A smart ocean observation system for reliable real-time measurements

1st Camilla Saetre
Department of Physics and Technology
University of Bergen
Bergen, Norway
camilla.satre@uib.no

2nd Astrid Marie Skålvik
Department of Physics and Technology
University of Bergen
Bergen, Norway
astrid.skalvik@uib.no

3rd Kjell-Eivind Frøysa
Dept. of Computer Science, Electrical Engineering and Mathematical Sciences
Western Norway University of Applied Sciences
Bergen, Norway
kjell.eivind.froysa@hvl.no

4th Marie Bueie Holstad
NORCE Norwegian Research Center
Bergen, Norway
maho@norceresearch.no

***Abstract*—This paper presents a research and innovation centre for a smart ocean observation system. The main goal of the centre, SFI Smart Ocean, is to enable sustainable ocean management through real-time measurements from autonomous and smart sensors. As for smart systems on-land, a smart ocean observation system of sensors requires wireless communication and a software platform gathering all required data. To ensure usability in real-time, minimize maintenance costs, and time-consuming delayed mode data analysis, it is paramount to ensure high reliability of the system. This can be achieved by online quality control, self-diagnostics, and self-calibration at the sensors.**

***Index Terms*—Ocean observation system, Smart sensor network, Internet of Underwater Things, Sensor reliability, Sensor diagnostics**

I. INTRODUCTION

Ocean observations have a long history with oceanographic measurements from ship, floating platforms like stationary buoys or ARGO floats, cabled observation systems on the seabed, and remote sensing by satellites, to mention the most common. Underwater measurements for marine industry operations have traditionally been cabled systems, where installation costs and the environmental footprint are significant causing limited sensor coverage. The observations are essential for knowledge-based ocean management, both for a sustainable marine environment and ecology, and for sustainable ocean industry operations. However, ocean instrumentation is costly and can be quite time-consuming both on gathering and interpreting the observation parameters. The development seen the last decade on smart sensor technology can be utilized also in the ocean, and OECD listed some of the possibilities for marine economic growth in their report [1]: "...the drive for miniaturization and automation, the growing demand for low-power, low-cost devices for the measurement and graphic display of the physical environment, and moves to endow the sensor itself with intelligence". European research strategy states: "Strengthening observation and monitoring capacities through enabling technologies, new platforms and sensors; addressing under-sampling, and ensuring that new environmental parameters can be rapidly and accurately measured" [2]. Internet of Underwater Things (IoUT), a marine version of the more known Internet of Things (IoT), addresses these topics of automation, low-power, low-cost, and smart sensors [3, 4]. The key enabling elements for IoUT are automated and smart devices connected through wireless communication and a common data acquisition and data handling platform, enabling data fusion and machine learning.

This paper provides a presentation of the existing and planned smart ocean observation system and the measurement strategies to ensure trustworthy data for reliable decision support, with focus on the sensor network for environmental marine measurements at the coast of Austevoll, Norway.

II. A SMART OCEAN OBSERVATION SYSTEM

SFI Smart Ocean is a centre for research-based innovation to enhance the ability of industry innovation and value creation through a greater focus on long-term research. The centre is hosted by the University of Bergen and consists of 20 partners from industry, public management, and research. It is partly funded by the Research Council of Norway, and the centre period is from 2020 to 2028. End users for the smart sensor network cover general ocean industries and ocean management, petroleum, offshore wind renewable energy, aquaculture, and marine science. Figure 1 illustrates the concept and lists the areas of application. The centre aims to enable Internet of Underwater Things by (i) autonomous smart sensors with onboard data processing and two-way wireless communication, (ii) modular-based sensor platforms with non-vendor specific wireless communication systems, (iii) anti-biofouling nano treatment, (iv) data storage in cloud, automated data

---

This work is part of the SFI Smart Ocean, a Centre for Research-based Innovation, funded by the end user partners in the Centre and the Research Council of Norway (project no. 309612).

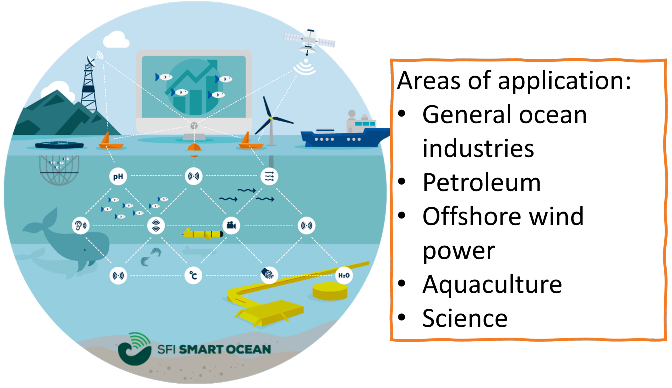

Fig. 1. The goal of SFI Smart Ocean is to develop a smart and wireless underwater sensor network, for the benefit of science and industry.

analysis, non-vendor specific data formats, and (v) data quality assurance and machine learning. The partnership facilitates active and long-term cooperation between innovation oriented industries and research groups, and encourages researcher training and transfer of knowledge and technology across marine areas with potential for great future value creation.

The main goal of SFI Smart Ocean is to enable sustainable ocean management through real-time measurements from autonomous, smart sensors. The sensors include both different oceanographic and geophysical instruments measuring environmental parameters, and instruments for measuring structural integrity of subsea installations and leakage detection. The observation system includes a data architecture for gathering of data from different sensors in the network, cloud-based ocean data services, and data management across the entire network, edge to cloud. The research and innovation focus is on creating a scalable and modular system where different types of sensors can communicate in an acoustic wireless network. The data is gathered and stored in existing databases like the Norwegian Marine Data Centre (NMDC), a data infrastructure for marine data in Norway [5].

Autonomous and smart sensors for a marine observation system require research and development of on-board data processing at the sensor or network edge, compatibility with underwater modem and communication protocols, automated and real-time data quality control, automated self check (validation and diagnostics), smart operation for energy saving, and the ability of adjustable sampling and threshold settings. The research challenges for underwater wireless communication is for the scope of SFI Smart Ocean focused on acoustic communication, mesh network capabilities, modem compatibility, modem and transmission reliability, and energy efficient and robust communication protocols [6]. It is also of high importance to ensure a minimal environmental impact of acoustic underwater communication, ensuring sustainable development of a smart marine network not affecting life underwater in a negative way. Studies of the environmental footprint of acoustic communication have been performed by partners in the centre [7] and [8].

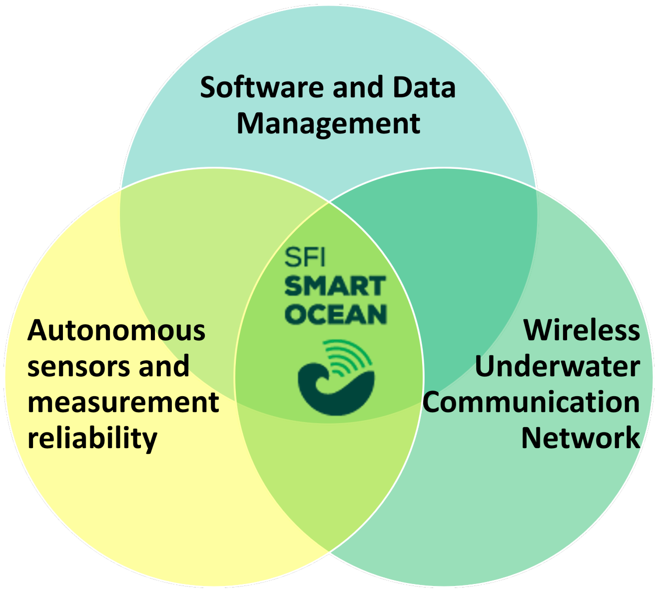

Fig. 2. Research areas to enable a smart ocean wireless sensor network.

Research and development related to software and data handling include system design with input from different sources of sensors, models or other available data. Data can be from data providers' systems, underwater sensor network (edge), or external data services. The software platform consists of data, messaging, and edge integration services, in addition to authorisation and authentication services. The data consumers get the output data from the software platform, for example in form of an information and decision support service, or data as input to existing dashboards for operation. The bottleneck of the smart ocean network is the underwater acoustic communication, requiring more data analysis and processing at the edge (sensor-side) of the network compared to similar smart systems on land. Hence, it is the collaboration between the three research areas of software, sensor technology, and communication that will enable value creation and innovation in easier accessible marine measurements and decision support (see Figure 2).

III. Existing and Planned Test Facilities

The components of the system, that is the sensor technologies, the communication network, and the software, will be tested in pilot demonstrators. One of these test facilities are located at the coast of Austevoll, Norway, where sensors for environmental monitoring are deployed. The equipment tested are among others a Seaguard Data processing Unit from Aanderaa Data Instruments, equipped with sensors for temperature, oxygen concentration, salinity, turbidity, pressure, and current profilers. The local environmental testing area of Austevoll is connected to existing infrastructure for aquaculture and marine research testing of the Institute of Marine Research [9]. The equipment under test is mounted close to the existing facilities of the test station, enabling cabled or GSM-modem communication for reference, in addition to the

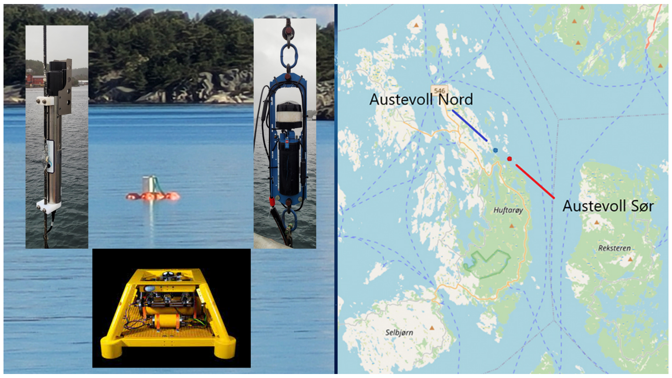

Fig. 3. Pilot demonstrator for environmental oceanographic monitoring at the coast of Austevoll, Norway. The Seaguard and Seabird were deployed i 2022, and the bottom lander is scheduled for deployment in 2023.

acoustic underwater communication network under test. Two rigs are operational, and a third rig is planned during 2023. Figure 3 shows the sensor platforms and location of the initial two moorings.

For mesoscale marine observations, there is planned for a High Arctic Ocean Observation System (HiAOOS), with the objecvtive of developing a nested multipurpose acoustic network of underwater positioning system, wireless communication (acoustic and inductive), and mesoscale acoustic tomography measurements [10]. SFI Smart Ocean will collaborate with HiAOOS with testing of equipment. The observation system will be located north of Svalbard and provide under-ice measurements and communication tests.

One of the applications of the smart sensor network, is integrity monitoring for offshore wind and for petroleum. The focus for the testing of the sensors and wireless communication modules includes load measurements (wave and currents) and grouting integrity (concrete fillings behind steel plates) by existing acoustic scanning technology and novel guided ultrasonic technology. The reasoning for wireless communication and smart sensors for this application is to ensure reliability in splash zones and on moving parts. There are intentions of collaboration between SFI Smart Ocean and the Norwegian hub METCENTRE, a marine energy test centre located at the west coast of Norway [11]. Here there are possibilities of tests at and around offshore wind turbines.

IV. ENSURING RELIABLE REAL-TIME OBSERVATIONS

An important part of the research in the centre is to ensure reliable measurements. In addition to research on novel sensor technologies and anti-biofouling, there are research tasks for automated near real-time quality control, self-diagnostics, and self-calibration. The goal is to reduce the measurement uncertainty in long term subsea operations. The on-line quality control will also provide valuable metadata for the final data analysis, enabling early identification of suspicious or bad data. The measured data should, however, not be eliminated from the collected data series. As different users may find different characteristics of the measured data useful, data labelled as suspicious or bad should still be saved. Measurements that appear as noise or spikes to some, could provide valuable information to others.

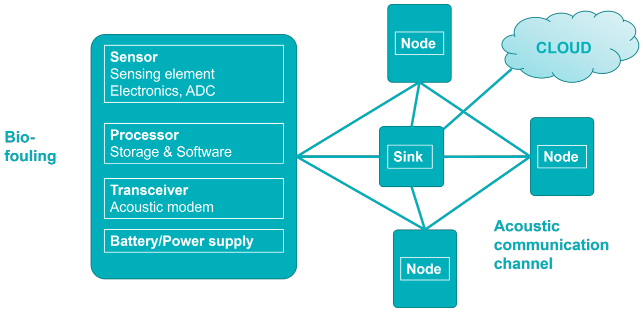

Fig. 4. Illustration of the components inside sensor nodes subject to errors and drift, external influence of biofouling, underwater acoustic communication, and above water communication and data processing to cloud storage.

Measurement strategies to ensure optimal operation are also essential, including optimal measurement layout. This includes modelling of how the measurement uncertainty propagates from the sensors in the sensor network, through the underwater acoustic communication network, to the data storage and analysis software. In a network of sensors, one may also utilize redundant or correlated measurements to enhance the reliability. Figure 4 illustrates the configuration of a smart underwater sensor network. The sensor nodes each include components subject to increased measurement uncertainty or errors, such as the sensing element itself, sensor electronics and processing unit, power supply, and modem. In addition, there are external parameters which can affect the measurement reliability, illustrated here by bio-fouling, however, other external issues can also cause reduced accuracy. Another aspect of measurement uncertainty is how representative the measurements are for the specific measurand (the parameter one measures). This could be increased uncertainty related to sampling technique, sampling interval, or non-homogeneity of the measurand. Oxygen measurements from a calibrated and accurate sensor can for example measure an oxygen concentration that is only valid for the close proximity of the sensor but not for the water masses intended to be measured. For example, the oxygen levels close to the sensor could be different from the surroundings due to sacrificial anode corrosion [12] or bio-fouling at the sensor equipment consuming the nearby oxygen [13].

The research questions we address are (i) can we develop generic sensor self-calibration and self-diagnostic properties for uncertainty reduction in long term subsea operations, and (ii) can we develop a generic methodology for optimization of measurement lay-out with respect to low uncertainty of selected output measurement parameters.

A. Automatic real-time quality control

Quality control (QC) of marine data can be vendor specific or can be based on best practise. For oceanographic measurements there are different initiatives on common data quality control, for example Ocean Best Practice Systems [14], Global Temperature and Salinity Profile Programme Real-Time Quality Control Manual [15], Argo Quality Control Manual for CTD and Trajectory Data [16], and QARTOD Manual for Real-Time Quality Control [17]. Quality control in this context is to check if there are missing data points, frozen values, non-physical values outside set thresholds, and outliers/spikes. Quality control can also include multi parameter comparisons, however to our knowledge this is not yet established in Real-Time quality control.

For real-time automated quality control there are different possibilities. One can apply machine learning on data stored in the cloud or at the network edge (sensor) if sufficient computational capacity and memory. Since power, communication, and computational power often are limited resources in a marine sensor network, our research focus includes automated simplified statistical methods for edge (sensor) data QC. Skålvik et al [18] describes this methodology for a data set of deep sea oceanographic data. As [18] demonstrates, a first and important part of setting up algorithms for sensor data QC is to identify external and internal factors which may influence the measurements, and evaluate the expected effect on the sensor signal. This process must be carried out for each involved sensor technology. Thresholds and other test parameters must then be tuned to take into account the expected natural or real variability of the environmental parameters.

Continued research on real-time QC includes testing these algorithms on oceanographic data for coastal and more shallow water (unpublished) [19]. Bio-fouling may cause sensor malfunction or drift in sensing signal, depending on how sensitive the sensor technology is to the bio-fouling. The basic QC procedures can include check for failure due to bio-fouling, for example if the measurements fall below a set threshold.

B. *Self-diagnostics*

Where quality control is related to checking the measured values from a sensor or a set of sensors, self-diagnostics are the sensor or sensor network ability to investigate if the measurement system is reliable. This can for example be regular monitoring of the battery power level, or checking if a measurement parameter like speed of sound is within expected thresholds or in line with a calculation of the same parameter from correlated measurements. For some measurement systems, like ultrasonic flow meters with several transmitting and receiving elements, the relative signal strength between the measurements form a ”fingerprint” of the meter which can be used as on-line diagnostics [20]. Both QC and self-diagnostics can flag the measurements as more or less reliable, in the sense that there are found no indication from the measurements and instruments themselves that there are any errors. A standardized system for data flagging and quality-related metadata is however not straight forward, as there are different best practises but no international standards or cross-disciplinary recommendations.

C. *Self-calibration*

Self-diagnostics and QC are used for error detection, but not for correcting or adjusting sensor readings for drift between calibrations. A highly reliable measurement system is a system with low measurement uncertainty. The different sensors have specified uncertainty based on initial calibrations fulfilling a traceability chain. However, when the sensors are deployed in the ocean there are numerous factors affecting the measurement uncertainty during operation and among others lead to sensor drift. Drift is when the sensing element or electronics gradually deviate from the original calibrated state. It is difficult to detect drift in measurements based on the measurements alone, since the gradual changes can be due to real changes in the measurement parameter. One method for automated real-time detection of drift is self-calibration. This could be zero check, where the sensor is able to shield the sensing element and the electronics providing a check of measuring nothing (zero). Self-calibration can also be by use of a known reference within or close to the sensor system, for example for oxygen optode sensors the illumination of the sensing foil using red light will provide a known reference [13]. Sensors mounted on ARGO floats can automatically calibrate when the float reaches the sea surface and measurements are done in air and at atmospheric pressure (Bittig et al. 2018, Bittig and Kortzinger, 2015, Johnson et al., 2015, Nicholson and Feen, 2017, cited in [18]). Another example of self-calibration is for acoustic echo sounders for leak detection. Here a metal sphere at a known distance from the instrument will provide a known acoustic echo pattern [21].

In a sensor network one can also utilize redundant or correlated measurements, for example multiple measurements of temperature from different sensors. Especially if the measurement principles are different, this can increase the redundancy and hence the reliability of the system. Similar sensors might experience the same drift, but a comparison will be able to detect if one or some of the sensors are malfunctioning.

D. *Uncertainty propagation in subsea wireless sensor networks*

As shown from the examples listed above, the self-calibration and often also self-diagnostic techniques are tailor-made for the specific sensing technology. To ensure reliability and end-user trust in the data, the measurement accuracy should be traceable from the sensor to the end user. Uncertainty propagation in a subsea wireless sensor network is part of the planned research tasks. In addition to the uncertainty at the sensor, there is uncertainty in the on-line data processing at the network edge, uncertainty of the underwater acoustic communication (for example missing data points in a measurement time series), and uncertainty of the data models and additional input data at the software platform level (cloud level).

V. SUMMARY

This paper presented the ongoing and planned work in SFI Smart Ocean innovation centre. Reliable real-time marine measurements enable better decision support and science through the combination of sensor technology, underwater wireless communication, and a common software platform. The system is modular based and scalable for use in different marine environments and for different end users. The research and development on these modules are demonstrated continuously at pilot demonstrators, the initial and most comprehensive test facility located at the coast of Austevoll, Norway. High reliability of the system is a key requirement, and self-diagnostics, self-calibration, and automated near real-time data quality control are important research topics in the centre.

Future plans of the centre include more testing facilities and collaboration with other research projects.

ACKNOWLEDGMENT

We thank the partners in SFI Smart Ocean: Aanderaa Data Instruments AS, Aker BP, Bouvet, Kongsberg Maritime, Metas, Reach Subsea, Tampnet Inc, TSC Subsea, W-sense AS, GCE Ocean Technology, GCE NODE, NCE Seafood Innovation, the Norwegian Directorate of Fisheries, the Norwegian Petroleum Safety Authoroty, Institute of Marine Research, Norwegian Defence Research Establishment, Nansen Environmental and Remote Sensing Center, and co-researchers at Western Norway University of Applied Sciences, NORCE, and the University of Bergen.

REFERENCES

[1] OECD, The Ocean Economy in 2030, OECD Publishing, Paris, 2016, https://doi.org/10.1787/9789264251724-en

[2] JPI Oceans Strategic Research and Innovation Agenda 2015-2020 Programming Initiative Healthy and Productive Seas and Oceans, Brussels, 2015.

[3] M. Jahanbakht, W. Xiang, L. Hanzo and M. R. Azghadi, ”Internet of underwater things and big marine data analytics—a comprehensive survey”. IEEE Communications Surveys and Tutorials, 23(2), 904-956, 2021

[4] T. Qiu, Z. Zhao, T. Zhang, C. Chen and C. L. P. Chen, ”Underwater Internet of Things in Smart Ocean: System Architecture and Open Issues,” in IEEE Transactions on Industrial Informatics, vol. 16, no. 7, pp. 4297-4307, July 2020, doi: 10.1109/TII.2019.2946618

[5] The Norwegian Marine Data Centre (NMDC), https://nmdc.no/nmdc

[6] A.-L. Kampen and R. Otnes, “MAC and Network Layer Solutions for Underwater Wireless Sensor Networks,“ International Journal on Advances in Networks and Services, Volume 15, Number 1 and 2, 2022.

[7] B. Tomasi et al., ”Environmental risk assessment of an underwater acoustic mobile network,” 2022 Sixth Underwater Communications and Networking Conference (UComms), Lerici, Italy, 2022, pp. 1-5, doi: 10.1109/UComms56954.2022.9905696.

[8] Lise Sivle Doksæter, Institute of Marine Research, internal report, ”Smart Ocean: Does the modems acoustics interfere with marine life?”, 2022

[9] Institute of Marine Research, Norway, Austevoll Research Station, https://www.hi.no/en/hi/laboratories/austevoll-research-station

[10] HiAOOS: High Arctic Ocean Observation System, https://www.polarcluster.eu/members/arctic/hiaaos-high-arctic-ocean-observation-system

[11] METCENTRE, Marine Energy Test Centre, Norway, metcentre.no

[12] N. Lo Bue, A. Vangriesheim, A. Khripounoff and T. Soltwedel (2011) Anomalies of oxygen measurements performed with Aanderaa optodes, Journal of Operational Oceanography, 4:2, 29-39, DOI: 10.1080/1755876X.2011.11020125

[13] A. Tengberg et al. (2006), Evaluation of a lifetime-based optode to measure oxygen in aquatic systems, Limnol. Oceanogr. Methods, 4, doi:10.4319/lom.2006.4.7.

[14] Pearlman, J., Bushnell, M., Coppola, L., Karstensen, J., Buttigieg, P.L., Pearlman, F., et al. (2019). Evolving and Sustaining Ocean Best Practices and Standards for the Next Decade. Frontiers in Marine Science 6. doi: 10.3389/fmars.2019.00277.

[15] GTSPP Real-Time Quality Control Manual, First Revised Edition. UNESCO-IOC 2010. (IOC Manuals and Guides No. 22, Revised Edition.) (IOC/2010/MG/22Rev.)

[16] Wong, A.K., R., Carval, T. and the Argo Data Management Team. 2022. Argo Quality Control Manual for CTD and Trajectory Data.

[17] U.S. Integrated Ocean Observing System (2020). ”QARTOD - Prospects for Real-Time Quality Control Manuals, How to Create Them, and a Vision for Advanced Implementation”. U.S. Integrated Ocean Observing System.

[18] Skålvik AM, Saetre C, Frøysa K-E, Bjørk RN and Tengberg A (2023) Challenges, limitations, and measurement strategies to ensure data quality in deep-sea sensors. Front. Mar. Sci. 10:1152236. doi: 10.3389/fmars.2023.1152236

[19] Skålvik AM, Tengberg A, Froysa K-E, Bjork RN and Saetre C, ”Automatic near real-time quality control tests for biofouling effect on measurement data”, OCEANS23, Limerick, (submitted) 2023

[20] ISO 17089-1:2019(E), ”Measurement of fluid flow in closed conduits – Ultrasonic meters for gas – Part 1: Meters for custody transfer and allocation measurement”, 2019

[21] Demer, D.A., Berger, L., Bernasconi, M., Bethke, E., Boswell, K., Chu, D., Domokos, R., Dunford, A., Fässler, S., Gauthier, S. and Hufnagle, L.T. 2015. Calibration of acoustic instruments. ICES Cooperative Research Report No. 326. 133 pp.