Distributed Simulation of Multi-Agency Coordination in Maritime Emergencies

Qingqing Yang*, Jing Xu, Yingying Gao, Pengcheng Yang
College of System Engineering,
National University of Defense Technology
Changsha, China
Email: yqq_1982@126.com, Jenniferxu98@163.com, 15222638242@qq.com, yangpengcheng@nudt.edu.cn

***Abstract*—Maritime emergency response systems face unique challenges due to the need for cross-regional coordination, limited communication infrastructure, and the involvement of multiple international jurisdictions. This paper proposes a novel distributed simulation framework to enhance multi-agency collaboration in maritime emergencies, covering a comprehensive spectrum of hazards including vessel collisions, oil spills, search and rescue operations, piracy incidents, and extreme weather events. The framework leverages distributed simulation technologies to create an integrated method supporting real-time decision-making, resource optimization, and training for emergency responders.**

Keywords—Distributed Simulation Framework; Hybrid Modeling Approach; Maritime Emergency.

I. Introduction

The 2021 Ever Given Suez Canal blockage exposed a fundamental architectural flaw in global maritime emergency response systems. Despite causing over $9 billion in daily economic losses, the incident's most significant revelation was not the scale of disruption, but rather the systemic failure of hierarchical command structures when confronted with multi-jurisdictional coordination requirements [1]. This catastrophic breakdown occurs precisely because maritime emergencies violate the core assumption underlying traditional response systems: that effective coordination requires centralized control. In reality, modern maritime operations span multiple sovereign territories, involve competing commercial interests, and engage diverse agencies.

Under operational realities, therefore, the complex interrelationships emergent from distributed optimization spread over three dimensions for responding to a maritime emergency. First, autonomy must be possessed by the actors who have to make choices about the allocation of resources that have to be made scarce without any capacity for global information or significantly centralized coordination. Then again, the decisions are nested in a three-dimensional critical environment, failing communications and incomplete data due to time-critical constraints that preclude centralized processing. Centralized architectures impede effective response when, for example, loss of connectivity in the command center results in network collapse-when local conditions call for immediate action; those approved by hierarchy may prove fatal-when agencies pursue conflicting objectives; centralized mediation becomes a bottleneck instead of a solution [2][3].

Our primary contribution is developing and proving convergence for three interconnected distributed algorithms specifically adapted to maritime emergency constraints. Section II presents our theoretical framework and problem formulation. Section III details the distributed optimization algorithms with convergence proofs. Section IV concludes with implications and future work.

II. Problem Formulation and Theoretical Framework

Consider n maritime agencies responding to emergency scenarios with m shared resources. Each agency i controls decision variables $x_i \in \mathbb{R}^d$ representing resource requests and task assignments. The global optimization problem is:

$$\text{minimize} \, \Sigma_{i=1}^{n} f_i\left(\mathbf{x}_i\right) + g\left(\Sigma_{i=1}^{n} \mathbf{A}_i \mathbf{x}_i\right) \qquad (1)$$

where f_i represents agency i's local cost (response time, fuel consumption), g enforces global resource constraints, and A_i are coupling matrices encoding resource sharing relationships.

III. Distributed Resource Optimization Algorithms

This section presents three distributed algorithms designed to address the unique coordination challenges in maritime emergency response.

A. Distributed Auction

Our distributed auction protocol extends classical market mechanisms by incorporating maritime-specific spatial-temporal constraints. Each resource j has time-varying availability $r_j(t)$ and position $p_j(t)$ following maritime navigation dynamics.

The iterative bidding rounds in the protocol allow agency i to build bids using marginal utility and spatial-temporal factors:

In Bid calculation, during round k, agency i's bid for resource j is expressed as:

$$b_{ij}(k){=}u_{ij}(k) \cdot \varphi_{ij}(k) \cdot \psi_{ij}(k) \qquad (2)$$

where $u_{ij}(k)$ is marginal utility, $\varphi_{ij}(k)$ is spatial accessibility, and $\psi_{ij}(k)$ is temporal urgency factor.

In Price dynamics, resource prices evolve through the following process:

 ISBN: 978-1-68558-300-2

$$p_j(k+1)=p_j(k)+\alpha(k)\cdot[D_j(k)-S_j(k)] \quad (3)$$

where $D_j(k)$ is aggregate demand, $S_j(k)$ is available supply, and $\alpha(k)$ is an adaptive learning rate ensuring convergence.

B. Dual-Decomposition for Collaborative Task Assignment

In tasks that involve collaboration among multiple agencies, such as area searching and pollution containment, we apply dual decomposition to the distribution of optimization while coupling constraints are retained [4].

The global maritime resource allocation problem can be formulated as a convex optimization problem:

$$\min_{\mathbf{t}} \sum_{i=1}^{n} f_i(\mathbf{t}_i) \quad \text{subject to} \quad \mathbf{Ct}=\mathbf{b}, \quad \mathbf{t}_i \in \mathcal{T}_i \quad (4)$$

where $t=[t_1^T, t_2^T,..., t_n^T]$ represents the concatenated vector of all agencies' task assignments, $f_i(t_i)$ denotes agency i's local cost function, Ct=b represents the global coupling constraints to ensure resource conservation and task completion.

The dual variables are updated through a distributed consensus mechanism that preserves global consistency. Each agency i updates its local estimate of the dual variables according to:

$$\lambda_i(k+1) = \Sigma_j \in N_i \; w_{ij}[\lambda_j(k)+\rho(C_j t_j(k)-b_j/n)] \quad (5)$$

where weights w_{ij} form a doubly stochastic matrix ensuring $\Sigma_i\lambda_i(k) = n\lambda(k)$ is preserved.

C. Federated Q-Learning

Agencies learn the optimal resource pre-positioning both through distributed reinforcement learning and sharing, of course, without operational security risking.

States of the system are constructed as state space:

$$S = g \times R \times W \quad (6)$$

where g is discretized geographic grid, R is resource availability vector, and W encodes risk conditions. Action space A includes repositioning commands and readiness levels.

Each agency maintains Q_i: S × A → $\mathbb{R}$ updated via:

$$Q_i(s,a) \leftarrow (1-\alpha)Q_i(s,a) + \alpha[r_i(s,a,s') + \gamma \cdot \max_{a'} \overline{Q}(s',a')] \quad (7)$$

where $\overline{Q}$ is the federated average Q-function and r_i is agency-specific reward incorporating response time, coverage area, and operational costs.

To address non-stationary dynamics, we use experience replay with importance sampling to make sure agencies maintain prioritized replay buffers with importance weights:

$$w_e = \left(\frac{1}{N}\cdot\frac{1}{P(e)}\right)^{\beta} \quad (8)$$

where:

$$P(e) \propto |\delta_e| + \epsilon \quad (9)$$

where δ_e represents TD-error, ϵ represents a smoothing term.

IV. Conclusion

This paper presents a distributed simulation framework for multi-agency coordination in maritime emergencies. It can enhance emergency responses by reducing the impacts of disasters through a solid architectural underpinning concerning advanced simulation technologies considering the inherent complexity of managing maritime emergencies. A distributed architecture is in line with the operational reality of maritime environments and provides ample opportunity for the required coordination in effectively responding to maritime emergencies.

With increasing maritime traffic and new challenges, such as autonomous ships and climate change, the framework remains relevant in flexibility and extensibility. It is, therefore, a contribution toward building resilient maritime transportation systems to cope with various emergencies. This framework will be further developed and validated by the world's maritime agencies to provide a standard procedure for coordinating emergency preparedness and response.

Acknowledgment

This research was supported by the National Natural Science Foundation of China (72374209).

References

[1] C. M. Lee, and E. Y. Wong, “Suez Canal blockage: an analysis of legal impact, risks and liabilities to the global supply chain,” in MATEC Web of Conferences, vol. 339, pp. 01019, 2021.

[2] Dinh, P. Yang, and J. Diesner, "From plan to practice: Interorganizational crisis response networks from governmental guidelines and real-world collaborations during hurricane events," Journal of Contingencies and Crisis Management, vol. 32, no. 3, pp. e12601, 2024.

[3] N. Andreassen, O. J. Borch, and A. K. Sydnes, "Information sharing and emergency response coordination," Safety Science, vol. 130, pp. 104895, 2020.

[4] S. Boyd, N. Parikh, E. Chu, B. Peleato, J. Eckstein, "Distributed optimization and statistical learning via the alternating direction method of multipliers," Foundations and Trends in Machine Learning, vol. 3, no. 1, pp. 1–122, 2011.