

Physical Intelligence: A Paradigm for Electronics-Free Adaptive Systems Based on Material Constitutive Behavior

Zhao Hanbin (Independent Inventor, Zhejiang Province, China)

Corresponding address: Zhejiang Province, People's Republic of China

ORCID: 0009-0007-6464-076X

DOI: 10.5281/zenodo.20571554

Correspondence: zhaohanbin@outlook.com

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Abstract

Conventional intelligent systems rely on electronic sensors, controllers, and power supplies to realize the sense-decide-act loop. This paper proposes the “Physical Intelligence” paradigm – using the physical properties of materials (phase transformation, superelastic plateau, shape memory effect, etc.) to replace electronic systems, accomplishing the entire intelligent loop. Physical intelligence is not a substitute for artificial intelligence, but another branch of intelligence – it opens domains that electronic intelligence cannot enter: deep space, inside the human body, high temperature, strong radiation, microgravity. This paper establishes a complete axiomatic system for physical intelligence – the master axiom “Material constitutive behavior is the fundamental carrier of intelligence” governs the entire framework, with three fundamental axioms and three operational axioms constituting a deducible theoretical system. On this basis, a cross-material toolkit and a taxonomy of physical intelligence are developed, four modes of multi-material synergy are proposed, and the Stiffness-Switching paradigm of SMAs serves as the core validation. The core contribution of physical intelligence is to provide an operable definition, a deducible axiomatic system, a cross-material design methodology, and a shareable terminology dictionary for “electronics-free intelligence”.

Keywords: Physical intelligence; shape memory alloy; phase transformation; morphological computation; embodied intelligence; cross-material paradigm

1. Introduction: Another Path to Intelligence

What is intelligence? Since Turing asked “Can machines think?”, the definition of intelligence has been dominated by the electronic computing paradigm. Sensors acquire data, processors run algorithms, actuators output actions – this is the standard architecture of almost all modern intelligent systems, from smartphones to autonomous vehicles, from industrial robots to spacecraft control systems. In this paradigm, intelligence resides in code and chips; materials and structures are merely passive executors.

Nature, however, provides an alternative pathway. A spider web senses vibrations and transmits information – no sensors, no CPU. A cat's paw pad collapses progressively upon landing to absorb impact – no algorithm, no power supply. The human heart beats to pump blood – no controller, no external command. The common feature of these biological systems is that sensing, decision-making, and actuation are unified in the material's own structure and physical properties. The anisotropic vibration conduction of spider silk, the graded stiffness of the paw

pad's multi-chamber structure, the pressure pulse generated by the heart muscle – physical laws are themselves the program; material constitutive behavior is itself intelligence.

This path has long been neglected in engineering – until the emergence of active materials: shape memory alloys (SMAs), piezoelectrics, magnetorheological fluids, dielectric elastomers. They together reveal a new way to realize intelligence. Among them, SMAs, because they simultaneously possess sensing, actuation, energy absorption, and memory capabilities, have become the most complete and systematic validation vehicle for physical intelligence.

The reversible phase transformation of SMA between the martensitic and austenitic states endows it with a unique physical capability: a temperature change triggers the phase transformation (sensing), the phase transformation temperature threshold is the decision logic (decision), and the phase transformation drives macroscopic deformation or latent heat transport (actuation). These three steps are unified in a single phase transformation of the material – no sensor, no CPU, no power supply.

The goal of this paper is to formalize the design philosophy of using material physical properties to replace electronic intelligence systems as the Physical Intelligence paradigm, establishing an operable, deducible, and cross-material theoretical framework. The contributions of this paper include: (1) establishing a complete axiomatic system for physical intelligence; (2) developing a cross-material toolkit and a taxonomy of physical intelligence; (3) proposing four modes of multi-material synergy; (4) validating the paradigm with the SMA Stiffness-Switching paradigm; (5) defining the applicable boundaries of physical intelligence.

Physical intelligence operates without electronic components, relying solely on mechanical and physical principles.

2. Definition of Physical Intelligence

2.1 Definition

Physical intelligence is defined as the use of physical properties of materials – phase transformation, superelastic plateau, shape memory effect, piezoelectrics, magnetorheological effects, etc. – to replace the sensors, controllers, and power supplies in conventional engineering solutions, thereby realizing a sense-decide-act closed loop with adaptive functionality.

This is not a metaphor but a physical fact. When the reverse transformation temperature (A_f) of an SMA is set to body temperature, the material automatically deploys at body temperature – temperature sensing is accomplished by transformation thermodynamics, the deployment decision is encoded by the A_f threshold, and actuation is driven by lattice restructuring. Sensing is decision; decision is actuation. All three are unified in a single phase transformation.

Physical intelligence constitutes a distinct paradigm complementary to electronic intelligence, rather than a direct replacement. It opens domains that electronic intelligence cannot enter – extreme temperatures and radiation in deep space, the minimally invasive requirements inside the human body, the extreme simplicity requirements of microgravity systems, and reliable operation in strong electromagnetic environments.

2.2 Essential Differences from Conventional Intelligence

Conventional intelligence employs a three-stage architecture: sense → information → decide → information → act, where sensors convert physical quantities into electrical signals, controllers process information through algorithms, and actuators execute commands. These stages are independent, dependent on electronic systems, code, and external power, with information and

energy flowing through separate channels.

Physical intelligence adopts an integrated sense-decide-act architecture: the shape memory alloy (SMA) functions as an integrated sensor-actuator, where temperature-induced phase transformations directly drive functional responses. The SMA's phase transformation temperature threshold is the controller – A_f and M_f encode all decision logic. The SMA's transformation-induced deformation or latent heat transport is the actuator – directly driving mechanical action or heat transport. Information is energy, and energy is information – no separate signal channel is needed.

Conventional intelligence's function is determined by algorithms. Physical intelligence's function is determined by material design and heat treatment – alloy composition and aging processes determine A_f , pre-training determines the preset shape memory morphology. Algorithmic control in conventional systems corresponds to material microstructure design in physical intelligence.

2.3 The Core Operation: Co-opting Materials' "Troubles"

The defining feature of physical intelligence lies in its utilization of material nonlinearities, hysteresis, and phase transformation phenomena. These characteristics are not defects to be compensated or corrected; instead, they are co-opted as computational resources.

- The phase transformation temperature threshold of SMA is not a drawback – it is a programmable parameter: when the temperature reaches the threshold, the material undergoes a predefined phase change; no external control logic is required.
- The hysteresis of SMA is not an imperfection – it is a thermomechanical memory: it retains the history of thermal cycling; no separate memory storage is required.
- The superelastic plateau of SMA is not a nonlinear behavior – it is a stress plateau: it maintains constant stress within a defined strain range; no external control mechanism is necessary.
- The phase interface propagation in SMA is not a byproduct of heat conduction – it is a mechanism for directed heat transport: it enables heat to flow along predefined paths; no external pumping system is required.

Leave the complexity to the material; leave the simplicity to the user. This is the fundamental divergence of physical intelligence from conventional engineering thinking.

3. Axiomatic System of Physical Intelligence

An axiom is the most fundamental proposition of a theoretical system – it does not need to be proved, but all inferences of the system are derived from it. This paper proposes a deductive axiomatic system for physical intelligence, derived from the SMA Stiffness-Switching paradigm: seven axioms form the foundational propositions from which all system behaviors are logically inferred.

Master Axiom: Material Constitutive Behavior Is the Fundamental Carrier of Intelligence

The fundamental distinction between physical intelligence and conventional electronic intelligence lies not in the absence of electrical energy, but in the nature of the intelligence carrier. Conventional intelligence is carried by code – instruction sequences written in programming languages and stored in memory. Physical intelligence is carried by material constitutive behavior and structural topology – rules of physical behavior “written” with the crystal lattice and stored in the material itself.

When the A_f of an SMA is set to 32 °C, this is not a “setting” but a program: when the temperature reaches 32 °C, the material executes reverse transformation and outputs shape recovery. When the superelastic plateau of an SMA is set to 30 N, this is not a “parameter” but a function: for any displacement within the plateau, the force remains constant at 30 N. Physical laws replace electronic code; the crystal lattice replaces the memory chip; temperature difference replaces the battery.

Fundamental Axiom 1: Material Constitutive Behavior Integrates Sensing, Decision, and Actuation

The three core functions of intelligence – sensing, decision, actuation – are unified in the material’s own physical behavior, requiring no separate sensors, controllers, or actuators.

An SMA element simultaneously plays three roles: sensing – when the temperature reaches A_s , transformation begins; no thermocouple is needed. Decision – the transformation temperature thresholds (A_s , A_f , M_s , M_f) are the decision logic; no conditional statements are needed. Actuation – the macroscopic deformation itself is the actuation. By modifying the material’s constitutive relation (e.g., A_f , superelastic plateau stress, hysteresis area), the designer directly “programs” the intelligent behavior.

When a force is needed, it is present by design. This is not a wish but a consequence of precise cross-sectional variation: the force automatically appears at the required displacement interval.

Fundamental Axiom 2: Distributed Self-Organization Is Superior to Central Control

Physical intelligence systems achieve global order through distributed self-organization, where local material interactions replace centralized controllers. Each unit makes autonomous decisions based on local physical conditions, and global order emerges naturally from local interactions.

In the Orange-Segment Autonomous Network of the pulsating heat pump, local thermal gradients trigger evaporation at irradiated segments – no central controller, no synchronization mechanism. In the Corner-Anchor Spatial Web of the impact protection container, whichever direction the impact comes from, the SMA wires in that direction are automatically stretched to absorb energy – no sensor detects the direction; the force itself activates the corresponding path. A distributed architecture achieves global stability through local interactions. No central controller is required as each unit autonomously responds to local conditions.

Fundamental Axiom 3: Active Compliance Is Superior to Passive Confrontation

Physical intelligence systems achieve energy efficiency by actively complying with environmental forces, using natural physical processes to drive adaptive behaviors. The highest form of physical intelligence is neither passive resistance to environmental change nor active external control, but rather using the environment’s own physical quantities (temperature difference, pressure, impact force, magnetic field) as the driving force, complying with the natural direction of physical processes and guiding them toward beneficial outcomes.

The SMA breathing spring actively extends at high temperature to help hydrogen release, and actively contracts at low temperature to help hydrogen absorption – every step complies with the natural direction of the chemical reaction, using the SMA’s shape memory effect to create the ideal pressure conditions needed by the chemical storage. Not constraint, not confrontation – active compliance.

Operational Axiom 1: Shape Is the Program

Geometric topology and material shape encode functional logic, replacing electronic programming with inherent material responses. Changing the cross-section changes the timing of

force control – the thin segment outputs force first, the thick segment takes over later. Changing the arrangement direction of honeycomb cells changes the direction of energy absorption – out-of-plane for strong absorption, in-plane for compliance. Changing the weave density of a mesh changes the elastic travel – sparse mesh for large travel, dense mesh for high force.

Replace parts with shape; realize functions with geometry. Between convexity and concavity lies the map of force. Shape is the most streamlined part.

Operational Axiom 2: Thermal Management Is Flow Management

Heat is managed as a directed flow vector, with thermal gradients naturally guiding energy distribution without passive dissipation mechanisms. The essence of heat is not an enemy to be eliminated, but a resource that can be directionally guided. Thermal management is not passive dissipation but creating a directed river for heat – heat flows from the high-temperature end to the low-temperature end; the river’s channel, driving force, gates, and direction are automatically provided by physical laws and material constitutive behavior.

Heat is no longer a burden but a resource. Move heat to where it is needed.

Operational Axiom 3: Energy Flow Carries Control Information

Energy transfer inherently carries control information, unifying energy and signal channels in a single physical process. Conventional electronic intelligence separates energy and information – power lines carry energy, signal lines carry data. Physical intelligence unifies the two: when the SMA reaches A_f , heat is simultaneously the energy that drives the phase transformation and the information that triggers the action. The pressure pulse of the pulsating cycle simultaneously pushes the working fluid and carries the status signal of “pacemaking successful”. The impact force itself in the Corner-Anchor Spatial Web is simultaneously the energy to be dissipated and the signal that indicates the direction of impact.

Every energy transfer process in a physical intelligence system naturally carries control logic. No additional sensor is needed to detect state changes – the state change is expressed by the energy flow that drives the process. No signal line is needed to transmit commands – the command is encoded in the timing, threshold, and intensity of the energy flow.

The energy flow is the signal flow; the work-doing process is the communication process. Physical intelligence does not need a “nervous system” because its “circulatory system” simultaneously performs the function of information transmission.

4. Distinction from Related Concepts

Physical intelligence is closely related to, but fundamentally different from, existing concepts such as morphological computation and embodied intelligence.

Dimension	Morphological Computation	Embodied Intelligence	Physical Intelligence (this paper)
Core claim	Body shape can bear part of computation	Intelligence must have a body	Material constitutive behavior is intelligence
Carrier of intelligence	Geometry, passive dynamics	Body + algorithms	Phase transformation, constitutive relations

Dimension	Morphological Computation	Embodied Intelligence	Physical Intelligence (this paper)
Electronic dependence	No (but usually reduces computation)	Yes (sensors, controllers)	No (completely electronics-free)
Active/Passive	Passive (deterministic response)	Active (algorithm-driven)	Active (phase-transformation-driven)
Source of “intelligence”	Shape assists computation	Algorithms learn through body	Material itself completes decision

Morphological computation uses geometry and passive dynamics to reduce computational burden; its behavior is deterministic and predictable. Physical intelligence employs the active phase transformation of materials to replace the entire sense-decide-act loop, with behavior being event-triggered and state-dependent. Morphological computation is passive; physical intelligence is active.

Embodied intelligence holds that intelligence must have a body, but its “body” is a collection of sensors and actuators, and its “intelligence” still comes from algorithms. Physical intelligence is an extreme realization of embodied intelligence – not “body assisting the brain”, but “body as the brain”.

Difference from Sitti’s (2021) “Physical Intelligence” program: Sitti (2021) proposed physical intelligence as a new paradigm for soft robotics, emphasizing the use of material physical properties to achieve adaptive behavior. The differences of this paper are: (1) it provides an operable definition and a complete axiomatic system; (2) it establishes “co-opting materials’ troubles” as the core operation; (3) it develops a cross-material toolkit and a taxonomy; (4) it demonstrates complete system implementations of physical intelligence in both mechanical and thermal domains. In short: Sitti’s “physical intelligence” is a research program; this paper’s “physical intelligence” is an operable theoretical framework.

5. Cross-Material Toolkit and Taxonomy of Physical Intelligence

Physical intelligence is not exclusive to SMAs. Any active material with a “sense-response” coupling can be incorporated into the framework of physical intelligence.

5.1 Candidate Materials and Their “Computable Physical Phenomena”

Material	Trigger	Physical response	Built-in “decision” logic	Co-optable computational resource
Shape memory alloy (SMA)	Temperature / stress	Phase transformation →	Transformation temperature	Hysteresis, nonlinear plateau,

Material	Trigger	Physical response	Built-in “decision” logic	Co-optable computational resource
		macroscopic deformation or latent heat transport	thresholds (A_f, M_f)	transformation window
Piezoelectric (PZT, PVDF)	Mechanical force / electric field	Force \rightarrow charge; electric field \rightarrow deformation	Curie temperature, resonance window	Force-electric coupling only efficient at specific frequencies
Magnetorheological fluid/elastomer	Magnetic field	Changes viscosity and stiffness (ms)	Nonlinear yield stress vs. magnetic field	Yield stress saturation
Dielectric elastomer	Electric field	Large-strain deformation	Dielectric breakdown threshold	Nonlinear creep before breakdown
Thermo-/pH-sensitive hydrogel	Temperature / pH	Swelling or shrinking, large volume change	Phase transition or pH critical point	Volume phase transition hysteresis
Liquid metal (Ga-based)	Temperature / current	Solid-liquid phase change, conductivity and volume change	Melting point as natural threshold	Volume jump at solid-liquid transition

All these materials inherently possess physical “decision conditions” (thresholds) and directly output mechanical work, electrical signals, or heat upon meeting the conditions, naturally possessing the integrated sense-decide-act feature of physical intelligence.

5.2 Taxonomy of Physical Intelligence

Physical intelligence can be systematically categorized into three types based on the implementation mechanism of “intelligence”:

Type 1: Threshold-triggered. Representative materials: SMA, thermosensitive hydrogel, liquid metal. Logic: “if-then”. The material switches state at a preset physical threshold (temperature,

stress, pH). The A_f temperature of SMA is the most typical threshold “program”. Engineering examples: SMA thermal switch, thermosensitive hydrogel valve.

Type 2: Continuous response. Representative materials: piezoelectric, magnetorheological fluid. Logic: “function mapping”. The output signal is a continuous function of the input signal (force → charge, magnetic field → viscosity); this functional relationship itself is a computation. Engineering examples: piezoelectric sensor, magnetorheological damper.

Type 3: Adaptive/memory. Representative materials: SMA (hysteresis), certain polymers. Logic: “state memory”. The material’s response depends not only on the current environment but also on the history it has experienced. The hysteresis of SMA is the most typical thermomechanical memory – it stores the maximum experienced temperature as a state variable; no separate memory storage is required.

6. Multi-Material Synergy: A System-Level Leap of Physical Intelligence

Single-material physical intelligence represents a component-level function, while multi-material synergy constitutes a system-level intelligent architecture, marking the leap of physical intelligence from the component level to the system level.

6.1 The Closed-Loop Logic of Mutual Causality

The key characteristic of multi-material synergy is the closed-loop causality: environmental stimuli activate material A → A’s response alters the local environment → material B is triggered → B’s response reciprocally affects A or sets conditions for subsequent steps. The responses of A and B share the same physical driving force (e.g., heat, pressure, magnetic field), and the causal chain is automatically transmitted by physical laws, requiring no external control.

Judgment criterion for mutual causality: removing any single material disrupts the causal loop. If this occurs, the two materials are not simply in parallel but in a symbiotic, mutually causal relationship.

6.2 Four Synergy Modes

Mode 1: Energy amplification (firing-pin/gunpowder mechanism). SMA pacemaker + water. The SMA senses temperature reaching A_f , its reverse-transformation deformation acts as a mechanical trigger, inducing explosive boiling of superheated water and releasing tens to hundreds of times the latent heat of vaporization. The SMA consumes a small amount of latent heat (20–30 J/g) to trigger a large energy release from the working fluid (water’s latent heat of vaporization ≈ 2260 J/g); the energy amplification ratio can reach 20–100.

Mode 2: Functional complementarity (sense-act division). Piezoelectric + electrostrictive material. The piezoelectric senses mechanical vibration and generates charge (sensing); the charge directly drives the electrostrictive material to deform (actuation); the deformation of the electrostrictive material changes the stress state of the piezoelectric (feedback), forming a closed loop. Piezoelectrics excel at sensing but not large deformation; electrostrictive materials excel at large deformation but not sensing – they complement each other.

Mode 3: State latching (bistable logic). SMA + permanent magnet. The SMA senses temperature and deforms, changing the gap between a permanent magnet and a soft magnetic material; beyond a certain threshold, the magnetic force takes over and latches the system in the second state. The SMA only needs to overcome the initial energy barrier; steady-state holding is performed by the magnetic force – a natural “set-reset” logic gate. This can be used for mechanical memory or state indicators that do not require continuous power.

Mode 4: Temporal pre-judgment (thermal response time difference). SMA spring + chemical storage (e.g., metal hydride). The SMA spring has small mass, low heat capacity, and fast response; the chemical storage has large mass, high heat capacity, and slow response. When a thermal peak arrives, the SMA spring completes reverse transformation before the chemical storage, actively expands the gas pocket, and pre-creates a low-pressure environment for the upcoming hydrogen release reaction. During cooling, the SMA spring completes forward transformation before the chemical storage, contracts and compresses the gas pocket to promote hydrogen absorption. Physical laws naturally guarantee the correct timing sequence without any electronic timer.

7. SMA as the Core Validation of Physical Intelligence

SMA is the most complete and systematic engineering realization vehicle for the Physical Intelligence paradigm. In the author's concurrently published Stiffness-Switching paradigm [1] and Heat Redistribution paradigm [2], physical intelligence has been fully validated in both mechanical and thermal domains.

7.1 Mechanical Realization

The Corner-Anchor Spatial Web of the impact protection container forms an isotropic pre-tension network. Impact force is automatically decomposed into axial tension of multiple SMA wires; the impact intensity automatically determines how many wires are stretched and the level of damping – a weak impact activates only a few fine wires; a strong impact mobilizes all wires. Sensing-decision-actuation is unified in the superelastic plateau of SMA. In the three-ring decoupled Parkinsonian wrist device, the SMA wires provide precision damping within a limited travel, while the decoupling layer provides free motion over large travel – achieving the intelligent function of “distinguishing voluntary movement from pathological tremor”. These mechanical realizations together validate Operational Axiom 1 (Shape is the program) and Operational Axiom 3 (Energy flow carries control information).

7.2 Thermal Realization

In the pulsating heat pump, the SMA actuator employs reverse phase transformation to induce nucleate boiling of superheated water, achieving energy amplification through a mechanical ignition mechanism. Multiple evaporation chambers form an Orange-Segment Autonomous Network – local thermal gradients trigger evaporation at irradiated segments, eliminating the need for centralized control. In the Liver-Lobule Microcirculation preheating network, a single SMA wire runs along bundled pipelines; wherever the phase interface propagates, preheating is delivered. The integrated system of SMA-sheet venous valves and microstructured capillary grooves enables fully passive, unidirectional liquid circulation in microgravity environments. These thermal realizations together validate Operational Axiom 2 (Thermal management is flow management) and Fundamental Axiom 2 (Distributed self-organization is superior to central control).

7.3 Thermal-Chemical Synergy

In the Thermal Peak Clamping system, the SMA and the chemical storage are arranged in parallel on the same thermal bus, sharing the thermal path. The SMA breathing spring, using the natural thermal response time difference, undergoes phase transformation before the chemical storage, pre-adjusting the pressure for the upcoming reaction – physical laws naturally guarantee the timing correctness. This synergy validates Mode 4 of multi-material synergy (temporal

pre-judgment).

7.4 From Single Agent to Swarm Intelligence

In the pulsating heat pump, a single orange segment is an independent physical intelligence agent; multiple orange segments form an autonomous network. Each segment beats autonomously according to its local temperature; global order emerges naturally from local interactions – thermal sovereignty is handed over seamlessly by sunlight. From single agent to swarm, the SMA network realizes distributed self-organization.

8. Boundaries of Physical Intelligence

Physical intelligence is not a panacea. It is an optimal design philosophy under specific constraints.

Scenarios where physical intelligence is irreplaceable:

- Strong electromagnetic environments (inside MRI machines, nuclear facilities) – electronic systems are prone to failure due to eddy current effects and ionizing radiation.
- Truly unattended deep space – no repair possible, no power supply; every added electronic component adds a failure point.
- Passive safety scenarios where any electronic control logic is prohibited (e.g., final line of defense against battery thermal runaway) – the electronic system itself could become an ignition source.
- Microgravity environments – solutions relying on gravity for return flow all fail; venous valves + capillary grooves are the only solution.

Scenarios where electronic solutions are superior:

- Need for precise timing control (sub-millisecond or synchronization with an external clock).
- Need for complex logical decisions (more than threshold triggers, multi-condition combinations, state machines with more than 3 states).
- Cost-sensitive, conventional terrestrial applications with already mature electronic solutions.

Grey zone (both possible):

Conventional industrial environments for adaptive fixtures, attitude adjustment mechanisms without high precision requirements, simple adaptive functions in consumer wearables. In these cases, the designer must trade off cost, reliability, development cycle, and power consumption.

The clearer the boundary, the stronger the academic legitimacy of the paradigm. Honesty is the foundation on which a paradigm stands.

9. Future Directions

The evolution of physical intelligence is proposed along three hierarchical axes: material migration, multi-material synergy, and theoretical formalization, each requiring distinct research trajectories.

Cross-material migration: Transfer the design principles extracted from the SMA paradigm to other active materials – piezoelectric, magnetorheological fluid, dielectric elastomer, thermosensitive hydrogel. Each material has its own unique “computable troubles”; the physical intelligence paradigm provides a unified design methodology for them.

Multi-material synergy: Explore more mutually causal material combinations. SMA +

piezoelectric could realize thermo-mechano-electric multi-field coupling; dielectric elastomer + magnetorheological fluid could realize electric-magnetic dual-mode intelligence.

Theoretical deepening: Establish a formal framework for physical intelligence theory, including: (1) boundary conditions for application domains, (2) standardized design protocols, and (3) verifiable validation criteria. Physical intelligence should not remain at the level of “a good story” but should become a teachable, deducible, falsifiable framework.

10. Conclusion

Physical intelligence is another branch of intelligence. It replaces electronic systems with the phase-transformation constitutive behavior of materials, replaces code with physical laws, and replaces batteries with temperature differences. It opens domains that electronic intelligence cannot enter – deep space, inside the body, high temperature, strong radiation, microgravity.

This paper has established a seven-axiom system for physical intelligence: the master axiom that material constitutive behavior is the fundamental carrier of intelligence; three fundamental axioms – material constitutive behavior integrates sensing, decision, and actuation, distributed self-organization is superior to central control, active compliance is superior to passive confrontation; and three operational axioms – shape is the program, thermal management is flow management, energy flow carries control information. A cross-material toolkit and a taxonomy of physical intelligence have been developed, four modes of multi-material synergy have been proposed, and the SMA Stiffness-Switching paradigm serves as the core validation.

Physical intelligence is different from the “passive utilization” of morphological computation, different from the “algorithm-learning-through-body” of embodied intelligence, and different from previous programmatic advocacy of physical intelligence. Its uniqueness lies in: co-opting materials’ “troubles” as computational resources – hysteresis, nonlinearity, and phase transformation windows are not defects but functions; the material itself completes the sense-decide-act closed loop, zero electronics, zero code, zero external power; it has been fully validated in both the mechanical and thermal domains; and it provides an operable, deducible, cross-material general framework.

From a single SMA wire trembling spontaneously between hot and cold, to a biomimetic heart pulsating and pumping heat – the core philosophy of physical intelligence remains the same throughout: **Material constitutive behavior is the fundamental carrier of intelligence.**

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Author Contribution

Zhao Hanbin independently completed all theoretical construction, paradigm definition, axiomatic system elaboration, cross-material analysis framework, and manuscript writing of this paper.

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Conflicts of Interest

The author declares no conflicts of interest.

Ethics Statement

This paper presents theoretical conceptual designs and does not involve any human or animal subjects, clinical trials, or patient data. No ethical approval was required.