objects are not in a cluster, then costs might be closer to $2000/object. If small mm fragments are in close proximity to the 2-4 cm object, then many of these may also be captured for eventual deorbiting.

By using a water thruster, these cubesats should be storable at launch sites for some time, allowing them to be added at the last moment to rideshares. The rides might be donated, or deeply discounted since this would be lost revenue anyway to the launch provider.

In Conclusion

Skimmer represents an idea that maximizes the use of solar power to conserve fuel for orbital debris removal operations. Many concepts involve capture and then the deorbit of the device as well as the orbital debris object. Skimmer emphasized energetic capture and de-orbit reuse with a minimal amount of fuel and a maximum amount of solar energy. The Skimmer can deorbit many orbital debris objects during its multi-year operational lifetime. The costs are low enough that building, deploying and operating a fleet of 100 Skimmers that can clear up to 30,000 objects over a few years will be more cost effective than any other solution.

Summary Tables

Challenge	**Solution**
Fine orbit determination of the target orbital debris objects.	Commercial services are emerging to track very small space debris objects, perhaps from this challenge. Companies like Privateer, LeoLabs, Scout are moving toward 2 cm wide object tracking: https://breakingdefense.com/2019/10/leolabs-new-radar-tracks-tiny-space-debris/
Good full time comms including video	In the short run, the orbital debris object de-orbit preps in the CONOPS would need to be performed during overflight of ground links. In the future, companies such as Quantum Space and Kepler are planning an "internet in space" that should allow on demand low latency video.
Low cost sensor for orbital debris object tracking for intercept	The use of a cubesat's Startracker can double as an orbital debris tracker. https://spacenews.com/upgraded-star-trackers-could-give-more-satellites-a-debris-monitoring-role. Slower capture velocities may be needed.

Risks

Risk	**Mitigation**
Normal Cubesat reliability risks	The use of COTS for everything but Skimmer unique functionality should mostly eliminate the reliability issues that are more common in hand built solutions.
Loss of comm/control	After a period of ground silence Skimmer would automatically point and thrust to de-orbit Skimmer
Orbital debris object disables the cubesat	The critical parts for Skimmer deorbiting are not in line with orbital object velocity vector at capture. Skimmer should be able to detumble automatically and then provide thrust to deorbit the entire system.
Orbital debris object destroys the cubesat creating more debris	With any capture system there is a small chance that an interaction will result in breakup of the mitigation satellite. The 1 mps relative velocity of capture with the Kevlar bag should prevent an interaction that would break apart the cubesat. The solar panels will be sized to be behind the Kevlar capture bag so a near miss won't result in solar panel interaction.
Orbital debris object breaks up on capture	In the event of orbital debris object breakup, the closing of the capture bag should contain most fragments. Human inspection can determine if the fragments are either embedded in the bag or are free floating. If free floating, can they be maneuvered into the ejection cup? If not, the Skimmer can apply a deorbit burn with its ion thruster to create a DV for deorbit, then open the bag and rotate the Skimmer away from the particles which will be free to deorbit. Skimmer can then apply thrust to go to another target. Please note this will be fuel expensive and cut down a Skimmer's lifetime by maybe 25%.

Requirements Coverage of this Proposal

Challenge and Physics-Based Justification	Clearly define the primary challenge that the proposed solution aims to overcome within the context of small debris detection, tracking, or remediation. Offer a feasible physics-based explanation of how the proposed solution effectively addresses the identified challenge. The physics-based explanation must include exemplary technical rigor including use of references, figures, and/or scientific algorithms	This Skimmer concept addresses small debris remediation. Fig 2, 6 Support for DV needed for deorbit is 20-50 mps is covered in: https://conference.sdo.esoc.esa.int/ proceedings/sdc7/paper/1008/SDC7-paper1008.pdf
Effectiveness of the System	Estimate the potential effectiveness of the system by specifying the number of millimeter and centimeter-sized debris objects that the solution can address on an annual basis. Provide a rough order of magnitude (ROM) cost estimate for the development and deployment of the proposed system, supported by relevant justification.	In the short run, a $150K system could mitigate 24 2-4 cm sized objects per year if greatly separated or up 300 total if clustered in a cloud, and many more millimeter objects. In the long run, mass production and lower launch costs might bring the cost down to $50K per Skimmer. It is suggested that 100 Skimmers be built and placed for $5M and a team of 3-5 staff operate them a $1M per year. For a total cost of $6M to up to 30,000 objects.
Discussion of Key Technical Risks	Identify and discuss the key technical risks associated with the proposed concept. Provide insights into potential challenges or obstacles that may arise during the implementation or operation of the solution.	Please see risk table above
Optional: Additional Visual Aids	Participants may include additional visual aids, such as graphs, charts, or diagrams, to enhance the clarity and understanding of their concept.	Hopefully the enclosed diagrams helped to explain this somewhat complicated concept.