
Autonomous Spatial Intelligence: A Survey of Agentic AI Methods for Physical World Understanding

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Abstract

The convergence of Agentic Artificial Intelligence and Spatial Intelligence represents a transformative frontier in creating machines capable of autonomous operation in physical environments. This survey provides the first unified taxonomy systematically connecting agentic AI architectures—encompassing memory, planning, and tool use—with spatial intelligence capabilities spanning navigation, scene understanding, manipulation, and geospatial analysis. We synthesize over 300 papers across foundational agentic frameworks [Yao et al., 2023b, Shinn et al., 2023, Wang et al., 2024b], vision-language-action models [Brohan et al., 2023, Team et al., 2024, Kim et al., 2024], graph neural networks for spatial reasoning [Kipf and Welling, 2017, Velickovic et al., 2018, Wu et al., 2019a], world models [Hafner et al., 2023, Hu et al., 2023a], and geospatial foundation models [Jakubik et al., 2024, Cong et al., 2022]. Our analysis reveals three key findings: (1) the critical role of hierarchical memory systems in enabling long-horizon spatial tasks, (2) the emergence of GNN-LLM integration as a powerful paradigm for structured spatial reasoning, and (3) the growing importance of world models for safe deployment in physical environments. We present a comprehensive evaluation framework and identify open challenges including robust spatial representation, sim-to-real transfer, and multi-agent coordination. This survey establishes a foundational reference for advancing spatially-aware autonomous systems.

1 Introduction

The pursuit of artificial general intelligence increasingly centers on creating agents that can perceive, reason about, and act within physical environments [McCarthy et al., 1955, Turing, 1950]. While large language models have demonstrated remarkable capabilities in reasoning and planning [Brown et al., 2020, OpenAI, 2023, Wei et al., 2022], their ability to operate effectively in spatial contexts remains a fundamental challenge [Chen et al., 2024, Yang et al., 2025].

We define **Agentic AI** as systems exhibiting goal-directed behavior through autonomous decision-making, characterized by three core capabilities: persistent memory for experience accumulation, planning for action sequencing, and tool use for capability extension [Wang et al., 2024b, Xi et al., 2023, Weng, 2023]. Complementarily, **Spatial Intelligence** encompasses the ability to perceive 3D structure, reason about object relationships, navigate environments, and manipulate physical objects [Chen et al., 2024, Thompson et al., 2025].

The convergence of these domains is essential for real-world AI applications. Autonomous vehicles must perceive dynamic environments and plan safe trajectories [Hu et al., 2023b, Caesar et al., 2020]. Robotic assistants require understanding of object affordances and spatial relationships [Brohan et al., 2023, Ahn et al., 2022]. Urban computing systems must model complex spatio-temporal dependencies [Jin et al., 2023, Li et al., 2018]. Despite this importance, existing surveys treat these areas in isolation, lacking a unified framework connecting agentic architectures with spatial requirements.

Contributions. This survey makes three primary contributions:

1. A **unified taxonomy** connecting agentic AI components (memory, planning, tool use) with spatial intelligence domains (navigation, scene understanding, manipulation, geospatial analysis), providing a structured framework for interdisciplinary research.
2. A **comprehensive analysis** of over 300 papers identifying key architectural patterns, including the emergence of GNN-LLM integration and world model-based planning as critical enablers for spatial reasoning.
3. A **forward-looking roadmap** identifying open challenges and research directions for developing robust, safe, and capable spatially-aware autonomous systems.

2 Unified Taxonomy

We propose a two-dimensional taxonomy (Figure ??) that maps agentic capabilities to spatial task requirements, enabling systematic analysis of existing methods and identification of research gaps.

2.1 Agentic AI Components

Memory Systems. Memory enables agents to accumulate and retrieve experiential knowledge. Short-term memory through in-context learning [Brown et al., 2020] supports immediate reasoning, while long-term memory via retrieval-augmented generation [Lewis et al., 2020, Packer et al., 2023] enables knowledge persistence. For spatial tasks, cognitive mapping [Gupta et al., 2019b, Chaplot et al., 2020b] and semantic spatial memory [Huang et al., 2023] are critical for navigation and scene understanding.

Planning Systems. Planning decomposes goals into executable action sequences. Chain-of-thought reasoning [Wei et al., 2022, Kojima et al., 2022] enables step-by-step problem solving. Tree-based search [Yao et al., 2023a, Besta et al., 2023] explores multiple solution paths. Hierarchical planning [Song et al., 2023, Huang et al., 2022] bridges high-level goals with low-level actions. For spatial domains, planning must account for geometric constraints, physical dynamics, and uncertainty.

Tool Use and Action. Tool use extends agent capabilities through external interfaces. API integration [Schick et al., 2023, Patil et al., 2023, Qin et al., 2024] enables access to specialized functions. Code generation [Gao et al., 2023, Liang et al., 2023] provides flexible action specification. The ReAct architecture [Yao et al., 2023b] interleaves reasoning with action execution, forming the foundation for many spatial agents.

2.2 Spatial Intelligence Domains

Navigation. Navigation requires path planning and execution in physical or simulated environments. Vision-language navigation [Anderson et al., 2018, Ku et al., 2020, Qi et al., 2020] follows natural language instructions. Object-goal navigation [Batra et al., 2020, Chaplot et al., 2020a] locates target object categories. Zero-shot approaches [Majumdar et al., 2022, Gadre et al., 2022] leverage vision-language models for novel object navigation.

Scene Understanding. Scene understanding encompasses 3D perception and semantic reasoning. Neural radiance fields [Mildenhall et al., 2020, Barron et al., 2022] and 3D Gaussian splatting [Kerbl et al., 2023] enable novel view synthesis. Point cloud processing [Qi et al., 2017a,b] supports 3D object detection. Scene graphs [Xu et al., 2017, Krishna et al., 2017, Armeni et al., 2019] represent object relationships for higher-level reasoning.

Manipulation. Manipulation involves physical interaction with objects. Vision-language-action models [Brohan et al., 2022, 2023, Team et al., 2024, Kim et al., 2024] directly map observations to robot actions.

Task and motion planning [Garrett et al., 2021, Ahn et al., 2022] integrates high-level reasoning with low-level control. Dexterous manipulation [Akkaya et al., 2019, Chen et al., 2022] addresses complex hand-object interactions.

Geospatial Analysis. Geospatial analysis reasons about large-scale geographic data. Remote sensing foundation models [Jakubik et al., 2024, Cong et al., 2022, Bastani et al., 2023] enable transfer learning across satellite imagery tasks. Spatio-temporal graph networks [Li et al., 2018, Yu et al., 2018, Wu et al., 2019b, Bai et al., 2020] model urban dynamics for traffic prediction and city planning.

3 State-of-the-Art Methods

3.1 Vision-Language-Action Models

VLA models represent a paradigm shift in robotics, directly mapping multimodal inputs to actions through end-to-end learning.

Proprietary Models. RT-1 [Brohan et al., 2022] demonstrated transformer-based policies trained on large-scale robot data. RT-2 [Brohan et al., 2023] co-trained on web-scale vision-language data, enabling emergent reasoning about novel objects. PaLM-E [Driess et al., 2023] integrated continuous sensor data into a 562B parameter language model for embodied reasoning.

Open-Source Models. Octo [Team et al., 2024] provides a generalist robot policy trained on the Open X-Embodiment dataset [Collaboration, 2023]. OpenVLA [Kim et al., 2024] offers a 7B parameter alternative with competitive performance. These models democratize VLA research and enable community-driven advancement.

Multimodal Foundations. LLaVA [Liu et al., 2023] pioneered visual instruction tuning. Flamingo [Alayrac et al., 2022] introduced few-shot multimodal learning. BLIP-2 [Li et al., 2023b] efficiently bootstraps vision-language pretraining. Qwen-VL [Bai et al., 2023, Wang et al., 2024c] and GPT-4V [OpenAI, 2023] represent frontier multimodal capabilities.

3.2 Graph Neural Networks for Spatial Reasoning

GNNs provide powerful tools for modeling spatial relationships and dependencies, with emerging integration with language models.

Foundational Architectures. GCN [Kipf and Welling, 2017] introduced spectral graph convolution. GAT [Velickovic et al., 2018] added attention mechanisms. GraphSAGE [Hamilton et al., 2017] enabled inductive learning. GIN [Xu et al., 2019] provided theoretical expressiveness analysis. These architectures form the basis for spatial graph learning.

Spatio-Temporal Networks. DCRNN [Li et al., 2018] models traffic as graph diffusion. STGCN [Yu et al., 2018] combines graph and temporal convolutions. Graph WaveNet [Wu et al., 2019b] learns adaptive graph structures. AGCRN [Bai et al., 2020] introduces node-specific patterns. Comprehensive surveys [Jin et al., 2023, Atluri et al., 2018] detail these advances.

GNN-LLM Integration. Recent work explores combining GNNs with LLMs for enhanced reasoning. GraphGPT [Tang et al., 2024] aligns graph encoders with language models. GNN-RAG [Wang et al., 2024a] combines graph retrieval with language generation. This integration holds significant promise for spatial reasoning requiring both structural and semantic understanding.

3.3 World Models

World models learn predictive representations enabling planning through imagination, critical for safe deployment in physical environments.

Model-Based RL. Dreamer [Hafner et al., 2019] introduced latent imagination. DreamerV2 [Hafner et al., 2021] achieved human-level Atari performance. DreamerV3 [Hafner et al., 2023] demonstrated cross-domain mastery. DayDreamer [Wu et al., 2023a] transferred world models to real robots.

Video World Models. Genie [Bruce et al., 2024] learns controllable world models from internet videos. WorldDreamer [Yang et al., 2024] generates driving world models. GAIA-1 [Hu et al., 2023a] produces realistic driving videos conditioned on actions.

LLM-Based World Models. LLMs can serve as world models for planning [Hao et al., 2023, Guan et al., 2023], predicting state transitions without explicit environment models.

3.4 Embodied AI Agents

Open-Ended Exploration. Voyager [Wang et al., 2023] demonstrated open-ended exploration in Minecraft through LLM-driven curriculum learning. MineDojo [Fan et al., 2022] provides benchmarks for open-ended embodied agents.

Grounded Language Agents. SayCan [Ahn et al., 2022] grounds language models in robotic affordances. Code as Policies [Liang et al., 2023] generates executable robot code. LLM-Planner [Song et al., 2023] enables few-shot grounded planning.

Simulation Platforms. Habitat [Savva et al., 2019, Szot et al., 2021, Puig et al., 2024] provides high-fidelity embodied AI simulation. iGibson [Shen et al., 2021, Li et al., 2021] offers interactive environments. AI2-THOR [Kolve et al., 2017] enables interactive visual AI research.

4 Industry Applications

4.1 Geospatial Intelligence

Palantir [Palantir, 2023, Bailey, 2021] integrates AI with geospatial analysis for defense and commercial applications. **ESRI** [ESRI, 2023] provides ArcGIS with integrated GeoAI capabilities. **Google** [Google, 2023] deploys AI for global-scale mapping and navigation.

4.2 Location Intelligence

Foursquare [Foursquare, 2023] provides location intelligence through movement pattern analysis. Smart city applications [Zheng et al., 2014, Allam and Dhunny, 2020] leverage spatial AI for traffic management and urban planning.

4.3 Autonomous Vehicles

Waymo [Waymo, 2023, 2024] has deployed autonomous vehicles at scale. End-to-end approaches including UniAD [Hu et al., 2023b], VAD [Jiang et al., 2023], and DriveVLM [Tian et al., 2024] unify perception, prediction, and planning.

5 Evaluation Framework

5.1 Navigation Benchmarks

R2R [Anderson et al., 2018], RxR [Ku et al., 2020], REVERIE [Qi et al., 2020] for vision-language navigation. Habitat ObjectNav [Batra et al., 2020] and SOON [Zhu et al., 2021] for object-goal navigation.

5.2 Manipulation Benchmarks

RLBench [James et al., 2020], Meta-World [Yu et al., 2020], BEHAVIOR [Srivastava et al., 2021, Li et al., 2023a] for robotic manipulation evaluation.

5.3 Spatial Reasoning Benchmarks

CLEVR [Johnson et al., 2017], GQA [Hudson and Manning, 2019], SpatialVLM [Chen et al., 2024], REM [Thompson et al., 2025], EmbodiedBench [Yang et al., 2025] for spatial reasoning evaluation.

5.4 Geospatial Benchmarks

BigEarthNet [Sumbul et al., 2019], fMoW [Christie et al., 2018],xBD [Gupta et al., 2019a], SpaceNet [Van Etten et al., 2018] for remote sensing evaluation.

6 Open Challenges and Future Directions

Robust Spatial Representation. Developing representations that generalize across scenes, viewpoints, and conditions remains challenging [Mildenhall et al., 2020, Kerbl et al., 2023]. Foundation models for 3D understanding [Hong et al., 2023b] represent promising directions.

Long-Horizon Planning. Creating agents that plan over extended horizons and decompose complex spatial tasks is essential [Song et al., 2023, Valmeekam et al., 2023]. Integration of neural and symbolic planning approaches shows promise.

Safe and Reliable Operation. Ensuring safe operation in safety-critical applications is paramount [Yin et al., 2025, Amodei et al., 2016, Bai et al., 2022]. Robust uncertainty handling and alignment with human values are critical.

Sim-to-Real Transfer. Bridging simulation and reality remains challenging [Zhao et al., 2020, Tobin et al., 2017]. Domain randomization and real-world fine-tuning are active research areas.

Multi-Agent Coordination. Scaling to multi-agent systems for complex spatial tasks requires advances in coordination and communication [Zhang et al., 2021, Wu et al., 2023b, Hong et al., 2023a].

7 Conclusion

This survey has provided a unified taxonomy connecting Agentic AI and Spatial Intelligence, synthesizing over 300 papers across foundational architectures, state-of-the-art methods, industry applications, and evaluation benchmarks. Our analysis reveals the critical importance of hierarchical memory, GNN-LLM integration, and world models for spatial reasoning. Key challenges remain in robust representation, long-horizon planning, and safe deployment. By establishing this foundational reference, we aim to accelerate progress toward capable, robust, and safe spatially-aware autonomous systems.

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