Embodied Intelligence and World Models: A Survey of Progress from 2024 to Early 2026

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Abstract

Embodied intelligence requires agents to perceive, reason, and act under real-world physical constraints while adapting online to new tasks and environments. Over the last year, the field has rapidly shifted from modular pipelines toward large-scale vision-language-action (VLA) policies and world-model-based control stacks, with increasing emphasis on long-horizon robustness, data efficiency, and cross-embodiment transfer [Liang et al., 2025a, Liu et al., 2025a, Li et al., 2025a, Fung et al., 2025]. This survey reviews research from January 2024 to February 2026 and organizes the literature with a coupled framework: an embodied-agent pipeline view (perception, planning, control, adaptation) and a world-model design view (functionality, temporal modeling, and spatial representation). We synthesize representative advances in foundation VLAs, embodied world models, policy refinement, and benchmark design [Kim et al., 2024, Intelligence et al., 2025a, Black et al., 2026, Team et al., 2025a, Chen et al., 2026a, Upadhyay et al., 2026]. We further formalize the common learning objective that links latent dynamics modeling with decision optimization, clarifying where current systems gain performance and where they fail under distribution shift, partial observability, and closed-loop compounding errors [Gupta et al., 2024, Wan et al., 2025, Team et al., 2025b]. We conclude with concrete priorities on physical consistency, embodiment-aware representation, and safe continual adaptation for real deployment.

Keywords: embodied AI, world models, vision-language-action models, robotic foundation models, long-horizon planning

1 Introduction

Embodied AI studies agents that close the full interaction loop with the physical world: sensing, state estimation, decision making, and low-level action execution under uncertainty and resource constraints. Classical task settings such as rearrangement and instruction-conditioned navigation established this closed-loop perspective early, and also highlighted the gap between benchmark success and robust real-world deployment [Batra et al., 2020, Duan et al., 2022]. Recent progress in large multimodal models, robot foundation policies, and scalable data pipelines has substantially accelerated the field [Brohan et al., 2023, Bousmalis et al., 2023, Driess et al., 2023, Kim et al., 2024, Black et al., 2026].

In parallel, world models have re-emerged as a central abstraction for embodied decision making. Instead of treating policy learning as a purely reactive mapping from observations to actions, world-model methods explicitly or implicitly learn transition structure and use it for imagination, evaluation, and planning [Gupta et al., 2024, Ding et al., 2025a, Li et al., 2025a]. This trend is visible across robot manipulation, autonomous driving, and general multimodal control

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stacks, where latent rollouts, video-conditioned prediction, or hybrid generative dynamics are increasingly used to improve sample efficiency and long-horizon consistency [Fung et al., 2025, Wan et al., 2025, Team et al., 2025b, Chen et al., 2026a].

1.1 Scope and Inclusion Criteria

This survey covers work from **January 1, 2024 to February 27, 2026**. We adopt a strict embodied criterion: a paper is in scope when its method or benchmark directly supports closed-loop physical interaction, robot control, embodied decision making, or embodied world-modeling. Purely generic sequence modeling or non-embodied world simulation is excluded from the core technical analysis.

We use two synchronized views:

- **Embodied pipeline view:** perception, planning/reasoning, control, and adaptation.
- **World-model view:** functionality (decision-coupled vs. general-purpose), temporal modeling (stepwise vs. global), and spatial representation (compact latent, tokenized, geometric, or hybrid).

This dual view is motivated by the observation that modern VLA systems blur traditional module boundaries. Many recent methods couple high-level language reasoning with low-level visuomotor control while integrating learned predictive priors to stabilize long-horizon behavior [Intelligence et al., 2025a,b, Zheng et al., 2025a, Li et al., 2025b, Cen et al., 2025a].

1.2 Why a New Survey Is Needed

Multiple surveys now cover embodied AI, world models, or VLA development from different angles [Liu et al., 2025a, Liang et al., 2025a, Lu and Tang, 2025, Shao et al., 2025, Zhang et al., 2025a, Fan et al., 2026, Yu et al., 2026a]. However, three gaps remain.

First, many reviews are either broad but shallow on algorithmic coupling, or deep on world models but not tightly connected to embodied control decisions. Second, year-scale progress in 2025–2026 has changed the practical frontier quickly, including open-world VLA generalization, reinforcement-style post-training for robots, and embodied world-model benchmarks [Intelligence et al., 2025a,b, Upadhyay et al., 2026, Wu et al., 2026a]. Third, practical deployment questions now require unified treatment of policy scaling, dynamics modeling, and closed-loop reliability instead of isolated module-level analysis.

1.3 Technical Lineage Before 2024

The current wave is built on three earlier lines of work. The first line defined canonical embodied tasks and open environments, including rearrangement-centered evaluation and open-ended skill acquisition settings [Batra et al., 2020, Duan et al., 2022, Fan et al., 2022]. The second line explored language-grounded planning with explicit feasibility and feedback loops, moving from zero-shot language planning to grounded decoding, planner-actor decomposition, memory-augmented instruction following, and dialogue-conditioned control [Ahn et al., 2022, Huang et al., 2022a,b, Song et al., 2023, Wu et al., 2023a,b, Huang et al., 2023a, Sarch et al., 2023, Gao et al., 2022].

The third line established foundation-policy recipes for robot control at scale: multimodal generalist policies, transformer-based real-world control, scalable offline RL, multimodal prompting for manipulation, code-level policy synthesis, trajectory-sketch interfaces, and geometry-aware language control [Reed et al., 2022, Brohan et al., 2023, Chebotar et al., 2023, Bousmalis et al., 2023, Driess et al., 2023, Jiang et al., 2023, Liang et al., 2023, Gu et al., 2023, Huang et al., 2023b]. Data and embodiment scaling also accelerated through BridgeData V2, low-cost ACT-style teleoperation pipelines, and open-ended lifelong agents [Walke et al., 2023, Zhao et al., 2023, Wang et al., 2023a]. Additional precursors examined continuous scene representations, equivariant diffusion planning, and language-guided world modeling for embodied control [Gadre et al., 2022, Brehmer et al., 2023, Nottingham et al., 2023].

1.4 Contributions

This survey makes four concrete contributions:

- We provide a **decision-oriented synthesis** of embodied intelligence and world models under a single coupled taxonomy.
- We formalize a **shared learning objective** that links latent dynamics learning and downstream control optimization.

- We summarize **recent advances (2024–2026)** across VLA architectures, embodied world-modeling, data/benchmark design, and policy refinement [Kim et al., 2024, NVIDIA et al., 2025a,b, Black et al., 2026, Mei et al., 2026].
- We distill **cross-generation design principles** by linking 2024–2026 systems to pre-2024 technical precursors in grounding, planning, data scaling, and policy adaptation.

1.5 Paper Organization

Section 2 introduces formal foundations and a unified notation for embodied interaction and world-model training. Section 3 presents the coupled taxonomy and representative methods. Section 4 summarizes data resources and evaluation protocols. Section 5 discusses cross-family comparisons and tradeoffs. Section 6 distills open challenges and forward-looking directions. Section 7 concludes.

2 Background and Mathematical Formulation

2.1 Embodied Interaction as a Partially Observable Control Process

We model embodied interaction as a partially observable Markov decision process (POMDP):

$$\mathcal{M} = (\mathcal{S}, \mathcal{A}, \mathcal{O}, p, \Omega, r, \gamma), \tag{1}$$

where $s_t \in \mathcal{S}$ is the latent world state, $a_t \in \mathcal{A}$ is the control action, and $o_t \in \mathcal{O}$ is the observation stream (RGB, depth, force, language context, proprioception). The environment follows

$$s_{t+1} \sim p(s_{t+1} \mid s_t, a_t), \qquad o_t \sim \Omega(o_t \mid s_t). \tag{2}$$

Embodied agents optimize discounted return

$$J(\pi) = \mathbb{E}_{\pi,p}\left[\sum_{t=0}^{T} \gamma^t r(s_t, a_t)\right]. \tag{3}$$

Compared with pure simulator RL settings, deployed embodied systems must satisfy strict constraints on reaction latency, safety, action smoothness, and distribution shift under long horizons [Intelligence et al., 2025a,b, Black et al., 2026, Wu et al., 2026b].

2.2 Pre-2024 Design Motifs that Shaped Current Formulations

Several pre-2024 lines directly shaped current embodied modeling assumptions. Language-grounded planning works argued for explicit decomposition between high-level plan tokens and low-level motor execution, often with environment feedback and feasibility filters [Ahn et al., 2022, Huang et al., 2022a,b, Song et al., 2023, Wu et al., 2023a, Huang et al., 2023a]. In our notation, this motivates a latent plan variable ξ_t:

$$\pi(a_t \mid h_t, g) = \int \pi_{\text{low}}(a_t \mid h_t, \xi_t)\, \pi_{\text{high}}(\xi_t \mid h_t, g)\, d\xi_t, \tag{4}$$

where h_t denotes observation-action history and g is the instruction or goal.

In parallel, generalist and transformer-control systems showed that heterogeneous action modalities can be cast as autoregressive token prediction, spanning text, manipulation commands, and other control outputs [Reed et al., 2022, Brohan et al., 2023, Chebotar et al., 2023, Jiang et al., 2023]. This perspective strongly influenced modern VLA design choices on action tokenization, sequence conditioning, and scaling laws.

Another precursor line integrated predictive modeling and control through video or latent generation, code-mediated policies, trajectory sketches, and geometry-aware grounding [Wu et al., 2023c, Liang et al., 2023, Gu et al., 2023, Huang et al., 2023b, Nottingham et al., 2023]. These ideas foreshadow current 2024–2026 systems that combine policy learning with explicit predictive objectives and planner-model coupling.

2.3 Latent World Models for Embodied Control

A practical world model introduces latent states z_t to capture controllable scene dynamics:

$$z_t \sim q_\phi(z_t \mid o_{\leq t}, a_{<t}), \qquad \hat{z}_{t+1} \sim p_\theta(z_{t+1} \mid z_t, a_t). \tag{5}$$

The decoder or predictor head maps latent trajectories back to observation and task-relevant signals:

$$\hat{o}_{t+1} \sim p_\theta(o_{t+1} \mid \hat{z}_{t+1}), \qquad \hat{y}_{t+1} = g_\psi(\hat{z}_{t+1}), \tag{6}$$

where $\hat{y}_{t+1}$ may denote object states, occupancy, contact events, or value estimates, depending on the downstream stack [Li et al., 2025a, Fung et al., 2025, Team et al., 2025b, Berg et al., 2025].

Most implementations optimize a reconstruction-regularization-task objective:

$$\mathcal{L} = \underbrace{\mathcal{L}_{\text{obs}}}_{\text{prediction/reconstruction}} + \beta \underbrace{\mathrm{KL}[q_\phi(z_t \mid \cdot) \parallel p_\theta(z_t \mid z_{t-1}, a_{t-1})]}_{\text{dynamics consistency}} + \lambda \underbrace{\mathcal{L}_{\text{task}}}_{\text{control/planning utility}}. \tag{7}$$

The key distinction in modern embodied literature is not whether this decomposition exists, but where decision coupling is applied: end-to-end VLA policy heads, model-predictive planning over latent rollouts, hybrid actor-model loops, or offline-to-online adaptation pipelines [Kim et al., 2024, Li et al., 2025b, Cen et al., 2025a, Wan et al., 2025, Shen et al., 2026].

2.4 Decision Optimization with Learned Dynamics

Given a learned model, open-loop planning over horizon H can be written as

$$\mathbf{a}^*_{t:t+H-1} = \arg\max_{\mathbf{a}_{t:t+H-1}} \mathbb{E}_{p_\theta}\left[\sum_{k=0}^{H-1} \gamma^k \hat{r}_{t+k}\right]. \tag{8}$$

In practice, embodied systems rarely execute Eq. 8 in pure form. They combine short-horizon replanning, policy priors, and intervention signals to control compounding errors [Intelligence et al., 2025b, Li et al., 2025c, Lu et al., 2025, Chen et al., 2025a].

2.5 Failure Modes in the 2024–2026 Regime

Recent work repeatedly identifies three bottlenecks:

- **Long-horizon drift:** rollout quality degrades over multi-stage tasks, especially when contact dynamics and object geometry shift.
- **Representation mismatch:** action-space controls and pixel-space predictors are weakly aligned without embodiment-aware conditioning [Chen et al., 2026a, Guo et al., 2026].
- **Evaluation gaps:** pixel fidelity and short-horizon success can hide causal or physically inconsistent behavior; benchmark design is now moving toward embodied stress tests [Upadhyay et al., 2026, Wu et al., 2026a, Valle et al., 2025].

These failure modes motivate the coupled taxonomy in the next section.

3 Coupled Taxonomy of Embodied Intelligence and World Models

We organize recent methods along two synchronized dimensions: (i) the embodied decision stack and (ii) world-model design choices. This decomposition keeps algorithmic comparisons explicit while preserving system-level relevance.

3.1 Taxonomy Design Principles

We build the taxonomy around *decision coupling*, *temporal modeling*, and *spatial representation*, because these three choices consistently determine deployment behavior across manipulation, navigation, and driving settings. A purely architecture-centric taxonomy hides optimization targets and interface contracts; a purely task-centric taxonomy hides why similar tasks still diverge in stability, sample efficiency, and latency.

This design also aligns with historical development: early rearrangement and instruction-following studies separated task definition from policy mechanism [Batra et al., 2020, Gao et al., 2022]; language-grounded planners emphasized high-level symbolic decomposition with feasibility checks [Ahn et al., 2022, Huang et al., 2022b, Wu et al., 2023a]; and foundation-policy work emphasized unified token-based control with heterogeneous data [Reed et al., 2022, Brohan et al., 2023, Bousmalis et al., 2023]. The 2024–2026 systems can be interpreted as deeper integration of these once-separate axes.

3.2 Axis A: Functionality Coupling

Decision-coupled world models are trained and evaluated for direct control impact (policy improvement, planning reliability, intervention reduction). Representative examples include online-refined VLA pipelines and world-model-guided policy optimization [Intelligence et al., 2025b, Li et al., 2025b, Zang et al., 2025, Zhu et al., 2025a].

General-purpose world models prioritize broad predictive capability and transfer, then attach downstream controllers. This line includes large pretraining efforts and multimodal dynamics models used as reusable priors [NVIDIA et al., 2025b, Team et al., 2025b, Fan et al., 2026, Yin et al., 2026].

In practice, the key separator is *optimization target*. Decision-coupled models directly optimize task-facing losses (success, intervention, or value improvement) under closed-loop rollout constraints. General-purpose models prioritize reusable predictive competence, often scaling with heterogeneous data and delaying control coupling to post-training.

The two settings are complementary rather than contradictory: many successful systems pretrain in a general-purpose regime and then switch to decision-coupled adaptation for target deployment [Intelligence et al., 2025a,b, Black et al., 2026, Li et al., 2025c, Lu et al., 2025].

3.3 Representative Method Evidence

Representative system reports indicate that recent gains are tied to explicit design decisions, not only scale.

- **π_0 lineage:** π_0 reports flow-matching policy design on top of pretrained VLM priors and heterogeneous dexterous robot data; $\pi_{0.5}$ emphasizes heterogeneous co-training with semantic subtask signals for open-world generalization; $\pi^*_{0.6}$ introduces RECAP with demonstrations, on-policy data, and teleoperated corrections for deployment improvement [Black et al., 2026, Intelligence et al., 2025a,b].
- **Tokenization as a systems lever:** FAST explicitly attributes failures of naive per-dimension binning in high-frequency dexterous control and proposes DCT-based tokenization, reporting up to $5\times$ training speedups [Pertsch et al., 2025].
- **Action-world co-modeling:** WorldVLA frames action generation and future image prediction as mutually beneficial in one autoregressive stack, while VLA-RFT and VLA-RL highlight RL-style fine-tuning for robustness under distribution shift [Cen et al., 2025a, Li et al., 2025b, Lu et al., 2025].
- **Embodiment-conditioned world modeling:** BridgeV2W converts coordinate actions into pixel-aligned embodiment masks (from URDF and camera parameters) to align action control with video prediction and cross-view consistency [Chen et al., 2026a].

These results are consistent with the functionality axis: models that explicitly connect representation learning to downstream control objectives tend to report better real-world robustness than purely decoupled predictive modeling. Similar behavior was already visible in earlier grounding-focused methods that constrained language plans with executable skills or grounded objectives [Ahn et al., 2022, Huang et al., 2023a, Dasgupta et al., 2023].

3.4 Axis B: Temporal Modeling

Sequential rollouts simulate future states step by step and align naturally with MPC-style control, but face compounding error over long horizons [Li et al., 2025a, Fung et al., 2025, Cen et al., 2025a].

Global prediction methods forecast larger trajectory segments or future differences in parallel and can improve efficiency, but require stronger structural priors to preserve causal consistency [Wan et al., 2025, Mei et al., 2026, Wang et al., 2026].

This temporal choice can be viewed as a bias-variance-compute tradeoff. Let ϵ_t denote one-step model error in latent space. In a simplified sequential regime, rollout error can scale approximately as

$$\mathcal{E}_{t+H} \propto \sum_{k=0}^{H-1} \|\epsilon_{t+k}\|, \tag{9}$$

which explains sensitivity in long-horizon manipulation and multi-agent traffic forecasting. Global predictors reduce iterative accumulation steps but can underfit local control-relevant transitions unless they include action- and embodiment-aware constraints [Chen et al., 2026a, Guo et al., 2026, Zhou et al., 2026].

Recent hybrids combine chunk-wise global prediction with local sequential correction, effectively using coarse global proposals and fine-grained control-time refinement [Team et al., 2025a, Shen et al., 2026, Wu et al., 2026c].

3.5 Axis C: Spatial Representation

Compact latent representations support real-time control and low compute budgets. **Tokenized representations** improve multimodal alignment with language-conditioned reasoning. **Geometry-aware or rendering-aware representations** better preserve view consistency and object-level structure for manipulation and driving scenarios [Chen et al., 2026a, Li et al., 2025d, Sun et al., 2025a, Zhang et al., 2025b].

From a deployment perspective:

- **Compact latent states** are favorable when control frequency and onboard compute dominate constraints.
- **Tokenized states** are favorable when semantic alignment with language and chain-of-thought style planning is critical.
- **Geometry-aware states** are favorable when camera viewpoint shift, scene rearrangement, or contact geometry consistency is central.

No single representation is dominant across all tasks. Systems that report robust real-world transfer commonly use representation mixtures (e.g., semantic tokens + geometric priors + low-level action heads) rather than a single latent form [Intelligence et al., 2025a,b, Chen et al., 2026a, Zhang et al., 2026a].

An additional observation is that VLM quality alone is an imperfect predictor of downstream VLA behavior: VLM4VLA reports consistent benefits from VLM initialization but weak monotonicity between generic VLM capability and embodied-policy quality, reinforcing the need for embodied adaptation objectives [Zhang et al., 2026a].

3.6 Embodied Pipeline Mapping

Across 2024–2026 papers, we observe a recurrent template:

1. foundation pretraining over heterogeneous robot or video data,
2. adaptation via task conditioning and action-space alignment,
3. post-training or online correction for deployment robustness.

This pattern appears in VLA scaling work, benchmark-driven systems, and world-model-centered planning frameworks [Kim et al., 2024, Intelligence et al., 2025a, Black et al., 2026, Upadhyay et al., 2026, Wu et al., 2026c].

To make this mapping operational, we define three interface contracts:

- **Representation contract:** what state is shared between perception, prediction, and control.
- **Temporal contract:** what horizon each module commits to and how uncertainty is propagated.
- **Feedback contract:** how online corrections (human interventions, reward feedback, safety filters) update policy/model components.

These contracts clarify why many failures are *interface failures*, not merely backbone failures. Two systems with similar backbone scale can show different field behavior because they differ in interface consistency across planning, control, and adaptation loops [Li et al., 2025b, Wang et al., 2025a, Wu et al., 2026a].

4 Data Resources and Evaluation Metrics

4.1 Data Regimes

Recent embodied research uses four complementary data regimes:

- **Simulation-first corpora** for scalable policy/world-model pretraining.
- **Interactive benchmark suites** for closed-loop reproducibility.
- **Large offline robot datasets** for foundation model initialization.
- **Real-world deployment logs** for post-training and robustness analysis.

Representative resources include OpenVLA/Open-X style pipelines, DROID-scale data, and newer embodied world-model benchmarks focused on rollout quality and control relevance [Kim et al., 2024, Collaboration et al., 2025, Khazatsky et al., 2025, Upadhyay et al., 2026, Wu et al., 2026a].

These resources extend earlier scaling efforts in diverse ways: web-scale open-world embodied environments, large real-robot manipulation corpora, and multimodal prompt-driven simulation suites [Fan et al., 2022, Walke et al., 2023, Jiang et al., 2023].

Simulation-first corpora remain the fastest path for broad pretraining and ablation-heavy development. **Interactive benchmark suites** improve comparability but can overfit to narrow task interfaces when evaluation protocols are static. **Offline robot datasets** enable large-scale behavioral priors but inherit teleoperation and sensor bias. **Real-world logs** are the only reliable source for intervention dynamics, recovery behavior, and edge-case calibration [Team et al., 2024, Fei et al., 2025, Intelligence et al., 2025b, Wu et al., 2026b].

4.2 Data Curation Dimensions

Beyond raw scale, we find four curation dimensions that strongly affect downstream behavior:

1. **Embodiment diversity** (single-arm, dual-arm, mobile manipulation, driving stacks).
2. **Task horizon composition** (short atomic skills vs. multi-stage household workflows).
3. **Interaction richness** (contact-heavy manipulation, tool use, intervention events).
4. **Annotation granularity** (language, subgoal, proprioceptive traces, safety labels).

Papers that only scale data volume without balancing these dimensions often improve headline benchmark averages but underperform in open-world deployment conditions [Intelligence et al., 2025a,b, Li et al., 2025b, Valle et al., 2025].

4.3 Metric Families

We group evaluation metrics into five families:

1. **Task success and completion quality** (success rate, throughput, long-horizon completion).
2. **Control stability and safety** (collision, intervention, recovery latency).
3. **Prediction fidelity** (perceptual quality, trajectory agreement, state consistency).
4. **Generalization** (new scene, new object, new instruction, cross-embodiment transfer).
5. **Efficiency** (token/action efficiency, runtime latency, memory/compute cost).

Several recent papers explicitly report tradeoffs between closed-loop gains and compute/latency costs, making efficiency metrics first-class rather than optional [Pertsch et al., 2025, Yang et al., 2025a, Guan et al., 2025, Shen et al., 2026].

4.4 Representative Quantitative Signals

Although protocols differ across papers, several reported numbers illustrate why evaluation must go beyond a single success metric:

- FAST reports up to $5\times$ training-time reduction under high-frequency dexterous settings [Pertsch et al., 2025].
- RECAP ($\pi^*_{0.6}$) reports more than doubling throughput and roughly halving failure rate on difficult tasks [Intelligence et al., 2025b].
- VLA-RFT reports surpassing strong supervised baselines with fewer than 400 fine-tuning steps in simulator-driven RL fine-tuning [Li et al., 2025b].
- ConRFT reports evaluation on eight real-world manipulation tasks with a unified offline+online consistency objective [Chen et al., 2025a].
- Valle et al. highlight that pure task success masks uncertainty and execution quality, motivating dedicated uncertainty and quality metrics [Valle et al., 2025].

These signals jointly support the same conclusion: **evaluation must be multi-objective**, combining competence, reliability, and efficiency.

A minimal closed-loop metric set can be formalized as:

$$\mathrm{SR} = \frac{1}{N}\sum_{i=1}^{N} \mathbf{1}[\text{task } i \text{ succeeds}], \tag{10}$$

Table 1: Qualitative comparison of representative embodied AI method families (2024–2026).

Family	Typical Strength	Typical Limitation	Representative Works	Deployment Fit
Foundation VLA policies	Strong instruction following, broad skill prior	Data and compute intensive; brittle OOD recovery	[Kim et al., 2024, Intelligence et al., 2025a, Black et al., 2026]	General-purpose manipulation
World-model-guided control	Better planning signal, sample efficiency, counterfactual reasoning	Model bias and rollout drift at long horizon	[Cen et al., 2025a, Wan et al., 2025, Chen et al., 2026a]	Long-horizon decision tasks
Post-training RL/refinement for VLAs	Improves task throughput and robustness in deployment	Requires safe data collection and intervention design	[Intelligence et al., 2025b, Li et al., 2025b, Lu et al., 2025]	Continuous improvement loops
Efficiency-oriented compression/adaptation	Lower latency and memory cost; easier edge use	Potential capability drop if over-compressed	[Pertsch et al., 2025, Yang et al., 2025a, Shen et al., 2026]	Resource-constrained systems

$$\mathrm{IR} = \frac{1}{N}\sum_{i=1}^{N}\frac{n_i^{\text{intervention}}}{T_i}, \tag{11}$$

$$\mathrm{RTF} = \frac{\text{inference} + \text{planning time}}{\text{control horizon time}}, \tag{12}$$

where SR measures task competence, IR captures autonomy reliability, and RTF captures real-time feasibility. This triad is often more diagnostic than isolated success-rate reporting.

4.5 Evaluation Protocol Recommendations

For reproducible and decision-relevant reporting, we recommend:

- reporting at least one metric from each family (task, safety, prediction, generalization, efficiency),
- separating in-distribution and shifted-distribution performance,
- reporting intervention-aware curves (success vs. allowed interventions),
- documenting compute budget, control frequency, and model update policy.

These elements are increasingly present in recent benchmark-oriented work and should become default for embodied world-model evaluation [Upadhyay et al., 2026, Wu et al., 2026a, Wang et al., 2025a].

In addition, recent diagnostic benchmarks explicitly target disentangled physical understanding. WorldBench emphasizes concept-level disambiguation rather than entangled aggregate physics tests, making failure attribution more actionable for model iteration [Upadhyay et al., 2026].

4.6 Current Gaps

Despite progress, metric mismatch remains common: image-level prediction quality may not imply physically correct interaction outcomes, and short-horizon gains may not transfer to multi-stage tasks [Gupta et al., 2024, Valle et al., 2025, Wang et al., 2025a]. This gap motivates evaluation protocols that jointly report dynamics realism, decision quality, and deployment behavior.

5 Cross-Family Comparison and Practical Tradeoffs

Table 1 summarizes high-level differences among major method families. We intentionally avoid aggregating incompatible absolute numbers across heterogeneous tasks; instead, we compare design tendencies and deployment implications.

5.1 Comparison Protocol

To avoid misleading cross-paper claims, we compare families under a normalized decision utility view:

$$\mathcal{U} = \alpha \cdot \mathrm{SR} - \beta \cdot \mathrm{IR} - \gamma \cdot \mathrm{RTF}, \tag{13}$$

where SR is task success rate, IR is intervention rate, and RTF is real-time factor (defined in Section 4). Coefficients (α, β, γ) are application-specific (e.g., higher β for safety-critical manipulation).

This formulation makes explicit that many published gains reflect different operating points, not universal dominance. For example, some models maximize SR under generous compute budgets, while others trade slight SR drops for stable real-time deployment [Pertsch et al., 2025, Yang et al., 2025a, Shen et al., 2026].

5.2 Where Each Family Wins

Foundation VLAs are strongest when broad instruction-space generalization and rapid task onboarding are primary goals. Their weakness is often intervention-heavy recovery under compounding distribution shift [Kim et al., 2024, Intelligence et al., 2025a, Black et al., 2026].

World-model-guided stacks are strongest in long-horizon reasoning and counterfactual evaluation, particularly when explicit predictive structure can guide planning. Their weakness is representation mismatch and rollout bias when embodiment-specific constraints are weakly encoded [Cen et al., 2025a, Wan et al., 2025, Chen et al., 2026a, Guo et al., 2026].

Post-training RL/refinement methods are strongest in closing deployment gaps. Notably, several reports show substantial throughput and failure-rate improvements after online or intervention-aware refinement, indicating that static imitation pretraining is no longer sufficient for robust field behavior [Intelligence et al., 2025b, Li et al., 2025b, Lu et al., 2025, Chen et al., 2025a].

Efficiency-focused methods are strongest for latency-constrained and edge scenarios, where compute-aware tokenization, pruning, and adaptation directly influence viability. Their main risk is capacity loss if compression is applied without task-specific calibration [Pertsch et al., 2025, Guan et al., 2025, Yang et al., 2025a, Shen et al., 2026].

5.3 Representative Case Studies

To anchor the comparison in concrete method behavior:

- **Scale-first foundation policy:** $\pi_0/\pi_{0.5}$ emphasizes heterogeneous multi-robot and multimodal co-training to improve open-world manipulation coverage [Black et al., 2026, Intelligence et al., 2025a].
- **Deployment-first refinement:** $\pi^*_{0.6}$ (RECAP), VLA-RFT, and VLA-RL emphasize online or simulator-mediated reinforcement fine-tuning, arguing that distribution-shift robustness requires explicit post-deployment adaptation [Intelligence et al., 2025b, Li et al., 2025b, Lu et al., 2025].
- **World-model-as-data-engine:** GigaWorld-0 and GigaBrain-0 present a synthesis view where world models are used to generate scalable embodied training data and reduce dependence on expensive physical collection [Team et al., 2025a,b].
- **Platform-level foundation world models:** Cosmos positions world foundation models as customizable infrastructure (data curation, tokenization, post-training), rather than a single monolithic policy component [NVIDIA et al., 2025b].

5.4 Historical Continuity Across Families

Current families are not isolated inventions. Foundation VLAs inherit multi-embodiment token-policy ideas from Gato, RT-1, and RoboCat [Reed et al., 2022, Brohan et al., 2023, Bousmalis et al., 2023]. World-model-guided and planner-policy hybrids extend earlier language-grounding and feasibility-constrained planning lines [Ahn et al., 2022, Huang et al., 2023a, Wu et al., 2023a]. Data-scaling and adaptation loops connect to BridgeData-style collection, trajectory- and code-mediated control interfaces, and lifelong skill-library designs [Walke et al., 2023, Gu et al., 2023, Liang et al., 2023, Wang et al., 2023a]. This continuity supports using content-level mechanisms, rather than publication date alone, to compare method families.

5.5 Observed System-Level Pattern

Across recent systems, we observe a stable two-stage recipe:

1. build a large prior (foundation VLA or general world model),
2. recover reliability by decision-coupled adaptation (online RL, intervention correction, or planner-policy co-training).

This pattern appears in both robot manipulation and embodied world-model pipelines and suggests that future gains will come less from single-model scaling alone and more from adaptive closed-loop training and evaluation infrastructure [Team et al., 2025a,b, Upadhyay et al., 2026, Wu et al., 2026a].

Three practical tradeoffs dominate implementation decisions:

- **Breadth vs. controllability:** broader pretrained priors improve zero-shot behavior, but explicit dynamics constraints often improve reliability under contact-rich manipulation.
- **Long-horizon quality vs. real-time compute:** richer predictive rollouts can improve planning quality but may violate deployment latency budgets.
- **Offline scale vs. online adaptation:** larger pretraining sets improve base competence, while online refinement remains critical for domain shift.

6 Open Challenges and Outlook

6.1 Challenge 1: Long-Horizon Physical Consistency

Many systems still degrade on multi-stage tasks where small model errors accumulate into irreversible failures. Future work should prioritize physically grounded temporal constraints and intervention-aware planning objectives, not only visual realism metrics [Gupta et al., 2024, Team et al., 2025b, Wang et al., 2026].

Two technical gaps are central: (i) weak causal invariants under contact and object rearrangement, and (ii) limited uncertainty calibration in long-horizon rollouts. Without these, planners over-trust model predictions and produce brittle control sequences under distribution shift.

6.2 Challenge 2: Embodiment-Aware Representation Alignment

A recurring issue is mismatch between action-space commands and visual prediction space. Approaches that inject embodiment structure (kinematics, camera geometry, contact priors) are promising but not yet standardized [Chen et al., 2026a, Guo et al., 2026, Sun et al., 2025a].

This mismatch is no longer a niche issue; it affects generalization across robot morphologies, viewpoint changes, and tool-based manipulation. A key direction is to define representation interfaces that are simultaneously planner-friendly, control-grounded, and computationally efficient.

6.3 Challenge 3: Evaluation for Deployment, Not Only Benchmarks

Benchmark success remains an incomplete proxy for field reliability. The community needs shared protocols that jointly evaluate safety, recovery, intervention rate, and sustained task throughput under shift [Upadhyay et al., 2026, Wu et al., 2026a, Valle et al., 2025].

In particular, evaluation suites should move from single-episode success to *session-level reliability*, including repeated-task stability, failure recovery quality, and operator load over extended runtime.

6.4 Challenge 4: Data Governance and Compute Efficiency

Scaling trends improve capability but increase data, compute, and reproducibility burdens. Efficient adaptation, model compression, and transparent data curation are central for practical adoption [Guan et al., 2025, Yang et al., 2025a, Shen et al., 2026].

Data governance is equally important: licensing, robot-operator privacy, and intervention traceability will increasingly influence which datasets can be reused for large-scale embodied pretraining.

6.5 Challenge 5: Continual Adaptation Under Safety Constraints

Recent post-training results indicate that online adaptation is a major performance driver, but safe adaptation protocols are still immature [Intelligence et al., 2025b, Li et al., 2025b, Lu et al., 2025]. Open questions include:

- how to schedule exploration under hard safety budgets,
- how to integrate teleoperator corrections without destabilizing pretrained priors,
- how to prevent catastrophic forgetting during continual specialization.

6.6 Scope Boundaries

This survey focuses on embodied and decision-relevant world modeling within 2024–2026. Broader non-embodied world-model literature is therefore not covered in depth in the core analysis. In fast-moving boundary areas, such as generic video world models later adapted to robotics, category boundaries will likely continue to shift as deployment evidence accumulates.

6.7 Near-Term Research Priorities

We identify three near-term priorities:

- **Disentangled diagnostic evaluation:** shift from monolithic benchmark scores to concept-isolated physical diagnostics and reasoning-action faithfulness checks [Upadhyay et al., 2026, Wu et al., 2026a].
- **Action-world alignment under embodiment constraints:** improve coordinate-to-pixel and language-to-control alignment using geometry-aware conditioning and consistency objectives [Chen et al., 2026a, Wang et al., 2025a, Chen et al., 2025a].
- **Scalable but safe adaptation loops:** combine synthetic or world-model-generated data with intervention-aware online refinement to improve robustness without uncontrolled exploration cost [Team et al., 2025a,b, Intelligence et al., 2025b, Li et al., 2025b].

6.8 Outlook

We expect the next phase of embodied intelligence to converge on hybrid systems that combine:

- reusable foundation priors,
- decision-coupled world models,
- online adaptation under safety constraints,
- standardized evaluation pipelines tied to real deployment targets.

The strongest near-term gains will likely come from better coupling between predictive modeling and actionable control feedback, while mid-term progress will depend on standardized deployment-centric evaluation and safer continual learning protocols.

7 Conclusion

This survey synthesized embodied AI and world-model research from 2024 to early 2026 under a coupled framework that links system-level embodied decision stacks with model-level dynamics design choices. The central conclusion is that strong embodied performance now depends on explicit coordination among representation, prediction, and control, rather than progress in any single module.

The technical trajectory is cumulative: pre-2024 advances in task definition, language grounding, and early generalist robot policies established the interfaces that 2024–2026 systems now optimize at scale. Recent progress therefore looks less like a paradigm replacement and more like integration of planning, world modeling, and policy adaptation into a single closed-loop training and deployment stack.

Our overall reading of the current frontier is pragmatic: foundation-scale pretraining has become necessary but not sufficient. Reliable embodied intelligence increasingly requires decision-coupled post-training, representation interfaces aligned with embodiment constraints, and deployment-oriented evaluation protocols that quantify not just task completion, but sustained autonomy quality.

A Full-Coverage Citation Map

A.1 In-Scope Citation Coverage (2024–2026)

This appendix groups all in-scope references by survey bucket and publication year to make coverage auditable.

A.2 agent-architecture

2026 Jian et al. [2026], Li et al. [2026a].

2025 Bai et al. [2025], Bendikas et al. [2025], Corsi et al. [2025], Dey et al. [2025], Fang et al. [2025a], Guo et al. [2025a], Hancock et al. [2025a], Hsieh et al. [2025], Intelligence et al. [2025a], Jabbour et al. [2025], Jang et al. [2025], Li et al. [2025e,f,g], Lin et al. [2025a], Liu et al. [2025b,c], Patratskiy et al. [2025]. Pertsch et al. [2025], Pugacheva et al. [2025], Sendai et al. [2025], Song et al. [2025a], Tan et al. [2025a], Turgunbaev [2025], Wang et al. [2025b,c,d], Wen et al. [2025a,b,c,d], Wu et al. [2025], Xiang et al. [2025], Xiong et al. [2025].

2024 Leal et al. [2024], Yang et al. [2024a].

A.3 data-benchmark-eval

2026 Black et al. [2026], Cai et al. [2026], Chen et al. [2026a,b], Hu et al. [2026], Lillemark et al. [2026], Liu et al. [2026a], Magne et al. [2026], Mei et al. [2026], Peng et al. [2026], Ren et al. [2026], Upadhyay et al. [2026], Wang et al. [2026], Wu et al. [2026b,c,a], Xiang et al. [2026], Xie et al. [2026a]. Xie et al. [2026b], Yang et al. [2026], Ye et al. [2026], Yu et al. [2026b], Zhang et al. [2026b,a].

2025 Argus et al. [2025], Bhat et al. [2025], Bi et al. [2025a], Cen et al. [2025b], Chen et al. [2025b,c], Chi et al. [2025], Collaboration et al. [2025], Cui et al. [2025], Deng et al. [2025], Din et al. [2025], Ding et al. [2025b], Du et al. [2025], Fan et al. [2025a,b], Fang et al. [2025b], Fei et al. [2025], Goyal et al. [2025]. Grover et al. [2025], Guo et al. [2025b], Guo and Zhang [2025], Han et al. [2025], Hancock et al. [2025b], Hannus et al. [2025], Hao et al. [2025], Hirose et al. [2025], Hu et al. [2025a], Huang et al. [2025a], Hung et al. [2025a], Jiang et al. [2025a,b,c,d], Jin et al. [2025], Jülg et al. [2025], Khazatsky et al. [2025]. Kim et al. [2025], Li et al. [2025h,i,j,k,l,m,n,d], Liang et al. [2025b,c], Liao et al. [2025], Lin et al. [2025b,c,d], Liu et al. [2025d,e,f]. Liu et al. [2025g], Lykov et al. [2025], NVIDIA et al. [2025a], Peng et al. [2025], Qian et al. [2025], Qu et al. [2025], Ray [2025], Serpiva et al. [2025], Shukor et al. [2025], Singh et al. [2025], Song et al. [2025b,c], Sun et al. [2025a], Syed et al. [2025], Tan et al. [2025b], Tarasov et al. [2025], Team et al. [2025a], Tharwat et al. [2025]. Valle et al. [2025], Wang et al. [2025a,e,f,g], Wei et al. [2025], Wen et al. [2025e], Won et al. [2025], Xiao et al. [2025], Xu et al. [2025a], Xue et al. [2025], Yan et al. [2025], Yang et al. [2025b,a,c], Ye et al. [2025a,b], Yin et al. [2025]. Yu et al. [2025], Yuan et al. [2025a,b], Zhai et al. [2025], Zhang et al. [2025b,c,d,e,f,g,h,i], Zhao et al. [2025a], Zheng et al. [2025a,b], Zhong et al. [2025a], Zhou et al. [2025a].

2024 AhmadiTeshnizi et al. [2024], Chi et al. [2024], Huang et al. [2024a], Kazemi et al. [2024], Kim et al. [2024], Lee et al. [2024], Li et al. [2024a,b,c], Lin et al. [2024], O'Neill et al. [2024], Salzer and Visser [2024], Team et al. [2024], Yehudai et al. [2024], Zeng et al. [2024], Zhen et al. [2024].

A.4 foundation-definition

2025 Zhou et al. [2025b], Li et al. [2025o], Wang et al. [2025h].

2024 Cheang et al. [2024], Hong et al. [2024], Yang et al. [2024b].

A.5 planning-reasoning

2026 Li et al. [2026b], Sapkota et al. [2026], Zhong et al. [2026].

2025 Budzianowski et al. [2025], Chen et al. [2025d,e], Driess et al. [2025], Feng et al. [2025a], Gao et al. [2025], Gu et al. [2025], Hu et al. [2025b], Huang et al. [2025b,c], Hung et al. [2025b], Koo et al. [2025], Li et al. [2025p,q], Liu et al. [2025h], Neary et al. [2025], Neau et al. [2025], Seong et al. [2025]. Song et al. [2025d], Sun et al. [2025b], Wang et al. [2025i], Xu et al. [2025b,c], Zang et al. [2025], Zhang et al. [2025j,k], Zhao et al. [2025b,c], Zhou et al. [2025c].

2024 Guo et al. [2024], Huang et al. [2024b], Yoshikawa et al. [2024], Zhang et al. [2024].

A.6 policy-learning

2026 Liu et al. [2026b].

2025 Chen et al. [2025a], Dong et al. [2025], Fu et al. [2025], Häon et al. [2025], Intelligence et al. [2025b], Kachaev et al. [2025], Li et al. [2025c,r,s,t,u], Liu et al. [2025i], Lu et al. [2025], Park et al. [2025], Xu et al. [2025d], Zhang et al. [2025l,m], Zhu et al. [2025b].

A.7 survey-meta

2026 Fan et al. [2026], Yin et al. [2026], Yu et al. [2026a].

2025 Ding et al. [2025a], Dolgopolyi and Tsevas [2025], Guan et al. [2025], Jiang et al. [2025e], Li et al. [2025a,v], Liang et al. [2025a], Liu et al. [2025a], Lu and Tang [2025], Shao et al. [2025], Tai et al. [2025], Zhang et al. [2025n,a], Zhong et al. [2025b].

A.8 world-model-core

2026 Guo et al. [2026], Shah et al. [2026], Shen et al. [2026], Zhou et al. [2026].

2025 Berg et al. [2025], Bi et al. [2025b], Cen et al. [2025a], Feng et al. [2025b], Fung et al. [2025], Guo et al. [2025c], Li et al. [2025b], NVIDIA et al. [2025b], Team et al. [2025b], Wan et al. [2025], Zhu et al. [2025a].

2024 Gupta et al. [2024].

B Exclusion Audit Log

B.1 Exclusion Audit

Entries excluded from the main in-scope set are listed by reason. Full row-level details are in `ref/paper_audit.csv`.

B.2 missing_year

Chen et al., Xie, Zhang et al..

B.3 not_embodied_related

Bruce et al. [2024], Savov et al. [2025].

B.4 out_of_window

Ahn et al. [2022], Batra et al. [2020], Bousmalis et al. [2023], Brehmer et al. [2023], Brohan et al. [2023], Chebotar et al. [2023], Dasgupta et al. [2023], Dorbala et al. [2023], Driess et al. [2023], Duan et al. [2022], Fan et al. [2022], Gadre et al. [2022], Gao et al. [2022], Gu et al. [2023], Huang et al. [2023a, 2022b,a, 2023b]. Jiang et al. [2023], Josifoski et al. [2022], Liang et al. [2023], Nottingham et al. [2023], Pugh et al. [2022], Reed et al. [2022], Sarch et al. [2023], Song et al. [2023], Walke et al. [2023], Wang et al. [2023b,a], Wu et al. [2023b,a,c], Xu et al. [2023], Zhao et al. [2023].

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