

SPACE LOGISTICS AND TRANSPORTATION

Physical AI for Space Logistics and Transportation: Composing the Velocity Budget with One Estimation-and-Control Stack

A Δv -composition framework, an on-orbit non-cooperative capture, and a headless physics core the whole chain runs on.

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Interactive companion: physicalai-bmi.org/research/charlot-lab/space-logistics · Code: github.com/dcharlot-physicalai-bmi/orbital-logistics

ABSTRACT. Moving mass to, through, and around space is one continuous logistics chain: launch, orbital transfer, rendezvous, capture, servicing, assembly, and return. This report advances a research position: across that whole chain the decisive capability is autonomy carried on the vehicle, and the same estimation-and-control primitive recurs at every link, so a single autonomy stack composes across all of them. We make the argument concrete in three parts. First, reaching a destination is a velocity budget, and reusable, shared infrastructure and autonomous in-space transport pay that budget down; we give the exact mass-ratio bookkeeping and a composition rule that reports payload as a real mass fraction and declines to reward a single vehicle for a mission it cannot physically fly. Second, the transport modes that pay the budget down — momentum-exchange tethers, electromagnetic launch, launch loops — each convert the barrier from materials into estimation and control: a tether catch is a one-second non-cooperative rendezvous, a launch loop is held up by a controller, a sled is a guidance-and-control handoff. Third, the on-orbit links — rendezvous, non-cooperative capture, servicing, assembly — are the same problem, now operational: we describe a chaser that estimates a tumbling target's pose with a Kalman filter and holds a certified approach corridor. Each transport mode is realized as an in-browser instrument running on its governing equations, backed by an open, headless physics core with regression checks against independently re-derived values. This is a position and methodology report. It reports no new experimental measurements; the velocity budgets used for illustration are representative mission values, while the mass-ratio, tether, orbital, and estimator mathematics are exact and checked in the released code, and all empirical claims are attributed to the cited primary literature.

1. Introduction: the transport chain as a velocity budget

Space logistics is usually pictured as launch — the moment a vehicle leaves the ground. But moving materiel to and around space is a chain with many links: ascent to orbit, transfer between orbits, rendezvous with another object, capture of that object, servicing or assembly, and, increasingly, return. Each link moves mass through a change in velocity, and the currency that unifies the chain is therefore the velocity budget, Δv . Reaching low Earth orbit costs on the order of 9.4 km/s of Δv once atmospheric and gravity losses are included; a geostationary slot, the lunar surface, or the surface of Mars cost successively more. Every link in the logistics chain is, at bottom, a Δv to be paid.

The reason that budget is hard is the rocket equation, which makes the propellant a vehicle must carry grow exponentially with the Δv it must supply on its own. This report takes as its subject the two ways that AI, Physical AI, and embodied AI change the shape of the problem. The first is composition: reusable, shared infrastructure and autonomous in-space transport can supply parts of the budget so the vehicle does not carry all of it, and the exponential works in the payload's favor as soon as the onboard share falls. The second is that the infrastructure and transport that do this are, without exception, autonomy problems — a momentum-exchange tether catch, an electromagnetic launch handoff, an on-orbit rendezvous with a body that neither holds still nor cooperates. The capability that opens the chain is estimation and control carried on the vehicle. The report's thesis is that this capability is *one* capability: the same estimation-and-control primitive recurs at every link, so a single autonomy stack, priced in Δv and joules and run at the edge, serves the whole chain.

The aim is practical. Efficiencies, new materials, and new optimizations from this direction expand what space transportation and the management of space logistics can do, and they do so in a way that many actors can build on rather than a few — a path toward an open and decentralized space economy. The remainder of the report develops the budget bookkeeping (Section 3), the shared estimation-and-control shape (Section 4), the on-orbit case that is hardest and most clearly Physical AI (Section 5), and the open instruments and core that make the whole argument runnable (Section 6).

2. Scope and method

This is a position and methodology report, not an experimental one. It proposes a framework and a set of instruments; it reports no original measurements and claims no benchmark result for any system it describes. Two categories of quantity appear, and the report is explicit about which is which. The mathematics of Sections 3–5 — the rocket equation and the payload-fraction composition, the constant-stress tether taper, the vis-viva and escape relations, and the constant-velocity Kalman filter — is exact standard astronautics and estimation, and it is implemented and regression-checked in the released code^[11]. The velocity budgets attached to destinations, and the per-segment Δv contributions attributed to each transport mode, are representative mission values used to make the composition legible; they are not predictions for a specific vehicle. The dynamics shown in the on-orbit capture instrument are illustrative, driven by the exact filter but not a validated flight simulation. Every empirical claim about the state of practice — that autonomous rendezvous and proximity operations, and non-cooperative inspection, already run in orbit — is attributed to the cited primary sources. Where this report proposes that one autonomy stack spans the chain, that is an organizing position offered for test, not a demonstrated result.

3. Composing the velocity budget

A vehicle that supplies a velocity change Δv from its own propellant, with effective exhaust velocity v_e , obeys the rocket equation of Tsiolkovsky^[1], which fixes the ratio of wet to dry mass:

$$\Delta v = v_e \ln \frac{m_0}{m_f}, \quad \text{so} \quad \frac{m_0}{m_f} = \exp\left(\frac{\Delta v}{v_e}\right).$$

Because the mass ratio is exponential in Δv , the deliverable payload fraction collapses as the required Δv rises. Writing the inert (structure) mass fraction as ϵ , the fraction of launch mass delivered as payload for a single stage supplying the whole budget T is $\lambda_0 = 1/\exp(T/v_e) - \epsilon$, which for a large enough T is negative — meaning no single vehicle of that class reaches the destination at all.

Composition changes the exponent. Suppose reusable, shared infrastructure and autonomous in-space transport supply a set of segment contributions $\{\delta_k\}$ — a launch handoff, a tether boost, an orbital-transfer stage, an aerocapture at arrival. The vehicle then supplies only the remainder, and its payload fraction follows from the reduced onboard budget:

$$\Delta v_{\text{onboard}} = T - \sum_k \delta_k, \quad \lambda = \exp\left(-\frac{\Delta v_{\text{onboard}}}{v_e}\right) - \varepsilon.$$

The honest accounting is to report λ directly, as a physical mass fraction, rather than a ratio against a single-vehicle baseline: when that baseline is itself infeasible ($\lambda_0 \leq 0$), a ratio is meaningless and inflates without bound. The composition instrument therefore states, for each destination, the share of the budget carried by shared infrastructure, the resulting payload fraction, and — only when a single vehicle could reach the destination at all — the multiple over that baseline. A destination a lone vehicle cannot reach is labelled as such, not scored. Figure 1 shows the composition against representative budgets.

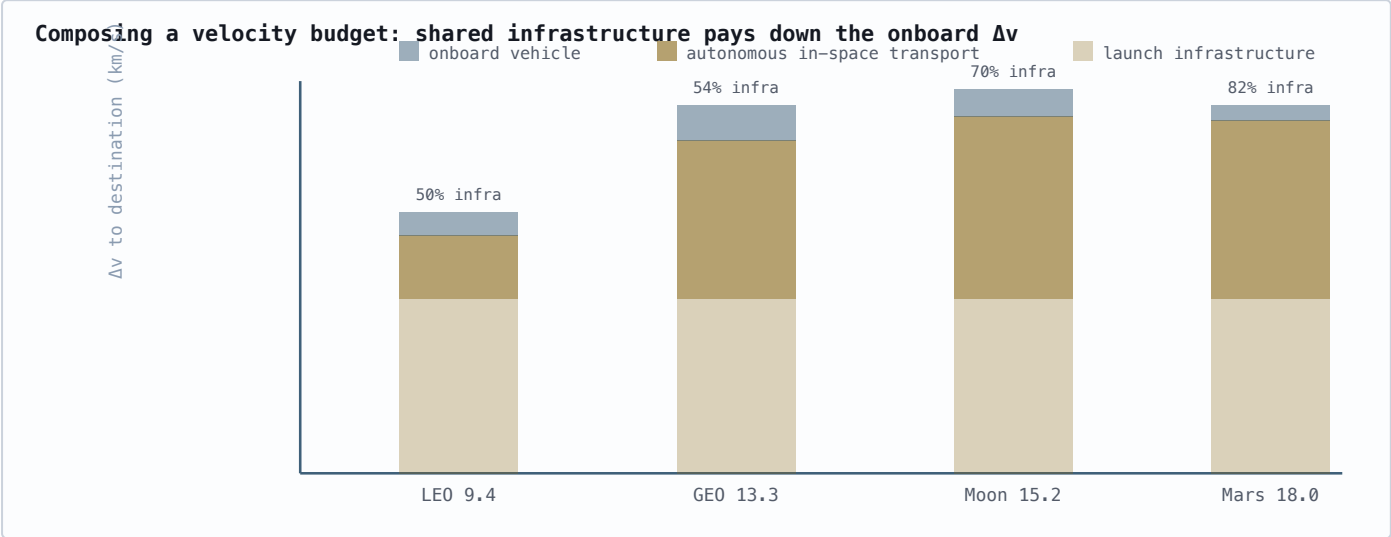


Figure 1. A representative composition per destination. Reusable launch infrastructure and autonomous in-space transport carry a growing share of the budget as the destination recedes, and the onboard vehicle carries only the remainder; its payload fraction follows from that remainder by the rocket equation. Budgets are representative mission values; the mass-ratio arithmetic is exact. Interactive version at physicalai-bmi.org/research/charlot-lab/space-logistics.

4. The shared shape: estimation and a certified corridor

The transport modes that supply the offload segments of Section 3 are not, at bottom, materials problems. A momentum-exchange tether — the rotating skyhook of Moravec^[2] and the later boost-tether studies^[3] — must catch a payload at a closing speed of kilometers per second in a window measured in a second, which is a non-cooperative rendezvous under a hard deadline. A launch loop^[4] is an elevated structure held in an unstable equilibrium by a fast internal rotor: it stands not because any material is stiff enough but because a distributed controller damps every span, and it buckles the instant that control is lost. An electromagnetic launch track^[5] ends in a guidance-and-control handoff at hypersonic speed. In each case the binding capability is estimation and control, and the material or power figure is downstream of it.

Stated as control, the modes share a shape. In each, an estimator resolves the state of the world from noisy, delayed measurements, and a controller holds that state inside a proven corridor to a deadline. The value of naming the shape is that the estimator and the certified controller are then *one* stack, developed once and specialized per link. Certification here is the companion to this lab's work on provable control^[10]: a controller that can carry a certificate of the region in which it will hold its corridor is a controller a vehicle can trust to run without a human in the loop, which — as Section 5 shows — is the only way the tightest links close at all.

Table 1. Links in the transport chain and the estimation-and-control primitive each reduces to. The gate in every row is autonomy carried on the vehicle; the material or power figure is downstream of it.

LINK / MODE	WHAT MUST BE ESTIMATED	WHAT MUST BE CONTROLLED	DEADLINE
Momentum-exchange tether catch	Payload relative state at the tip	Tip trajectory into the catch envelope	~1 s

Launch loop	Track displacement, span by span	Distributed stabilization of an unstable equilibrium	continuous
Electromagnetic launch track	Vehicle state through the coils	Guidance handoff at exit	seconds
On-orbit rendezvous / capture	Non-cooperative target pose & tumble	Approach along a certified corridor; match spin	minutes → seconds
Servicing / assembly	Relative pose of parts	Contact forces within tolerance	task-dependent

5. On-orbit non-cooperative capture

The clearest instance of the shared shape, and the one furthest from the launch pad, is on-orbit rendezvous with a body that neither holds still nor helps. This is no longer hypothetical. Astroscale's ADRAS-J spacecraft approached a spent, tumbling rocket upper stage — a non-cooperative object of several tonnes — held station within tens of meters, flew around it under autonomous guidance, and validated autonomous collision avoidance^[6]. Northrop Grumman's SpaceLogistics Mission Extension Vehicles docked with client satellites in geostationary orbit to extend their operational lives^[7]. These are the first operational links of an in-space logistics layer, and the capability under them is exactly the estimator-and-certified-controller of Section 4.

Relative translation near a target on a circular orbit is governed by the Clohessy–Wiltshire equations^[8]; the estimation problem is to recover the target's relative position, velocity, and — for a tumbling body — attitude and angular rate, from noisy and latency-bearing returns. The lab's instrument runs a per-axis constant-velocity Kalman filter^[9] for the relative position. Writing the per-axis state as position and velocity ($x, \dot{x}$) with covariance P , the filter predicts and then corrects on each measurement z of noise variance r :

$$\hat{x}^- = x + \dot{x} \Delta t, \qquad K = \frac{P_{xx}^-}{P_{xx}^- + r}, \qquad \hat{x}^+ = \hat{x}^- + K (z - \hat{x}^-).$$

The controller then holds the chaser inside a certified approach corridor about the rotating capture axis, shrinking its standoff only as the pose covariance falls and the corridor is held — an estimator gating a certified maneuver. Capture succeeds when relative position, closing velocity, and the corridor condition are simultaneously inside tolerance. The instrument makes the reason for autonomy legible by offering a human-in-the-loop mode: at a coarse control rate and a quarter-second lag, the estimator never even converges inside the window that a real catch allows, and the approach misses. Autonomy is not an optimization of this link; it is its precondition.

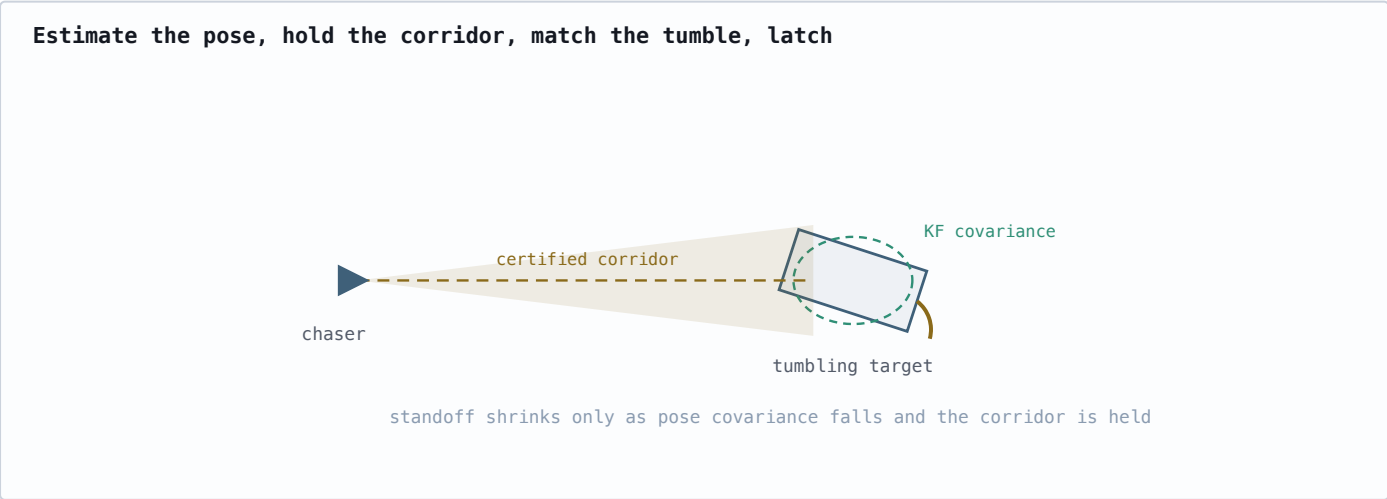


Figure 2. The on-orbit capture link. A Kalman filter resolves the tumbling target's relative pose (its covariance shrinks as it converges); the controller holds the chaser inside a certified corridor about the rotating capture axis, closes only as the estimate

6. Instruments and an open, headless core

The argument is made runnable rather than only asserted. Each transport mode is realized as a self-contained instrument that executes in the browser, on the device, on its governing equations: a Δv -architecture composer, the on-orbit capture of Section 5, a momentum-exchange tether on real orbital mechanics and the constant-stress taper, an electromagnetic sled, and a launch loop on a distributed-instability model. The load-bearing equations are additionally extracted into a headless core that runs parameter sweeps without a display and is checked against independently re-derived values^[11]. Those checks pin, among others, that a maglev sled reaching 2.9 km/s at 10 g needs 42.9 km of track; that a constant-stress tether at a 3 km/s tip has a mass ratio of $13.6\times$ in aramid and $0.26\times$ in carbon nanotube; and — a correction the checks caught — that a rotovator's release must be compared against escape velocity at the tether tip radius, not at the station, which is where the 10.56 km/s release of a 600 km, 400 km-arm hook correctly exceeds the 10.40 km/s escape at the ≈ 1000 km tip. The instruments and core are released openly^[11] so the capabilities can be tested, applied, and extended by others — a working expression of the open, decentralized aim.

7. Position and discussion

The position is that space logistics and transportation should be organized around autonomy carried on the vehicle, because the estimation-and-control primitive that opens the tightest links is a single capability that composes across the whole chain, and because Δv and joules are the honest units in which to price it. The efficiencies this direction offers are not incremental: composing the velocity budget moves the exponential of the rocket equation in the payload's favor, and destinations a single vehicle cannot reach at all become reachable when infrastructure carries most of the budget. New materials — high-strength tethers, multifunctional surfaces — enter the framework as parameters that change where a mode becomes buildable, not as the thing that gates the chain. And the optimization that matters is at the level of the network: composing modes into a chain and managing the flow of mass through it.

The report is equally clear about what it does not claim. It does not claim a fielded system or a benchmark; the instruments are computational, and their dynamics, where not exact mathematics, are illustrative. It does not claim the per-segment Δv contributions as design values; they are representative. It does not claim novelty for the underlying astronautics or estimation, which are standard and cited. What it claims is organizational: that the links of the transport chain reduce to one estimation-and-control shape, that the shape is where autonomy is the enabling capability, and that building the shape once — provable, physically grounded, priced in Δv and joules, and run at the edge — is the way the space economy opens to many actors rather than few. That last claim is a position offered for test, and the released instruments and core are the first move in testing it.

8. Conclusion

Every link in the space-logistics chain is a velocity budget to be paid, and the rocket equation makes paying it alone exponentially expensive. Reusable, shared infrastructure and autonomous in-space transport pay the budget down, and the modes that do so — momentum-exchange tethers, electromagnetic launch, launch loops, and the on-orbit links of rendezvous, capture, servicing, and assembly — are, without exception, estimation-and-control problems carried on the vehicle. Because they share that shape, one autonomy stack, provable and priced in Δv and joules, serves the whole chain. The non-cooperative capture that is already operational in orbit is the clearest case and the report's centerpiece: a Kalman filter resolving a tumbling body's pose, a certified corridor held to a deadline, a latch that a human in the loop cannot make. The instruments and the open core make the framework runnable today; what remains is the work

the report does not shortcut — fielding the stack, certifying it link by link, and measuring it against the budgets it is built to pay.

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AI-use disclosure. Preparation of this report used a large language model (Claude, Anthropic) for drafting and editing text, organizing the reviewed literature, and preparing the figures, instruments, and interactive companion. Cited references were checked to resolve to their sources. The author reviewed the content and is solely responsible for it. Consistent with ICMJE, COPE, and IEEE guidance, the model is a tool and is not credited as an author.