

Centralized Control Architecture for Mission-Critical Unmanned x Systems Swarms: An Analysis of Control Paradigms and Human Factors

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Abstract

Unmanned Systems (UxS) are increasingly deployed in defense, search and rescue, and infrastructure monitoring missions, often as heterogeneous swarms. A key challenge is how to optimally control such swarms while maintaining meaningful human oversight. This paper presents a comprehensive framework for centralized control of mission-critical UxS swarms, focusing on human-factors requirements arising from the complexity of swarm operations. The paper defines a UxS swarm as a coordinated collection of three or more unmanned platforms operating under unified command authority toward a shared mission objective. Five structural components are identified: the Command and Control (C2) layer, Communication Infrastructure, Individual Platform Capabilities, Coordination Algorithms, and the Operator Interface as the critical link between human decision-makers and autonomous swarm behavior. A systematic comparative analysis of centralized and decentralized C2-architectures is conducted. The analysis shows that centralized architectures, augmented with redundant command nodes and mesh-based communication, outperform alternatives across all metrics. Decentralized architectures, while theoretically scalable, exhibit fundamental limitations in human oversight and global optimization incompatible with high-consequence operations. Within centralized architectures, varying levels of autonomy create different human-system integration requirements. Highly autonomous systems require decision transparency as a core design principle, including decision rationales, reasoning, and confidence metrics to support operator trust calibration and meaningful intervention. Situation awareness must also be ensured through optimal human-machine interface design. These findings are directly relevant to next-generation human-swarm interaction systems in safety-critical environments.

Keywords: Unmanned aerial systems, Human-system integration, Heterogeneous swarms, Centralized control architecture

INTRODUCTION AND MOTIVATION

Unmanned x Systems (UxS) are unmanned platforms that can be operated with varying degrees of onboard autonomy to execute tasks without a human physically on board, with “x” denoting the operational domain such as aerial, ground, surface or underwater. UxS have fundamentally transformed operational capabilities in environments characterized by high risk, limited infrastructure or geographic constraints, because they reduce

exposure of human operators. In disaster management, for example, fleets of unmanned aerial vehicles have been used to provide rapid situation awareness, victim localization and communications relay where ground access is blocked or unsafe. Similarly, in defense applications, unmanned combat air systems and unmanned surface vehicles are expected to increase survivability and mission effectiveness through stand-off sensing, distributed strike capabilities and reduced risk to human crews (Aydin et al., 2024; Vannini et al., 2025; Keen, 2019). Building on these single unmanned platforms to multi-vehicle deployments, swarms are coordinated groups of unmanned systems that pursue a shared mission objective by exploiting local interactions and collective decision-making. Swarm-based approaches promise several advantages over traditional single-platform or loosely coordinated multi-vehicle systems. They can scale the number of units to the size of the operational area, provide redundancy against individual failures and reassign units to tasks as mission needs change. In this paper, the focus is on mission-critical operations, understood as missions in which failure would have severe consequences for human safety, strategic objectives or critical infrastructure and which therefore impose strict requirements on reliability, responsiveness and human oversight. In such missions, not only must the swarm complete its tasks efficiently under time pressure, but human commanders must also be able to understand, supervise and when necessary, override autonomous decisions (Ekelhof and Paoli, 2020; MacDonald, 2026; Madsen et al., 2023). One example would be search and rescue operations, where swarm-based concepts have been shown to improve area coverage, reduce mission time and increase robustness against individual vehicle loss compared to single-platform deployment (Aydin et al., 2024; Dimakos et al., 2025; Price, 2025; Ekelhof and Paoli, 2020).

At the core of any swarm lies its control architecture, which is the way decision-making authority, information flow and coordination logic are organized across the swarm and its human operators. Systems can be either organized in a centralized or decentralized control architecture. In a centralized control architecture, a central command node aggregates information and makes decisions for the entire swarm, issuing commands that individual units execute. In a decentralized control architecture, decision-making authority is distributed across swarm members. Global behavior emerges from local interactions and peer-to-peer communication without a single point of command. Each paradigm exhibits distinct trade-offs in terms of efficiency, robustness, predictability, scalability and the degree of human oversight it supports (Dimakos et al., 2025; Price, 2025; Ekelhof and Paoli, 2020; MacDonald, 2026).

The role of the human operator or human oversight as part of swarm control can be characterized according to the level of human involvement or the system's degree of autonomy. Accordingly, swarm control can be designed as a "Human-in-the-loop" (HITL) or "Human-on-the-loop" (HOTL) system (Baum and Laux, 2026; Vyhmeister et al., 2023). For the purpose of this paper, according to Baum and Laux (2026) we define a system, process or system function as HITL if it cannot proceed or produce output without a

decision input by the human operator. In HOTL, a system, process or system function can produce output without human involvement but the human operator can still supervise and alter the systems actions if necessary. Thus, in HITL mode the human operator remains as an active part, while in HOTL mode the operator has a supervisory role. A further distinction results from the point in time the human supervisor can alter the actions of a HOTL system (Baum and Laux, 2026). HOTL can be either

- synchronous, meaning the operator is constantly supervising the system and can intervene in real-time;
- asynchronous, meaning the operator reviews the system periodically or after specific actions have been completed, leading to interventions only affecting future system processes; or
- anticipatory, meaning the operator imparts or alters constraints of the system before the system begins its decision processes, i.e. the operator shapes the space in which potential decisions of the system could take place (Baum and Laux, 2026).

Despite growing interest and progress in swarm robotics and networked unmanned systems, a critical uncertainty persists in the fundamental architectural design of UxS swarms. The literature addressing autonomous swarm coordination frequently lacks standardized terminology for describing swarm composition, control topologies and decision-making authority (Dimakos et al., 2025). Therefore, this paper addresses three fundamental themes in this context. The first part defines what constitutes a heterogenous or homogenous UxS swarm as well as mission-critical operations. The second part compares the performance of centralized or decentralized control in mission-critical operations using a set of mission-critical performance metrics. The third part gives an overview of relevant human factors regarding the control of swarms.

FOUNDATIONAL DEFINITIONS

UxS and Swarm Definitions

A UxS is defined as a remotely operated or autonomous platform executing designated tasks without continuous human input with “x” representing the operational domain. This broad definition covers unmanned combat air systems, logistics drones, unmanned ground vehicles and many more (Keen, 2019). In this paper, and in some literature, a UxS swarm is defined as a coordinated collection of unmanned platforms, with a minimum of three units, operating under unified command authority towards a shared mission objective. The coordination mechanisms range from centralized control to distributed consensus approaches. A unified command authority is in control, when all units subordinate to a common mission objective. The coordination scope then extends beyond a point-to-point control to a collective action and the applicability across different operational domains (Keen, 2019; Price, 2025; Ekelhof and Paoli, 2020). A complete UxS swarm comprises five structural components. A command and control (C2) Layer including human oversight responsible for decision-making authority and strategic

planning, a communication infrastructure enabling information exchange among all the swarm members, the individual platform capabilities including sensors, actuators and computational resource, a coordination algorithm implementing the mapping between objectives and actions and an operator interface providing human-machine interactions and situation awareness. In Figure 1 an example is shown, which illustrates these structural components and their relationships at a conceptual level. Two Swarms are deployed to show the possibility of re-integration into another one, if all the task of one swarm are finished. The figure shows the C2 layer and human operator interface at the top, interconnected via the communication infrastructure to a set of heterogeneous unmanned platforms at the bottom. The deployed algorithms and control architecture are used for the command and communication of the platforms. The visualization is intended to show how information, commands and feedback flow between the human operator, the central control logic and the distributed units and to emphasize that failures in any one component can have system-level consequences in mission-critical operations (MacDonald, 2026; Madsen et al., 2023; Mayer, 2023; Karatzia et al., 2026).

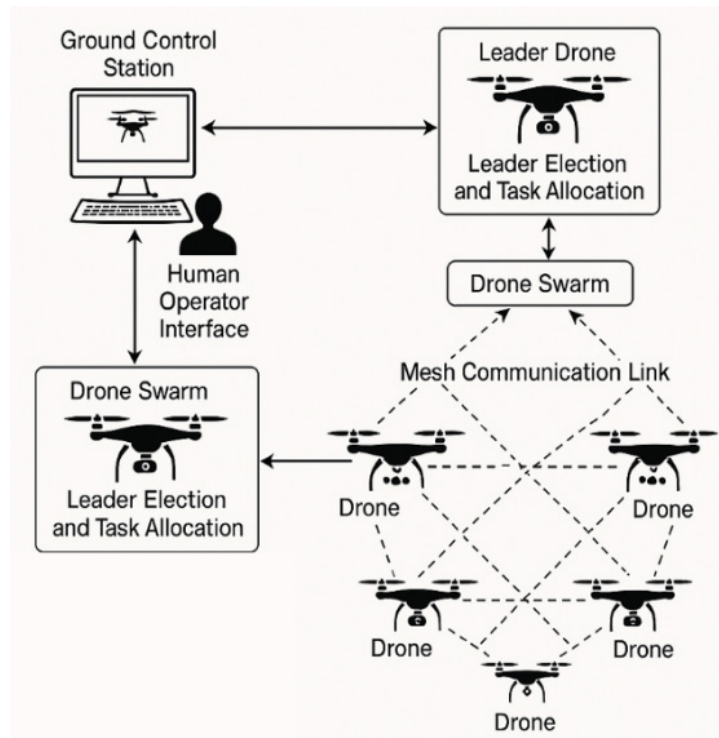


Figure 1: Structural components of a uxs swarm system.

Heterogeneous and Homogeneous Swarm Composition

A homogeneous swarm includes identical platforms executing identical algorithms. While simple, homogeneous swarms suffer from mission

inflexibility and resource inefficiency (Valentini et al., 2022; Navivkienè et al., 2025; Burger, 2012). A heterogeneous swarm combines specialized platforms optimized for specific domains with generalist platforms providing flexible resource allocation. Research by Quigley et al. demonstrates that heterogenous teams achieve 40% reduction in mission completion time and 60% improvement in area coverage compared to homogeneous alternatives in complex, dynamic environments (Kinsler et al., 2023; Phadke and Medrano, 2024; Cao et al., 2022). For mission-critical operations, heterogenous composition provides critical advantages, such as mission-specific optimization with each unit type optimized for designated roles, efficient resource utilization deploying specialized sensors and platforms only when needed, graceful degradation where loss of specialized units does not eliminate core capability and environmental adaptability enabling response to diverse mission scenarios (Kinsler et al., 2023; Phadke and Medrano, 2024; Cao et al., 2022).

Mission-Critical Operations: Defining Characteristics

Mission-critical operations in the context of UxS swarms are distinguished by several recurring characteristics. First, they involve a high consequence of failure, where unsuccessful task execution may lead to loss of human life, strategic disadvantage or severe damage to critical infrastructure (Vannini et al., 2025). Second, such operations are subject to time pressure, requiring real-time or near real-time decisions under uncertainty, because delays can render information obsolete or allow threats to escalate (Madsen et al., 2023). Third, they impose strict human oversight requirements. Even when leveraging autonomy, human commanders and operators are expected to retain meaningful control, be able to understand system behavior and intervene when necessary; i.e. the system needs to be designed as HOTL, ideally with synchronous control (MacDonald, 2026; Madsen et al., 2023; Clark et al., 2021). Fourth, mission-critical operations demand a high operational tempo, in which systems must rapidly adapt to changes in the environment, mission objectives or available resources (Karatzia et al., 2026). These characteristics collectively shape the requirements for swarm architectures. In particular, they motivate the need for predictable and explainable decision-making, robust communication and control structures and architectures that can handle failures without mission degradation. In the following, advantages and disadvantages of centralized and decentralized control with regard to mission-critical operations are elaborated further and connected to the level of human involvement, i.e. HITL and HOTL.

CONTROL ARCHITECTURE PARADIGMS AND COMPARATIVE ANALYSIS

Centralized Control Architecture

In a centralized control architecture, all decision-making authority resides with a central command node, in which individual platforms execute commands from this central authority. For mission-critical operations,

centralized control offers several important advantages, such as a global optimization, in which a central control station has the authority. The central authority has access to aggregate information from the entire swarm and can therefore optimize across all units, eliminating suboptimal local strategies that may arise in purely decentralized schemes (Aydin et al., 2024; Dimakos et al., 2025). Another advantage is the rapid adaptation. Centralized control enables rapid replanning in response to changed conditions, such as new targets, dynamic threats or unit failures and distributes updated commands to all units consistently (Dimakos et al., 2025; Karatzia et al., 2026; Kinsler et al., 2023).

Furthermore, centralized decision logic displays deterministic behavior, meaning it can be engineered to be deterministic or at least reproducible under given inputs, which simplifies mission planning, verification and after-action analysis (Dimakos et al., 2025). In addition, centralized control has a high accountability. A clear decision-making authority simplifies responsibility assignment and auditing, which is particularly relevant in military and safety-critical domains (Kinsler et al., 2023; Seon Kim et al., 2025).

Heterogeneous swarm composition naturally integrates with centralized control, in which the central authority allocates mission tasks to diverse platform capabilities. In such architectures, the central C2 node maintains a global overview of platform states, mission priorities and environmental constraints. This leads to solving a constrained optimization problem to assign tasks to units in a way that maximizes mission effectiveness, while including operational constraints (Kinsler et al., 2023; Seon Kim et al., 2025; Navivkienè et al., 2025). This integration enables optimal resource allocation, where specialized units perform optimally while generalist units provide fallback capability.

Finally, centralized architectures naturally support meaningful human oversight and intervention and thus easier human command integration, because human operators interact primarily with the central decision-making entity rather than with each individual unit (MacDonald, 2026; Madsen et al., 2023; Mayer, 2023). System functions in centralized control can be designed as HITL or HOTL, meaning the operator can be actively involved in some decision-making processes (HITL) while mainly supervising other processes (HOTL). Especially in mission-critical operations, it can be necessary for human operators to remain in the loop to ensure success (e.g. identifying the exact position of the victim using a camera feed in a search and rescue mission). Looking at HOTL, centralized control lends itself especially to synchronous and anticipatory supervision; with the operator supervising the swarm in real time or shaping swarm behavior before the mission by imparting constraints and boundaries.

Disadvantages of a centralized control-system, like a single communication node or a single authority for the swarm, can be addressed by contemporary centralized architectures. Measured that can be implemented to limit the risks include:

- A redundant command node with an automatic failover principle;
- A mesh-based communication network providing multiple communication paths;

- A distributed decision-making authority with delegation protocols and
- A localized autonomy where individual units make autonomous decision within broad command parameters (Dimakos et al., 2025; Sartoretti et al., 2019).

Decentralized Control Architecture

In a decentralized control architecture, decision-making authority is distributed across swarm members. Coordination emerges from local interactions without central command. The advantages for mission-critical operations are robustness to individual unit failures, theoretical scalability, local communication efficiency and autonomous operation independent of external authority, which may be desirable in highly contested or communications-degraded environments (Karatzia et al., 2026; Seon Kim et al., 2025). Nevertheless, a decentralized control architecture shows significant limitations for mission-critical operations. Emergent behavior can be unpredictable, complicating formal verification, safety assurance and mission analysis (Karatzia et al., 2026; Kinsler et al., 2023). Local optimization can lead to globally suboptimal outcomes, for example, when individual units greedily choose tasks that conflict with broader mission objectives. (Dimakos et al., 2025). Further, behavioral adaptation often requires changing local interaction rules across the swarm, which is less direct and slower than updating a central plan and redistributing it (Dimakos et al., 2025; Magg and te Boekhorst, 2007). In addition, the control of heterogenous swarms in a purely decentralized architecture is challenging, because no single agent has a full picture of platform capabilities and mission requirements. Local decision rules may lead to conflicts or suboptimal global distributions of roles (Kinsler et al., 2023; Raja Chowardhary et al., 2021). Finally, in decentralized control, human oversight is limited, because it is difficult for operators to understand and influence the emergent behavior of many decentralized agents in real time (Karatzia et al., 2026; Kinsler et al., 2023; Seon Kim et al., 2025). Thus, synchronous HOTL does not lend itself to decentralized control and being actively involved, i.e. HITL, becomes virtually impossible. However, asynchronous and anticipatory control still remain possible.

Comparative Performance Analysis

The decision how the control architecture of an UxS swarm should be designed can be influenced by a comparison of mission-critical performance metrics. Here, we chose to focus on efficiency, fault tolerance, predictability, human integration, adaptability and communication robustness. Table 1 compares the performance metrics for centralized and decentralized control as well as hybrid approaches. The qualitative ratings reflect consensus trends in comparative studies and case analysis rather than absolute values (Raja Chowardhary et al., 2021). For operational efficiency, fault tolerance, decision predictability, human integration and adaptability, the centralized architectures demonstrate superior performance when augmented with redundancy. Especially with regard to heterogenous swarms, the ability of a central authority to reason explicitly about heterogeneity and constraints

is a strong argument in favor of centralized architectures (Kinsler et al., 2023; Raja Chowardhary et al., 2021; Phadke and Medrano, 2024) The decentralized approaches excel only in communication robustness; however, this advantage is negated in mission-critical contexts by the disadvantages in human oversight and optimization.

Hybrid architectures aim to combine the strengths of both by using central coordination for mission-level decision, while retaining local autonomy for low-level behaviors (Dimakos et al., 2025; Mayer, 2023; Seon Kim et al., 2025). This results in high efficiency, fault tolerance, adaptability and communication robustness. However, compared to centralized control, human integration is more difficult and the system is less predictable. Overall, for mission-critical operations, the decision between centralized and hybrid control architectures has to be made as a trade-off between the need for fault tolerance and communication robustness on the one hand and the ease of integrating meaningful human oversight and control on the other hand.

Table 1: Comparing the performance metrics.

Metric	Centralized	Decentralized	Hybrid
Efficiency	High	Medium	High
Fault Tolerance	Medium*	High	High
Predictability	High	Low	Medium
Human Integration	High	Low	Low
Adaptability	High	Low	High
Communication	Medium*	High	High
Robustness	*with redundancy and mesh-networks		

HUMAN FACTORS IN SWARM CONTROL

The integration of a human operator in a system for the centralized control of heterogenous swarms in mission-critical operations has several human factors implications, depending on the definition of human oversight implemented in the system (i.e. HITL or HOTL or a combination of both).

Trust in the System: Transparency and Explainability

In general, the success of the teaming of an autonomous system with a human operator depends on several factors. For effective collaboration, the human operator needs to have an accurate mental model not only of the domain and their own task, but also of the way the autonomous system functions (Holstein and Satzger, 2025). Further, the human operator needs to have an appropriate level of trust in the system (Endsley, 2023). Thus, there needs to be a match between the systems behavior and human expectations, aided by the explainability and transparency of the system (Friedrich, 2023). Research demonstrates that explainable and transparent autonomous decisions enhance operator understanding, reduce decision latency and improve mission effectiveness (Madsen et al., 2023; Mayer, 2023) Centralized architectures

are particularly suited to provide a comprehensive explanation, as the central authority maintains complete mission context, enabling the generation of decision rationales including confidence metrics (Kinsler et al., 2023; Seon Kim et al., 2025; Raja Chowardhary et al., 2021). However, transparency and explainability are not the only necessary prerequisites for an appropriate trust in the autonomous system, as operators need an appropriate situation awareness to deduct if the system is able to perform correctly under the current circumstances (Endsley, 2023).

Situation Awareness

Situation awareness in general is a requirement for optimal performance in human-autonomy teams (Endsley, 2023; Grigsby et al., 2017). However, several factors in swarm control could negatively affect operator situation awareness. First: If in swarm control the operator constantly needs to switch between macro situation awareness of the situation as a whole and micro situation awareness of single tasks or swarm platforms, situation awareness can suffer (Holstein and Satzger, 2025). Thus, decentralized control architectures, where human operators would need to interact with the swarm on a platform level might be detrimental to situation awareness and a centralized control architecture preferable. Second: Situation awareness can suffer when human operators work in a highly autonomous system in a supervisory role (Endsley, 2023; Hammarbäck et al., 2024; Brewer et al., 2018; Paul and Brämer, 2013), as humans have difficulty maintaining vigilance and cognitive engagement in passive monitoring tasks over prolonged periods of time (Endsley, 2017; Endsley and Kiris, 1995). This can be a problem especially in synchronous HOTL tasks, where the operator needs to constantly monitor system functions and intervene if necessary. If synchronous HOTL is necessary for the functioning of the system, measures need to be taken in the design of the operator interface to counteract negative effects on situation awareness (Endsley and Jones, 2012).

Workload

Especially with regard to the implementation of synchronous HOTL supervision, operator mental workload needs to be taken into account (Endsley, 2023). Optimal performance is most likely achieved if the operator remains within an optimal, medium level of workload, as under- and overload can both have detrimental effects. Further, sudden spikes in workload can lead to performance decrements (Young et al., 2015; Dobson, 2015). This can be problematic in synchronous supervision tasks, as the operator mostly needs to monitor the system passively (leading to low mental workload and potentially monotony) and if necessary, quickly intervene (sudden workload spike). This interplay between lower, passive workload and sudden, potentially safety-critical active work needs to be considered when designing a system for swarm control.

Task Allocation

On the fundamental level, task allocation in swarm control involves mapping complex mission objectives into optimal assignments of swarm units, considering platform constraints, mission requirements and communication limitations. Here, centralized task allocation enables global optimization through algorithms including integer linear programming for optimality and heuristic approaches for real-time solutions (Burger, 2012; Clark et al., 2021). However, task allocation needs to be analyzed with a broader scope when a human operator is integrated in the swarm control system. Ideally, task allocation between the human operator and the system is defined with both human and system capabilities and constraints in mind to achieve an optimal performance (Ahlstrom, 2016). Similarly, how system and human collaborate and who retains final decision authority needs to be established (Neubauer and Schulte, 2025; Dudek and Schulte, 2022). With regard to maintaining situation awareness and counteracting negative effects of monotony, allocating a more active role to the human operator instead of limiting the task to synchronous supervision would be beneficial (Endsley, 2023).

DESIGN PRINCIPLES FOR MISSION-CRITICAL UXS SWARMS

Based on the preceding analysis of definitions, control architectures, swarm compositions, and human factors, several evidence-based design principles emerge for mission-critical UxS swarms. First is the need for a clear definition of command authority. A centralized command authority is appropriate for mission-critical contexts and the main authority should be explicitly assigned and clearly understood by all units and human stakeholder, consistent with doctrines for human-autonomy teaming (MacDonald, 2026; Madsen et al., 2023; Mayer, 2023). Second is the implementation of redundancy. A single point of failure in the command and communication infrastructure should be mitigated through redundant command nodes with automatic failover, resilient mesh networks and fallback local autonomy behaviors to ensure continuity of control under failures (Kinsler et al., 2023; Seon Kim et al., 2025; Sartoretti et al., 2019). Third is the design for heterogeneity, because the system architecture should accommodate diverse unit types and capabilities to evolving mission tasks to exploit the performance and robustness benefits of heterogeneous swarms (Cao et al., 2022). Fourth is to maintain transparency and explainability. Decision transparency and explainable decision-making mechanisms should be treated as a fundamental design principle rather than a post-hoc addition. This should foster the development of appropriate trust in the system, facilitate the development of an accurate mental model and effective human oversight (Clark et al., 2021; Endsley, 2023). Lastly, special care must be taken in the design of the system with regard to maintaining an appropriate situation awareness and mental workload, especially if the human operators are to engage in synchronous HOTL supervision tasks (Endsley, 2023). These principles align with documented best practices in defense and emergency response operations, where centralized command

authority with distributed execution has proven superior across decades of operational deployment (Price, 2025; Phadke and Medrano, 2024).

CONCLUSION

The key findings can be summarized as follows. First, centralized control with heterogeneous composition emerges as the optimal architectural paradigm for mission-critical UxS deployments, because it exploits global optimization and explicit reasoning about diverse platform capabilities, while still permitting robust designs through redundancy. Second, redundancy and failover mechanisms in both C2 layers effectively mitigate the classic centralization risks of single points of failure, enabling high levels of reliability even under adverse conditions. Third, heterogeneous compositions provide mission-specific optimization and graceful degradation that homogeneous swarms cannot easily match, particularly in complex, dynamic environments. Fourth, human oversight and decision transparency are essential design principles in mission-critical contexts and centralized architectures are naturally compatible with embedding explainable AI techniques and intuitive operator interfaces to meet these requirements.

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