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[KSxAOV1I-18] From Marine Ecosystem Monitoring to an AI-Enabled Digital Twin: An Integrated Framework for Ecosystem Knowledge, Prediction, and Decision Support

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Marine ecosystem monitoring programs generate extensive observations of environmental conditions, biological communities, and habitat characteristics, yet these data are often fragmented across surveys, disciplines, and spatial and temporal scales. Consequently, monitoring results are frequently used for retrospective assessment rather than for integrated ecosystem understanding, prediction, and adaptive decision-making. This study proposes an AI-enabled framework for transforming long-term marine ecosystem monitoring data into a dynamic Digital Twin of the marine ecosystem.

The proposed framework consists of seven interconnected components: (1) systematic ecosystem observation, (2) an integrated ecosystem database linking environmental, biological, habitat, and human-pressure information, (3) an AI-based ecosystem knowledge platform, (4) ecosystem state assessment and anomaly detection, (5) ecological process and interaction models, (6) scenario-based simulation and prediction, and (7) decision support and ecosystem governance. Large language models, vector databases, geospatial analysis, and machine-learning techniques are incorporated to enable natural-language queries, automated report analysis, spatial pattern detection, and identification of ecological anomalies.

The framework is being developed using the long-term datasets of the National Marine Ecosystem Monitoring Program of Korea as a representative application. Rather than treating the Digital Twin as a simple three-dimensional visualization or data repository, we conceptualize it as an evolving digital representation that integrates observed ecosystem states with ecological processes and predictive models. The system is designed to progress from an AI-based marine ecosystem knowledge platform toward a fully integrated Digital Twin capable of scenario simulation and adaptive monitoring.

This approach provides a pathway for transforming conventional monitoring programs from data collection systems into intelligent, process-oriented, and decision-support platforms for ecosystem management and governance. This research was supported by Korea Institute of Marine Science & Technology (KIMST) Promotion funded by the Ministry of Oceans and Fisheries, Korea(RS-2026-25538840, Incheon-Gyeonggi-Chungcheong Sea Grant)

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