Enhancing IoT Cloud Infrastructure and Data Visualization for Real-Time Monitoring of the Venice Lagoon with SENSWICH

Matin Ghalkhani, Federico Marin, Filippo Campagnaro, Michele Zorzi

Abstract—**Monitoring coastal areas and biodiversity hotspots often requires costly solutions such as expensive buoys, leading to significant financial concerns. At the previous MetroSea Conference, the first version of the SENSWICH prototype was presented as a cost-effective, real-time monitoring solution designed specifically for the Venice Lagoon, one of the important areas for research due to its importance as a biodiversity ecosystem and its challenging environment. Despite its initial success, the first-generation SENSWICH encountered specific challenges, including high power consumption, the need for two Arduinos to manage sensors, and sensitivity to electrical interference in saline environments. Also, its design needed some improvements to be more user-friendly. To overcome these limitations, the next generation of SENSWICH has been developed to address these issues comprehensively. The new version discussed in this paper uses one Arduino for managing sensors, lowers power consumption for better efficiency, and has a redesigned and more user-friendly shape with a new plastic cube-shape prototype. Furthermore, data collection has been optimized through the integration with Amazon Web Services (AWS), and Grafana enhances data visualization. Field-tested in the Venice Lagoon, the new SENSWICH demonstrates sustained monitoring capabilities, offering a good solution for coastal area observation.**

Index Terms—**WAN, IoT, LoRa, Sensor Networks, SENSWICH, AWS, Climate Change, Biodiversity**

I. Introduction

In our rapidly evolving world, climate change is considered as one of the most important challenges. Global warming affects all areas, but coastal regions are the most sensitive. These areas deal with increasing sea levels, more frequent seaquakes, and floods. Moreover, climate change and pollution also impact ecosystems in rivers, seas, and lakes, including important protected areas like Natura 2000 [1]. Climate change, a pressing global issue, is driving sea levels higher. This happens mainly because polar ice caps and glaciers are melting as global temperatures rise. The effects are serious: faster coastal erosion, lost land, and communities around the world face displacement. Moreover, the link between climate change and underwater earthquakes and floods is becoming clearer. Warmer ocean waters can weaken tectonic plates, increasing the chance of sea quakes. Moreover, increased temperatures contribute to heavier rainfall. Heavy rain and rising sea levels often lead to serious coastal flooding. Pollution makes climate change even worse, with industrial runoff and agricultural chemicals seeping into rivers and oceans. These pollutants harm sea life and add more pressure on coastal ecosystems. In response, the European Union introduced the European Biodiversity Strategy for 2030. This comprehensive plan aims to protect natural habitats, restore degraded ecosystems, weave biodiversity considerations into all policies, and face threats such as climate change. On a global scale, the United Nations designated 2021-2030 as the Decade of Ocean Science for Sustainable Development [2]. The aim is to enhance global collaboration in ocean science to better understand and address coastal challenges. Monitoring coastal systems is a complex task due to their dynamic nature. However, innovative technologies like intelligent sensors are now being deployed to monitor environmental parameters in real time, helping in the management and reduction of climate change and pollution effects. The Venice lagoon in Italy, known for its unique and complicated ecosystem, has been the focus of extensive research. This shallow, brackish water body, characterized by salt marshes and significant tidal variations, poses unique challenges for the monitoring of water conditions.

In 2023, SENSWICH was introduced as an affordable, real-time monitoring device designed specifically for the sensitive coastal ecosystems of the Venice Lagoon [3]. However, that initial study served as just a preliminary test. This paper marks an advancement as we have addressed the issue of electrical interference and transitioned from utilizing The Things Network (TTN) to the infrastructure of AWS (Amazon Web Services).

Additionally, we have also improved the data analysis framework by adding a visualization component. Now, with the integration of Grafana, our monitoring results are presented in a visually intuitive manner through dynamic graphical representations. This feature allows for simultaneous observation of multiple results on a single page, facilitating comprehensive analysis. Furthermore, users can also explore detailed sensor data and compare results over different periods, like a certain month versus the same month in previous years [4]. This feature greatly helps researchers access, store, and compare data over long periods. In subsequent sections, we are going into the structural enhancements implemented since the publication

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of the preceding paper. Our work is still ongoing, with future updates to SENSWICH aiming to add more user-friendly features and improve its durability in tough environments.

II. Related Works

In modern technology, the development of smart sensor buoys began in the early days of meteorological research [5]. These first devices were designed to closely observe atmospheric conditions at sea and quickly became crucial tools, providing valuable data on weather patterns and the changing climate. The evolution of smart sensor buoys grew alongside technological advancements. With each step forward, researchers found new ways to use these buoys, such as their important role in studying ocean currents [6]. This marked a significant shift in their utility, transcending the confines of meteorology to embrace broader horizons of scientific inquiry. Ocean currents play a key role in shaping the Earth's climate and distributing heat globally, greatly impacting weather systems. Understanding them has become essential for aims like improving maritime navigation and advancing climate change research. Smart sensor buoys were adapted to accurately measure the speed, direction, and depth of ocean currents, providing scientists with important data to create detailed current maps. This information not only improved navigation safety for ships but also enhanced our understanding of how currents affect marine ecosystems. Ocean observatories represent a network of strategically positioned marina systems outfitted with sophisticated sensor arrays capable of gauging an array of water parameters at diverse depths [7]. These observatories serve as gateways to previously inaccessible oceanic realms, facilitating the acquisition of invaluable data. Situated strategically, these observatories deploy smart sensor buoys equipped with a collection of sensors including Conductivity-Temperature-Depth (CTD) probes, Acoustic Doppler Current Profilers (ADCPs), fluorometers, and meteorological sensors. These sensors work together to gather crucial data for improving our understanding of the complex dynamics of the oceans and keeping track of the health of ecosystems. CTD probes meticulously evaluate seawater attributes such as salinity, temperature, and pressure, while ADCPs offer precise insights into ocean currents. Fluorometers are essential for detecting chlorophyll levels, helping to monitor phytoplankton populations. To ensure continuous data acquisition, these buoys are fortified with solar panels and robust batteries capable of storing in excess of 30 MJ of energy, imperative for powering onboard industrial-grade PCs and sustaining high-capacity communication systems [7]. In essence, keeping smart sensor buoys running in remote ocean areas is a major challenge.

The SubCULTron project, described in [8], marks a major change in exploring and understanding underwater environments by using a variety of underwater and surface sensors and vehicles. Engineered with precision and incorporating cost-effective acoustic modems and WiFi modules, these sensor systems possess the potential to redefine the landscape of coastal sensor networks. A noteworthy byproduct of the SubCULTron endeavor is the inception of H2ORobotics [9], a startup affiliated with the University of Zagreb. H2ORobotics has successfully transitioned some of the sensor systems devised in the project to the commercial sphere. Particularly commendable is their roll-out of a budget-conscious surface vehicle, marking a substantial leap forward in democratizing advanced underwater and surface sensor technologies on a global scale.

In previous MetroSea 2023, we introduced the SENSWICH device for real time monitoring of the Venice lagoon via LoRaWAN technology which could send the data to our cloud server [10]. This was a good beginning for monitoring coastal areas and important sea hotspots like the Venice lagoon. Now, we are showcasing the effectiveness of our efforts in real-world scenarios.

III. Structure

Using a method similar to the one described in the previous study [10], our experiment utilized a prototype with two wooden panels on either side of a central buoy. However, unlike the previous setup, we used a different board configuration. As shown in Figure 1, in this updated version of SENSWICH we used a printed circuit board (PCB) instead of breadboards, resulting in a more compact and user-friendly design. Furthermore, by integrating relays, we physically separated the electrical feedback signals, a critical choice especially pertinent in saline environments.

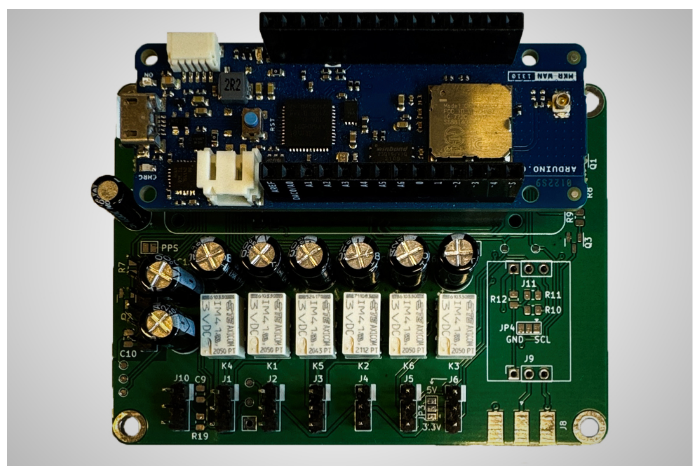

Fig. 1: PCB of the updated SENSWICH.

All sensors utilized in our study were procured from the DFRobot company. In contrast to the previous model presented at MetroSea 2023 [10], we removed the temporary GPS module for upcoming tests to conserve more power and extend the SENSWICH's operational time. We are currently developing an alternative method for localizing the SENSWICH without relying on GPS. Although GPS was not used in the tests described in this paper, the GPS section remains on the PCB, and is programmed via Arduino to be activated upon request by the operator. By sending the "gps" command through the cloud infrastructure, which in our case is AWS, the GPS can be activated. The resulting location data can then be visualized on the Grafana map (Figure 2).

Fig. 2: The location of the SENSWICH is mapped using GPS data and visualized in Grafana. In this case, the device is located in the Piovego River, Padova, Italy.

Given the dynamic conditions of our experimental setup, where water levels may vary and the sensors are in direct contact with water, ensuring their complete waterproofing was paramount. Consequently, in contrast to the previous investigation, we bolstered the waterproofing of the turbidity and temperature sensors following observations during testing that exposed their previous inadequacies in this regard. While the material composition facilitates buoyancy, enabling the structure to float effortlessly on water, it still exhibits limited compatibility with high waves. We explored potential structural modifications for SENSWICH to address this limitation. For the first step, we will continue with a new prototype, which is made from floating plastic for the main structure, and PSV for the sensor shelf and top cover. A detailed discussion on the new structure will be included in further investigations.

A. Measuring Process

When booted, the program running in the Arduino board kicks off by inspecting the isolation circuit, ensuring that the relays are operating correctly. Following this, the system shifts into calibration mode to confirm whether all sensors are calibrated. If any sensors are not calibrated, the system initiates calibration using a serial monitor from development tools like Arduino IDE or Microsoft Visual Studio with the Arduino extension. Should calibration be skipped, the system moves straight to the sensors acquisition procedure. In operation, the system reads data sequentially from the sensors, gathers this data, and encodes it using the CayenneLPP structure. This method ensures efficient transmission with minimal payload. The encoded data is then transmitted via LoRaWAN communication to the gateway, where it can be visualized using Grafana. Once this step is complete, the Arduino enters a deep sleep mode for ten minutes before the cycle starts again.

As we mentioned before, when utilizing GPS, as shown in Figure 2, a request can be made through a button on the Grafana web page. Pressing this button sends a "gps" string message to the Arduino as a downlink message. In the next data packet, the latitude and longitude of the SENSWICH location can be retrieved.

IV. Test Setup

Fig. 3: Setup of sensors in a bucket.

For testing purposes, all sensors were placed in a bucket filled with saline solution, as illustrated in Figure 3. The data collected from the sensors, using the Arduino MKR WAN and the SENSWICH circuit, was transmitted via LoRaWAN to the Gateway, which is connected to the AWS cloud infrastructure. To measure energy consumption, a regulator was initially used to supply 5.25 V as the input voltage to the Arduino. Table I provides a detailed summary of power consumption during different sensor phases, helping to identify the energy usage patterns of the Arduino MKRWAN 1310 in each phase.

TABLE I: Energy Consumption Using a Regulator

Phase	Duration (s)	Current (mA)	Energy (J)
pH	80	18.2	12.37
pH + TB	10	30	2.55
Analog Reading	5.12	39	1.69
DO	80	16.5	11.22
DO + LV	10	26.1	2.21
Analog Reading	5.12	35	1.52
EC	20	24.7	4.19
Analog Reading	5.12	33.9	1.47
LoRa TX	2	41.8	0.71
Standby	382.64	15.7	51.06

We can infer that Table II illustrates power consumption measurements based on information gathered from Table I. The current is measured directly at the battery terminals, thus the discharge time estimate takes into account the quiescent power consumption of the DC-DC regulator.

TABLE II: Power Consumption Using a Regulator

Parameter	Value
Idle power (mW)	133.45
Energy/sample (mWh)	24.73
Average current (mA)	17.45
Average power (mW)	148.38
Discharge time (h)	733.20
Discharge time (days)	30.55

This indicates that the device may remain active for one month with a single battery charge. Table III shows the energy consumption assuming a 100% efficient converter from battery voltage to 5.25 V, and Table IV illustrates power consumption measurements based on information from Table III. These values are estimated by measuring the current at the output of the regulator, which includes only the active currents of the various components, and are thus indicative of the system's minimum possible power consumption.

TABLE III: Estimation of Energy Consumption Without a Regulator

Phase	Duration (s)	Current (mA)	Energy (J)
PH	80	12.4	5.208
PH+TB	10	26.5	1.39
Analog Reading	5.12	38.2	1.02
DO	80	10.2	4.28
DO+LV	10	21.7	1.13
Analog Reading	5.12	33.2	0.89
EC	20	17	1.78
Analog Reading	5.12	28	0.75
LoRa TX	2	38	0.39
Standby	382.64	9.3	18.68

TABLE IV: Estimation of Power Consumption Without a Regulator

Idle power (mW)	48.82
Energy/sample (mWh)	9.87
Average current (mA)	11.28
Average power (mW)	59.267
Discharge time (h)	1552.27
Discharge time (days)	64.67

These results indicate that the device can remain operational for approximately 64 days on a single charge. However, they also reveal that the voltage regulator is inefficient, wasting nearly half of the available energy. Additionally, the standby current of the Arduino can be significantly reduced by removing the onboard LEDs used for status indication, which would further extend the battery life.

As we mentioned before, given the effectiveness of the developed prototype, we have recently created the first SENSWICH PCB to facilitate the rapid production of additional units. The first PCB shown in Figure 1 was used in our tests. We deployed SENSWICH in the Piovego Canal for two weeks (Figure 4a) during the first half of May 2024, and subsequently for fifty days from mid-May in Chioggia (Figure 4b), near the Hydrobiological Station Umberto D'Ancona in the Venice Lagoon. The SENSWICH ran out of battery in the second week of July 2024. However, the current system's limitations are not related to power consumption or data transmission to the cloud via the LoRaWAN network. Instead, the main issue is the need for weekly sensor cleaning to ensure accurate data collection due to high bio-fouling activity during this time of the year. In winter, we expect cleaning to be less frequent (e.g., once a month or less) as bio-fouling will significantly decrease due to colder temperatures. In the meantime, we aim to reduce the bio-fouling effect by covering the sensors with a copper net, a material known for its natural anti-fouling properties [11].[1]

V. Results

We utilized Grafana to integrate and display data from various sensors simultaneously, as shown in Figure 5. As an

[1]This solution will require careful testing to ensure that copper does not affect the sensor measurements or the organisms being studied.

(a) Piovego Canal (b) Chioggia

Fig. 4: Deployment in Padova, in the Piovego Canal (a), and in the Venice Lagoon, in Chioggia (b).

example, in the picture we can observe the data collected from all sensors (and sent through LoRaWAN to the AWS server) over a period spanning from May 6, 2024, to May 10, 2024 in the Piovego Canal in Padova. To provide clearer visualizations, we extracted the .csv files for each sensor, containing the data for that period, from Grafana's panel. These were subsequently plotted using a Python script. From a biological standpoint, temperature and dissolved oxygen (DO) levels are interrelated, as demonstrated in Figure 6, which shows their correlation.

In our experiments, we expected that increasing temperatures would typically result in a reduction in DO levels. However, this expectation did not account for the influence of another environmental factor, i.e., photosynthesis. During the day, sunlight triggers photosynthesis, an instantaneous process [12], which leads to an increase in oxygen dissolved in the water. This significantly affects DO levels during daylight hours. Moreover, although temperature and DO levels follow a similar pattern, the rise in temperature is slightly delayed compared to the increase in DO levels. This is due to the fact that water temperature rises more slowly than the rapid response of photosynthesis to sunlight.

Regarding the Liquid Level sensor, this digital device indicates whether the SENSWICH was submerged in water at a given time. If data was received while the Liquid Level sensor indicated "false," it suggests that the data from the other sensors may not be reliable. To illustrate the Liquid Level sensor's results, we considered data from a few hours before and after the SENSWICH was submerged, highlighting the differences between the readings inside and outside the water, as shown in Figure 7.

Figure 8 presents the results from the pH sensor, Figure 9 shows data from the Electrical Conductivity sensor, and Figure 10 displays the results of the Turbidity sensor. The fluctuations in the turbidity plot are due to small particles becoming lodged between the plastic head of the sensor. Since it is an optical sensor, even minor obstructions can influence the measurements. Once these particles were naturally dislodged by the water current, the measurements returned to accurate values. As previously mentioned, we expect this issue to be mitigated by applying a copper cover to the sensor in future versions of the SENSWICH platform. Optionally, in Grafana, turbidity can be displayed in NTU by converting voltage values to NTU units using the following equation [13]:

$$y = -1120.4x^2 + 5742.3x - 4352.9,$$

where y represents turbidity in NTU units, and x represents the voltage in volts.

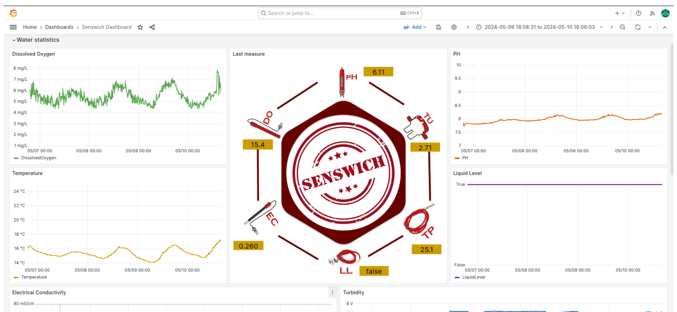

Fig. 5: Visualization in Grafana.

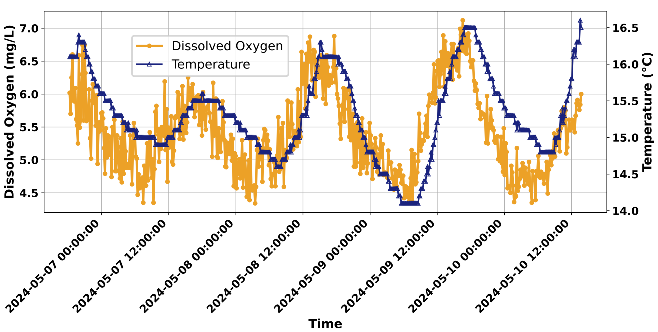

Fig. 6: Comparison of Dissolved Oxygen (DO) and Temperature sensor measurements.

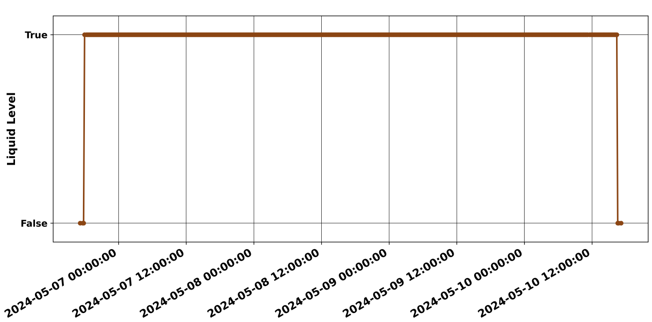

Fig. 7: Results from the Liquid Level sensor measurement experiment.

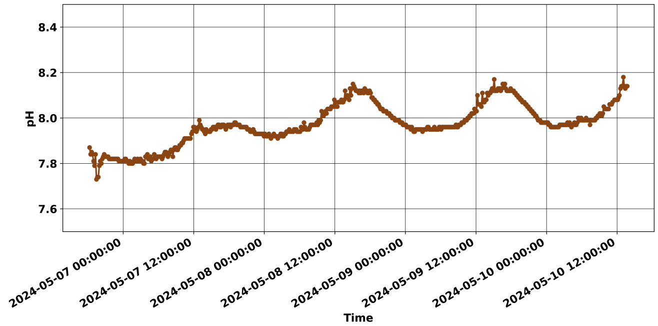

Fig. 8: Results from the pH sensor measurement experiment.

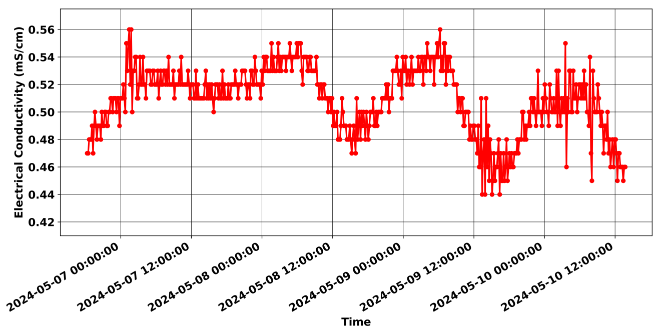

Fig. 9: Results from the Electrical Conductivity (EC) sensor measurement experiment.

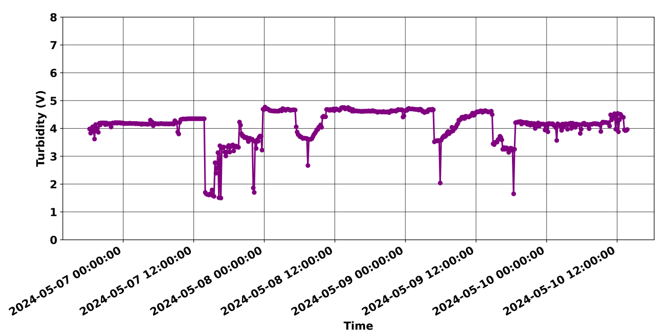

Fig. 10: Results from the Turbidity sensor measurement experiment.

VI. Conclusion and Future Work

The methods we implemented to enhance the IoT cloud infrastructure have simplified both our current tests and future testing processes. We can see that the combination of AWS and Grafana proves to be a powerful solution, providing researchers with a comprehensive, real-time view of data collected from the SENSWICH surface device. The data analysis shows consistent sensor performance over consecutive days, confirming the sensors' reliability. There are considerations for upgrading certain sensors, such as the electrical conductivity sensor, for improved results. Additionally, redesigning the SENSWICH floating case is being considered, aiming for enhanced water stability and resistance to strong winds and sea storms, while maintaining the previous configuration for river and open sea tests [10]. The device's affordability, costing less than a thousand US dollars, makes it a cost-effective alternative to other measuring buoys. Focus is now shifting toward further investigation and the production of more SENSWICH units. Future plans also include analyzing data from deployments in the Venice Lagoon and expanding the use of SENSWICH platforms.

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