Operational Geometry (Interaction Geometry): Perceiving Space through Interaction

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Abstract

The PETRONUS framework introduces Operational Geometry, also called Interaction Geometry, as a reconceptualization of how adaptive agents relate to space. Classical approaches treat geometry as explicit representation—maps, meshes, occupancy grids, or SLAM reconstructions. These representations can be effective in stable scenes, but they become fragile under change, uncertainty, occlusion, deformability, and contact-rich interaction. Operational Geometry reframes geometry as a field of constraints revealed through action. Perception becomes perception-through-consequence: contact forces, slips, micro-failures, delays, and correction bursts expose the structure of an environment as it matters to the agent. We formalize this view with two primitives: an Alignment Field $F_A(x,t)$, expressing local constraint directionality over configuration space, and an Alignment Charge $Q_A(t)$, expressing accumulated mismatch between the agent's ongoing behavior and the encountered constraints. In this framing, friction and adhesion appear as invariant signatures of geometry, sensed not as shape but as resistance, slippage, and coupling stability. Incompatible interaction induces structural drift (persistent translational mismatch) and operational spin (persistent rotational mismatch) in the agent's motion. We also discuss Adaptive Internal Time (AIT) as an operational timing modulation that emerges under constraint-dense interaction, so that geometry is felt through subtle changes in temporal rhythm and correction cadence. Throughout, we use short everyday vignettes—squeezing through a gap, walking on ice, and hesitating at a glass door—to clarify the difference between geometry-as-representation and geometry-as-experience. This preprint is presented as a prior-art conceptual foundation and intentionally does not disclose implementation details.

Note on Scope and Reading This work is intended to be read as a foundational and architectural preprint. It does not specify a particular algorithm, controller, or implementation, nor does it aim to optimize or benchmark performance against existing systems. Instead, it introduces a conceptual and operational reframing of geometry for adaptive agents, focusing on interaction, constraint, and consequence as primary carriers of spatial structure.

The terms Alignment Field, Alignment Charge, and Adaptive Internal Time are introduced as architectural primitives rather than fully specified mathematical objects. Their role is to define an operational layer at which geometry can be discussed independently of any particular sensing modality, control law, or learning mechanism. Implementation details are deliberately left unspecified, as this document serves to establish conceptual priority and structural scope for subsequent technical work, rather than to disclose mechanisms.

Readers are therefore encouraged to interpret the arguments in terms of coherence, persistence, and interaction structure over time, rather than in terms of explicit reconstruction, optimization, or representational accuracy.

1 Introduction

Autonomous systems have traditionally treated geometry as something to be reconstructed and stored. Cameras, LiDAR, and other sensors are fused into maps, point clouds, meshes, or occupancy grids, and those representations are used for localization and planning. This paradigm presumes that geometry is primarily a stable, externally describable structure that an agent can internalize and consult.

Real environments are rarely stable in the way this paradigm implicitly assumes. People move through scenes, objects shift, lighting and visibility change, contact occurs in unexpected ways, surfaces deform, and small discrepancies compound over time. Even if an agent can maintain a map, the relevance of that map is not guaranteed when the environment is dynamic or when interaction occurs at close range. In practice, many pipelines attempt to repair the mismatch by detecting dynamic objects or filtering inconsistent points, but the underlying premise remains representational: geometry is "out there" as shape, and the agent's job is to rebuild it reliably.

Operational Geometry proposes a different premise. For an adaptive agent, geometry is not primarily shape. Geometry is constraint. It is the structured pattern of what actions succeed, what actions fail, what actions become costly, and how those successes and failures change with location, orientation, and time. Under this premise, the agent does not need to reconstruct the environment as a model of surfaces. Instead, the agent must remain coherent under interaction by continually aligning its behavior to the constraints the environment imposes.

This preprint develops that reframing as a prior-art theoretical layer. It focuses on defining the primitives and the interpretive consequences while avoiding proprietary mechanisms.

2 Geometry-as-Representation and Its Fragility

Representation-based geometry is powerful when conditions are favorable. If an environment is sufficiently static and an agent's sensors provide consistent coverage, explicit maps support global planning, loop closure, and long-range navigation. However, the same machinery becomes brittle when geometry changes faster than it can be updated, when contact occurs in ways not predicted by perception, or when sensor streams contain systematic gaps.

The brittleness has a structural character. The system relies on a stable correspondence between sensed features and stored geometry. When that correspondence is disrupted—by moving obstacles, by transparent surfaces, by repetitive corridors, by occlusion, by slight rearrangements—the agent's internal picture becomes an increasingly unreliable basis for action. Error can be controlled locally, but the representation itself degrades in relevance: the map remains a map, but not of the world the agent is actually in.

A second limitation is that representational geometry often treats interaction as downstream. The map is built first; contact is handled later as collision avoidance or as a failure condition. Yet in many domains, interaction is not an exception—it is the main channel by which geometry becomes meaningful. Softness, stickiness, compliance, narrowness, and load-bearing capacity are not reliably inferred from shape alone. They must be discovered through doing.

These limitations motivate a shift in what is meant by "geometric perception" for an adaptive agent.

3 Action-Centric Perception: Perception-through-Consequence

Operational Geometry begins from the premise that the agent's primary access to geometry is not a static picture but the lawful coupling between action and sensory consequence. An environment becomes known by how it shapes what the agent can do next.

Consider a basic physical property like softness. Softness is not perceived by passively looking; it is perceived by applying force and registering deformation. The relevant structure is in the relation between an action and its outcome. The same holds for friction, adhesion, compliance, and constraint density. A surface becomes "slippery" only when a step fails to couple; a doorway becomes "too narrow" only when the body's envelope encounters resistance; a transparent barrier becomes "a wall" only when action meets reaction.

In this view, geometry is operational. It is not the catalog of forms in space but the structured field of constraints and affordances that an agent can only learn by engagement. The environment does not merely contain obstacles; it contains interaction laws that become legible under probing and correction.

This is not a denial of vision, mapping, or shape cues. It is a priority claim: for robust behavior in dynamic, contact-rich settings, the decisive geometric information is carried by consequence signals that appear during action.

4 Formal Primitives: Alignment Field and Alignment Charge

To make Operational Geometry more than metaphor, we introduce two primitives that express constraint experience without requiring explicit surface reconstruction.

The Alignment Field $F_A(x, t)$ is a generalized field over configuration space and time. Here, x denotes the agent's relevant configuration—position, orientation, and possibly internal degrees of freedom—and t denotes time. $F_A(x, t)$ represents the local directionality of constraint: how the environment "pushes back" against occupying or transitioning through a configuration. In some settings this push-back is literally mechanical force. In others it is a generalized incompatibility signal that can be expressed through resistance, correction demand, delay, or coupling loss. The field is not assumed to be explicitly known. It is an operational concept: the environment's constraint structure exists as a field whether or not it is represented.

The Alignment Charge $Q_A(t)$ is an agent-carried quantity expressing accumulated misalignment with the encountered constraint field. Intuitively, $Q_A(t)$ rises when the agent persists in actions that conflict with local constraints and falls when behavior becomes compatible. $Q_A(t)$ is not a classical trajectory error and not a reward deficit. It is a mismatch measure that is meaningful even when the agent remains within nominal task performance. It expresses structural conflict: the difference between "moving" and "moving coherently under the encountered constraint laws."

Operational Geometry is the dynamical interplay between these two. The agent acts, consequences reveal constraint directionality, $Q_A(t)$ responds, and behavior adapts to reduce sustained misalignment. In the ideal operational regime, geometry is "known" not because it is mapped, but because action remains aligned and $Q_A(t)$ stays bounded.

Operationally, the Alignment Charge can be understood as a dynamically accumulated quantity updated through ongoing interaction. At an abstract level, its evolution may be written schematically as

$$Q_A(t + \Delta t) = Q_A(t) + \Psi(F_A(x, t), u(t), y(t)),$$

where $u(t)$ denotes the agent's action and $y(t)$ denotes the resulting sensory or interaction outcome. The functional Ψ represents an implementation-dependent mismatch accumulation law and is not specified here. This expression is intended only to indicate that Q_A evolves through the joint influence of environmental constraints, agent action, and experienced consequences, without committing to any particular computational form.

This framing supports a different meaning of navigation. A path is not only a curve through coordinates; it is a sequence of interactions that can be more or less coherent, more or less costly in terms of sustained mismatch.

5 Frictions and Adhesion as Invariant Signatures of Geometry

When geometry is treated as constraint, friction and adhesion become primary signatures. They are not simply material parameters appended to a shape model; they are the way geometry manifests in consequence signals.

Friction appears as resistance to relative motion and as the boundary between stable coupling and slip. An agent does not need to "see" friction. It experiences friction as the difference between intended motion and realized motion, and as the correction effort required to maintain coupling. What matters operationally is not the absolute coefficient, but the pattern: where slip thresholds change, where micro-slip begins, where corrective bursts cluster, and how those patterns persist under repeated contact.

Adhesion appears as coupling persistence. It is experienced through effort required to detach, through delay between command and release, and through hysteresis in contact transitions. Adhesion makes the environment "sticky" not as a property stored in a database, but as a constraint pattern that forces particular action styles to remain coherent.

These signatures have a useful invariant character. A surface can look different under changing light and still impose the same slip thresholds. A barrier can be visually ambiguous and still reveal itself instantly through resistance. A narrow gap can be poorly sensed and still announce itself through contact distribution and correction cadence.

Operational Geometry therefore treats friction and adhesion as part of the geometry field: stable consequences that define the environment in the only sense that matters for robust embodied agency.

6 Structural Drift and Operational Spin under Incompatibility

Structural Drift and Operational Spin under Incompatibility

When an agent's behavior conflicts with constraint structure, the resulting effects are not always immediate failure. Often the environment induces persistent, accumulating mismatches that shift the agent's trajectory in ways that are subtle yet irreversible at the operational level.

We refer to accumulated translational mismatch as structural drift. Drift is the persistent deviation between intended evolution and realized evolution under constraint, not reducible to instantaneous noise. It manifests as a bias in where the agent ends up relative to where it expects to be, even if local corrections keep the agent nominally stable.

We refer to accumulated rotational mismatch as operational spin. Spin is the persistent tendency for the agent's frame or orientation to "twist" under constraint structure. This can appear as repeated yaw corrections, asymmetric coupling across contact points, or systematic turning induced by uneven resistance.

In representational paradigms, such effects are often treated as sensor drift or model mismatch. Operational Geometry treats them as evidence: the environment's constraint field is not trivial, and the agent is moving through a space that is operationally curved by interaction laws. The drift and spin are not merely errors to cancel; they are signatures that the agent must interpret as structure.

This perspective also clarifies why a system can remain locally stable and still degrade over time. Persistent small mismatches can accumulate even when a controller keeps instantaneous errors bounded. Drift and spin are the long-horizon trace of misalignment with the field.

7 Adaptive Internal Time as a Constraint-Density Effect

Operational Geometry includes time not as a background clock but as an operational rhythm. When interaction becomes constraint-dense, the agent's effective timing changes. This is not a mystical claim. It is an engineering observation: under dense constraint, an agent either compresses or expands its internal processing cadence to remain coherent.

We call this Adaptive Internal Time (AIT). AIT is the modulation of internal cycle timing under constraint exposure. Under smooth, compatible conditions, actions can be executed with regular cadence and low corrective demand. Under constraint-heavy conditions, the agent must allocate more correction, more monitoring, and more micro-adjustment per unit of external progress. This changes the experienced temporal rhythm of action. The same external distance can require a different internal sequence length. The same motor command can require multiple corrective sub-steps. The same plan can fragment into constraint-managed segments.

AIT therefore becomes an additional channel by which geometry is felt. Constraint density does not only slow or speed external motion; it restructures how time is used internally to preserve coherence. Operationally, this shows up as increased correction cadence, increased control loop activity, and altered timing between command and stable coupling.

In Operational Geometry, these timing modulations are not incidental. They are part of how the environment's geometry is revealed: a region of space can be "temporal rough" even when visually smooth, because it forces the agent into a different internal rhythm.

8 Coherence Degradation and Jerk as Misalignment Indicators

When behavior is aligned, motion tends to be smooth and predictable. When behavior is misaligned, sudden corrections appear. These corrections can be operationally summarized through coherence degradation and jerk.

Coherence here means the short-horizon consistency between intended evolution and realized evolution under ongoing coupling. It is not a task reward and not a map accuracy score. It is the stability of the agent's own action-perception loop.

Jerk, as the time derivative of acceleration, captures abrupt changes. In contact-rich settings, jerk spikes are often the first measurable sign that the environment's constraints diverge from the agent's implicit expectations. A smooth region yields low jerk; a suddenly incompatible region yields corrective bursts and jerk spikes, even if the agent avoids catastrophic failure.

Operational Geometry treats these signals as data. Rising jerk and coherence loss indicate that the agent is encountering constraint structure that its current behavior does not respect. The proper response is not merely to "smooth the trajectory" but to update alignment so that the agent's action style becomes compatible and jerk decreases as a consequence of regained coherence.

This reframes the meaning of smoothness. Smoothness is not only an aesthetic objective; it is a structural indicator of successful alignment with geometry-as-constraint.

9 PETRONUS-Style Interaction Geometry versus Classical Planners

A classical planner constructs geometry, localizes within it, and then selects actions that minimize a cost under constraints derived from that geometry. Interaction is treated as a downstream concern. If the geometry changes unexpectedly, the planner must update its model or it fails.

An Operational Geometry agent does not treat geometry as a static representation to consult. It treats geometry as the ongoing field of constraints revealed through action. It does not need to know "where the wall is" in a map to behave coherently near the wall. It needs to sense resistance, adjust coupling, and keep $Q_A(t)$ bounded.

This distinction becomes decisive in environments where contact and uncertainty are primary. A classical system can be highly capable in structured scenes but brittle under unexpected interaction. An interaction geometry agent is designed to remain coherent precisely because it assumes that geometry is something felt and negotiated, not something fully known in advance.

This preprint does not claim exclusivity. Many systems blend representational planning with reactive control. The claim here is foundational: robust long-horizon embodied agency requires treating interaction consequences as a first-class geometric channel, not as an afterthought.

10 Real-World Vignettes: Geometry Felt Rather than Seen

The following vignettes are included because they capture, in ordinary terms, what Operational Geometry means in practice.

10.1 Squeezing Through a Tight Gap

A person approaches a narrow passage and rotates their shoulders at the last moment. The action is not preceded by explicit measurement. The adjustment emerges from contact distribution, from the friction of fabric against surfaces, from micro-stops, and from the immediate increase in resistance when the body's envelope mismatches the available clearance. The person's posture changes until contact becomes tolerable, and then motion continues. The "geometry" of the gap is not an internal mesh; it is the constraint pattern that governs which body orientations remain coherent. The moment of scraping is a spike in $Q_A(t)$, and the sideways rotation is a behavioral move that reduces sustained misalignment. The passage is perceived as narrow because action reveals constraint, not because the person consulted an internal model of millimeters.

10.2 Walking on an Icy Sidewalk

An ordinary sidewalk becomes a different geometry when covered in ice. Visually, the scene can look unchanged. Operationally, each step becomes an experiment in coupling. Micro-slips appear, corrections cluster, cadence changes, and the body adopts a new gait to reduce the probability of loss of traction. The ground is perceived as slippery because the consequence of stepping is different: intended forward motion produces lateral or rotational mismatch, and the system responds by changing posture, step length, and timing. In Operational Geometry terms, the alignment field has changed, and the agent's behavior must shift to keep $Q_A(t)$ bounded. The geometry is in the slip threshold and the correction rhythm, not in the shape of the pavement.

10.3 Mistaking a Glass Door for Open Space

A transparent door can defeat representational perception. The person moves toward what appears to be open space until their hand meets resistance. The correction is abrupt; jerk spikes; posture resets; the person begins tapping or probing to infer what happened. The door's geometry becomes real at the instant of constraint encounter. A representation-first system may fail here if the door is not detected. An interaction geometry system would not need the door to be reconstructed as a surface to behave coherently: the first resistance event is enough to restructure the agent's actions. The geometry is revealed as the incompatibility between intended motion and possible motion.

These vignettes share the same point. Geometry becomes meaningful as constraint; perception emerges through consequence; and coherent behavior is the process of aligning actions to the encountered field rather than executing a plan against a static representation.

11 Biological and Physical Grounding

Biological systems illustrate Operational Geometry through proprioception and active touch. Animals do not rely exclusively on static reconstruction; they continually probe, contact, adjust, and re-time actions. Proprioceptive sensing gives direct access to resistance and coupling, allowing an organism to perceive constraint even without visual certainty.

Physical interaction further supports the invariant nature of frictional and adhesive signatures. Contact mechanics, stick-slip behavior, hysteresis, and compliance are not decorative details. They are the stable laws through which environments reveal themselves to embodied agents. An agent that treats these laws as geometric information can remain robust when visual or representational cues become unreliable.

This preprint does not attempt to settle debates about representation in cognition. It makes a narrower, operational claim: if an adaptive agent must persist under dynamic interaction, then constraint consequences must be treated as geometry.

12 Discussion: Prior-Art Scope and the Role of Minimal Formalism

This document is written as a preprint intended to fix conceptual priority without disclosing implementation. For that reason, it emphasizes operational primitives and interpretive consequences rather than concrete algorithms or parameterizations.

Within that scope, the key contribution is a structural reframing and a minimal set of terms that allow further work to remain coherent. The Alignment Field and Alignment Charge establish a language for geometry-as-constraint. Drift and spin establish a language for long-horizon mismatch that is not reducible to instantaneous noise. AIT establishes a language for timing modulation under constraint density. Coherence and jerk establish a language for dynamic indicators of misalignment.

Future technical elaborations can refine these primitives into specific estimators, controllers, or learning laws, but the prior-art claim does not depend on those details. The conceptual boundary is deliberate: it aims to be specific enough to be operationally meaningful and general enough to remain implementation-agnostic.

12.1 Positioning Relative to Related Work

Operational Geometry intersects with several established lines of research, including active SLAM, tactile exploration, impedance and compliance control, and the broader family of embodied and enactive approaches (often grouped under 4E cognition or sensorimotor contingency theory). These frameworks have convincingly shown that perception is inseparable from action, and that interaction plays a constitutive role in how agents relate to their environment.

However, most existing approaches retain an implicit representational core. Active SLAM and tactile exploration typically treat interaction as a means to improve or complete an underlying geometric model. Impedance and compliance control regulate force and motion at the control level but do not, by themselves, elevate interaction consequences to the status of geometry. Similarly, 4E and sensorimotor accounts provide a qualitative and philosophical foundation for action-centric perception, yet often stop short of introducing explicit operational primitives that can function as architectural variables over long horizons.

Operational Geometry differs in emphasis and scope. It does not aim to refine geometric reconstruction, nor to replace classical controllers. Instead, it introduces an explicit operational layer in which geometry is defined as a field of constraints revealed through consequence, formalized via Alignment Fields, Alignment Charge, and Adaptive Internal Time. In this view, interaction effects such as resistance, slippage, drift, timing distortion, and correction structure are not auxiliary signals but constitute geometry itself at the agent level. The contribution is therefore not another sensing or control technique, but a reframing of geometry as an operational quantity that governs coherence, persistence, and adaptation across time.

12.2 Illustrative Simulation Trace

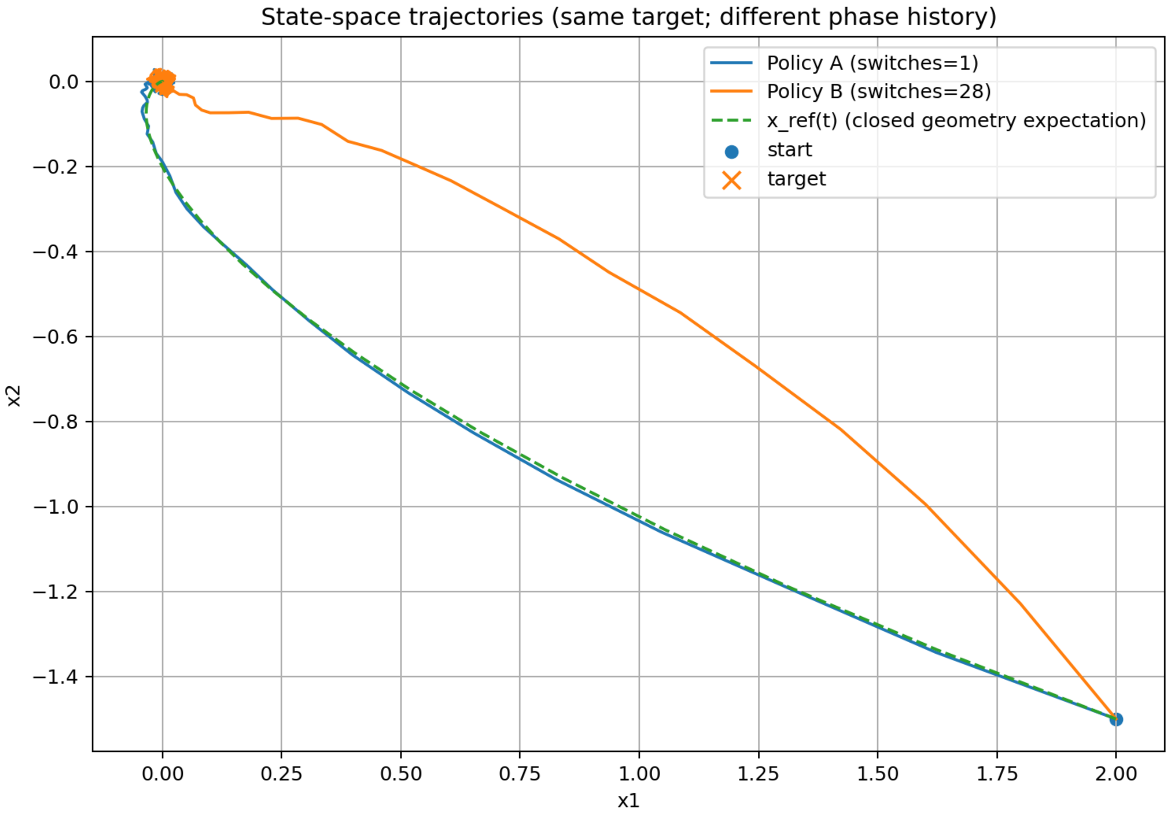

Figure 1: State-space trajectories reaching the same target under identical task objectives, but with different phase histories. Despite convergence to the same endpoint, the trajectories differ substantially due to interaction-induced effects accumulated over time. This illustrates that geometric outcome alone is insufficient to characterize behavior: phase history and interaction structure shape the realized path, even when final state and nominal geometry coincide.

This trace is not presented as a benchmark or validation of a specific control law. Its purpose is illustrative: to show that two policies can satisfy the same task-level objective and converge to the same geometric target, while remaining operationally distinct due to differences in phase transitions and interaction history. These distinctions are invisible to representation-centric descriptions of geometry, but become explicit when geometry is treated as an interaction-dependent quantity.

13 Conclusion

This work advances a single, operational claim: for adaptive agents acting in dynamic and contact-rich environments, geometry is not primarily a matter of representation, but of interaction. What governs coherent behavior over time is not the fidelity of reconstructed shape, but the structure of constraints revealed through action and consequence.

By introducing Alignment Fields and Alignment Charge, we formalize geometry as an operational quantity: a field that manifests through resistance, slippage, correction structure, drift, and timing distortion. Friction and adhesion emerge as invariant geometric signatures, while structural drift and operational spin capture long-horizon incompatibilities that cannot be reduced to instantaneous error or noise. Adaptive Internal Time reflects the fact that constraint density reshapes not only motion, but the internal temporal rhythm required to sustain coherence.

The implication is not philosophical but practical. As illustrated in Figure 1, two agents may reach the same target and satisfy the same task objective, yet differ fundamentally in their realized geometry due to accumulated interaction history, mismatch, and long-horizon viability. These differences are invisible to representation-centric metrics, but become explicit when geometry is treated as interaction.

Operational Geometry therefore does not compete with mapping or planning. It exposes a missing layer beneath them: a geometric substrate defined by consequence rather than description. An agent that operates at this layer can remain coherent without relying on brittle internal reconstructions, because it treats constraint itself as geometry.

This reframing establishes a foundation for subsequent technical work. It asserts that persistence, coherence, and survivability under uncertainty depend less on knowing where things are, and more on remaining aligned with how the environment pushes back.

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