Digital Twin Framework for Autonomous Drone Swarm Coordination in Maritime SAR Operations

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***Abstract*—Maritime Search and Rescue(MSAR) operations rely on effective coordination and perfect readiness among several assets. This project proposes a modular Digital Twin framework to enable autonomous drone swarms to coordinate SAR missions in maritime environments. The framework seeks to integrate real-time sensor data, digital-physical system synchronization, and Human-in-the-Loop (HITL) interactions to enhance situational awareness and decision-making. A simulation-based approach will be employed to validate that framework, focusing on swarm coordination, Human-Computer Interaction principles, and overall situational awareness. This work seeks to address the critical gap between centralized SAR systems and decentralized autonomous operations, with the aim of improving response times and increasing readiness by enabling the utilization of more economic assets.**

***Index Terms*—Digital Twin, Autonomous Unmanned Aerial Vehicles (UAVs), Swarm Coordination, Maritime Search and Rescue, Human-in-the-Loop, Real-time Data Integration, Human-Computer Interaction, Cyber-Physical Systems, Real-time Simulation**

I. Introduction

A. Context and Motivation

Maritime Accidents are critical emergencies where survival rate is directly correlated to response time. The European Maritime Safety Agency (EMSA) reported over 278 Maritime Search and Rescue operations, of which 56% (158 of 278) were fishing vessels. These vessels tend to be smaller, and tend to struggle more when calling for help at sea [1].

Traditional Maritime Search and Rescue(MSAR) methods face substantial limitations including difficulties with environmental estimation, resource allocation, planning, and C3I frameworks. Reliance on traditional assets like vessels, helicopters, and aircraft can be difficult to maintain full operational readiness with, due to high operating costs. Due to this, MSAR operations often have to grapple with difficult questions around economics, budgetary restrictions, and human cognitive loads [2]. This issue is only exacerbated in regions where governments cannot maintain those assets themselves, with MSAR often being left to ad-hoc volunteer labour.

Recent advances in Unmanned Vehicle technology and Swarm Coordination present real, transformative opportunities for Maritime SAR missions. Drone swarms consisting of Unmanned Aerial Vehicles (UAVs) and/or Unmanned Surface Vessels (USVs) allow for rapidly-deployed, cost-effective, and redundant systems that could supplement traditional MSAR assets. For example, a drone swarm could be deployed to help decide which specific operational areas to focus on and where to send more expensive assets like helicopters, manned vessels, and aircraft. However, deploying autonomous drone swarm systems in maritime environments, usually in open ocean, requires a sophisticated C3I framework that can handle dynamic weather conditions, communication constraints, and real-time decision-making under uncertain conditions [3].

Digital Twin (DT) technology, which creates virtual replicas of a physical system, which enables real-time simulation and monitoring. The framework that DT provides offers a promising framework for addressing the challenges in coordination that may arise when attempting to use drone swarm technology at sea [4]. By maintaining a synchronized virtual representation of physical unmanned vehicle swarms, Digital Twins enable a user to more efficiently coordinate swarms of drones. If carried out effectively, it presents an opportunity to reduce the chance for a human operator to experience cognitive overload, and still manage to provide equivalent if not increased coverage. Digital Twins could also, hypothetically, enable predictive analysis, what-if“

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