Context-Aware Mission Planning and Decentralized Execution for Heterogeneous Teammates in Dynamic Environments

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Abstract

This paper presents a novel concept for a context-aware framework for mission planning and decentralized execution that integrates heterogeneous teammates such as autonomous drones, agents, and human responders into a unified, resilient system for dynamic operational scenarios. At the operational level, the system utilizes a Mission Planning function that receives high-level objectives, interprets mission intent, and decomposes complex objectives into a series of clear, actionable Mission-Essential tasks and sub-tasks. The process leverages contextual information from various sources such as sensor feeds, human reports and operational databases to dynamically assess resource availability and execution timing, while also considering operational constraints, including ethical constraints, and cost considerations. The system orchestrates a two-tier command structure, where the first level ensures that subordinates possess a robust understanding of mission objectives and the autonomy to adapt to changes in its operational environment. The second level comprises of diverse agents with varying levels of autonomy and capabilities, enabling iterative adaptation and collaboration. Experiments will be conducted in dynamic scenarios, such as deploying diverse drone platforms for Intelligence, Surveillance and Reconnaissance, and Search and Rescue missions to validate the framework's feasibility. This research aims to develop context-awareness for system adaptation to its operational environment with a safety-monitoring function to enhance the safety, adaptability, and efficiency of coordinated drone-human teams in operational applications.

Keywords: context-aware mission planning, decentralized execution, heterogeneous teammates, autonomous drones, mission monitor

1 Introduction

This paper proposes a framework for the *Context-Aware Mission Planning and Distributed Execution of Heterogeneous Teammates* (CAMP) project, designed to decompose complex tasks into explainable *Mission Essential Tasks* (METs) and subtasks while ensuring safe, transparent, and trustworthy operations. The framework is applicable, but not limited, to collaborative *Search and Rescue* (SAR) missions and *Intelligence, Surveillance, and Reconnaissance* (ISR) missions. The system leverages real-time contextual data, including sensor feeds, human reports, and operational databases, to adapt to evolving operational conditions. This work builds on prior research in task allocation and multi-objective optimization [1], aiming to enhance coordination between human and robotic agents in complex scenarios, such as industrial accidents or ISR missions.

The paper is structured as follows: Section 2 describes the operational scenario. Section 3 outlines the system´s logical architecture and subsequent sections detail the mission planning, decentralized execution, and mission monitoring components of the architecture. Section 4 briefly discuss some of the ethical challenges addressed in this work and Section 5 concludes the paper.

2 Operational Scenario

The framework is contextualized within a cascading industrial accident at the fictional GreenPower Lithium Manufacturing Complex in Västervik, Sweden. An explosion triggers toxic gas releases, fires, and potential secondary explosions, with risks escalating over 96 hours due to dynamic weather, flooding, and wildfires threatening nearby residential zones and critical waterways. A Task Force, led by CAMP, coordinates human teams (*Hazardous Materials* (HAZMAT), firefighters, medical) and autonomous agents with varying levels of autonomy, to contain hazards, mitigate environmental damage, and prioritize human safety.

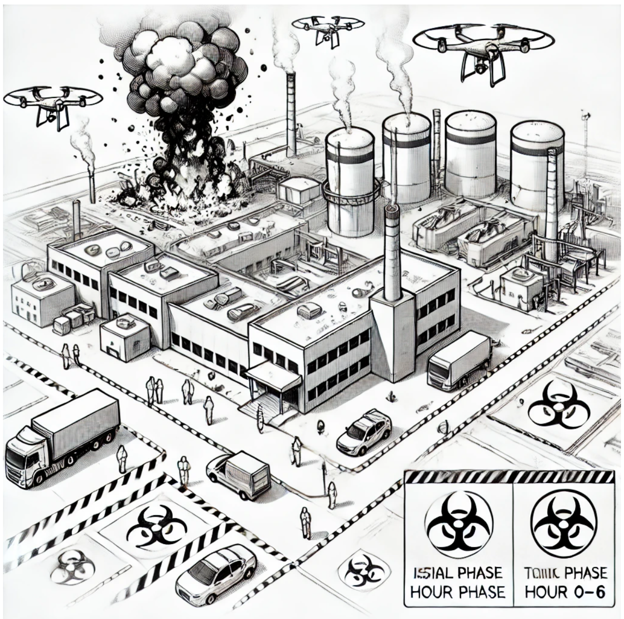

Figure 1: An illustration of the cascading industrial accident at GreenPower Lithium Manufacturing Complex. Image generated by OpenAI's DALL·E 3, January 1, 2025.

3 System Architecture

The CAMP framework integrates three core functional components: Mission Planning, Decentralized Execution, and Mission Monitoring. Mission Planning, based on an AI approach, receives high-level objectives, interprets mission intent, and decomposes complex objectives into a series of clear, actionable METs and sub-tasks, considering constraints, including resources, execution time, and ethical requirements. Decentralized Execution enables heterogeneous agents such as drones, robots, and humans to coordinate tasks with varying autonomy levels, from manually operated to fully autonomous. Mission Monitoring ensures system alignment with mission intent through continuous performance evaluation, triggering re-planning when discrepancies arise. This architecture supports dynamic environments by integrating data from various data sources, ensuring robust *Command and Control* (C2), and addressing ethical dilemmas.

3.1 Mission Planning

Mission Planning receives high-level directives and decomposes them into sub-tasks using real-time data from sensors, human reports, and databases [2, 3, 4, 5, 6]. For example, in the initial response, CAMP tasks sensors to monitor gas dispersal, robots to assess structural damage, and issues missions to isolate critical zones. The planning process balances objectives like containment and rescue while adapting to constraints such as resource availability and ethical considerations. The ability to integrate conflicting data (e.g., open-source information vs. restricted satellite imagery) ensures robust decision-making.

The aim of Mission Planning is to move beyond the traditional planning role of simply crafting a plan by champion a more comprehensive and dynamic approach, where it assumes a central and overarching responsibility for the entire mission execution process. To ensure mission success we adopt the *Plan, Direct, Monitor, and Assess* (PDMA) framework. This framework encapsulates four critical functions Mission Planning must fulfill to ensure mission success. It's not just about creating an operational plan; it's about actively guiding, overseeing, and adapting the mission in real-time based on incoming information and changing circumstances.

We believe this shift in perspective is crucial in today's complex operational environments, where autonomous systems and human operators must work together seamlessly in dynamic and often high-stakes scenarios. Mission Planning, in this context, acts as the central nervous system, ensuring coherence, responsiveness, and adaptability throughout the mission lifecycle. Mission planning, along with the other functional components and basic information entities is depicted in Figure 2.

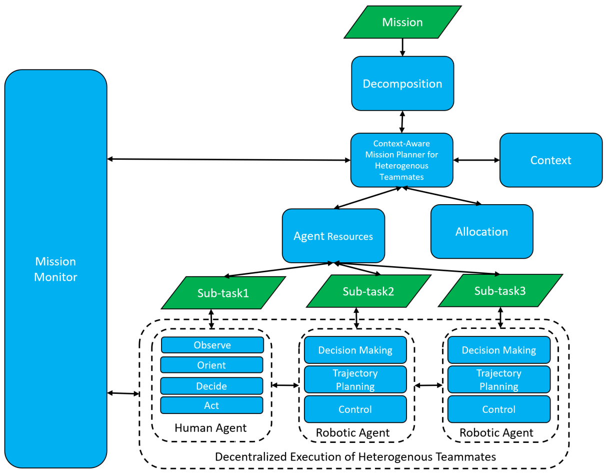

Figure 2: The CAMP conceptual architecture.

Internally, Mission Planning communicates with the assets allocated to the mission and Mission Monitoring, which plays a supervisory role, ensures smooth execution of the plan. Externally, Mission Planning receives directives from the authority granting the mission and gathers contextual information from various sources like sensors, databases, and human operators.

3.2 Decentralized Execution

Decentralized Execution [7, 8, 9] involves a two-tier command structure. The first tier ensures mission intent is communicated to agents, granting autonomy to adapt to dynamic conditions (e.g., communication loss or unmodelled threats). The second tier comprises heterogeneous agents with varying autonomy levels inspired by [10]:

- Level 1: Sensors for continuous data collection (e.g., air quality monitoring).
- Level 2: Drones/robots able to execute specific tasks (e.g., soil sampling).
- Level 3: Coordinated missions requiring some level of oversight (e.g., gas spread surveys).
- Level 4: Fully autonomous agents handling high-level objectives (e.g., chemical containment).

Agents report back for re-tasking, enabling iterative adaptation. For instance, in Hour 6–48, Level 2 drones collect water samples while Level 4 agents deploy barriers to limit chemical leaks.

3.2.1 Task Allocation

Decentralized execution is a method of decision-making in which responsibilities and authority to perform tasks are distributed at different levels of an organization.

Task Decomposition is a key enabler in such a framework to decompose a mission into sub-tasks. Once decomposed, each decomposed task also contains information on all the resources needed for completing the task.

Once the mission has been decomposed, Mission Planning coordinates agent execution across levels (1–4) through dynamic task assignment. An orchestration engine allocates tasks based on agent capabilities and mission urgency to achieve objectives. This orchestration will be adaptive and supports both centralized and distributed decision flows. This is a large optimization challenge and there are different algorithms to accomplish this [11], each with its specific advantages and drawbacks:

- Market-Based Algorithms are based on actions where asset/agents competitively bid on tasks based on a cost function based on e.g. energy, time or capability etc.
- Consensus-Based Algorithms are based on assets/drones continuously sharing information with each other and reach a consensus who does what.
- Heuristic Algorithms are a class of algorithms using strategies/rules based on experience to reach a solution, not always the best solution, but a good solution. Heuristic algorithms are good when the problem is NP-hard and we don't know if it is possible to find "the most optima solution" in efficient (finite) time.

In reality, if the context changes, or available assets/drones and their capability change, we have to redo task allocation in order to ensure that mission(s) or task(s) still can be achieved, and if necessary, redo task allocation.

Table 1: Example of resource allocation.

Agent	Task	Priority	Resource
Level 1	Gas monitoring	High	Sensors
Level 2	Structural assessment	Medium	Robots
Level 3	Zone isolation	High	Drones
HAZMAT	Containment barriers	High	Human teams

3.3 Mission Monitoring

Mission Monitoring is a mechanism that continuously assesses system performance against mission intent, detecting discrepancies like sensor inaccuracies or drone malfunctions [12, 8]. For example, when wildfires threaten residential zones, it triggers re-allocation of Level 3 drones to map evacuation routes and Level 4 agents to prioritize resident safety. It ensures transparency by logging decisions for post-incident analysis, addressing ethical dilemmas (e.g., prioritizing evacuation vs. containment) and maintaining trust through human-readable explanations.

Mission Monitoring in a mission planning system is crucial for:

- **Real-time tracking**: Continuously monitoring mission execution using data from various sources like sensors, telemetry, and human reports.
- **Deviation detection**: Identifying any discrepancies between the planned mission and the actual execution, such as delays, agent issues, or unexpected threats/opportunities.
- **Human intervention**: Potentially incorporating a human-in-the-loop control mechanism for situations requiring human judgment or intervention.
- **Ethical Dilemmas**: Balancing human safety vs. environmental protection requires transparent decision-making.

Mission Monitoring incorporates guardrails to ensure safe and trustworthy operations, with human supervisors retaining authority over critical decisions. Essentially, Mission Monitoring acts as a vigilant watchdog, ensuring the mission stays on track and alerting the system (and potentially humans) to any issues that need addressing.

4 Challenges and Ethical Considerations

The framework addresses several challenges:

- **Information Integration**: Conflicting data sources (e.g., social media vs. satellite imagery) require robust validation mechanisms.

- **Uncertain Conditions**: Dynamic weather and flooding necessitate adaptive planning.
- **Resource Constraints**: Limited drone battery life and payload capacity demand optimized task allocation.
- **Ethical Dilemmas**: Balancing human safety vs. environmental protection requires transparent decision-making.

Mission Monitoring incorporates guardrails to ensure safe and trustworthy operations, with human supervisors retaining authority over critical decisions.

5 Conclusion

This paper presents a novel conceptual framework for context-aware mission planning and decentralized execution, integrating heterogeneous teammates such as autonomous drones, agents, and human responders into a unified, resilient system for dynamic operational scenarios. The framework's core strengths lie in its ability to decompose complex missions into actionable sub-tasks, adapt to real-time contextual data, and ensure safe and transparent execution through continuous monitoring.

By leveraging a two-tier command structure and Mission Monitoring, the concept enables collaboration between agents with varying autonomy levels. We believe this approach to be of value in complex, time-sensitive situations like the Green-Power Lithium Manufacturing Complex accident scenario described in the paper.

The framework addresses key challenges in multi-agent coordination, including information integration from diverse sources, adaptation to uncertain conditions, and ethical decision-making. While the framework offers a promising solution for enhancing the efficiency and safety of drone-human teams in operational applications. It's important to note that the framework, while conceptually promising, is still in its very early stages of development. The framework outlined here represents a theoretical model and many of the technological challenges, are still being actively researched.

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