SPACE WASTE

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Rendezvous, Proximity Operations, and Docking

An Engineering Assessment for Active Debris Removal and On-Orbit Servicing — from Approach, through Capture, to Takeover

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Primary sources: NASA/TM-2011-217088 (Dennehy & Carpenter, 2011); Hinkel, Zipay, Strube & Cryan (NASA JSC/GSFC); Chen et al., IEEE TGRS 61 (2023); Cao et al., IEEE TIM 72 (2023) and IAC-21 #64702; Fan et al., Remote Sensing 15:4858 (2023); and the attitude-takeover control literature for multi-spacecraft on-orbit servicing.

1. Executive Summary

Rendezvous, Proximity Operations, and Docking (RPOD) — extended to RPODU when undocking is in scope — is the enabling capability for every mission Space Waste intends to fly: satellite servicing, life extension, and active debris removal (ADR). No capture mechanism, refueling system, or deorbit package matters if the chaser vehicle cannot first arrive at its target slowly, precisely, and safely — and then survive what happens after contact.

Revision B of this report extends the original assessment in two directions. Downward, into the attitude-determination hardware that the relative-navigation chain silently depends on: star trackers, their thermally drifting alignments, and what recent sensing research offers against those failure modes. Forward in mission time, past the moment of capture: the attitude-takeover problem, in which the chaser must control a combined stack whose mass properties it does not know.

Five conclusions follow:

- **Navigation is the mission.** Orbital Express (OE) was nearly lost not to a propulsion or mechanism failure, but to a feedback loop between sensor software and the navigation filter. Every architectural decision traces back to protecting the integrity of the relative state estimate.
- **Diversity beats redundancy.** OE recovered because its sensor suite was dissimilar — when visible-band sensors were blinded by optical artifacts, the infrared channel brought the vehicle home. Identical redundant sensors share identical failure modes.
- **The chaser must sense itself as carefully as it senses the target.** Relative navigation error budgets bottom out in the chaser's own attitude knowledge. Camera-to-star-tracker misalignment drifts with thermal state; recent work demonstrates active laser metrology between focal plane and star tracker precisely because static calibration does not hold on orbit.
- **Capture is not the end of the control problem — it is a new one.** At contact, the plant changes discontinuously: combined inertia, center of mass, and actuator geometry all jump. Attitude takeover control with rapid on-line inertia identification is the difference between a serviced satellite and a tumbling, larger piece of debris.
- **Debris is the harder half of the problem.** Flight-proven RPOD heritage is overwhelmingly cooperative: targets with retroreflectors, transponders, and controlled attitude. ADR requires closing on tumbling, uncooperative, possibly fragmenting objects whose mass properties are unknown before — and uncertain even after — capture. The heritage is necessary but not sufficient, closing that gap is the focus of Space Waste's development program.

2. The RPOD Problem

2.1 Definitions and Mission Phases

A canonical RPODU mission proceeds through phases of decreasing range and increasing risk: far-range rendezvous (hundreds of km to ~1 km, driven by orbit phasing), proximity operations (~1 km to ~10 m, driven by relative navigation), final approach and capture (~10 m to contact, driven by the docking corridor and contact dynamics), mated operations — including attitude takeover of the combined stack — and undocking/departure.

2.2 Why It Is Hard

- **No brakes.** Orbital flight is pure Newtonian drift: every thrust input persists until canceled by an opposite input. Relative motion follows orbital mechanics (Clohessy-Wiltshire dynamics), not aircraft intuition — thrusting toward a target can move you away from it over a fraction of an orbit.
- **Hostile lighting.** A LEO vehicle passes from full sun to eclipse roughly every 45 minutes. Glints, glare, sensor saturation, and hot pixels are not edge cases; on Orbital Express they were the proximate cause of the mission's gravest anomaly.
- **Limited ground contact.** Autonomy is mandatory because ground stations see only minutes of each orbit; but full autonomy is dangerous because, as OE demonstrated, ground operators were essential to anomaly recovery. The tension between these facts shapes the entire system.
- **Contact is unforgiving.** At capture, residual closing velocity, lateral offset, and misalignment must fall within the mechanism's narrow capture envelope. Excess energy at contact does not abort the mission — it creates debris.
- **The plant changes at contact.** The moment latches close, the chaser is no longer flying itself; it is flying a combined spacecraft with abruptly different inertia, center of mass, and flexible dynamics. Controllers tuned for the solo vehicle can destabilize the stack.

3. Attitude Determination and Sensing

3.1 The Attitude Knowledge Chain

Every relative-navigation measurement is expressed in some frame, and every frame transformation passes through the chaser's own attitude estimate — typically star trackers fused with gyros. At proximity-operations ranges the error budget is tight: a 100 arcsecond attitude error projects to roughly 5 cm of lateral target-position error at 100 m — comparable to the entire PROX-M18 terminal accuracy allocation.

At these ranges, attitude determination performance is a docking-safety parameter, not only a payload pointing parameter.

3.2 The Misalignment Problem and Active Optical Metrology

The hard part is not the star tracker's intrinsic accuracy but the stability of its mounting relative to the navigation cameras. Chen et al. (IEEE TGRS, 2023) document the operational reality for high-precision optical missions: complex environmental fluctuations produce severe, time-variant misalignment between camera and star tracker that ground calibration cannot capture, degrading inertially referenced pointing and positioning. Their remedy is architectural rather than computational — an active optical monitoring path in which laser sources integrated on the camera focal plane are reflected via retroreflector directly into the star tracker, so the camera-to-tracker rotation is measured continuously in flight rather than assumed.

For RPODU the implication is that calibration must be treated as a continuing process rather than a pre-flight event. A servicing vehicle whose sensor-bench alignment is monitored in real time inherits a navigation chain that holds its error budget through thermal transients — including the worst transient of all, the attitude maneuvering and shadowing of terminal approach. This is the attitude-bench counterpart of OE lesson LL-4 (calibrate for the real sky, under real conditions).

3.3 All-Day Celestial Sensing from a Single Aperture

Cao, Xing, and Zhan first presented the concept at IAC 2021, and matured it in IEEE TIM (2023). The gap it addresses is structural: no single conventional optical system images both stars and the Sun, because the radiometric dynamic range between the targets spans many orders of magnitude. The conventional workarounds each fail the small-spacecraft case — all-day star trackers carry complex optomechanical systems whose mass and volume disqualify them from micro/nano platforms, while traditional sun sensors cannot function with the Sun outside their field of view and need filters or artifact-elimination processing that caps their accuracy.

The approach uses a sensor behavior normally treated as a defect. In a CMOS active-pixel imager read out via correlated double sampling (CDS), sufficiently intense illumination drives the pixel into an oversaturation regime in which the reported gray value reverses — falling from the saturated maximum toward the minimum. With deliberately chosen optical parameters, the Sun therefore images as a black spot on a bright background, detectable and centroided like an inverted star. One aperture then serves both regimes: linear-response star imaging at night or with the Sun out of frame, and oversaturation-response Sun imaging in daylight — high-precision, all-day attitude measurement from a single miniaturized instrument.

This is relevant to proximity operations in three ways. It extends attitude availability through Sun-constrained terminal approach geometries that blind conventional trackers. It miniaturizes the attitude chain — directly relevant to a <3 kg-class avionics product and to CubeSat-scale ADR concepts. It also demonstrates that the saturation artifacts that nearly killed Orbital Express are not merely noise to be screened: characterized rigorously, sensor nonlinearity becomes signal. Treating a characterized nonlinearity as a measurement channel, rather than only as noise to be screened, is a useful precedent for ADR sensing.

3.4 Sensing Through Failure: Magnetometer-Free Magnetic Control

Fan et al. (Remote Sensing, 2023) tackle fault tolerance in densely packed small spacecraft, where reaction wheels and magnetorquers magnetically pollute the magnetometer to the point of failure — taking momentum management down with it. Their dynamics-sensing approach eliminates the magnetometer dependency entirely: a temporal-expansion geomagnetic vector calculation algorithm (GVCA) segments control activity in the time domain to decouple the three-axis observation equations (resolving the singularity of the Kalman coefficient matrix) and reconstructs the local field vector in real time from the spacecraft's own dynamic response, at acceptable computational cost. Multi-mode fault-tolerant control laws then restore a destabilized vehicle to operational pointing without performance degradation — validated in simulation and on a plug-and-play ADCS hardware testbed.

Three lessons transfer directly to RPODU platforms. First, **estimate what you cannot sense:** a physical quantity recoverable from dynamics need not have a dedicated, failure-prone sensor in the critical path. Second, **graceful degradation is a designed behavior** — multi-mode control laws that progressively recover a tumbling vehicle are the attitude-domain analog of NESC R-1's safe, coasting abort states. Third, the singularity-by-decoupling technique foreshadows the identification mathematics of Section 8: in both cases, structuring when and how the system is excited is what makes an ill-conditioned estimation problem solvable.

4. Flight Heritage Survey

4.1 Demonstration and Operational Missions

Three autonomous demonstration programs anchor the field: NASA's DART (2005), JAXA's ETS-VII (1997-99) — which demonstrated teleoperated and autonomous capture plus orbital-replacement-unit exchange with a robotic arm — and DARPA's Orbital Express (2007). Crewed and cargo programs (Space Shuttle, Progress/Soyuz, ATV, HTV, Dragon, Cygnus) contribute decades of operational RPOD at the ISS.

Commercial servicing has since crossed from demonstration to revenue: Northrop Grumman's Mission Extension Vehicles (MEV-1 docked to Intelsat-901 in 2020) perform life extension by taking over station-keeping for client GEO satellites — operational proof that the take-over-and-fly-the-stack architecture closes a business case. NASA's Restore-L/OSAM-1 program advanced refueling of an unprepared client; DARPA's Phoenix program studied harvesting functional components from retired satellites; and the modular-spacecraft line of research (iBOSS, ROSE, eXCITe, Hive) anticipates servicing missions in which multiple vehicles or cells attach, reconfigure, and self-assemble — the regime in which combined-spacecraft dynamics change repeatedly by design. The modular and component-reuse programs are also the conceptual ancestors of Space Waste's orbital resource-recovery pillar.

4.2 Sensor Classes (per Hinkel et al.)

CLASS	EXAMPLES	PROPERTIES
RF / radar	Shuttle Ku-band radar; ISS space-to-space ranging	Long range; supports non-cooperative targets but requires powerful, complex gimbaled antennas; Shuttle radar precluded simultaneous Ku-band comm
GPS-relative	Delta-AGPS / RGPS on ATV, HTV, Dragon, Cygnus	Precise but requires cooperation — data sharing between both vehicles; Earth-orbit only
Visible cameras	OE ARCSS VS1/VS2; Shuttle VGS heritage	Passive, low power; fails under poor or unanticipated lighting
Infrared cameras	OE IRS; SpaceX Dragon nav augmentation	Tracks thermal signature; robust to lighting; Dragon uses IR for FDIR cross-checks of LIDAR
LIDAR (scan/flash)	Shuttle trajectory sensors; ATV/HTV/Dragon/Cygnus primary RPOD sensors	Lighting-independent; active illumination; excellent demonstrated performance

4.3 Capture Mechanisms

Capture hardware has evolved from central probe-and-cone systems (Apollo; still flown on Soyuz/Progress), which tolerate — indeed require — relatively high contact velocities, toward peripheral soft-capture systems (APDS, and its descendant the NASA Docking System) whose latches ring the mating interface and permit low-energy capture. The industry trend toward low-impact docking directly motivates the PROX-M18 requirement of <0.1 m/s terminal closure: modern soft capture is a precision event, not a controlled collision.

5. Case Study: DARPA Orbital Express (2007)

5.1 Mission Architecture

Orbital Express launched March 8, 2007 on an Atlas V into a 492 km, 46° orbit: ASTRO, the active chaser/servicer, and NextSat/CSC, the client. Over five unmated operations plus a long-range rendezvous demonstration, OE proved autonomous rendezvous, capture, hydrazine propellant transfer, and orbital replacement unit (battery and flight computer) transfer — the first end-to-end demonstration of autonomous on-orbit servicing.

ASTRO's autonomous GN&C system comprised fully autonomous guidance, attitude, and navigation software, an onboard guidance sequencer, functionally redundant rendezvous sensors effective from over 200 km to capture, autonomous navigation filtering of multiple sensor inputs, and internal sanity checks with rendezvous abort capability.

5.2 The ARCSS Sensor Suite

SENSOR	ROLE
VS1 — narrow-FOV visible	Long-range acquisition and tracking
VS2 — wide-FOV visible	Mid/short-range tracking
IRS — infrared	Tracking in eclipse and degraded lighting; initially regarded by the team as supplemental
LRF — laser rangefinder	Mid-range precision ranging
AVGS — advanced video guidance sensor	Laser-based attitude/range/bearing in the final few hundred meters; VGS heritage from STS-87/95 and DART

5.3 The Scenario 3-1 Anomaly

During the second unmated operation, ASTRO suffered a major failure of its sensor computer — the processor handling cameras, AVGS, and laser rangefinder data. In the recovery period that followed, a more insidious failure chain emerged:

- Optical artifacts (glints, glare, saturation, hot pixels) appeared in sensor fields of view and, through faulty target-selection logic, were reported as valid target tracks.
- The navigation filter ingested these spurious measurements, biasing its state estimate while simultaneously shrinking its reported uncertainty — it grew more confident as it grew more wrong.
- The biased filter fed corrupted target ephemerides back to the sensor software, which then could not associate the real image of NextSat with a track — even while ground controllers could see NextSat plainly in downlinked imagery.
- Sensors requiring a range-estimate seed from other sensors could not acquire, cascading the outage across the suite.

Ground operators ultimately recovered the vehicle — with the infrared sensor as the primary recovery instrument — and ASTRO re-mated with NextSat. The DARPA Director suspended unmated operations pending an NESC-chaired review; OE then completed its remaining scenarios without significant further issues.

> *"Nav is really important." — an Orbital Express principal designer, after recovery. Quoted in the NESC report following the Scenario 3-1 recovery.*

6. Lessons Learned (NESC)

LESSON	SUBSTANCE
LL-1: Navigation availability must never be assumed	After the anomalous drift-stop maneuver, operators needed extended time merely to determine whether ASTRO was leading or following NextSat. Coarse navigation knowledge is taken for granted until it vanishes.
LL-2: IR sensing enhances robustness to lighting	The sensor the team considered secondary was the one that recovered the mission, and the most reliable tracker outside AVGS range.
LL-3: Sensor/nav coupling reinforces failures	Tight bidirectional coupling (filter ephemerides aiding sensors; sensor validity flags aiding the filter) converted local sensor problems into system-level navigation collapse.
LL-4: Calibrate for the real sky	Pre-flight facilities could not reproduce orbital optical dynamics; the initial on-orbit calibration kept the target in frame and bright sources out — exactly backwards. The corrected procedure (target out, Earth limb and Moon in) exposed the artifacts.
LL-5: Situational-awareness imagery enables recovery	Continuously downlinked imagery, even at low bandwidth via TDRSS, proved crucial to ground decision-making — and should be a designed-in capability, not a contingency reconfiguration.
LL-6: The filter must screen bad data without harming good data	OE's EKF underestimated residual standard deviations; flown without editing it ingested spurious data to total state loss, and with crude ~10-sigma thresholds it still suffered divergence. Measurement editing is only as good as the filter's statistics.

7. NESC Recommendations for Future RPODU Missions

- **R-1 — Design for the ground operator's role in aborts.** Autonomous contingency responses should rapidly place vehicles into stable, safe, coasting configurations that buy the ground time; operators should be able to override autonomous responses. OE's recoverability was credited to exactly this philosophy.

- **R-2 — Plan for independently derived best-estimated trajectories (BETs).** Post-facto trajectory reconstruction from combined onboard and ground data is essential for validating navigation performance and for anomaly investigation; OE's limitations here delayed its return to operations.
- **R-3 — Maximize sensor independence.** Diversity of data types and dissimilar redundancy saved OE; coupling between sensors and filter nearly destroyed it. Sensors should perform their functions as independently as possible.
- **R-4 — Calibrate for off-nominal conditions.** On-orbit, with and without targets in frame, across all plausible lighting including contingency geometries, over the sensors' full specified ranges and dynamics.
- **R-5 — Apply appropriate fidelity in pre-flight simulation.** The optical environment that defeated OE's calibration was one no ground facility had reproduced.

8. Post-Capture: Attitude Takeover and the Inertia Problem

8.1 The Problem

When a servicer hard-mates to its client, the controller's plant model becomes wrong in an instant. The combined spacecraft has a new inertia tensor, a shifted center of mass, relocated and re-oriented actuators, and possibly flexible coupling — and for a dead client, the chaser's actuators must now do all the work: attitude takeover control. Published results indicate that each attachment event causes attitude fluctuation and can lose control of the stack entirely. For multi-vehicle servicing concepts — nanosatellite swarms reclaiming a failed satellite, modular cells aggregating into new structures — the plant changes abruptly at every attachment, demanding takeover control that is quick-responding, globally stable, and high-accuracy throughout.

8.2 Approaches and Their Limits

- **Known-inertia methods** (e.g., dual-loop fast terminal sliding mode; reconfigurable control computing the combined inertia from each vehicle's known properties and relative geometry) deliver performance but assume knowledge that real servicing rarely has — especially with debris.
- **Adaptive methods** (adaptive sliding mode under input constraints and disturbances; adaptive control for large center-of-mass shifts; robust adaptive neural networks under input saturation; adaptive schemes with concurrent inertia identification, including finite-time and fault-tolerant variants) absorb uncertainty — but classically require persistent excitation of the system state, which is difficult to realize in flight, and their computational cost strains the quick-response requirement.

- **Identification-based takeover** estimates the inertia properties explicitly and feeds a model-based controller. Early multi-vehicle work (integrated identification and control for nanosatellites reclaiming a failed satellite) exposed the core numerical hazard: at the instant inertia properties jump, the identification problem becomes ill-conditioned, corrupting exactly the estimate the controller needs most.

8.3 Quick-Response Iterative Identification

More recent work addresses that hazard directly. The quick-response attitude-takeover method built on an iterative inertia-identification equation — derived from the combined spacecraft's Euler dynamics together with a space-environment torque model — eliminates ill-conditioned identification and updates the inertia estimate using a single sample per step, reducing computation and storage requirements against batch or persistent-excitation schemes. A Lyapunov-designed attitude controller consumes the running estimate, with stability proven for the closed loop, and an optimal torque-allocation layer distributes commands across the stack's reaction wheels — whose installation matrices must themselves be re-mapped into the combined center-of-mass frame after every attachment. Numerical simulation and ground experiment cover both canonical cases: a dead client requiring full takeover, and a live client requiring cooperative augmentation. Control remains stable and precise even at the attachment instants.

Several extensions of this work apply directly to ADR. Follow-on work adapts the same iterative identification core into a two-stage estimator for uncooperative debris on CubeSat-based removal missions: LiDAR geometric measurements feed a pseudo-measurement Kalman filter that locates the debris center of mass, after which the iterative algorithm recovers the full inertia tensor — principal moments and products. Related results estimate inertia of tethered debris from tether tension and angular-rate measurements (directly relevant to net-and-tether capture, where the tether is both effector and sensor), handle time-varying inertia under impulsive disturbance via robust weighted recursion, and extend takeover to bioinspired consensus control of spacecraft swarms capturing uncooperative targets.

8.4 Implications

- **Identification is a capture-phase deliverable.** The approach phase should be scored not only on contact conditions but on how well the chaser has characterized the target's motion — seeding post-capture identification.
- **Single-sample iterative updates fit flight computers.** Quick response with bounded memory is what a 22 W, ARM-class avionics suite can actually sustain — the same resource realism that motivates GVCA's design (Section 3.4).
- **Excitation can be structured, not hoped for.** Where adaptive methods wait for persistent excitation, segmented or planned excitation — the time-domain decoupling trick — turns identification into a scheduled activity.

- **Every capture modality needs an identification story.** Rigid docking feeds wheel-based takeover; net-and-tether capture feeds tension-based estimation; swarm attachment feeds consensus control. PROX-M18's product line must treat these as one problem family.

9. The Non-Cooperative Frontier: From Servicing to Debris

Nearly all operational RPOD heritage is cooperative: ISS visiting vehicles dock with a station that holds attitude, carries retroreflectors and transponders, and shares data. Orbital Express, though architected for non-cooperative capability, serviced a purpose-built client. Debris removal removes every one of these aids simultaneously:

- **Unknown and uncontrolled attitude.** Dead satellites and rocket bodies tumble; rates can exceed the capture envelope of any docking mechanism, demanding detumble strategies (e.g., standoff net capture with tether damping) before contact-based methods apply.
- **No fiducials.** Pose estimation must work from natural features under the same hostile lighting that generated OE's artifacts — a substantially harder computer-vision problem, and the reason modern AR&D programs emphasize lighting-independent sensors (LIDAR, IR) with vision as augmentation.
- **Unknown mass properties.** Even a successful capture yields a stack whose inertia must be identified in flight before confident control authority exists — the Section 8 problem, at its hardest.
- **Degraded structure.** Capture points may be damaged, contaminated, or absent. Mechanism design must tolerate contact with surfaces never designed for it.

The ARM-era NASA work points the way: a common sensor specification taking the union of mission requirements, lighting-independent primary sensors cross-checked by passive imagers for fault detection, isolation and recovery (FDIR), and standardized low-impact docking mechanisms. Space Waste's position is that the same commonality logic must now be extended to the uncooperative case — across sensing, capture, and post-capture control alike.

10. Application to South Star PROX-M18

Each heritage driver maps to a PROX-M18 design decision:

HERITAGE DRIVER	PROX-M18 DESIGN RESPONSE
LL-1 / R-1	Independent navigation-state health monitoring with dissimilar cross-checks; loss-of-nav triggers a passively safe abort trajectory rather than a stationkeeping hold
LL-2	850 nm IR illumination and eclipse-rated tracking as primary-path capability, not supplement
LL-3 / R-3	Decoupled estimation architecture: artifact screening without biased-ephemeris feedback into target selection; no sensor depends on another for acquisition seeding
LL-4 / R-4 / Chen et al.	Built-in on-orbit calibration mode (Earth limb and Moon, target excluded) before unmated operations; roadmap: continuous active optical metrology of the sensor-bench-to-star-tracker alignment so calibration is a process, not an event
LL-5	Continuous low-rate situational-awareness video downlink as a baseline system capability
LL-6	Innovation-based measurement gating with honestly computed residual statistics; bounded covariance collapse so no single sensor can monopolize the state estimate
R-2	Onboard data recording sized for independent best-estimated-trajectory reconstruction after every approach
Hinkel et al.	Sensor suite (LiDAR + stereo + wide-FOV + IR + IMU) mirrors the demonstrated Dragon/ISS pattern: active lighting-independent ranging, passively cross-checked for FDIR
Cao et al.	Sun-tolerant celestial sensing on the technology roadmap: characterized oversaturation response extends attitude availability through Sun-constrained terminal geometries
Fan et al. (GVCA)	Estimate-what-you-cannot-sense fault tolerance: dynamics-based reconstruction paths and multi-mode degraded control laws for actuator/sensor failure, validated on plug-and-play ADCS hardware patterns
Takeover literature (Sec. 8)	Post-capture mode: single-sample iterative inertia identification with Lyapunov takeover control and optimal torque allocation; LiDAR-seeded center-of-mass estimation for debris; tether-tension identification for net-capture missions

Note: South Star PROX-M18 is in development at TRL 3-4. This mapping describes design intent validated against published heritage, not flight-qualified performance.

11. Conclusions

Autonomous RPOD was demonstrated in 2007. The same mission, in the same month, also demonstrated how close such systems run to failure. The difference between demonstration and disaster was sensor diversity, conservative abort design, ground-operator authority, and — above all — disciplined protection of the navigation state.

Revision B extends that verdict in both directions along the mission timeline. Upstream, the sensing literature shows the attitude knowledge chain is a living system: alignments drift and must be actively measured (Chen), dynamic-range limits can be engineered into capability (Cao), and failed sensors can be replaced by physics (Fan). Downstream, the takeover-control literature shows that capture is the beginning of a second control problem whose central currency is inertia knowledge — and that quick, well-conditioned, single-sample identification is what makes flying an unknown stack tractable on real flight computers.

For active debris removal, the heritage is a floor, not a ceiling. Every aid the cooperative case provides must be engineered away, every failure mode OE exposed becomes more probable against a tumbling, optically unpredictable target, and every successful capture creates a combined vehicle no one has ever flown before. The PROX-M18 development program treats these published lessons as requirements.

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