A Cloud-Based Virtual Sensor Approach for Intelligent Marine Water Quality Monitoring

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Abstract

Recent studies indicate that the practical implementation of virtual sensors is closely associated with Internet of Things (IoT) technologies, which enable continuous data acquisition and reliable transmission from distributed sensing devices. The rapid scalability of IoT systems and the exponential growth of telemetric data streams have created an increasing demand for cloud computing integration, allowing efficient storage, processing, and real-time analysis of large-scale datasets [1], [2]. The literature emphasizes that cloud platforms provide a favorable environment for the deployment of virtual sensing frameworks, as they support centralized data management, dynamic allocation of computational resources, and advanced analytical capabilities [3], [4].

The integration of Artificial Intelligence (AI) and Machine Learning (ML) algorithms with IoT-based cloud infrastructures is widely recognized as a key enabler for the development of intelligent monitoring systems. Numerous studies demonstrate that AI/ML techniques significantly enhance anomaly detection accuracy, predictive analytics performance, and real-time decision support, particularly when virtual sensors are employed to estimate environmental parameters or validate physical measurements [1], [5], [6]. This approach reduces the impact of measurement noise and sensor drift while improving the overall reliability and robustness of monitoring systems.

Although peer-reviewed publications specifically focused on Azure IoT Central remain relatively limited, the broader scientific and technical literature confirms the potential of cloud-based IoT platforms to provide secure communication, scalable analytics, real-time data ingestion, and predictive insight generation [2], [3], [7],[8]. Therefore, existing research suggests that the

integration of virtual sensors, IoT technologies, and cloud infrastructures represents a promising and still underexplored direction for the development of intelligent marine water quality monitoring systems, reinforcing the scientific relevance and practical significance of this study.

Keywords: Marine Water Quality Monitoring, Virtual Sensors, Internet of Things (IoT), Azure IoT Central, AI-Based Monitoring, Cloud-Based Analytics

Introduction

Marine water is a critical resource for both human well-being and ecosystem health, playing an essential role at environmental, economic, and societal levels. Climate change, domestic and industrial waste discharges, as well as pollution caused by fertilizers and pesticides, have increasingly negative impacts on the stability and biodiversity of marine ecosystems [9],[10]. Under these conditions, continuous and reliable monitoring of marine water quality has become a fundamental requirement for effective environmental management and informed decision-making.

Conventional marine water quality monitoring systems are predominantly based on physical sensors that directly measure parameters such as temperature, pH, electrical conductivity, and other physicochemical indicators. However, the deployment of physical sensors in marine environments is associated with significant costs and operational challenges, including sensor drift, biofouling, corrosion, and the need for frequent calibration. As a consequence, data reliability may degrade over time, while the overall operational resilience of monitoring systems is reduced [11],[12].

In this context, the adoption of innovative approaches, such as virtual sensors and the integration of Internet of Things (IoT) and Artificial Intelligence (AI) technologies, has gained increasing attention. Virtual sensors enable the estimation of environmental parameters through the exploitation of existing measurements, historical datasets, and predictive models, thereby allowing monitoring systems to become more cost-effective, scalable, and intelligent. Rather than relying exclusively on direct physical measurements, virtual sensing introduces a data-driven paradigm that enhances system flexibility and robustness [13],[14],[15].

The rapid evolution of IoT technologies has significantly expanded the capabilities of environmental monitoring systems. Distributed sensing devices now enable real-time observation of physical, chemical, and biological parameters across both terrestrial and marine environments. Nevertheless, the harsh and dynamic conditions of marine settings continue to limit the effectiveness of approaches based solely on physical sensors. Consequently, alternative and hybrid solutions, particularly those leveraging cloud-based virtual sensing frameworks, have emerged as a promising direction in contemporary environmental research [16].

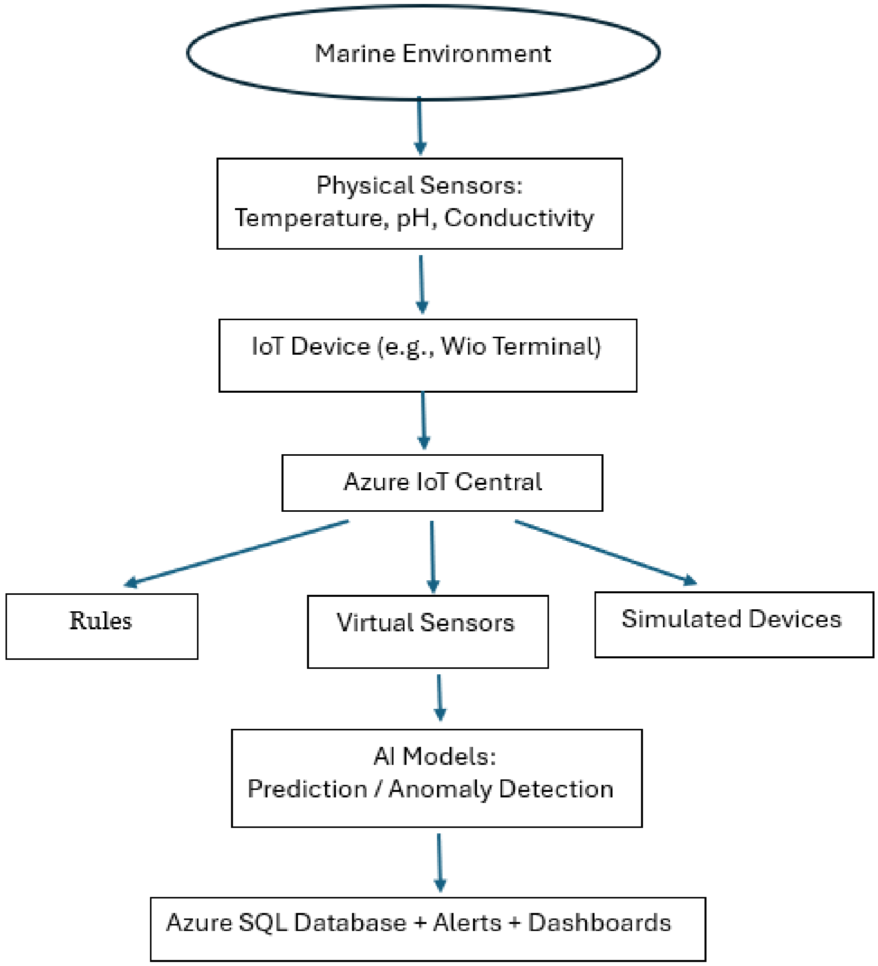
The objective of this paper is to present a conceptual and practical evaluation of virtual sensors implemented on the Azure IoT Central platform for marine water quality monitoring. The study focuses on assessing data reliability, predictive capabilities, and system scalability, highlighting the potential of cloud-based and AI-driven virtual sensing approaches to enhance the efficiency and intelligence of marine environmental monitoring systems.

System Architecture Overview

The system architecture is based on a multi-layered model, comprising physical sensors, IoT devices, cloud platforms, and analytical components. Virtual sensors are deployed at the cloud layer, functioning as an intelligent intermediary between physical sensors and final decision-making processes [17].

Figure 1 illustrates a modern, cloud-based IoT platform architecture for marine water quality monitoring, integrating physical sensors, virtual sensors, AI models, and automated decision-making mechanisms.

Figure 1 – A Cloud-Based Virtual Sensor Architecture for Marine Water Quality Prediction



Monitoring begins in the marine environment, where physical sensors measure key parameters including temperature, pH, conductivity, and other physicochemical attributes. These sensors serve as the primary data source, and their regular measurements provide real-time insights into environmental stability and changes. Data collected by physical sensors is first processed by IoT devices, such as the Wio Terminal, which securely transmits the measurements to the cloud platform. Azure IoT Central serves as the cloud hub for data ingestion, management, and preparation for subsequent processing.

Virtual sensors are data-driven models that do not correspond to physical hardware. Their primary functions include:

- Integration of physical sensor data

- Computation or derivation of new metrics (e.g., Water Quality Index, predicted parameters)
- Provision of input data for AI models and rules engines

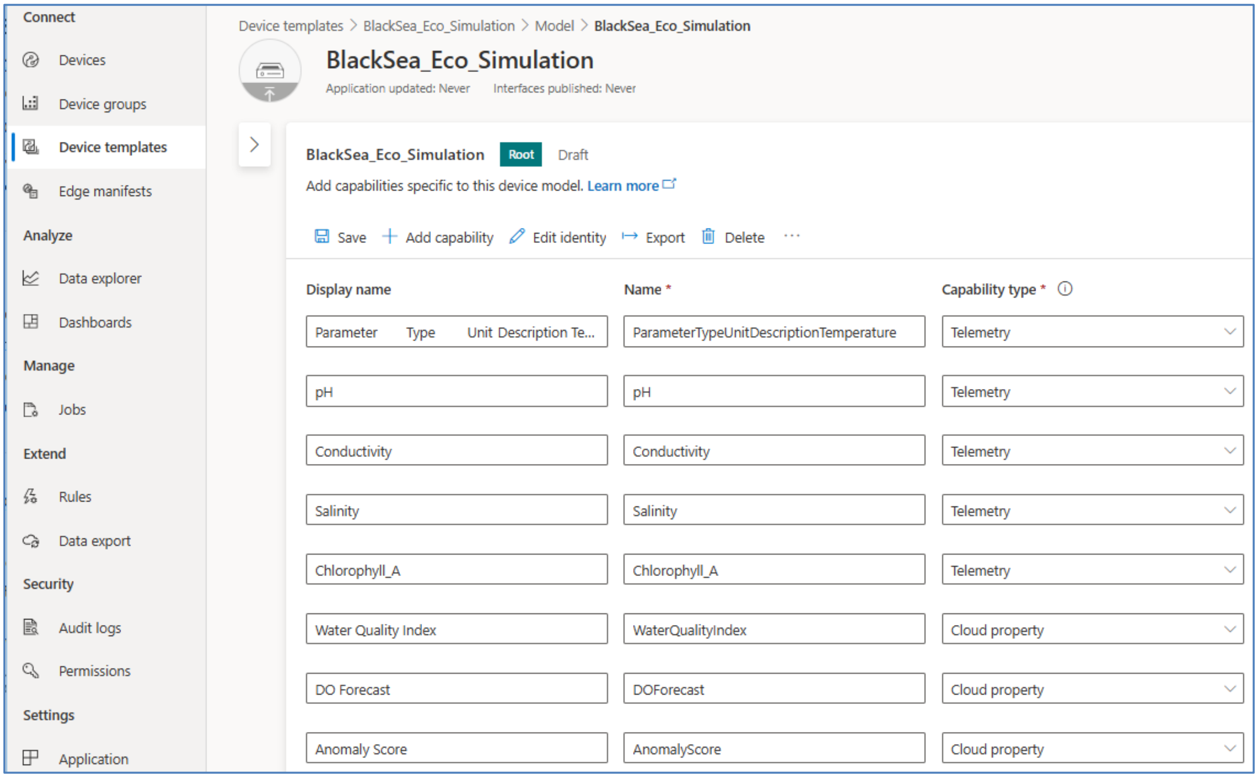
Rules and AI models (e.g., prediction, anomaly detection) utilize virtual sensor outputs to detect unusual water parameter variations and generate forecasts for future changes. All processed data, predictions, and alerts are stored in an Azure SQL Database, which ensures historical record keeping and enables real-time visualization on dashboards accessible to monitoring teams.

Simulated devices are employed for testing and system modeling, generating artificial data streams to validate the resilience of the platform and the accuracy of virtual sensor computations. These devices do not produce real environmental measurements but are essential for verifying anomalies and forecast generation.

Forecasting within the Marine IoT Water Monitoring System involves estimating future values of physicochemical water parameters based on historical measurements from physical sensors combined with additional analytical processes. Data is pre-processed on the virtual sensor layer, including outlier removal, missing value imputation, and normalization or standardization for AI models.

Figure 2 illustrates the Device Template in Azure IoT Central, combining both physical and virtual sensors.

Figure 2 – Azure IoT Central Device Template



Physical sensors (Telemetry) represent the primary data source and include parameters such as:

- Temperature (°C);
- pH;
- Conductivity (μS/cm);
- Salinity (PSU);
- Chlorophyll_A (μg/L).

These telemetry parameters are continuously recorded and transmitted to IoT Central, where they are ingested, stored, and visualized on dashboards in real time. Telemetry data provides a basis for environmental monitoring and forms the foundation for virtual sensor computations and AI models.

Virtual sensors (Cloud properties) represent computed or forecasted values not directly sourced from physical devices. In the Device Template, virtual sensors are implemented as cloud properties and include:

- Water Quality Index (WQI) – calculated from physical sensor measurements to indicate overall water quality;
- DO Forecast – AI-generated prediction of future dissolved oxygen levels (mg/L);
- Anomaly Score – AI-derived anomaly indicator (0–1).

Cloud properties enable automatic updates of virtual sensor data for AI models, allowing rules engines to detect abnormal variations and trigger automated alerts. The Device Template also includes a Simulated Device, containing both physical and virtual sensor parameters for system testing, validation of virtual sensor calculations, and AI model verification.

Conclusion

This study presents a cloud-based virtual sensor approach for intelligent marine water quality monitoring, implemented on the Azure IoT Central platform. The results demonstrate that virtual sensors significantly enhance data reliability, reduce dependence on physical sensors, and enable real-time, intelligent analytics.

The integration of physical sensor measurements, AI models for forecasting and anomaly detection, and automatic cloud-based updates of virtual sensors produces a scalable and cost-efficient monitoring system. The use of simulated devices for system testing and verification further strengthens operational resilience and ensures the accuracy of virtual sensor computations.

The findings confirm that Azure IoT Central–based virtual sensors provide an effective solution for both research and practical applications, particularly in geographically distributed or environmentally challenging marine monitoring sites. Future work may focus on improving the generalization capabilities of AI models across seasonal and hydrological variations, optimizing cloud architecture for real-time analytics, and evaluating long-term operational performance.

Overall, this approach establishes a foundation for the development of modern, intelligent, scalable, and economically sustainable systems for marine water quality management.

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