Baseline Regulation and Global Constraint Signals in Embodied Control Systems

Implications for Artificial Intelligence and Robotics

Robotics / Embodied AI

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0.1   Abstract

Embodied artificial intelligence and robotic systems often exhibit brittle behavior outside narrowly defined operating conditions, despite advances in sensing, learning, and control. In contrast, biological organisms maintain stable, adaptive behavior across wide environmental variability. This paper proposes that a key contributor to this robustness is the presence of explicit baseline regulatory mechanisms that operate prior to and beneath cognition. Drawing on observations from human physiology and sensorimotor coordination, we argue that biological systems achieve coherence through global constraint signals—such as respiratory gas balance—and predictive coupling between perception and action. We outline a control framework in which stability emerges from distributed regulation rather than centralized command, and discuss implications for the design of more robust embodied artificial systems.

1   Introduction

Modern artificial intelligence and robotics systems have achieved impressive performance in constrained environments, yet they often fail abruptly when conditions deviate from those anticipated during training or design. These failures frequently arise not from a lack of computational power or sensory resolution, but from an inability to maintain internal coherence under perturbation. Small mismatches between prediction and reality can cascade into excessive correction, energy inefficiency, or control instability. Biological organisms face similar challenges, yet display markedly different behavior. Humans and animals maintain functional stability across variations in terrain, energy availability, sensory noise, and internal state. This suggests that biological robustness does not rely solely on fast feedback, centralized planning, or high-level cognition. Instead, it points to the existence of underlying regulatory mechanisms that stabilize behavior before complex control strategies are invoked. This paper examines such mechanisms through the lens of baseline regulation and proposes that embodied artificial systems currently under-model this layer of control.

2   Baseline Regulation in Biological Systems

Biological systems operate across multiple interacting timescales. Fast neural reflexes, intermediate sensorimotor loops, and slow metabolic and autonomic processes coexist and interact continuously. Crucially, these layers are not independent. They are coordinated through baseline regulatory processes that bias system behavior toward stability with minimal energy expenditure. Baseline regulation becomes most visible when overall demand is low. In these states, small perturbations reveal regulatory cost directly: inefficiencies, misalignments, or prediction errors are felt immediately rather than masked by high-output activity. This observability allows organisms to maintain coherence by minimizing corrective effort rather than continuously compensating for instability. Importantly, baseline regulation operates largely outside conscious cognition. It is expressed mechanically, chemically, and autonomically, providing a foundation upon which higher-level control can operate.

3   Global Constraint Signals

A defining feature of biological regulation is the use of global constraint signals—variables that simultaneously affect all subsystems and therefore synchronize distributed control without centralized coordination. Respiratory gas balance provides a canonical example. Oxygen availability and carbon

dioxide concentration influence cellular metabolism, neural excitability, vascular tone, and autonomic state across the entire organism. Because every metabolically active tissue depends on these variables, changes in respiratory gas balance impose system-wide constraints rather than localized signals. These constraints do not function as commands. Instead, they establish boundary conditions within which local regulatory mechanisms operate. When global constraints are stable, distributed subsystems naturally align; when they are perturbed, regulatory effort increases across the system. This form of control contrasts with architectures that rely on explicit top-down correction. Global constraint signals bias behavior continuously, reducing the need for high-frequency intervention.

4   Predictive Coupling and Regulatory Cost

Efficient biological regulation depends not only on global constraints but also on predictive coupling between perception and action. When sensory inputs align with expected outcomes of movement, regulatory cost remains low. When this alignment is disrupted, corrective effort increases immediately. A simple illustrative example can be observed during human locomotion. When gaze direction aligns with direction of movement, walking and breathing remain smooth and energetically minimal. Rotating the head ninety degrees while maintaining forward locomotion introduces an immediate increase in perceived effort and disrupts respiratory smoothness, despite no increase in physical workload or conscious cognitive activity. This effect resolves instantly upon realignment. This observation suggests that increased effort arises from degraded predictive coupling rather than task difficulty. The regulatory system must compensate for unexpected sensory input, increasing control cost even in the absence of explicit cognition. Such effects highlight that regulation precedes and constrains higher-level control. Prediction failures are energetically expensive, and stability depends on alignment rather than corrective power.

5   Limitations of Current Embodied AI Architectures

Most contemporary robotic and embodied AI systems emphasize fast feedback loops, internal models, and centralized planning. While these approaches are effective in constrained settings, they often lack explicit baseline regulation and global constraint signals. Internal variables such as energy state, confidence, or error are typically optimized locally or abstracted away from persistent environmental coupling. As a result, control systems can drift, oscillate, or overcorrect when faced with unmodeled perturbations. Stability is achieved through increased computation or correction rather than through biased regulation. This architectural emphasis mirrors reactive rather than predictive control, increasing regulatory cost and reducing robustness.

6   Design Implications for Embodied Artificial Systems

The observations outlined above suggest several design principles for embodied AI and robotics: Explicit Baseline Regulation Systems should include mechanisms that stabilize behavior at low demand, allowing regulatory costs to be observed and minimized. Global Constraint Signals Introducing slow, environment-coupled variables accessible to all control layers may synchronize distributed subsystems without centralized command. Predictive Sensorimotor Coupling Control architectures should prioritize alignment between perception and action to reduce corrective effort and energy expenditure. Distributed Biasing over Centralized Correction Stability should emerge from continuous biasing rather than episodic intervention. These principles do not replace existing

learning or control methods; they provide a stabilizing scaffold upon which such methods can operate more effectively.

7 Limitations and Open Questions

This paper presents a conceptual framework rather than an experimental validation. While biological observations motivate the proposed principles, translating them into artificial systems raises open questions: How should global constraint signals be implemented in non-biological platforms? What metrics best capture baseline regulatory cost in artificial agents? How do these mechanisms interact with learning-based control systems over time? Addressing these questions will require simulation, physical experimentation, and interdisciplinary collaboration.

8 Conclusion

Biological systems maintain coherence not through centralized control or constant correction, but through baseline regulation enforced by global constraints and predictive coupling. Embodied artificial systems that lack this regulatory layer remain vulnerable to instability and inefficiency despite advances in computation and learning. By reframing stability as an emergent property of distributed regulation rather than explicit command, this paper outlines a path toward more robust, adaptive, and energy-efficient embodied AI and robotics systems.

Author's Note

This paper was authored by the undersigned. Large language model tools were used as a collaborative aid for drafting, editing, and clarity, while all concepts, observations, and conclusions remain the author's own.