A Hierarchical Behavior Tree Architecture for Multi-Robot Mission Planning, Task Allocation, and Execution

Colton Kuzdzal[1], Audrey L. Aldridge[1], Tyler Errico[1], Dominic Larkin[1], Michael Novitzky[1]

***Abstract*— Multi-robot teams operating in complex environments require mechanisms for coordinating shared objectives, assigning roles, and synchronizing execution across heterogeneous platforms. While behavior trees have demonstrated advantages for robotic autonomy due to their modularity and reactivity, they are typically authored manually or generated from robot-centric planning frameworks that do not leverage mission representations already used by human operators. This work presents a hierarchical behavior tree architecture that translates human-authored mission-planning products into coordinated behaviors for multi-robot teams.**

Unlike traditional robot-centric approaches, the proposed framework integrates autonomous systems into existing human planning processes by deriving robot behaviors directly from artifacts used to coordinate teams across multiple organizational echelons. Planning information, including mission objectives, control measures, synchronization constraints, and graphical and textual planning artifacts, is transformed into a team-level behavior tree that captures shared objectives, task dependencies, and execution constraints. Team behaviors are subsequently decomposed through capability-aware task allocation into individual robot behavior trees, mirroring the hierarchical refinement of mission intent used in human organizations while enabling heterogeneous robots to assume specialized roles.

We extend the Planning, Execution, to After-Action Review (PETAAR) Toolset to support the translation of operational planning artifacts into executable robot behaviors. The resulting architecture supports scalable supervision by allowing operators to command robot teams through familiar planning representations while preserving coordinated execution across multiple autonomous systems. Although demonstrated using military planning products, the framework is applicable to other domains that employ structured planning artifacts, including emergency response, public safety, and disaster relief. This work highlights the potential of hierarchical behavior tree representations as a bridge between human planning processes and collaborative multi-robot autonomy.

I. INTRODUCTION

The operational environment facing soldiers today is becoming increasingly complex as autonomous and remotely operated unmanned systems (UxSs) are integrated into military missions. While individual autonomous platforms are becoming increasingly capable, many operational tasks require teams of heterogeneous systems acting in coordination. Examples include distributed reconnaissance, communications support, security operations, and collaborative mission execution across large geographic areas. Effective deployment of these teams requires mechanisms for expressing mission intent, allocating tasks, synchronizing actions, and adapting to changing operational conditions while minimizing operator workload.

Existing mission-planning approaches for robotic systems frequently rely on robot-centric interfaces, waypoint generation, or manually scripted behaviors that are disconnected from the planning products already used by military units [1], [2]. In contrast, military operations are planned using shared representations such as operation orders (OPORDs), graphical control measures, and tactical overlays that communicate objectives, constraints, sequencing requirements, and responsibilities across multiple echelons. As autonomous systems become integral members of military and other coordinated operational teams, a key challenge is enabling robot teams to participate in existing planning processes and execute mission intent expressed through familiar planning artifacts.

We propose a hierarchical behavior tree architecture that transforms mission-planning artifacts into coordinated multi-robot behaviors. Rather than generating isolated behaviors for individual robots, the approach first constructs a team-level behavior tree that captures mission objectives, task dependencies, synchronization requirements, and coordination constraints. This team-level tree acts as a coordination layer that governs shared team behaviors and mission progression. Individual robot behavior trees are then automatically generated through capability-aware task allocation, enabling robots to assume specialized roles while maintaining compliance with mission-level objectives and coordination constraints. Together, these complementary behavior tree layers support scalable planning, execution, and supervision of heterogeneous robot teams.

To support this approach, we extend the Planning, Execution, to After-Action Review (PETAAR) Toolset, a modular software framework for human-autonomy teaming that integrates existing military planning processes with autonomous execution [3], [4]. Whereas prior PETAAR efforts focused on translating planning artifacts for autonomous execution, this work extends PETAAR with hierarchical team-level coordination and capability-aware decomposition into robot-specific behavior trees. PETAAR currently supports the translation of a limited subset of mission graphics into behavior-tree representations, enabling the exploration of team-level coordination and task decomposition for au-

*We gratefully acknowledge the support of Army Research Labs (ARL) Distributed and Collaborative Intelligent Systems and Technology (DCIST) Collaborative Research Alliance (CRA) W911NF-17-2-0181 for this work.

[1]Colton Kuzdzal (former Cadet), Audrey Aldridge, Tyler Errico, Dominic Larkin, and Michael Novitzky are with the Robotics Research Center in the Department of Electrical Engineering and Computer Science at the United States Military Academy - West Point, NY 10996 kuzdzal.colton@gmail.com, [audrey.aldridge, tyler.errico, dominic.larkin, michael.novitzky] @westpoint.edu

tonomous systems. These initial capabilities serve as a foundation for future integration of additional planning artifacts, including operational documents, tactical tasks, and graphical control measures. Through this framework, we investigate how mission-planning artifacts can be converted into hierarchical team and individual behavior trees that support coordinated multi-robot execution.

The primary contributions of this work are (1) a hierarchical behavior-tree architecture that separates team-level coordination from robot-level execution, (2) a framework for integrating autonomous systems into existing human planning processes through mission-planning artifacts, and (3) a capability-aware task-allocation process that generates robot-specific behavior trees from shared mission objectives. The resulting architecture encodes coordination constraints, shared task dependencies, and dynamic role assignments within a common mission representation, enabling scalable task allocation and coordinated execution across teams of autonomous systems.

II. BACKGROUND AND RELATED WORK

Operational planning products encode objectives, constraints, control measures, task relationships, and coordination requirements across multiple echelons. Translating these human-oriented planning representations into executable behaviors for autonomous teams remains an open challenge.

A. Mission Planning and Human-Autonomy Teaming

Existing robotic mission-planning tools provide capabilities for simulation, waypoint generation, and low-level control, but generally emphasize robot-centric command and execution rather than shared, human-oriented representations of mission intent. Prior work in automated and mixed-initiative planning has translated human goals into executable robot plans using classical planners and hierarchical task networks [1], [2]. However, these approaches generally rely on planner-centric task representations rather than planning artifacts already used by human teams. Mission-planning systems such as ATAK [5], [6] and Tactical Decision Kit [7] support shared situational awareness through graphical planning products. However, current integrations of autonomous systems are largely limited to telemetry display, video streaming, and waypoint assignment, treating robots as assets rather than autonomous teammates.

B. Multi-Robot Planning and Task Allocation

Multi-robot systems require mechanisms for coordinating shared objectives, allocating tasks, and enforcing synchronization constraints among heterogeneous agents. Prior work has explored centralized and distributed task allocation, coalition formation, hierarchical planning, and behavior-based coordination strategies [8], [9]. While such methods provide mechanisms for decomposing team objectives into robot-level tasks, they generally assume that mission goals are specified directly within planning frameworks rather than extracted from human-authored operational plans.

C. Behavior Trees for Multi-Robot Coordination

Behavior trees have emerged as a powerful representation for robotic autonomy due to their modularity, reactivity, and formal execution semantics [10]. Beyond single-robot applications, behavior trees have been used to coordinate multi-robot teams by representing task dependencies, synchronization conditions, role assignments, and shared execution constraints [11]. Recent work has explored hierarchical behavior-tree architectures for mission planning and supervision in autonomous systems [12]. However, most existing approaches assume that both team-level and robot-level behavior trees are manually authored or generated from planner-internal representations. Comparatively little attention has been given to deriving hierarchical multi-robot behavior trees directly from human-authored planning artifacts while preserving coordination requirements, role assignments, and the hierarchical decomposition of mission intent used by human teams.

D. Research Gap

Prior work has explored mission planning, hierarchical behavior trees, and multi-robot coordination largely as separate problems. Consequently, autonomous systems are rarely integrated into the planning structures already used to coordinate human teams. This work addresses this gap through a hierarchical behavior-tree architecture that derives team- and robot-level behaviors directly from mission-planning artifacts, preserving mission semantics while enabling coordinated multi-robot execution.

III. APPROACH

A. Architecture Overview

The proposed framework extends the PETAAR toolset to integrate autonomous systems into existing human planning processes through a hierarchical behavior-tree architecture. Human-authored mission-planning artifacts are transformed into coordinated multi-robot behaviors while preserving the planning hierarchy used to communicate mission intent across organizational levels. Rather than generating independent plans for each robot, the framework first constructs a team-level representation (behavior tree) of mission intent that captures shared objectives, coordination constraints, synchronization requirements, and task dependencies, taken from various planning products.

Once the team-level behavior tree has been generated, mission responsibilities are distributed among individual robots through capability-aware task allocation. The resulting assignments generate robot-specific behavior trees that define platform-specific actions and contingencies. In this manner, team-level behaviors govern collective mission execution while robot-level behaviors provide the autonomy necessary for individual task completion.

This hierarchy separates mission coordination from platform execution. Team-level behaviors define what the team must accomplish, while robot-level behaviors define how individual platforms contribute. The resulting architecture preserves mission semantics while enabling coordinated

multi-robot execution through hierarchical team- and robot-level behaviors. Figure 1 illustrates the overall framework, including mission extraction, team-level behavior tree generation, task allocation, and robot-specific behavior execution.

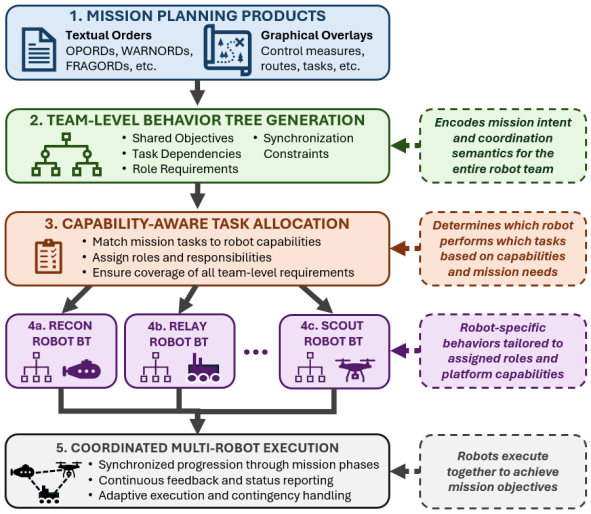


Fig. 1. Hierarchical behavior-tree architecture for coordinated multi-robot execution. Mission-planning artifacts are translated into team-level behaviors and decomposed into robot-specific behavior trees through capability-aware task allocation.

B. Example Mission Representation

To illustrate the proposed framework, we consider a mission consisting of two phase lines and a named area of interest (NAI). These control measures encode mission phases, synchronization points, and observation objectives that are translated into coordination constraints and robot-level responsibilities.

C. Extracting Mission Constraints

Mission artifacts encode both spatial information and coordination semantics. The proposed framework interprets mission graphics as coordination primitives within behavior-tree representations. Phase lines serve as synchronization boundaries between mission phases, while NAIs generate observation objectives. These relationships are used to construct team-level behaviors and coordination constraints.

D. Team-Level Behavior Tree Generation

The first layer of the proposed architecture is the team-level behavior tree. This behavior tree serves as a coordination mechanism that represents mission objectives, synchronization requirements, and shared task dependencies across the robot team. Rather than assigning actions to individual robots, the team-level tree defines the conditions that must be satisfied collectively before mission execution can progress. Figure 2 presents an example team-level behavior tree generated from the example mission.

Team-level behaviors encode phase transitions, synchronization checks, shared reporting requirements, and mission-level objectives, while individual behavior trees define platform-specific execution actions. Team-level nodes encode

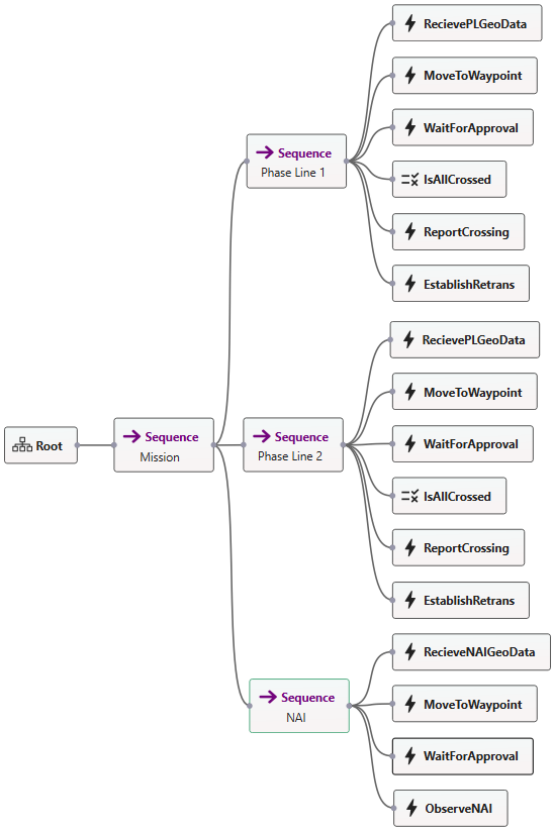


Fig. 2. Example team-level behavior tree.

activities that require coordination among multiple robots and establish the roles required for mission execution. This structure mirrors the hierarchical decomposition of mission intent used within human teams, where higher-level objectives are refined into responsibilities for subordinate elements. Because these behaviors exist at the team level, new requirements can be added once rather than replicated across every robot.

E. Task Allocation and Individual Behavior Trees

Once a team-level behavior tree has been generated, mission responsibilities are decomposed into robot-specific tasks. This decomposition process functions as a task-allocation mechanism that assigns mission responsibilities according to platform capabilities, operational requirements, and team objectives. In the current implementation, tasks are assigned using capability-based matching between mission requirements and available robot resources, providing a simple mechanism for generating robot-specific behavior trees while preserving team-level coordination constraints. Capabilities considered during allocation may include mobility, sensing, communications, or payload capacity, ensuring that mission requirements are matched to the robot best suited for the task.

Each assigned task is translated into an individual behavior tree that inherits relevant constraints and objectives from the team-level plan while defining platform-specific actions.

These individual trees enable robots to make local decisions regarding navigation, sensing, communication, and task execution while remaining synchronized with the broader mission. For the example mission, observation objectives derived from the NAI may be assigned to sensing-equipped platforms, while communications-support tasks are assigned to robots capable of maintaining a retransmission site. Team-level synchronization requirements remain shared across all platforms regardless of their individual assignments. In this manner, the team-level behavior tree specifies what must be accomplished, while task allocation determines which robots are responsible for accomplishing it.

Although robots execute different behaviors, their actions remain coordinated through the synchronization requirements encoded within the team-level behavior tree. Thus, the team-level behavior tree provides mission-level coordination, synchronization, and role assignment, while individual behavior trees define platform-specific execution strategies. Because coordination constraints are maintained within the team-level behavior tree, tasks may be reassigned to alternative robots without modifying the overall mission structure when platforms become unavailable or mission conditions change. This hierarchical decomposition enables heterogeneous robots to assume specialized roles while maintaining alignment with shared mission objectives and team execution status.

F. PETAAR Implementation

The proposed framework is implemented within the Planning, Execution, to After-Action Review (PETAAR) Toolset. Mission graphics are entered into ATAK and transmitted as CoT messages, which PETAAR parses to construct team-level behavior trees. The current implementation generates team-level and robot-level behavior trees from control measures including phase lines and named areas of interest, supporting allocation across heterogeneous reconnaissance and communications-support robots.

IV. Conclusion

This work presented a hierarchical behavior-tree architecture that transforms human-authored mission-planning artifacts into coordinated multi-robot behaviors. Team-level behavior trees capture shared objectives, synchronization requirements, coordination constraints, and role assignments, while capability-aware task allocation generates individual robot behavior trees tailored to platform capabilities. By leveraging planning representations already familiar to human operators, the framework enables autonomous systems to participate in existing planning processes while supporting coordinated execution by heterogeneous robot teams.

The current implementation demonstrates the feasibility of generating coordinated multi-robot behaviors from a limited set of military mission graphics. Although demonstrated using military mission-planning artifacts, the proposed hierarchy is agnostic to the specific planning domain and can be applied wherever mission intent is expressed through structured objectives, constraints, and control measures. Potential applications include emergency response, public safety, disaster relief, and other ATAK-enabled operational domains. Future work will expand support for additional planning artifacts, automated information extraction, and adaptive task-allocation mechanisms to further strengthen human-autonomy teaming.

Acknowledgments

Research was accomplished under Army Research Laboratory's Cooperative Agreement Numbers W911NF-25-2-0077 and W911NF-23-2-0153. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation herein.

References

[1] K. Erol, J. Hendler, and D. Nau, "Htn planning: Complexity and expressiveness," in *Proceedings of the AAAI Conference on Artificial Intelligence*, vol. 12, 1994.

[2] A. Tate, " The "Helpful Environment": Geographically Dispersed Intelligent Agents That Collaborate ," *IEEE Intelligent Systems*, vol. 21, no. 03, pp. 57–61, May 2006.

[3] J. S. Kay, T. Errico, A. L. Aldridge, J. James, and M. Novitzky, "Planning, execution, to after-action review (petaar): A toolset for human-robot teaming," in *Companion Proceedings of the 21st ACM/IEEE International Conference on Human-Robot Interaction*, ser. HRI Companion '26. New York, NY, USA: Association for Computing Machinery, 2026, p. 233–237. [Online]. Available: https://doi.org/10.1145/3776734.3794389

[4] A. L. Aldridge, T. Errico, M. Morrell, C. L. Bethel, J. James, C. M. Chewar, and M. Novitzky, "Integrating human-robot teaming dynamics into mission planning tools for transparent tactics in multi-robot human integrated teams," in *2025 IEEE International Conference on Robotics and Automation (ICRA)*, 2025, pp. 1876–1882.

[5] K. Usbeck, M. Gillen, J. Loyall, A. Gronosky, J. Sterling, R. Kohler, K. Hanlon, A. Scally, R. Newkirk, and D. Canestrare, "Improving situation awareness with the android team awareness kit (atak)," in *Proc. SPIE 9456, Sensors, and Command, Control, Communications, and Intelligence (C3I) Technologies for Homeland Security, Defense, and Law Enforcement XIV*, 2015, p. 295–305.

[6] J. Kim, T. Gregory, J. Freeman, and C. M. Korpela, "System-of-systems for remote situational awareness: Integrating unattended ground sensor systems with autonomous unmanned aerial system and android team awareness kit," in *2022 International Conference on Unmanned Aircraft Systems (ICUAS)*, 2022, pp. 1418–1423.

[7] M. C. R. C. Office, "Tactical decision kit (tdk) system overview," *Presentation*, 2017.

[8] H. Chakraa, F. Guérin, E. Leclercq, and D. Lefebvre, "Optimization techniques for multi-robot task allocation problems: Review on the state-of-the-art," *Robotics and Autonomous Systems*, vol. 168, p. 104492, 2023. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0921889023001318

[9] K. Arjun, D. Parlevliet, H. Wang, and A. Yazdani, "Optimizing coalition formation strategies for scalable multi-robot task allocation: A comprehensive survey of methods and mechanisms," *Robotics*, vol. 14, no. 7, 2025. [Online]. Available: https://www.mdpi.com/2218-6581/14/7/93

[10] M. Colledanchise and P. Ogren, *Behavior Trees in Robotics and Al: An Introduction*, 1st ed. USA: CRC Press, Inc., 2018.

[11] A. Marzinotto, M. Colledanchise, C. Smith, and P. Ögren, "Towards a unified behavior trees framework for robot control," in *2014 IEEE International Conference on Robotics and Automation (ICRA)*, 2014, pp. 5420–5427.

[12] S. Choi and J. Jung, "Dynamic mission planning framework for collaborative underwater operations using behavior trees," *Journal of Marine Science and Engineering*, vol. 13, no. 8, 2025. [Online]. Available: https://www.mdpi.com/2077-1312/13/8/1458