Where Do We Go from Here? Charting the Future of Unmanned Vehicles

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***Abstract*—Unmanned vehicles (UVs), including aerial (UAVs), ground (UGVs), and sea-based (USVs) systems, are advancing rapidly, where the combined market is projected to go from over $29.3 billion in 2025 to more than $46 billion by 2030 [1]. Despite the market growth, the development occurs in isolated silos. However, real-world missions increasingly demand coordinated operations across multiple UV domains. In this paper, we argue the need for a unified approach to UV development and propose a Synergistic UxV Ecosystem architecture to enable heterogeneous UVs to share information, collaborate, and dynamically allocate tasks. The proposed high-level conceptual framework integrates collaborative intelligence, decentralized communication, and service-oriented design to improve mission effectiveness. We demonstrate how such an ecosystem can enhance situational awareness, adaptability, and operational efficiency, enabling unmanned systems to achieve what isolated entities cannot, through real world inspired scenarios as examples.**

***Index Terms*—Unmanned Vehicles, Autonomous Vehicles, Unmanned Aerial Vehicles, Unmanned Ground Vehicles, Unmanned Surface Vehicles, Ecosystem, Information Fusion.**

I. Introduction

Unmanned vehicles (UVs), also known as uncrewed vehicles, operate without a human onboard, either remotely or autonomously. Significant amounts of money, energy, and manpower are invested in making unmanned vehicles autonomous [2] [3] [4]. Unmanned vehicles can be broadly classified into three categories based on the environment in which they operate: Unmanned Aerial Vehicles (UAVs)/Unmanned Aerial Systems (UAS) operate in the air/sky; Unmanned Ground Vehicles (UGVs) operate on the ground/land; and Unmanned Surface Vehicles (USVs) operate in the water/sea. Advancements in these categories often occur independently of one another. For instance, research on UAVs typically focuses on optimizing their operational efficiency. This is not inherently problematic, but in real-life applications, such as military, manufacturing, and transportation, operations involve more than one category of UVs in completing a mission. The different categories of UVs can either complement or compound or contradict each other in achieving the mission at hand. Therefore, aspects of operational efficiency should not be considered in isolation, but rather from the perspective of a broader UxV ecosystem. Table I shows, how UAVs, UGVs, and USVs are deployed across diverse sectors, including transport, industry, military, and entertainment, each serving a wide range of use cases from combat operations to environmental monitoring.

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TABLE I: Structured overview of the application landscape for key unmanned platforms (UAV, UGV and USV).

Platform	Domain	Applications
UAV	Transport	Package delivery, Urban Air Mobility, etc.
	Industrial	Infrastructure inspection, agri-monitoring, etc.
	Military	Intelligence, Surveillance, Reconnaissance, etc.
	Entertain.	Cinematography, drone racing, light shows, etc.
UGV	Transport	Delivery bots, autonomous transportation, etc.
	Industrial	Warehouse automation, mining bots, etc.
	Military	Combat vehicles, Explosive disposal, etc.
	Entertain.	Battle robots, theme park animatronics, etc.
USV	Transport	Autonomous cargo ships, robotic ferries, etc.
	Industrial	Oceanography, offshore maintenance, etc.
	Military	Naval patrol, mine countermeasures, etc.
	Entertain.	Autonomous tours, remote boat racing, etc.

We strongly believe that unmanned vehicles should not evolve in isolated silos, but as part of a unified UxV ecosystem. This approach unlocks new opportunities and applications. We illustrate with cases where siloed deployments underperform, but a coordinated UxV ecosystem succeeds.

Consider a forest wildfire where the primary goal is safe evacuation. UGVs may deliver emergency supplies [5] or transport individuals, yet locating people and planning optimal routes remain difficult. Relying only on UGVs limits mission effectiveness. A swarm of UAVs can assist with human localization and route-planning, greatly enhancing UGV performance. This shows how different unmanned vehicles complement one another.

Similarly, in a maritime combat mission to neutralize a threat, USVs can detect targets with sonar. While this may suffice for engagement, response time and impact improve in a UxV ecosystem. UAV surveillance, UGV coastal targeting, and USV underwater tracking together compound strengths and reduce time-to-neutralization.

These examples reveal that current UV silos reflect a deeper bottleneck: not just communication, but the underlying fusion model. Present methods work well for multimodal data from a single vehicle (intra-vehicle fusion), and are being extended to homogeneous swarms (intra-swarm fusion). Yet they fall short for missions like wildfire response or maritime security, which are multi-objective, dynamic, and demand trade-offs and synergistic action across platforms.

We term this challenge **Cross-domain Mission Intelligence**. It requires mission-level information fusion, moving beyond raw data or object locations to sharing high-level intelligence such as capabilities, intent, priorities, and progress toward strategic goals. This demands an architecture that transforms heterogeneous swarms into a cohesive, goal-oriented collective. In this paper, we propose the *UxV Ecosystem Architecture*, a high-level blueprint for mission-level fusion to unlock the full potential of unmanned systems.

The rest of the paper is structured as follows: Section II reviews the history of unmanned vehicles, fusion evolution, and current cross-domain collaboration methods; Section III details the proposed architecture; Section IV outlines challenges and future directions; and Section V concludes.

II. Background and Related Works

In this section we provide a hierarchical analysis of information fusion and prominent related works on the collaboration of cross-domain unmanned system.

A. Evolution of Information Fusion

To understand the architectural needs of the ecosystem, information fusion should be seen as a hierarchy of increasing abstraction and intelligence, not a monolithic process. While lower levels are well-studied, the highest level—which we term *Mission Intelligence*—poses the greatest challenge and promise.

1) Intra-Vehicle Fusion: Intra-vehicle fusion creates a robust state estimate for a UV from its noisy and disparate sensors. The goal is to mitigate sensor noise, complement modalities (e.g., IMU and GPS), and manage redundancy to yield an accurate local understanding. Established methods include Kalman Filters and non-linear variants [6], as well as factor graph-based SLAM [7]. However, this level is egocentric: essential for autonomy but blind to wider mission context and the knowledge of other agents.

2) Intra-Swarm Fusion: This frontier aggregates data from multiple UVs to build a shared tactical picture. A key challenge is data association, determining whether observations from different entities match [8]. By exploiting redundancy across viewpoints and modalities, it enhances scene understanding. Active research spans distributed multi-object tracking, Collaborative SLAM (C-SLAM) [9], and decentralized fusion techniques like Covariance Intersection for unknown correlations [10]. Yet this level remains largely syntactic and geometric: it answers “what” and “where” but not “why” or “so what?”, lacking the semantics for mission reasoning.

3) Mission Level Fusion: Our focus, *Cross-domain Mission Intelligence*, advances from fusing states to abstract concepts such as intent, capability, and causality. It enables heterogeneous UV teams to share a goal-oriented understanding of the mission. This includes resolving competing objectives (e.g., delivery vs. surveillance), reasoning about missing capabilities (e.g., aerial scouting for ground paths), and predicting cross-domain impacts. Achieving this requires new primitives beyond state-based approaches: structured world models that capture dependencies among agents, tasks, and environments. Such models enable reasoning over context, marking the leap toward mission intelligence and forming the core capability of our system.

B. State Of The Art

The vision of collaboration of a swarm of cross-domain unmanned vehicles is not new. Few prior works have given the glimpse of its potential. Table II gives a brief comparison of the State Of The Art works. Stolfi et al. [11] envisioned a similar system in which a swarm of cross-domain unmanned vehicles collaborated on a task to find evaders in a surveillance zone. They considered a swarm of UAVs, USVs, and UGVs working on a surveillance task. However, their approach simplified the core challenge by assigning each swarm to a dedicated, non-overlapping area. This static spatial partitioning precluded any possibility of inter-swarm communication or synergistic fusion of sensor data, fundamentally limiting the system to a collection of co-located but independent operations rather than a truly integrated team.

A significant amount of work has focused on establishing interoperability standards to enable communication between heterogeneous systems. The work of Wang et al. [12] and the long-standing Joint Architecture for Unmanned Systems (JAUS) [13] provides a comprehensive, message-based standard designed to achieve plug-and-play interoperability between unmanned systems, payloads, and control stations. However, the focus of these efforts is fundamentally on syntactic interoperability. They define the ”verbs” and ”nouns” of communication and provide the means for systems to exchange data but do not prescribe a mechanism for semantic understanding or autonomous, decentralized decision-making. While they enable a human operator to control disparate assets, they do not provide a blueprint for those assets to reason and collaborate among themselves to solve complex, multi-objective missions.

Wu et al. [14] used principles from evolutionary game theory and complex networks to model how collaboration emerge in heterogeneous UAV swarms. Their work provided a powerful analytical framework for understanding the trade-offs between individual and collective payoffs (e.g., the cost of cooperation vs. the group benefit) and how network topology influences collaborative stability. However, such models are inherently capable of abstracting the mission into a simplified strategic game (e.g., cooperate/defect). While they are valuable

TABLE II: Comparative Summary of Cross-Domain UxV Systems

Work / System	UVs	Collaboration	Information Sharing	Information Fusion	Generalizability	Semantic Understanding
Stolfi et al. [11]	UAV, UGV, USV	✓				
Wang et al. [12]	UxV		✓		✓	
JAUS [13]	UxV		✓		✓	
Wu et al. [14]	UAV	✓		Intra-swarm		
Xu et al. [15]	UAV, USV	✓	✓	Inter-Vehicle		
Ecosystem (Proposed)	UxV	✓	✓	Mission Level	✓	✓

for theoretical analysis, they do not provide a functional architecture for real-world systems that must manage dynamic, multi-objective missions, fuse heterogeneous sensor data, and reason about a rich, semantic understanding of the world that goes beyond game-theoretic payoffs.

Other research addresses collaboration at the level of specific, critical sub-tasks. Xu et al. [15], for example, demonstrated a collaborative system for a manipulator arm on a USV to safely capture and land a UAV in disturbed sea states. They employed model predictive control and adaptive estimators to solve a challenging physical coordination problem. However, the scope of collaboration is fundamentally physical and operational. The system is not designed to address the broader challenges of a swarm and UxV ecosystem, such as how the UAV and USV might fuse disparate sensor intelligence to track a third-party target, or how a swarm of such pairs would negotiate and deconflict multiple, competing mission objectives.

In summary, prior works have addressed fragmented bits and pieces of the cross-domain collaboration challenge (simplified multi-swarm operations, syntactic interoperability standards, abstract theoretical models, and task-specific physical coordination). There is clear lack of a holistic architecture that moves beyond syntactic messaging and single-objective tasks to enable autonomous, multi-objective, mission-level collaboration across heterogeneous swarms. The challenge is not just to make vehicles talk to each other, but to provide them with a framework to reason collectively. Our proposed UxV Ecosystem Architecture directly addresses this gap by focusing on the mechanisms for high-level information fusion and decentralized decision-making that are necessary to unlock true cross-domain synergy.

III. Architecture

To give life to the envisoned UxV ecosystem, we propose UxV Ecosystem Architecture, a high-level conceptual blue print designed for Scalability, Resilience and collaboration despite heterogeneity as shown in Fig. 1. The architecture is developed with the following principles: layered abstraction to separate concerns, decentralization to avoid single point of failure, and service oriented design for plug and play modularity. This architecture will provide formal way for heterogeneous entities (hereafter referred to interchangeably as “systems,” or “vehicles,” or “Agents,” or “UV,” or “entities”) to share information, construct a unified world/global model, collaborate and complete complex high level tasks. Our architecture is predicated on the following set of assumptions:

1. Each unmanned vehicle possesses a certain degree of intelligence (Local Intelligence Core) to carryout tasks (Eg. move to waypoint, detect objects) autonomously and ensure its own safety by avoiding obstacles and necessary fail-safe protocols. 2. They are ”swarm-enabled,” meaning they are capable of moving in a coordinated way such that they avoid collision and their software stack is designed with an interface (an ”Gateway”) for connecting to a broader ecosystem and adhering to its communication and data standards. 3. While the architecture is resilient to transient connections, we assume there is undisturbed connection between the entities in the ecosystem. 4. The high level mission assigned is within the collective capability of the deployed swarm in the ecosystem. The architecture aim is to unlock the capabilities.

A. Heterogeneous Asset Layer

This layer consists of physical UxV assets and their software to extend the hardware and provide a baseline autonomy.

1) **Local Intelligence Core (LIC):** It is responsible for safety of the entity and execution of primitive commands. This may include activities like state estimation (using techniques like Kalman Filters), local perception for collision avoidance etc., For example, a UGV’s LIC would prevent it from driving off a cliff.
2) **Platform Abstraction Layer (PAL):** Provides a standardized software interface that separates LIC from platform specific hardware. This abstraction eases hardware agnostic software development that is portable across different UxV systems.
3) **Gateway:** Serves as an entity’s interface to the broader ecosystem, and it performs three crucial functions.
   a) Semantic Translation: To convert local sensor and system data into the Canonical Data Model (CDM) [16] used by the ecosystem.
   b) Task Marshalling: To translate high-level, abstract tasks into low-level executable primitives.
   c) Service Broadcasting: To advertise the system’s capabilities and services to other components within the ecosystem.

B. Ecosystem Fabric

This is the backbone of the ecosystem and it facilitates decentralized communication, and service discovery. It is not a centralized server, but a set of protocols and services that create a unified operational medium for information exchange.

1) **Decentralized Communication Bus:** It will employ a publish-subscribe messaging pattern [17] that will

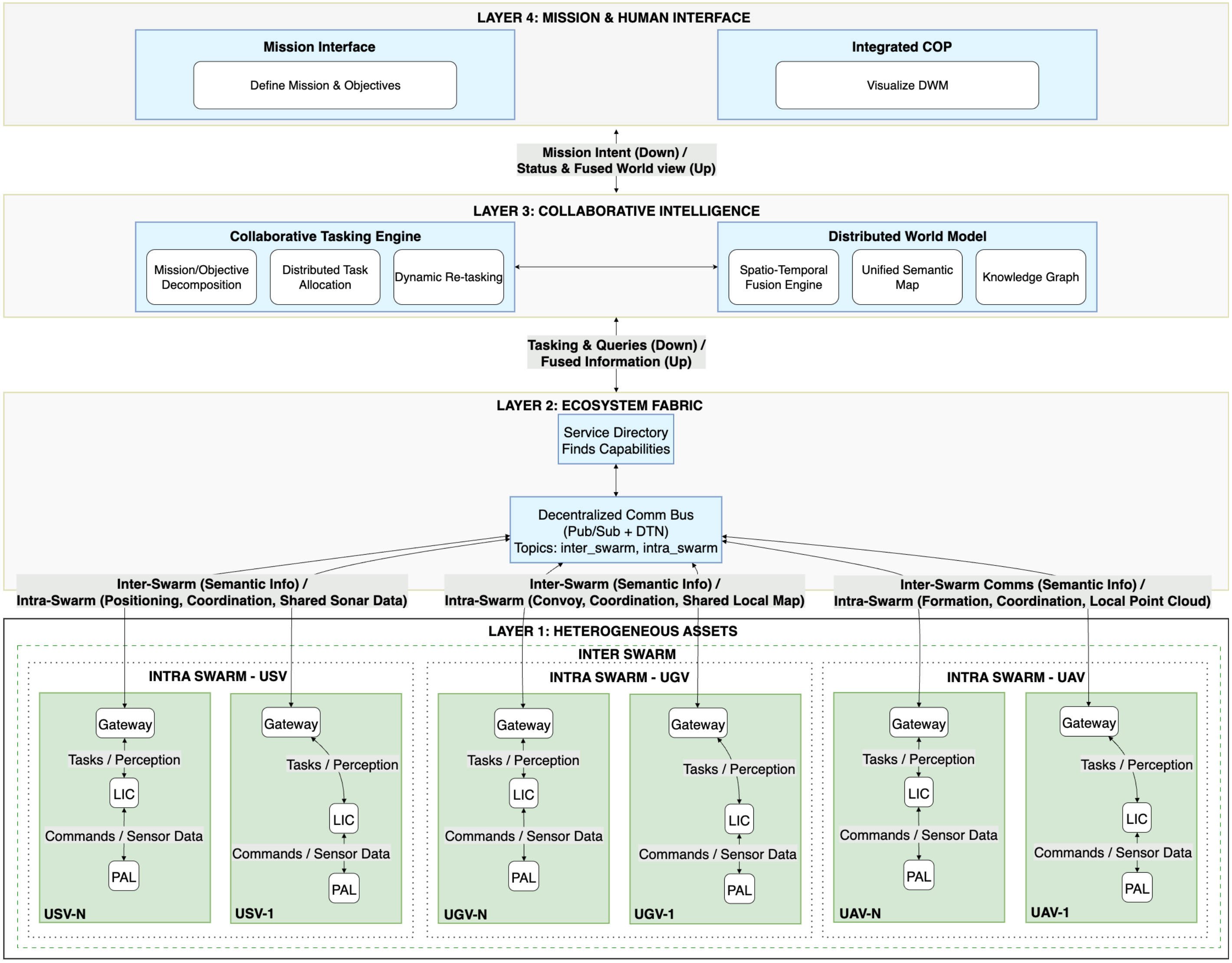

Fig. 1: UxV Ecosystem Architecture: This diagram shows the flow from high-level human command (Layer 4) to coordinated action across heterogeneous assets (Layer 1). The core of the system is the Collaborative Intelligence Layer (Layer 3), which uses a Distributed World Model and Task Engine to enable autonomous, cross-domain operations, all facilitated by the Ecosystem Fabric (Layer 2).

allow a system to produce and consume data without directly coupling other entity. It can manage different types of channels for different types of information. Importantly, it also incorporates protocols for Delay-Tolerant-Networking (DTN) [18], to enable store-and-forward messaging that will ensure data delivery even in communication denied environments. For instance, a UAV that went out of range can automatically upload its collected data to the Distributed World Model (DWM) once it reconnects with the network.

2) **Service Directory:** It is an *yellow pages* for system capabilities in the form of Distributed Hash Table [19]. When a new entity joins the ecosystems, its gateway will register its services based on a service ontology [20]. This allows other entities to query the directory and find which platforms can fulfill a specific need. For example, a UGV that has been tasked with assessing a damage in the power plant, may find chemical spill in a contaminated area. It can query to find a vehicle with nuclear / chemical sensing capability and find a specialized UAV nearby.

C. Collaborative Intelligence Layer:

This is the core of the proposed ecosystem architecture. It transforms raw data and information into a shared understanding and coordinated action. Its processes are distributed, running on nodes that have sufficient computations resources.

1) **Distributed World Model:** It is the corner stone of the architecture [21]. It is logically centralized but physically distributed representation of the environments

shared reality. The evolution of information fusion is more apparent here, as it moves from traditional fusion strategies like sensor and data fusion to a higher level information fusion to create a multi-layered knowledge base which includes mission intelligence, geometry, objects and semantics.

a) Spatio-Temporal Fusion Engine: It collects observations from all unmanned vehicles and performs data association (correlating information about the same object) and state fusion to produce a more precise unified track. For example, if a USV's radar and UAV's camera detect a boat, the engine fuses these observations to a single object ID with more accurate location and velocity estimate than either entities could produce alone.
b) Enironment Map: This map contains three layers. A Geometric layer that contains information about the terrain, and obstacles. An Object layer that contains information about the state of all dynamic entities in the environment. A Semantic layer that annotates space with mission related information like `No Fly Zone`, `Area Already Searched`, or `Objective 1 complete`.
c) Knowledge Graph: Models the relationship between entities, objects, and the environment to achieve complex high level reasoning and prediction. For example, *`UGV-2`* `is escorting` *`civilian-1`*, *`UAV-3`* `is performing` *`Objective-1`*.

2) **Collaborative Task Engine:** This is a decentralized decision making and task allocating engine of the swarm. It receives a mission composed of multiple objectives from the Mission Layer and it does the following:

a) Mission and Objective Decomposition: Break down complex mission into smaller objectives and further simplify each objective to a smaller manageable tasks. For example, the objective `Evacuate Area` is decomposed into tasks like `search grid A, search grid B, guide to exit 1`, etc.
b) Distributed Task Allocation: Assigning tasks to the most suitable system across all swarms considering the payload and other information. This can be achieved either via market based auction strategies [22] where entities bid on tasks based on their capability and estimated cost (e.g., energy, time) or priority based allocation strategies [23]. For example, a task requiring aerial imagery would receive low-cost bids from UAVs and prohibitively high bids from UGVs, ensuring a natural and efficient allocation.
c) Dynamic Re-tasking: Continuously monitors the DWM and task progress to dynamically reallocate tasks in response to environmental changes, failures, or the emergence of new, higher-priority objectives.

D. Mission and Human Interface Layer

This is the highest layer of abstraction, providing an interface through which human operators can exert strategic command and control—rather than engage in micromanagement.

1) **Mission Interface:** The human operator specifies the mission using a standardized format that defines objectives, constraints, and rules of engagement. For example: `MISSION: Secure Facility. OBJECTIVE 1: Establish Perimeter. OBJECTIVE 2: Investigate Anomaly at (lat, lon).`
2) **Integrated Common Operating Picture:** A multimodal interface that offers live visualization of the DWM, enabling the operator to monitor a unified, real-time understanding of the operational environment.

E. Summary

The UxV Ecosystem Architecture provides a foundational blueprint for enabling mission-level intelligence across heterogeneous unmanned systems. By integrating layered abstraction, decentralized communication, and collaborative reasoning, it transforms isolated agents into a cohesive, goal-oriented collective. This architecture is not merely a technical framework but a paradigm shift in how unmanned systems perceive, reason, and act. In the following section, we explore the practical challenges of implementing this vision and identify promising directions for future research.

IV. Challenges, Opportunities, and Future Work

The proposed UxV Ecosystem represents a shift from siloed autonomy to coordinated, mission-driven collaboration. While promising in concept, its realization introduces technical challenges and opens new research opportunities.

A. Major Challenges

- **Scalability and Synchronization:** Maintaining a consistent, low-latency DWM across agents requires scalable fusion algorithms and efficient communication protocols.
- **Resilience in Adversarial Environments:** Ensuring communication and coordination amid jamming, spoofing, or intermittent connectivity demands robust techniques.
- **Trust, Security, and Verification:** Decentralized architectures face risks of data poisoning and malicious agents. Verifiable task execution, secure data sharing, and distributed trust models are critical.

B. Opportunities for Future Work

- **Cross-Domain Missions:** The architecture enables heterogeneous teams for tasks like disaster response, infrastructure inspection, and logistics driving new approaches to coordination and planning.
- **Open Standards:** Defining shared formats for data exchange, task negotiation, and capability description will support interoperability across platforms and vendors.

- **Formal Mission Semantics:** Modeling goals, constraints, and roles formally can improve cross-agent reasoning and enable dynamic task decomposition at scale.
- **Simulation at Scale:** Developing high-fidelity environments for testing cross-domain swarms under real-world constraints is essential for validation and benchmarking.
- **Emerging Technologies:** Integration with 6G networking, edge AI, and quantum-safe cryptography can enhance performance, autonomy, and security in future deployments.

V. Conclusion

In this paper we identified a critical bottleneck in the current development and deployment of unmanned vehicles (UVs): the siloed nature of information fusion, limited to individual platforms or homogeneous swarms. To address this, we proposed a paradigm shift toward Cross-domain Mission Intelligence, embodied in the UxV Ecosystem architecture. By framing our analysis around an evolutionary hierarchy, from intra-vehicle to intra-swarm to mission-level fusion, we justified the need for a fundamentally new architectural approach. The proposed ecosystem centers on a multi-layered DWM and a Collaborative Intelligence Layer, enabling semantic and relational reasoning essential for coordinated, high-level missions.

Crucially, the architecture moves beyond data exchange to support intent sharing, contextual awareness, and collective decision-making across heterogeneous agents. This work is not a conclusion, but a beginning to a conceptual foundation and a call to action for developing the tools, standards, and algorithms that will realize mission-level autonomy across domains.

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