Requirements analysis in ARCAD-IA project*

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Abstract

Within the framework of transnational cooperation initiatives (e.g., SEA-EU), recent efforts have increasingly focused on the protection and valorization of marine cultural heritage. The ARCAD-IA (context-AwaRe deCision-making for Autonomus unmmaneD vehicles in mArine environmental monitoring) project aims to develop an intelligent, context-aware system for autonomous marine vehicles to support environmental and archaeological monitoring. The system integrates heterogeneous sensor data and applies a Computational Intelligence model to perform both quantitative and qualitative (e.g., High, Medium, Low) risk assessments. To this end, the project employs Artificial Intelligence techniques to preprocess multimodal data (e.g., signals and video sequences), including scenarios involving temporary data loss. A cognitively inspired reasoning approach, such as Fuzzy Logic, is used to enable adaptive, context-sensitive decision-making. The system is designed for integration into a marine drone (USV-ARGO) and will be validated through monitoring operations in the Marine Protected Area "Parco Sommerso di Gaiola," located in the northwestern Gulf of Naples an area of high ecological and archaeological value within the Special Area of Conservation "Fondali Marini di Gaiola e Nisida."

Keywords

Computational Intelligence, Decision-Making, Deep Learning, Environmental Monitoring, Fuzzy Logic, Microservices

1. Introduction

Marine coastal areas contain a high density of cultural heritage sites, including submerged archaeological remains and ancient harbor structures. These sites are highly vulnerable to environmental degradation and anthropogenic threats. Their preservation has become an environmental and cultural priority, aligned with frameworks such as the UNESCO Convention on the Protection of Underwater Cultural Heritage [1].

Monitoring these dynamic and complex environments requires intelligent, context-aware systems capable of real-time data acquisition, interpretation, and response. Autonomous platforms that integrate multimodal sensing and AI-driven analysis enable continuous surveillance and anomaly detection in settings where manual intervention is limited or unsafe.

Recent advances in intelligent systems, particularly adaptive sensing, machine learning, and reasoning, have proven effective in high-risk domains and are increasingly applied to monitoring underwater heritage. In this context, sensor fusion from video, sonar and spectral data provides a richer understanding of ecological and anthropogenic impacts, although challenges remain in data synchronization, transmission reliability, and robustness under uncertainty.

To address these, cognitive models, such as fuzzy logic, offer adaptive reasoning under ambiguous or incomplete information. ARCAD-IA introduces a resilient and AI-enhanced monitoring platform

Ital-IA 2025: 5th National Conference on Artificial Intelligence, organized by CINI, June 23-24, 2025, Trieste, Italy
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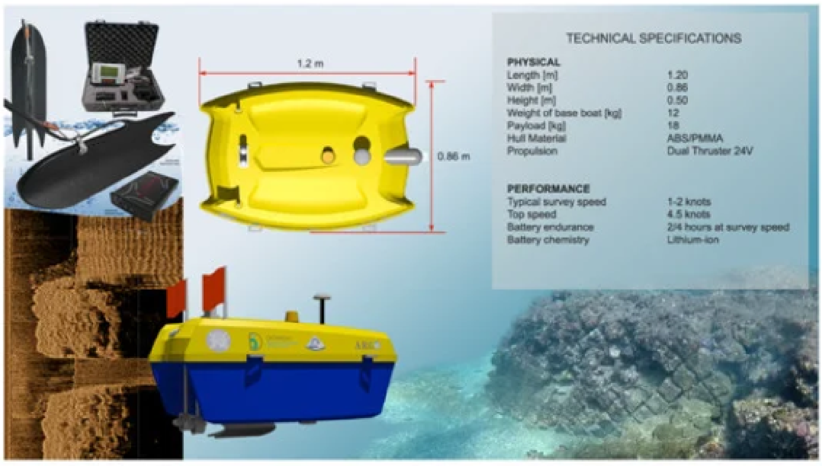

Figure 1: USV-ARGO and its technical specifications.

embedded in the USV-ARGO marine drone, aimed at real-time autonomous assessment of marine environments. The system could be validated for the monitoring of archeological areas, such as in the "Parco Sommerso di Gaiola", a Marine Protected Area in the Gulf of Naples known for its archaeological and ecological value, providing a real-world testbed for conservation-oriented innovation.

2. Methodology

In the context of the ARCAD-IA project, the process began with a comprehensive requirements analysis, which informed the definition of formal technical specifications and a system-level study to align project targets with environmental and archaeological monitoring objectives. The system architecture was designed to support real-time risk assessment by merging data from heterogeneous sensors with AI algorithms, allowing adaptive responses in complex marine contexts. One example is the "Parco Sommerso di Gaiola" marine protected area in the Gulf of Naples, is a site within the Natura 2000 network characterized by its unique ecological and archaeological features. This setting provides an ideal environment for evaluating threats arising from both natural and anthropogenic factors.

The early development stage focused on continuous stream processing and predictive modeling for sensor and video data. Techniques include advanced sensor fusion, underwater color correction via monocular depth estimation [11], and probabilistic forecasting using attention-based neural networks with Maximum A Posteriori estimation [5]. Federated Learning models were also explored to enhance distributed prediction accuracy [6].

Subsequent efforts addressed underwater object recognition using Deep Learning frameworks combined with eXplainable AI (XAI) for interpretable feature extraction. This includes an optimized marine waste detection pipeline [4,7] and Vision Transformer models evaluated through a dual-validation strategy [8,9]. An integrated decision support system was developed using neuro-symbolic architectures, combining symbolic reasoning with neural adaptability to enhance robustness in uncertain conditions.

The complete system is deployed on the USV-ARGO unmanned surface vehicle (Figure 1), featuring multimodal sensors (Figure 2) and the ArgonautAI distributed computing framework [1,3]. Its heterogeneous hardware includes CUDA-enabled GPUs, FPGAs, and custom I/O modules within a Kubernetes-managed containerized environment. Initial validations have demonstrated effective AI-driven marine litter detection using hierarchical vision pipelines.

2.1. Pre-Processing of Signals and Images

Signal acquisition is the foundational layer of the ARCAD-IA system, addressing the challenges of dynamic marine environments through the integration of optical, acoustic, and environmental sensors

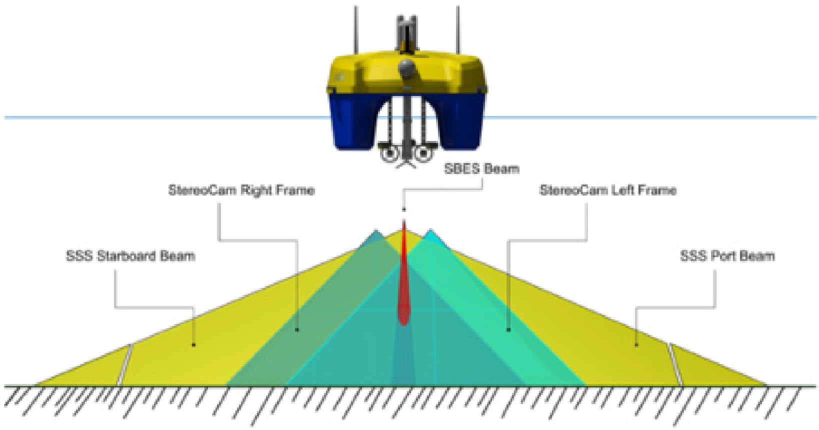

Figure 2: USV-ARGO and example of sensors.

[1][10]. High-resolution cameras, sonar systems, and probes provide spatiotemporal data on underwater sites, with synchronization and sampling strategies optimized for bandwidth and energy constraints [10].

Noise filtering, calibration, and edge computing support real-time pre-processing and onboard compression [10][11], and pre-processing techniques such as wavelet denoising, blind source separation, and adaptive gain control enhance signal quality across modalities [1][2][11][15].

To ensure robust performance under sensor interruptions or missing data, the system incorporates probabilistic modeling, including Gaussian processes and a Bayesian attention-based neural network for time series forecasting with uncertainty estimation [16] (see Figure 3).

Multimodal fusion further improves reliability by leveraging cross-sensor redundancy, designed for embedded edge computing environments [1][2][3][6][10][11], and supports downstream tasks such as object detection and risk assessment in real time.

In the same context also high-quality image acquisition is essential for autonomous marine monitoring, supporting inspection, ecological assessment, and archaeological documentation [1][2]. Underwater imaging is challenged by light attenuation, scattering, and turbidity, leading to severe color distortion and contrast loss [11].

Color degradation varies with depth, water composition, and subject distance. Conventional correction methods are insufficient due to the nonlinearity of underwater spectral filtering. Physically based models like Sea-Thru address this by reconstructing true color through optical modeling [11] (see Figure 4).

Recent methods combine physics-based models with ML, using depth-aware and spectrally calibrated networks to restore color while preserving physical plausibility [11]. These enhancements are critical for downstream tasks in ARCAD-IA, such as object recognition and site condition analysis, improving both interpretability and data quality for long-term monitoring.

2.2. Automatic Extraction of Concepts from Images and Videos

Automatic concept extraction from underwater imagery is key to semantic interpretation in marine monitoring, supporting applications in archaeology, environmental analysis, and risk detection [1][2].

Deep learning models, particularly Convolutional Neural Networks (CNNs), are used to extract features robust to occlusions and distortions common in underwater imaging. Efficiency is improved through depth-wise separable convolutions and attention mechanisms, enabling real-time deployment on autonomous systems. Vision Transformer (ViT) models, combined with Graph Convolutional Neural Networks (GCNNs), offer interpretable object recognition and concept localization [9] (see Figure 5).

Color restoration techniques like Sea-Thru correct spectral distortion using physics-based models, improving concept identification in degraded imagery [11]. Temporal analysis with 3D convolutions,

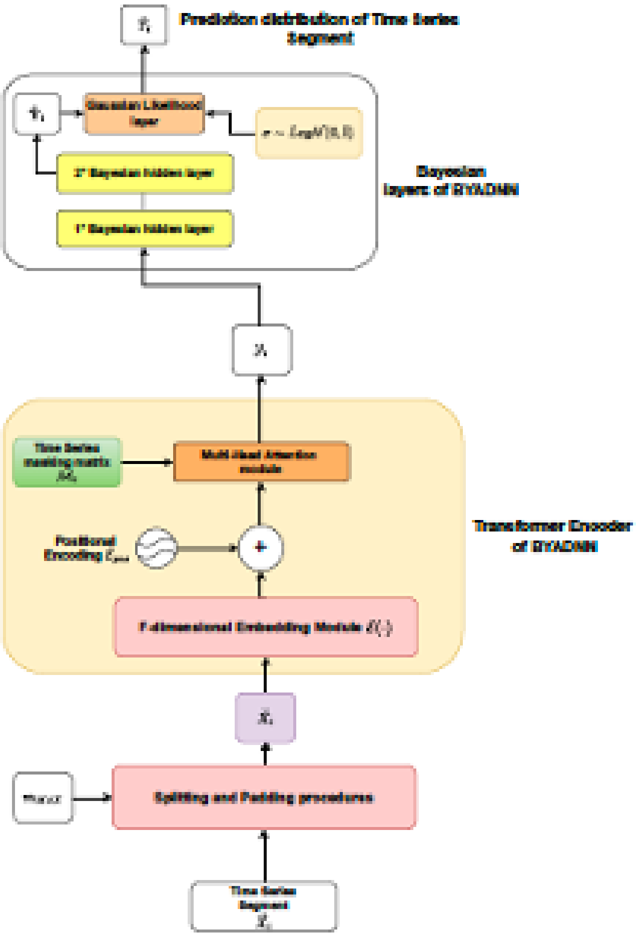

Figure 3: Scheme of the Bayesian attention-based deep neural network model.

Figure 4: Result of the Sea-Thru approach.

recurrent models, and optical flow enhances object tracking in video streams.

Due to limited annotated underwater datasets, transfer learning, domain adaptation, and self-supervised learning are applied. Explainability is achieved through attention maps, activation vectors, and hybrid neuro-symbolic architectures, supporting transparent decision-making.

Hybrid neuro-symbolic architectures combine the pattern recognition strengths of deep networks

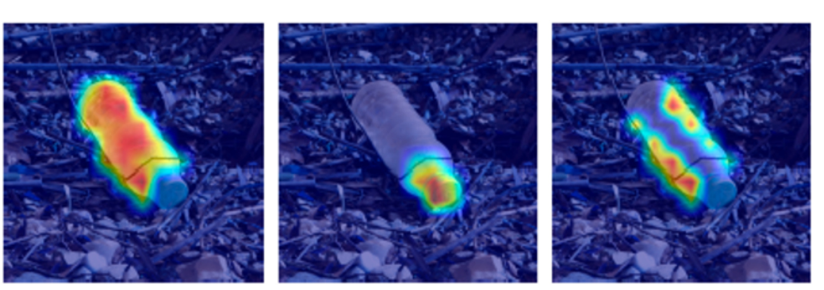

Figure 5: Example of extraction of concepts from images by GNN Explainer.

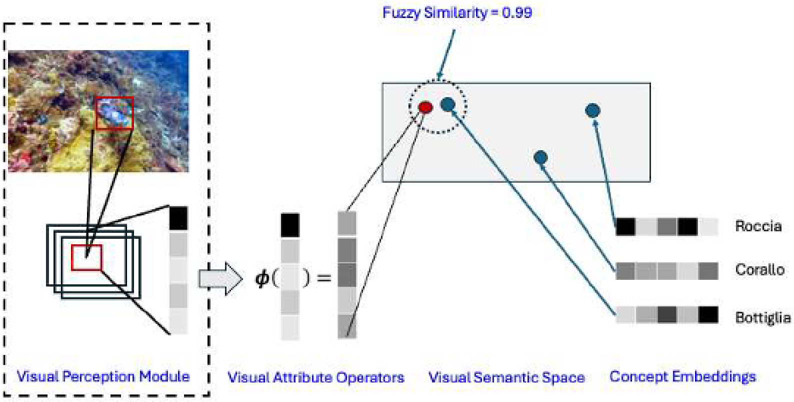

Figure 6: Visual perception and automatic extraction of visual concepts.

with explicit knowledge representations, enabling more transparent reasoning about extracted concepts and their relationships. In Figure 6 we show an example of visual perception and automatic extraction of visual concepts that can be adopted in ARCAD-IA.

For onboard use, models are optimized via pruning, quantization, and adaptive inference. Multi-task learning further improves generalization, enabling continuous, efficient, and interpretable analysis in marine conservation and heritage applications [1][2][9][11].

2.3. Decision-Making Systems Based on Artificial Intelligence

AI based decision-making is fundamental to autonomous marine operations, enabling adaptive, data-driven responses to dynamic environmental and archaeological conditions. These systems integrate multimodal sensor inputs and optimize strategies in real time using machine learning and reinforcement learning, even under uncertainty and resource constraints [13].

Neural networks transform heterogeneous data streams into structured situational awareness, enhanced by eXplainable AI (XAI) for transparency crucial in heritage sensitive contexts. Neuro-symbolic systems combine perception with rule based reasoning, supporting context-aware decisions that align with expert knowledge and conservation policies [13].

Neuro-fuzzy architectures, for example, add interpretability to learning based systems, using fuzzy inference to handle incomplete or noisy sensor data and assess priorities like site vulnerability or ecological risk [11]. These systems support flexible sensor fusion and maintain performance in degraded sensing conditions (see Figure 7 for an example).

Fuzzy Cognitive Maps (FCMs) provide lightweight, graph based reasoning suited for embedded deployment [14]. They model causal dependencies among mission parameters, sensor states, and environmental factors, and can be adapted through neuro-fuzzy learning or evolutionary optimization. On

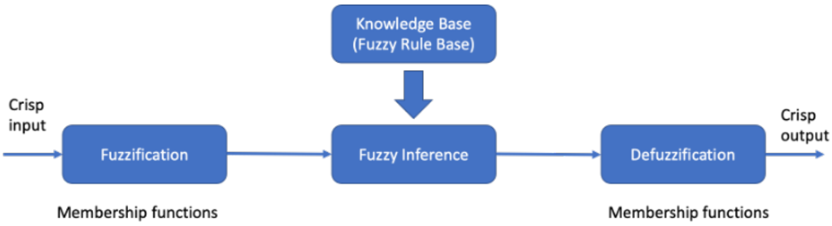

Figure 7: Fuzzy control system.

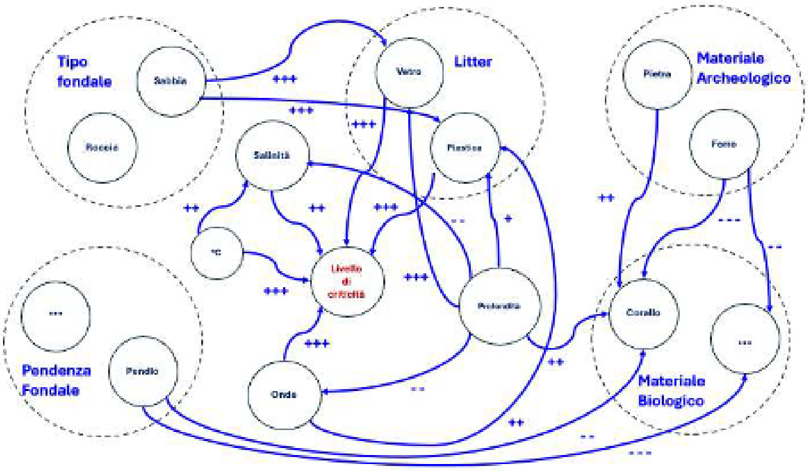

Figure 8: Example of Cognitive Map for environmental risk assessment.

platforms like USV-ARGO, FCMs offer interpretable, real-time decision support aligned with regulatory and conservation objectives (see Figure 8).

ARCAD-IA's hybrid AI framework combining neural, symbolic, and graph-based models enables robust, efficient, and explainable autonomy for marine monitoring in sensitive and unpredictable underwater environments.

2.4. Development of the Microservice-Based Platform for USV-ARGO

The development of a microservice-based platform for the USV-ARGO marks a significant evolution in autonomous marine systems, replacing monolithic designs with a modular, scalable architecture tailored for complex operational environments [1][10][11]. This architecture decomposes system functionality such as navigation, sensor fusion, and mission control into independent services communicating through well-defined interfaces. Such modularity enhances configurability, fault tolerance, and maintainability, especially critical in the variable and constrained conditions of marine operations.

Microservices are encapsulated in lightweight containers, enabling deployment across heterogeneous onboard hardware from GPU-accelerated nodes for AI inference to embedded systems for low-level sensor control [11]. The system is built on cloud-native principles adapted to edge computing, using technologies like Docker and K3S for distributed orchestration. Service discovery mechanisms support dynamic reconfiguration, while orchestration layers allocate computational resources based on mission demands and environmental conditions.

The platform supports sensor-specific pipelines for data from multibeam sonar, hyperspectral imaging, and video feeds, with each stream processed by dedicated, optimized services. ArgonautAI, the middleware layer developed for USV-ARGO, manages these components, ensuring efficient task scheduling and system cohesion (see Figure 9).

Reliability is embedded via architectural patterns like circuit breakers and service bulkheads, enabling graceful degradation under partial failure. Service meshes provide secure, encrypted communication

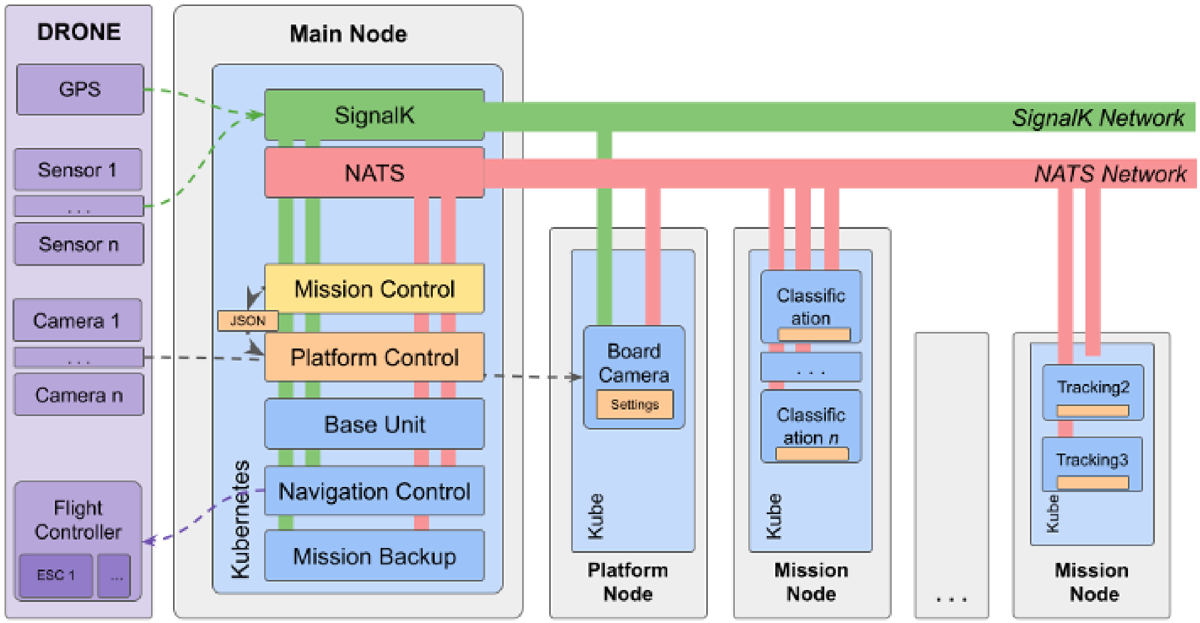

Figure 9: ArgonauticAI Architecture prototype.

with fine-grained access control. Real-time health monitoring allows for proactive fault mitigation and continuous mission assurance.

Performance optimization focuses on edge-specific constraints. Location-aware service placement ensures intensive tasks execute on suitable nodes, and adaptive data reduction minimizes onboard bandwidth usage. The architecture supports in-mission reconfiguration, allowing dynamic adaptation to changing objectives or environmental conditions.

Critically, this microservice model accelerates integration of scientific payloads and mission-specific software. New capabilities such as archaeological analysis tools or ecological assessment algorithms can be added as standalone services without altering the core system. This flexibility enables rapid iteration and responsiveness to evolving mission needs in protected marine areas [1][10][11].

2.5. Development of Strategies for Environmental Monitoring

Effective protection of marine ecosystems requires advanced environmental monitoring strategies that capture the complexity and variability of underwater environments [1]. Modern approaches have shifted from periodic sampling to continuous, multidimensional assessment, integrating real-time sensor data and intelligent analytics to track water quality, biodiversity, and habitat conditions across spatial and temporal scales [10].

These strategies address key challenges in marine observation, including broad spatial extents, limited accessibility, and dynamic oceanic variability. Adaptive sampling frameworks optimize data collection based on current conditions, while hybrid networks of autonomous platforms and fixed stations enable both wide-area surveillance and high-frequency local monitoring. This combination enhances detection of localized disturbances and systemic environmental changes.

Technological advances have expanded capabilities through high-resolution in situ sensors, autonomous samplers, and remote sensing platforms. Strategic deployment considers energy efficiency, data bandwidth, and durability under harsh marine conditions. Machine learning further improves monitoring efficiency by extracting patterns and flagging anomalies for targeted analysis.

Standardized protocols and quality assurance procedures ensure data comparability and reliability across diverse regions and research efforts. Interdisciplinary integration of ecological science with engineering design enhances system robustness and operational practicality.

In ARCAD-IA, environmental monitoring strategies are tailored to marine protected areas and submerged archaeological sites, integrating ecosystem assessment with cultural heritage risk analysis. This holistic approach supports adaptive management by correlating environmental dynamics with preservation conditions, enabling timely responses to both gradual and acute stressors affecting underwater cultural assets.

3. Conclusions

This work presented the design and implementation of an intelligent multimodal monitoring system for autonomous marine platforms within the ARCAD-IA framework. Through a structured requirements analysis and technical integration process, the system was developed to support environmental and archaeological risk assessment by fusing heterogeneous sensor inputs with AI-driven models.

Field validation is planned at the Parco Sommerso di Gaiola Marine Protected Area, chosen for its combined ecological and archaeological significance. System development addressed continuous data stream processing using sensor fusion and neural networks; automated object recognition with explainable AI; neuro-symbolic reasoning for decision support; and full deployment on the USV-ARGO platform.

Key achievements include attention-based neural networks for predictive modeling, optimized computer vision pipelines for underwater waste detection using XAI, and Vision Transformer frameworks for object classification. The system is supported by a heterogeneous computing infrastructure with GPU acceleration and containerized orchestration, delivering a scalable and interpretable platform for intelligent marine monitoring in sensitive and dynamic underwater environments.

Acknowledgments

This work was supported by: context-AwaRe deCision-making for Autonomus unmmaneD vehicles in mArine environmental monitoring (ARCAD-IA) project (PE000000131 - CUP E63C22002150007) cascade call of the Future Artificial Intelligence Research (FAIR) project Spoke 3 - Resilient AI, within the National Recovery and Resilience Plan (PNRR) of the Italian Ministry of University and Research (MUR).

Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

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