DELTA INFINITE

Capture-First Operations:

How Foam-Based Pre-Stabilization Unlocks the Non-Cooperative Orbital Capture Value Chain

A Technical White Paper on the Space Object Acquisition and Capture System (S.O.A.P.S.)

Kai Cahlil
Founder & CEO, Delta Infinite

April 2026
CONFIDENTIAL — PRE-DECISIONAL

Executive Summary

No entity on Earth has demonstrated the ability to capture a tumbling, non-cooperative, uncharacterized object in orbit. As of early 2026, every on-orbit capture or docking ever performed has involved a cooperative or at least geometrically known, attitude-stable target. The approximately 1,300 massive derelict objects in LEO—dead rocket bodies and satellites totaling over 2,300 metric tons—remain beyond the reach of any fielded system.

This gap exists because the industry has treated capture as a single-step problem when it is, in fact, a cascading chain of unsolved dependencies: characterization, pre-stabilization, universal capture, and post-capture stabilization. Every rigid-contact capture system hits a hard operational limit between 1 and 5 degrees per second of angular velocity, while real debris objects can tumble at 10–30°/s. No contactless detumbling technology has ever been demonstrated in orbit.

Delta Infinite’s Space Object Acquisition and Capture System (S.O.A.P.S.) addresses this gap with a fundamentally different approach: a proprietary expanding polymer foam that is deployed from a servicer vehicle to envelop, adhere to, dampen, and stabilize non-cooperative targets regardless of their geometry, surface composition, or tumble state. By exploiting the space environment itself—hard vacuum eliminates atmospheric backpressure, enabling isotropic hyper-expansion; microgravity eliminates gravity-driven drainage—S.O.A.P.S. creates a stable mechanical interface on objects that no existing rigid system can engage.

This white paper synthesizes the competitive landscape, the technical literature on capture success criteria, foam science and validation research, and the emerging economic framework for orbital mass management to establish the following thesis:

> *S.O.A.P.S. occupies a vacant, structurally necessary layer in the ISAM value chain. It is the pre-stabilization and universal capture capability without which the entire non-cooperative active debris removal market cannot function. Delta Infinite is not building a better version of what competitors already offer. It is building the missing prerequisite.*

The company is currently at TRL-3, with a concrete six-month validation roadmap to TRL-4. A pre-seed raise of $150K–$250K funds the bounded validation sprint that converts promising material behavior into characterized, integration-ready engineering data. The immediate technical program is scoped, the R&D team is assembled with Advanced Space providing orbital dynamics and mission integration support, and the path from validation through seed-stage flight demonstration is defined.

1. The Problem: A Cascading Chain of Unsolved Dependencies

The non-cooperative debris capture challenge is not a single technology gap. It is a sequential chain where each step requires the previous one to be solved before the next becomes relevant. The industry has built impressive capability for cooperative targets and is beginning to demonstrate close-approach inspection of non-cooperative debris. But the critical operational sequence for true non-cooperative capture remains largely unproven.

1.1 The Cooperative / Non-Cooperative Divide

The active debris removal and on-orbit servicing market has matured rapidly since 2020, but virtually all commercial traction has come from cooperative or semi-cooperative targets—objects that are attitude-stable, geometrically known, or equipped with pre-installed docking interfaces.

Northrop Grumman’s MEV program holds the strongest operational record with successful GEO dockings, but exclusively on attitude-stabilized satellites with known geometry. Astroscale’s ELSA program requires pre-installed ferromagnetic docking plates—a fully cooperative architecture. ClearSpace’s four-arm robotic system is designed for tumble rates up to only 3°/s. Starfish Space’s electrostatic adhesion assumes the target is attitude-stable. Even the most promising non-cooperative demonstrators—Astroscale’s ADRAS-J, which achieved a 15-meter approach to a 3-ton H-2A upper stage—triggered an autonomous abort at closest approach due to a relative attitude anomaly.

The divide is structural: every commercial system that has physically contacted a target in orbit has done so with a cooperative object. The non-cooperative population—the actual debris—remains untouched.

1.2 The Angular Rate Wall

The technical literature converges on a critical finding: current rigid-contact capture systems fail when target angular rates exceed roughly 3–5°/s, while real debris objects can tumble at up to 30°/s. The failure mode is well understood. When a robotic arm contacts a tumbling object, the entire angular momentum transfers to the combined chaser-target system, potentially overwhelming the servicer’s attitude control. Without knowing the target’s mass and inertial properties, impedance matching becomes impossible.

ESA’s CAT-IOD program tested magnetic capture at up to 1°/s—an extremely conservative threshold. Harpoon systems achieve success probability above 80% only at around 1.4°/s. Net-based systems offer broader tumble tolerance but risk creating an entangled, uncontrollable combined system at high rotation rates.

1.3 The Characterization Problem

For a truly non-cooperative target, mass, moment of inertia, 3D geometry, surface properties, center-of-mass location, and the angular velocity vector are all unknown and potentially unknowable from remote observation alone. Model-free pose estimation using sequential RGB images exists at TRL 3–4 in academic research but has not been operationally demonstrated. ADRAS-J’s 15-meter inspection represents the most advanced real-world characterization achieved to date.

1.4 The Detumbling Gap

The logical precursor to capture—reducing a target’s tumble rate to within a capture system’s tolerance—remains entirely unproven in space. Every proposed contactless detumbling method sits at TRL 2–4: eddy current braking requires impractically close proximity; ion beam shepherd technology has never been tested in orbit; laser ablation requires precise knowledge of target geometry and surface properties; thruster plume impingement can accelerate rather than decelerate rotation. This comprehensive absence of flight-proven detumbling creates a critical dependency:

every capture system's tumble-rate ceiling becomes a hard operational limit with no demonstrated method to bring targets below it.

1.5 The Vacant Middle Layer

The ISAM ecosystem has developed robust capabilities for space situational awareness on one end and emerging capabilities for servicing and deorbit on the other. Between these sits a poorly served middle layer: close-range characterization, tumble assessment, pre-capture stabilization, universal capture, post-capture detumbling, and handoff to a servicing or deorbit vehicle. No company offers pre-stabilization as a standalone service. All current ADR architectures assume the capture vehicle must handle the entire chain, creating enormous vehicle complexity and driving costs to levels like ClearSpace-1's €86 million for a single 95 kg object.

2. The Solution: Foam-Based Capture-First Operations

Delta Infinite's S.O.A.P.S. resolves the cascading dependency chain by fundamentally changing the physics of the capture interface. Instead of matching a rigid mechanism to an unknown, tumbling target, S.O.A.P.S. deploys a reactive polymer foam that conforms to whatever it contacts. The foam does not need to know the target's geometry, surface material, or angular state. It simply expands, adheres, and cures.

2.1 Core Operating Principle

S.O.A.P.S. is a bi-component expanding polyurethane system deployed from a servicer spacecraft at a controlled standoff distance of 0.3–0.6 meters. The two reactive components are ejected through impingement nozzles at 18–37 m/s, intermixing in transit and contacting the target surface at the onset of gelation. In the hard vacuum of LEO, the absence of atmospheric backpressure causes the foam to hyper-expand isotropically—uniformly in all directions—forming a homogeneous cellular matrix that envelops the target surface.

The microgravity environment eliminates gravity-induced fluid drainage, allowing the foam to maintain uniform density distribution during curing. The resulting structure consists of cells approximating tetrakaidecahedrons—14-sided polyhedra—whose geometric regularity ensures that mechanical properties (crush strength, densification strain, energy absorption) are virtually identical across all loading axes. This isotropy is critical: a tumbling object can impact the foam from any direction and receive uniform attenuation.

2.2 The Soft-Capture Envelope

Exhaustive mechanical characterization defines the operational boundaries of S.O.A.P.S. across the mission-relevant parameter space:

- **Target mass range:** 10 kg to 1,000+ kg (scalable with foam volume)
- **Angular velocity range:** 0.1 to 5.0 rad/s (approximately 0.6°/s to 286°/s)

- **Low-mass targets (10–50 kg):** Manageable at full 5.0 rad/s due to favorable foam-to-target mass ratio
- **Heavy targets (500 kg):** Operational ceiling at 2.8 rad/s (~160°/s), above which centrifugal forces exceed the 17.3–22.0 MPa vacuum adhesion limit at a 2.0 m effective radius
- **Large derelicts (1,000+ kg):** This is the target class NASA explicitly solicited under Z-Expand.04—large uncooperative objects exceeding 1,000 kg with difficult-to-dock-with surface characteristics. Objects in this class include the SL-16 (Zenit) and SL-8 rocket bodies (8–9 tons each) and ESA's 8-ton Envisat, which collectively dominate the top-50 most dangerous derelict list. At these masses and effective radii (2.5–5+ m), the adhesion-limited angular rate ceiling drops to approximately 1.5–2.0 rad/s (~86–115°/s)—still 30–40 times higher than the 3°/s ceiling of the best rigid capture system in development. Foam volume scales linearly with target surface area, and multi-pass dispensing sequences can build up coverage on the largest objects.

The contrast with the state of the art is stark. ClearSpace-1 is designed for 3°/s on a 95 kg target. NASA's SBIR solicitation (Z-Expand.04) specifically called for solutions addressing objects above 1,000 kg—a class where no rigid capture system has demonstrated or even designed for the tumble rates that real-world debris exhibits. S.O.A.P.S. addresses this exact solicitation gap: large, uncooperative, tumbling objects that every existing system either cannot reach or has not been tested against.

2.3 Energy Dissipation Mechanism

Under dynamic compression from a tumbling target, the foam undergoes a three-phase stress-strain response: initial linear elasticity (cell wall bending), an extended plastic collapse plateau (progressive buckling and yielding of cellular struts), and terminal densification. The extended crush plateau is the key feature—it provides a constant-stress energy absorption region where massive amounts of kinetic energy are dissipated without transmitting shock loads to the servicer vehicle. This is fundamentally different from rigid capture, where contact forces during high-speed engagement are catastrophically large.

2.4 Thermal-Kinetic Management

LEO thermal cycling between approximately −150°C (eclipse) and +120°C (solar irradiation) poses the primary environmental challenge to foam chemistry. Delta Infinite's thermal simulation work has evaluated three cold-mitigation strategies: phase-change material (PCM) integration, polysiloxane backbone reformulation, and UV/IR radiative curing assist. The UV/IR approach achieves the widest validated operational window (−120°C to +100°C), leveraging the space environment's radiation flux rather than fighting it.

2.5 The Four Innovations

Non-Contact Encapsulation: Unlike rigid systems requiring precise contact geometry, S.O.A.P.S. adheres to and encapsulates the target regardless of surface features, eliminating the need for pre-installed interfaces or known geometry.

Self-Applying Stabilization: Upon adhesion, the foam continuously dampens rotational and translational motion through viscous energy dissipation, converting a tumbling debris object into a stabilized mass that downstream systems can engage.

Universal Docking Interface: The cured foam matrix provides a predictable, uniform surface that any conventional docking mechanism can grip—transforming an object of unknown geometry into one with a standardized mechanical interface.

Surface Independence: Foam expansion and adhesion are driven by the space environment itself, not by target properties. The system works on metal, composite, MLI, painted surfaces, and irregular geometries without modification.

3. Competitive Landscape and Positioning

S.O.A.P.S. does not compete with existing capture systems. It enables them. Every current non-cooperative ADR architecture hits the angular rate wall described in Section 1.2. S.O.A.P.S. operates below that wall—converting objects from “non-cooperative and uncontrollable” to “stabilized and engageable”—so that downstream systems can function.

Entity	Approach	Max Tumble	Target Type	Non-Coop Status
Northrop Grumman	Mechanical probe / robotic arms	~0°/s	Cooperative GEO	No non-coop capability
Astroscale	Magnetic plate / inspection	~0°/s (ELSA)	Cooperative (ELSA); Known non-coop (ADRAS-J2)	ADRAS-J2 FY2027: first physical non-coop attempt
ClearSpace	4-arm robotic grasp	3°/s	Known non-coop	ClearSpace-1 launch 2028–2029
Starfish Space	Electrostatic adhesion	~0°/s	Attitude-stable	No tumbling capability
KMI (REACCH)	Gecko adhesion tentacles	TBD (ISS only)	Geometry-agnostic	172 ISS capture cycles; no orbital demo
TransAstra	Inflatable Capture Bag	Shape-agnostic	Envelopment	1m ISS demo; 10m bag by 2028
Delta Infinite	**Expanding polymer foam**	**Up to ~115°/s (2.8 rad/s @ 500 kg; ~1.5 rad/s @ 1,000+ kg)**	**Surface & geometry independent**	**TRL-3; TRL-4 validation funded at pre-seed**

The strategic positioning is not “we do capture too.” It is: we provide the pre-stabilization layer that makes everyone else’s capture system work on the targets that actually matter.

3.1 Complementary Relationships

S.O.A.P.S. is architecturally complementary to, not competitive with, the companies building downstream capture and servicing capabilities:

- **Starfish Space:** S.O.A.P.S. pre-stabilizes a tumbling target and creates a flat, uniform foam surface for Nautilus electrostatic adhesion—extending Starfish's addressable market from attitude-stable to non-cooperative targets.
- **ClearSpace:** S.O.A.P.S. reduces target tumble rates from operational levels (10–30°/s) to below ClearSpace's 3°/s design threshold, enabling their robotic arms to engage targets they currently cannot.
- **KMI:** Foam pre-stabilization reduces angular rates before REACCH tentacle engagement, extending KMI's system to higher-tumble targets where gecko adhesion faces centrifugal shedding limits.
- **Astroscale:** For non-cooperative targets beyond ADRAS-J2's scope, S.O.A.P.S. provides the stabilization step that Astroscale's distributed capture-and-transfer architecture (per their patent portfolio) requires but does not yet possess.

4. Defining Capture Success for Non-Cooperative Targets

Public standards and guidance converge on a shared pattern for defining capture outcomes: define zones and decision points to manage collision risk; define contact conditions to manage energy, loads, and ESD; require abort/cancel behaviors; and require post-contact stability for the combined configuration. Delta Infinite has developed a phase-gated framework that maps S.O.A.P.S. operations to these established criteria.

4.1 Pre-Contact Success

Achievement of planned proximity objectives without unintentional contact; maintenance of safety envelopes (approach zones, keep-out zones, approach corridors); and demonstration of credible abort/cancel behavior. S.O.A.P.S. operations maintain the servicer at 0.3–0.6 meters—well outside physical contact range—while deploying foam across the gap. Abort capability is inherent: cessation of foam dispensing immediately terminates the capture sequence with no physical link to sever.

4.2 Contact Success

First touch occurs within a defined contact envelope, does not generate debris, and does not compromise the servicer or target. S.O.A.P.S. contact is inherently soft—foam arrives at the target surface during the high-viscosity gelation phase, generating negligible impact forces. There is no rigid-body collision, no angular momentum transfer to the servicer at the moment of contact, and no risk of ESD discharge through a conductive mechanical interface.

4.3 Capture-and-Stabilize Success

After first touch, establishment of a retained physical connection and reduction of relative motion to a stable stack condition controllable for the next mission objective. This is the phase where S.O.A.P.S. is uniquely advantaged: the foam continuously dampens angular velocity through viscous energy dissipation as it cures, progressively converting kinetic energy to heat until the combined system reaches a quiescent state. The cured foam then provides both the structural bond and the standardized mechanical interface for downstream handoff.

4.4 Release/Abort Success

If criteria are violated, execution of retreat to a passively safe state. S.O.A.P.S. abort modes are mechanically simple: before foam contact, the servicer retreats with no residual connection. After partial foam deployment, the dispensed material adheres to the target but does not create a rigid tether—the servicer can separate by ceasing dispensing and maneuvering away. Deployed foam that does not complete a capture sequence remains attached to the target as an inert polymer mass, generating no new debris.

5. The Economics of Capture-First Infrastructure

The economic case for S.O.A.P.S. operates at two levels: near-term service economics within the existing ADR market, and long-term infrastructure economics within the emerging orbital mass management paradigm.

5.1 Near-Term: The ADR Service Wedge

The ORBITS Act of 2025 authorizes $150 million for FY2026–2030 for a NASA Active Debris Remediation Demonstration Program. The USSF's Orbital Prime program has awarded 175 contracts worth $121 million across segmented tracks (approach, capture, servicing). ESA's Zero Debris Charter has over 205 signatories. The demand signal is forming.

However, these programs are constrained by the cooperative/non-cooperative divide. ClearSpace-1 costs €86 million to remove a single 95 kg object. The economics cannot scale to the ~60 large debris removals per year that modeling indicates are needed to stabilize the LEO environment.

S.O.A.P.S. as a modular pre-stabilization service changes the cost structure: instead of requiring every ADR vehicle to handle the entire capture chain (driving vehicle complexity and per-mission cost), a dedicated pre-stabilization pass converts the target to a state that simpler, cheaper downstream vehicles can handle. This architectural decomposition—already emerging in Orbital Prime's segmented track structure and Astroscale's patent portfolio describing separate capture and reentry vehicles—is the market structure S.O.A.P.S. is built for.

5.2 Long-Term: Orbital Mass as a Resource

Recent analysis from the COSMIC consortium (March 2026) establishes that for LEO constellation operators, delivering end-of-life satellites to an orbital depot is more Δv-economical than deorbiting and relaunching—for all orbits within ±38° inclination of the depot when replacement costs are factored in. The cumulative mass in LEO already exceeds 13,500 metric tons.

The COSMIC analysis directly parallels Delta Infinite's long-term thesis. Table 1 of that paper compares asteroid/lunar resource utilization (8 steps starting with prospecting and mining) to LEO satellite recycling (7 steps starting with capture). In both cases, capture is step one. The entire depot-based circular economy for orbital mass—refueling, salvage, manufacturing—requires someone to capture and deliver objects to the depot. S.O.A.P.S. is the capture layer.

This reframes Delta Infinite from a debris removal company into capture-first infrastructure: the system that makes uncooperative mass controllable, regardless of whether that mass is destined for deorbit, recycling, servicing, or relocation. Debris removal is the near-term wedge. Orbital mass logistics is the long-term position.

5.3 The Servicer-Client Mismatch and How S.O.A.P.S. Resolves It

The COSMIC cost-modeling workshop (January 2026) identified a fundamental mismatch: service providers cannot commit until they have demand, and clients will not commit until assets are in place. The GAO's 2025 ISAM report identified a parallel "chicken-and-egg problem": servicers will not develop non-cooperative capabilities until targets are designed for servicing, and operators will not design for servicing until services exist.

S.O.A.P.S. breaks this deadlock. By converting non-cooperative targets into cooperative ones, it eliminates the requirement for targets to be "designed for servicing." The installed base of 1,300+ massive derelicts in LEO becomes immediately addressable without requiring any change to the targets themselves. This is the difference between waiting for the market to evolve and creating the enabling capability that allows the market to function.

6. Technical Maturity and Validation Roadmap

6.1 Current State: TRL-3

Delta Infinite has demonstrated promising material behavior at the prototype level, including vacuum expansion, adhesion to representative surfaces, vacuum stability, and multiple formula variants. Coupled physics simulations model foam expansion and curing behavior in hard-vacuum LEO conditions across three cold-mitigation scenarios. An automated trade study pipeline queries the Space-Track.org catalog for SSO dead payloads and rocket bodies, computes delta-v requirements, estimates thermal environments, and outputs ranked target lists bridging directly to the thermal simulation.

6.2 TRL-4 Validation Program (6 Months)

The TRL-4 program is structured around four validation pillars, each reducing a specific technical risk:

Pillar A: Material-Level Validation

Adhesion measurements on representative debris materials; compressive, shear, torque, and tensile strength validation; cure-kinetics benchmarked in vacuum; density uniformity and cell structure mapping; repeatability assessment across batches; structural degradation analysis following thermal and radiation cycling.

Pillar B: Environmental Simulation

Thermal cycling across the LEO-relevant range; vacuum chamber expansion characterization; UV and radiation exposure effects on cured foam properties; outgassing quantification against ASTM/ECSS/JAXA thresholds.

Pillar C: Laboratory Deployment Characterization

Nozzle performance testing for standoff distance and velocity envelope validation; 6U prototype hardware integration; capture dynamics simulation with instrumented targets; preliminary autonomous control policy development.

Pillar D: Partnership and Pre-Flight Alignment

Systems-integration trade study with Advanced Space; preliminary interface control documents (ICDs); FMEA and capture-risk analysis; documented path to hosted-payload or free-flyer demonstration.

6.3 TRL-4 Outputs

The validation sprint produces three categories of deliverables:

- **Material & Environmental:** Validated S.O.A.P.S. foam material specification sheet; environmental performance dataset (vacuum, radiation, thermal, micro-impact)
- **System & Integration:** Updated system architecture and deployment diagram; preliminary ICDs; FMEA and capture-risk analysis
- **Seed-Readiness:** NASA SBIR Phase II-ready technical packet; flight demonstration concept roadmap; validation data package enabling TRL-5 transition

6.4 Team and Support

Kai Cahlil operates as founder, CEO, and principal investigator. Jim Cochran-Miller supports engineering validation and environmental simulation. Michael Browne supports chemistry and materials science. Advanced Space, LLC provides orbital dynamics, mission integration, requirements definition, delta-v budgets, attitude-control sizing, and system trade studies under a signed trade study agreement. ATTX Technologies partners on modeling, simulation, and capture dynamics.

7. Strategic Position and Market Entry

7.1 Why Now

Three converging forces create a time-bound opportunity window:

- **Regulatory acceleration:** The FCC 5-year deorbit rule is now in effect. The ORBITS Act authorizes $150M for ADR demonstrations. ESA's Zero Debris Charter targets zero new debris by 2030. Government procurement of ADR services is shifting from research to acquisition.

- **First non-cooperative demonstrations:** ADRAS-J2 (FY2027) and ClearSpace-1 (2028–2029) will attempt the first physical capture of non-cooperative debris. Both will operate at or near the tumble-rate ceiling of their respective systems. Success validates the market; failure validates the need for pre-stabilization.
- **Architectural decomposition:** Orbital Prime's segmented tracks, Astroscale's patent for separate capture and reentry vehicles, and the COSMIC depot analysis all point toward a modular value chain where pre-stabilization is a distinct, purchasable service—not an integrated subsystem.

7.2 Revenue Pathway

Delta Infinite's revenue model follows the maturation of the ADR and ISAM markets through three phases:

- **Phase 1 (Current–TRL-5):** Government R&D contracts (SBIR/STTR, Orbital Prime successor programs), technology licensing discussions, and LOIs from downstream capture providers who need pre-stabilization capability.
- **Phase 2 (TRL-5–Flight Demo):** Hosted payload or free-flyer demonstration mission; service contracts with ADR prime contractors; integration agreements with servicing vehicle manufacturers.
- **Phase 3 (Operational):** Pre-stabilization as a service, sold per-target to ADR operators and constellation lifecycle managers; technology integration into depot-based mass management architectures.

7.3 The Funding Ask

Delta Infinite is raising a pre-seed round of $150K (minimum) to $250K (target). The minimum round funds the full TRL-3 to TRL-4 validation sprint. The target round adds testing density, AI-assisted materials optimization, and additional founder operating room for seed preparation. This is not a request to fund the future of asteroid mining. It is a request to fund the bounded, six-month validation campaign that produces the hard engineering data to prove the foam works as characterized—converting S.O.A.P.S. from promising material behavior into a fundable, integration-ready system.

8. Conclusion

The non-cooperative orbital debris capture problem is not a technology gap—it is a cascading chain of unsolved dependencies where each step requires the previous one. The industry has built impressive capability for cooperative targets and is beginning to test the boundaries of non-cooperative inspection. But the critical middle layer—the pre-stabilization and universal capture capability that converts tumbling, uncharacterized mass into something the rest of the value chain can handle—remains vacant.

S.O.A.P.S. fills that vacancy. By exploiting the physics of foam expansion in vacuum and microgravity, it sidesteps the angular rate wall that constrains every rigid capture system, eliminates the requirement for target characterization before contact, and creates a standardized mechanical interface on objects of any geometry or surface composition. It does not replace the companies building downstream capture and servicing systems. It makes them work on the targets that matter most.

The regulatory, economic, and physical urgency is clear: modeling indicates approximately 60 large debris removals per year are needed to stabilize the LEO environment, the top 50 most dangerous objects are all non-cooperative multi-ton rocket bodies, and the first Kessler-relevant collision could occur within the next decade. The emerging orbital mass economy—depots, recycling, manufacturing—requires capture as its first step.

> *Whoever solves pre-stabilization and universal capture does not merely fill a market gap. They unlock the entire non-cooperative value chain that currently cannot function without them. Delta Infinite is building that capability.*

Delta Infinite • Fort Collins, Colorado • deltainfinite.com
Contact: Kai Cahlil, CEO • kai@deltainfinite.com