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Form 3

Abstract of Thesis

Name (DE LA ROCHEFOUCAULD Virgile)	
Title	Planning and Acting in Multi-Environment Aerial, Surface, and Aquatic Missions with Multi-Robot Teams （マルチ環境（空中・地上・水中）におけるマルチロボットチームによる任務の計画と実行）

Abstract of Thesis

Recent years have witnessed the emergence of increasingly complex robotic systems, operating in different environments while collaborating within heterogeneous teams. These advances have opened the way to new applications, such as the exploration of rough terrains, environmental monitoring, or, more simply, the development of autonomous logistics platforms. Nevertheless, planning and executing missions in such contexts remains a major challenge: coordinating robots with diverse capabilities, ensuring the synchronization of their actions, and guaranteeing the robustness of plans in the face of unforeseen events are central issues for the development of such robotic systems.

With the recent emergence of trans-media robots capable of operating across several domains (aerial, aquatic, and terrestrial), new challenges arise in both planning and execution. Their ability to adapt and operate in various environments introduces additional planning complexity, execution uncertainties during complex tasks, and a higher frequency of mechanical failures-particularly during transitions between environments.

To address these challenges, we present the Adaptive Modular Architecture (AMA), composed of two main components: AMA-Plan, a planner that restructures the problem to be solved, and AMA-Exec, a distributed execution system that integrates temporal reasoning and plan monitoring through an extended Simple Temporal Network (STN), combined with a multi-level failure detection and recovery mechanism.

- AMA-Plan decomposes and restructures complex problems into sequentially linked sub-problems: each team is responsible for solving one of these sub-problems, while the robots follow resolution paths in which they join different teams according to their capabilities, in order to satisfy the constraints specific to each sub-problem.

- AMA-Exec ensures the operational management of the plan through the coordination of the distributed real-time execution of plans, the monitoring of temporal constraints for each team's concurrent actions, and the maintenance of mission continuity in the event of desynchronization or the failure of one or more robots.

We evaluated AMA through a series of experiments in simulated environments involving homogeneous, heterogeneous, and trans-media robot teams. These experiments validated the system's ability to maintain temporal coherence and mission continuity despite action desynchronizations, various robot failures, and dynamic variations in the mission environment. The results highlight three key insights:

- modularity as a central factor of system robustness and scalability;

- the importance of temporal supervision to resynchronize teams and absorb temporal drifts;

- and the effectiveness of centralized planning combined with a distributed and reactive execution system, enabling multiple levels of adaptation.

Through this thesis, we sought to demonstrate that a clear articulation between centralized symbolic planning and reactive distributed execution provides an effective approach to strengthening the robustness and continuity of multi-robot missions in dynamic environments.

様式 7

論文審査の結果の要旨及び担当者

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論文審査の結果の要旨

This thesis investigates how large-scale multi-robot teams—including trans-media robots operating across aerial, surface, and aquatic environments—can effectively plan and execute complex missions.

The work addresses two central challenges:

(1) achieving scalable task allocation and temporal coordination among a large number of robots with diverse action sets, operational media, and mission sites (Chapter 4), and
(2) ensuring robust execution in the presence of delays and failures (Chapter 5).

Chapter 4 presents AMA-Plan, the planning component of the Adaptive Modular Architecture. Classical monolithic planners based on PDDL suffer from exponentially increasing computation times as the number of robots and sites grows, making them unsuitable for large-scale trans-media missions. In contrast, AMA-Plan decomposes the global planning problem into a sequence of linked sub-problems. Using spatio-cost clustering and robot allocation, it determines each team's sub-problem and corresponding execution path. Inter-team synchronization constraints are modeled using a Simple Temporal Network (STN). By avoiding monolithic optimization and solving each sub-problem independently, AMA-Plan efficiently produces tractable solutions even for missions involving dozens of robots and hundreds of goals. The scalability of the proposed approach arises from its modular decomposition, which closely aligns with the underlying mission structure and significantly reduces computational complexity.

However, even with a high-quality plan, execution can be disrupted by action delays and robot failures. Existing execution frameworks often lack sufficient temporal monitoring and localized recovery mechanisms, such that a fault affecting a single team can trigger costly replanning of the entire mission.

To address this limitation, Chapter 5 introduces AMA-Exec, the execution component of the architecture. AMA-Exec extends PlanSys2 by integrating STN-based temporal monitoring through an STNController and a Distributed Execution Manager (DEM). The system continuously monitors temporal constraints among concurrent team actions and restores synchronization by waiting or injecting controlled delays when temporal drift occurs. Upon failure detection, AMA-Exec diagnoses the affected scope and selects an appropriate recovery strategy, including local replanning, robot reallocation, or full mission replanning. Experimental results demonstrate that most injected failures were successfully handled through local replanning (typically within 5–10 seconds) or robot reallocation (mostly within 20 seconds), with full replanning required only in a limited number of cases. These results confirm that

the proposed framework effectively absorbs execution-time desynchronization while maintaining mission continuity.

Chapter 6 presents comprehensive simulation-based evaluations of AMA-Plan and AMA-Exec using homogeneous, heterogeneous, and trans-media robot teams. The results show that AMA-Plan significantly outperforms classical planning solvers in terms of planning time and scalability, while AMA-Exec achieves robust temporal coherence and effective failure recovery during execution.

Overall, this thesis demonstrates that the robustness and scalability of planning and execution for multi-robot missions spanning multiple environments can be substantially improved through modular decomposition and distributed execution management. The proposed framework is highly relevant to real-world applications such as environmental monitoring and disaster response. The work exhibits strong originality, technical depth, and practical significance, and therefore is fully recognized as having the value of a doctoral dissertation in Information Science.