

THE SURFACE THAT PAYS TWICE

The Surface That Pays Twice: Multi-Material Active Skins for Persistent Embodied Systems

A single persistence inequality, one physics-informed solver, and a skin that harvests and hides at the same time.

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ABSTRACT. An embodied system that must persist — a stratospheric glider aloft for months, a Mars rover across a Martian year, a subsea drone that stays dark — is governed by a single inequality: the energy it harvests must meet the energy it spends, integrated over the mission. This report develops Multi-Material Active Skin Technology (MMAST), a research position in which the vehicle's outer surface is treated as its power plant and every gram of that surface is read against the mission energy ledger. The central observation is that the same multi-material stack that harvests energy also reshapes the vehicle's signature. A radiative-cooling film that lowers photovoltaic cell temperature is also an infrared-suppression layer; a metasurface that raises optical absorption is, in a different band, a radar-absorbing coat; a triboelectric skin that scavenges vibration is also a distributed structural-health sensor. Each module pays back twice. We frame the design problem as one physics-informed energy-balance solver evaluated over three orthogonal axes — vehicle archetype, operating medium, and surface module — so a single formulation covers a glider, a subsea drone, and a rover. The simulator is built on CadFuture, the lab's computable-world-model engine; it runs headless for parameter sweeps and renders in the browser through WebGPU. This is a review and research position. It reports no new experimental measurements; all quantitative claims are attributed to the cited primary literature.

1. Introduction: persistence is one inequality

Most engineering of embodied systems optimizes a peak: top speed, maximum payload, best-case range. Persistence optimizes an integral. A system that has to keep operating for a long time, far from resupply, is not constrained by any instantaneous figure but by a running

account of energy in against energy out. Over a mission of duration T , the system survives if and only if the energy it harvests is at least the energy it demands, at every moment and in total. Everything else — aerodynamic refinement, thermal design, sensor selection, autonomy — is subordinate to keeping that account solvent.

This reframing has a consequence that this report takes as its subject. If the account is what matters, then the largest lever on it is usually the vehicle's outer surface. The skin is the single component that sees the sun, radiates to the sky, contacts the water, and vibrates with the structure. It is the largest area the system owns and the interface across which nearly all energy exchange happens. Treating the skin as an incidental enclosure wastes that area. Treating it as the power plant, and grading every layer of it against the mission ledger, is the design stance this report calls Multi-Material Active Skin Technology, or MMAST.

The demand side of the ledger is not free either. For an embodied controller the dominant recurring costs are actuation, communication, and computation, and the last of these is itself dominated by data movement and arithmetic rather than by logic^[8]. Persistence therefore couples the physics of the skin to the design of the payload: a lighter, cheaper decision loop relaxes the harvest requirement, and a richer skin relaxes the compute requirement. The two sides are one problem.

2. Scope and method

This is a review and a research position, not an experimental report. It surveys established primary results in passive radiative cooling, triboelectric energy harvesting, metamaterial absorbers, structural health monitoring, and solar-powered continuous flight, and it proposes a common formulation and a simulator that unifies them. It reports no original measurements. Where a number appears, it is attributed to a cited source; no benchmark result is claimed for MMAST itself. The formulation in Section 3 is standard energy bookkeeping and is offered as an organizing device, not as a novel theorem. The dual-use pairings in Section 4 are engineering conjectures grounded in the cited physics; the report is explicit that co-optimizing two functions in one stack is harder than either alone, and that MMAST is at the stage of a simulator and a design argument rather than a fielded system. The CadFuture implementation described in Section 6 is a working prototype for parameter sweeps and visualization, not a validated design tool; its outputs are hypotheses to be tested, not results.

3. The skin as power plant: harvest $\geq$ demand over the mission

Let the vehicle carry a set of surface modules indexed by i , each occupying area A_i with a time-varying conversion efficiency $\eta_i(t)$ against an environmental flux $\Phi_i(t)$ — solar irradiance for a photovoltaic layer, vibrational or flow power for a triboelectric layer, and so on. The instantaneous harvested power is the sum over modules, and the persistence condition is that its integral dominates the integral of demand:

$$\int_0^T P_{\text{harvest}}(t) dt \geq \int_0^T P_{\text{demand}}(t) dt, \quad P_{\text{harvest}}(t) = \sum_i A_i \eta_i(t) \Phi_i(t).$$

The integral form alone is necessary but not sufficient, because storage is finite. A glider that banks a surplus by day and spends it by night must never let its store fall below a floor. Writing the state of charge of the store as $E(t)$, with round-trip efficiency ρ and a reserve $E_{\min}$, the pointwise constraint that actually governs survival is:

$$E(t) = E_0 + \int_0^t \left(\rho P_{\text{harvest}}(t') - P_{\text{demand}}(t') \right) dt' \geq E_{\min} \quad \forall t \in [0, T].$$

The demand term collects the recurring loads of the mission — propulsion or station-keeping, thermal regulation, communication, sensing, and computation — each of which is itself a function of state and environment. The design problem MMAST poses is to choose the surface stack, the area allocation $\{A_i\}$, and the payload duty cycle so that the second inequality holds for the whole mission with margin, at the least mass. Because η_i depends on temperature, and temperature depends on the radiative properties of the very same skin, the harvest and demand sides are coupled through the surface: cooling a photovoltaic layer raises its efficiency and simultaneously lowers a thermal-management load, so one film moves both integrals in the favorable direction^[1,2]. This coupling is the reason the surface is worth optimizing as a whole rather than layer by layer.

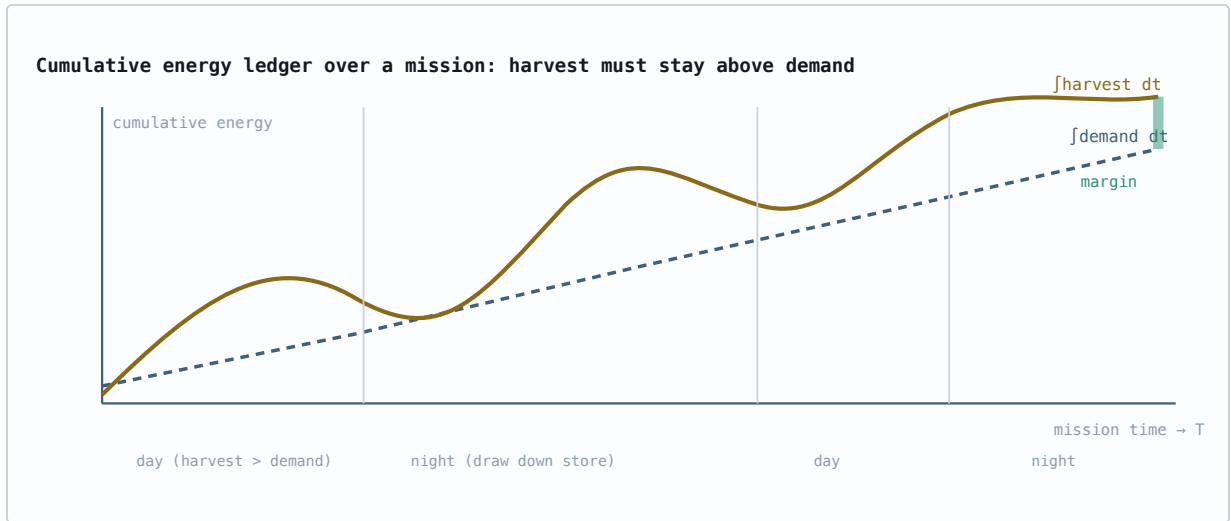


Figure 1. The persistence ledger. The mission survives only if the cumulative harvest (solid) stays above cumulative demand (dashed) for all t , with a reserve margin at the horizon T . The harvest curve is steep by day and flat by night, so the binding constraint is the depth of the night draw-down against the finite store, not the mission-average balance. Schematic; not a measurement. An interactive version is at physicalai-bmi.org/research/charlot-lab.

4. Paying twice: dual-use modules

The economic argument for MMAST is that a surface layer added for one reason often delivers a second function for free, because the physics that governs energy exchange also governs signature. Three pairings are established well enough in the primary literature to state plainly.

Passive daytime radiative cooling uses a photonic film that is emissive in the atmospheric transparency window near 8–13 μm while reflecting sunlight, and can hold a surface below ambient air temperature under direct sun^[1], with scalable glass–polymer versions since demonstrated^[2]. The same spectral control that dumps heat to the sky is, from a sensing adversary's point of view, control over the vehicle's thermal emission — the film that cools the cells is also an infrared-suppression layer. Metamaterial and metasurface absorbers, since the first near-unity perfect absorber^[3], engineer where and how strongly a surface absorbs incident radiation; used one way a metasurface lifts optical absorption into a photovoltaic layer, and used in another band the same design principle is a radar-absorbing coat. Triboelectric nanogenerators convert mechanical motion into charge through contact electrification^[4], scavenging vibration and flow; because their output is a direct electrical signature of the mechanical input, the same skin doubles as a distributed, self-powered sensor of that input^[5] — which for a structure is exactly the measurement that structural health monitoring seeks^[6].

Table 1. Dual-use surface modules: the layer added for the primary energy or thermal function delivers a second signature or sensing function from the same physics. Pairings are engineering conjectures grounded in the cited primary results, not co-optimized demonstrations.

SURFACE MODULE	PRIMARY FUNCTION (LEDGER)	SECOND FUNCTION (FREE)	SHARED PHYSICS	PRIMARY SOURCE
Radiative-cooling film	Cools PV cells; sheds thermal load below ambient	Infrared-signature suppression	Spectral emissivity in the 8–13 μm sky window	Raman 2014 ^[1] ; Zhai 2017 ^[2]
Absorber metasurface	Raises optical absorption into PV layer	Radar-absorbing coat (different band)	Engineered near-unity resonant absorption	Landy 2008 ^[3]
Triboelectric (TENG) skin	Scavenges vibration and flow to storage	Distributed structural-health sensor	Contact electrification maps mechanics $\rightarrow$ charge	Fan 2012 ^[4] ; Wang 2014 ^[5] ; Farrar 2007 ^[6]

The honest qualification is that paying twice is not free of engineering cost. Two functions in one stack impose competing material and geometric constraints, and a design that is optimal for harvest is rarely optimal for signature. The claim is not that the second function comes at zero penalty but that it comes at far less mass and volume than a separate subsystem would, which on the persistence ledger is what counts.

5. One solver, three orthogonal axes

The reason a single formulation can serve a stratospheric glider, a subsea drone, and a Mars rover is that the persistence inequality of Section 3 does not know which vehicle it describes. What changes between vehicles is not the equation but the values that populate it. MMAST

organizes those values along three orthogonal axes. The first is the vehicle archetype, which sets the demand profile and the storage budget — a glider spends most of its power on staying aloft through the night, a rover on traverse and survival heating, a subsea drone on propulsion against drag and on acoustic communication. The second is the operating medium, which sets the environmental fluxes and the loss channels — solar spectrum and thin-air convection in the stratosphere, dust and a weak, cold sun on Mars, near-total darkness and high thermal conductivity underwater. The third is the surface module, the choice of which layers from Table 1 populate the skin and how their areas are allocated.

Because the axes are orthogonal, the same solver evaluates any cell of the resulting cube. A stratospheric glider is the archetype for which the continuous-flight energy balance is best documented, since a solar aircraft achieves indefinite endurance exactly when its collected energy over a day covers night flight with reserve^[7] — a direct instance of the pointwise storage constraint. Moving one axis at a time from that anchor to a rover or a subsea drone changes the fluxes and loads but not the bookkeeping, which is the property that lets one physics-informed solver span media that share no hardware.

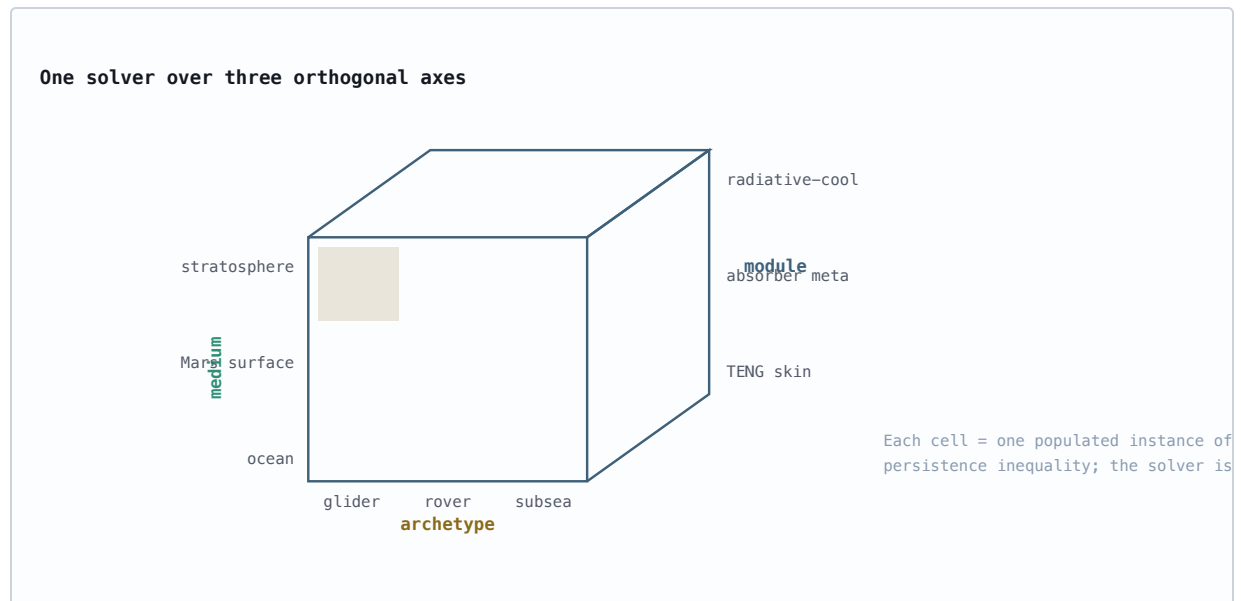


Figure 2. The design space as a cube over vehicle archetype, operating medium, and surface module. The persistence inequality of Section 3 is evaluated per cell; only the environmental fluxes, demand profile, and storage budget change from cell to cell. The stratospheric-glider cell is the anchor, being the archetype for which continuous-flight energy balance is best documented^[7].

6. Built on CadFuture: headless sweeps and WebGPU rendering

The MMAST simulator is implemented on CadFuture, the lab's computable-world-model engine, which represents a vehicle and its environment as a differentiable, inspectable model rather than as a static geometry file. Two properties of that substrate matter for this problem. First, the model runs headless, so the solver can be swept across the three axes of Section 5 without a display — thousands of parameter combinations of area allocation, duty cycle, and environmental profile evaluated in batch to map where the persistence inequality holds with margin and where it fails. Second, the same model renders in the browser through WebGPU,

so a single design can be inspected interactively: the skin stack, the running ledger of Figure 1, and the state-of-charge trajectory are all views of one underlying computation, not a separate visualization pipeline. The intent is that a headless sweep proposes candidate designs and the WebGPU view lets a designer interrogate any one of them without re-deriving it. The code is open at github.com/dcharlot-physicalai-bmi/physics-mmast-sim. It is a prototype: it computes the energy bookkeeping and the module models described here, and its outputs are design hypotheses to be validated against hardware, not verified predictions.

7. Position and discussion

The position this report advances is narrow and, deliberately, unglamorous. It is that for the class of embodied systems defined by persistence, the surface is the correct unit of optimization, and the correct objective is the mission energy integral rather than any instantaneous figure of merit. This inverts the usual design order, in which the surface is chosen last, as a consequence of aerodynamics and manufacturing, and asks instead that the surface be designed first, as the power plant, with the rest of the vehicle sized to the ledger it can sustain. The dual-use argument is what makes this affordable: because the physics of energy exchange and the physics of signature are the same physics, a surface designed for the ledger tends to also be a surface that manages heat, hides, and senses itself, and those functions arrive at a fraction of the mass they would cost as separate subsystems.

The report is equally clear about what it does not claim. It does not claim that any specific dual-use stack has been co-optimized and fielded; the pairings in Table 1 are grounded in established primary results for each function separately, and their combination is an engineering hypothesis. It does not claim quantitative advantage for MMAST; the simulator produces candidate designs, not validated performance. And it does not claim that the surface removes the demand-side problem: a persistent system still has to keep its recurring computation and communication within a power envelope, which is why the demand side draws on the separate, and equally physical, program of energy-efficient embodied computation^[8]. The two halves of the ledger are one design.

8. Conclusion

Persistence reduces to a single inequality: harvest must meet demand, integrated over the mission and bounded below at every instant by a finite store. Read through that inequality, the vehicle's skin stops being an enclosure and becomes the power plant, and the largest lever a persistent system owns. MMAST is the design stance that grades every layer of that skin against the ledger and exploits the coincidence that the physics of harvest is also the physics of signature, so that a radiative-cooling film hides in the infrared, an absorber metasurface hides from radar, and a triboelectric skin reports its own structural health — each module paying back twice. Because the inequality is indifferent to the vehicle, one physics-informed solver, evaluated over the orthogonal axes of archetype, medium, and module, spans a stratospheric glider, a subsea drone, and a Mars rover. The CadFuture implementation makes that solver concrete, sweepable headless and inspectable in the browser. What remains is the

hard part the report does not shortcut: building the stacks, co-optimizing the paired functions in real materials, and measuring them against the ledger they are designed to keep solvent.

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