Data-collection, - processing and status monitoring manual

D5.3

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Table of Contents

Table of Tables

Table of Figures

Executive summary

This report considers the outline of a remote monitoring system for a floating island configuration. The objective of the system is to facilitate O&M operations and enable validation of design models as used to dimension floater modules, moorings and the inter connectors. The focus is only on the island infra structure and not on the payload superstructure.

The challenge for O&M monitoring was explained by the Endsley model that describes control of a process characterised by a “state” as stages for perception (measuring), comprehension (what does it mean), projection (what will happen in the future) , decision and control.

The functional requirements of the monitoring system were thus related to: The external influences or stressors affecting the island in terms of wind, waves, current and traffic; The stationary (and adjustable) condition of the island in terms of mooring loads and ballast conditions; the dynamic response of the island in terms of motions, mooring and connector dynamics, and structure loads in the floaters; the structure condition of the island and mooring arrangement in terms of fatigue consumption, integrity, and marine growth and; the effect of the island itself on the surrounding marine environment.

The key in collecting and conveying relevant information is not to just measure everything but to convert relevant observed “data” into “information”. Data can refer to pretty much everything e.g. measured time series, camera pictures, video footage, sound recordings and even hand written inspection notes. Information on the other hand is more easily digestible. For O&M application in particular it should allow for comparison and correlation. ISO guidelines on metrology refer to the “quantity” concept. Each quantity should have a quantitative value in combination with a reference unit. Approaches were highlighted to obtain quantitative indicators for each of the functional requirements above. These were based on either: Direct readings from measuring instruments or combinations of instruments, machine learning in combination with image processing from fixed (underwater) camera or ROV/UUV camera footage or from combination of measured data with numerical models. Options were listed for each functional requirement so in principal all O&M monitoring requirements can be met.

With respect to an implementation it was referred to the classic Process Control and Automation industry. Classic plant solutions as in use in industry for past 40 years can be used in theory as well on floating islands. These systems comprise of a data collection layer (DCS), an operator open loop feedback and control layer (SCADA) and closed loop Alarm and emergency shutdown services (CAMS and ESD). Straight forward application of this concept on a floating island however would raise practical issues. Interconnecting sensors and measuring devices across floaters is difficult as the modular concept of the floaters makes it unlikely that monitoring systems per floater will be “de facto” compatible. Separate DCS systems are thus expected for each separate floater that have to be able to communicate downstream to a central SCADA layer. The multitude of sensors that may be connected to the various floater DCS systems impose big challenges to the SCADA layer. It will be very unclear what parameters need to be visualised and against which criteria and boundaries they should be evaluated.

Instead of the classic SCADA approach that provides control feedback based on measured data from individual sensors, it is thus proposed to represent the relevant state of the floating island in a digital twin model that is updated using all relevant connected sensors and use the SCADA layer to provide a principal view on the digital twin. Several challenges are identified in this aspect. The first is the compatibility of classic DCS and SCADA systems with the technology that is being considered with Digital Twins. There is a standardisation challenge in using DCS sensor data from truly modular floaters from various manufacturers with possibly different makes of DCS systems. An open communication standard is needed to interconnect the DCS systems with the central SCADA layer and the Digital Twin model. A second challenge is the outline and implementation of the Digital Twin itself. It is challenging to represent global behaviour of the floating island by data fusion of connected sensor data along with sensor fault suppression, numerical characteristics from structural FE type calculations, hydro mechanical and CFD tools. Direct approaches and machine learning type of approaches are being developed in the academic world at the moment. More mature and validated multi body dynamics algorithms need to become available in in the near future. This is of interest as well in other industrial fields (e.g. cargo dynamics on container ships) so it is recommended that further research is spent in this field in the coming years.

1 Introduction

1.1 O&M - remote monitoring

Operating and Maintenance efforts are aimed at operating a structure to perform its intended tasks and making sure that it stays in proper condition to keep doing so. Feedback from the structure to its operators is required to coordinate ongoing procedures, and to monitor structural health in order to schedule preventive or corrective maintenance. On smaller structures this feedback can often be done with visual inspections and a limited scope of monitored parameters. Visual feedback becomes unpractical for larger and complex structures which is why these structures typically rely on automated monitoring systems. This report addresses specific considerations with respect to monitoring and in particular "remote" monitoring on large floating modular structures. The contents include:

- Monitoring systems in general
    - Overview of ISO standards on metrology and taking the right measurements.
    - Monitoring systems in Process Control and Automation technology.
    - Developments that are taking place in monitoring and related technology at this moment
- The floating island monitoring challenge
    - Infrastructural difference between a floating island and a single plant configuration
    - Aspects of floating islands to be included in a (remote) monitoring regime
    - Operator feedback, digital twin, closed loop alarms,
    - Requirements on data sharing infrastructure to accommodate the flow of "data" from the individual modules across the entire island configuration.
    - Considerations with respect to "remote" monitoring of listed parameters.
- The monitoring system
    - Type of sensors and systems needed to capture data on listed aspects
    - Types of information and data to be anticipated from these sensors
    - Considerations with respect to quality insurance of collected information and data aggregation to minimise bandwidth of data flow, and maximise efficiency of data processing infrastructure on the island

1.2 Reading guide

The first content chapter of this report (chapter 2) reviews the basics of monitoring. It starts off with the ISO defined principals and semantics of a single "measurement" and principal requirements to a generic "measurement system". chapter 2 continues with an overview of the process control and automation field of technology that provides monitoring and control systems to all sorts of industrial plants since many decades. The principal outline and semantics of classic industrial monitoring and control systems is reviewed along with technical developments and innovations that are occurring now in the field, and the role of statutory requirements and rules with respect to monitoring systems in industrial systems.

Chapter 3 is focused on generic monitoring system requirements for a floating island. Monitoring systems are common on modern ships and offshore structures. These are designed generally as monolithic systems with a specific objective related to the type of vessel and its mission. The basic design concept of what is measured, how that data is handled, distributed and stored, and how it is processed and presented to operators is usually fixed. A floating island may be comprised of dozens of individual modules. If the modules are supposed to be truly modular, then the data collection and monitoring systems should also have the intrinsic ability to be scalable, interconnect, exchange relevant measured parameters and facilitate evolving processing algorithms and operator views. Functional requirements to the monitoring system are reviewed, along with the impact of multi modular floating island configurations on the topology of a monitoring system, and the specific impact of floating island installations on the DCS, SCADA and CAMS and ESD layers.

In Chapter 4 the attention shifts more specifically to the parameters that (may) have to be measured and monitored, and what type of sensors, measurement principals and data may be required and expected. The focus of the monitoring system is explicitly restricted to the parameters related to the floating island itself and not the payload superstructure.

Chapter 5 addresses the "Digital Twin concept" which is a virtual representation of a priori identified relevant state parameters that are to be used for O&M monitoring. It also reviews the developing technology to derive these relevant state parameters from multiple sensor inputs, and how to qualify sensor inputs with respect to data integrity and sensor failures. It is noted that that although many sensors and observation techniques are available, they do not always provide easily interpretable output to operators. In particular interpretation of more global phenomena that are the combination of multiple inputs along multiple floaters requires data aggregation, and representation in different output format then what is provided by the sensors themselves. Chapter 5 reviews the options and developments for algorithms to combine sensor inputs using various data fusion, model based and machine learning approaches.

A small scale solution for "a" monitoring system aimed at capturing floater and global motions, connector and mooring loads is evaluated in Chapter 6. It was proposed to be included in the demonstrator model tests at the end of the project in WP10. It was focused around local storage of measured motion and connector load data per floater including a synchronised high resolution time stamps. The objective to demonstrate successful reconstruction of the overall motion behaviour in the demonstrator tests of July/August was unfortunately not achieved because of a data storage malfunction during the tests that caused all stored local data to be systematically corrupted.

2 Monitoring basics

2.1 Metrology

The concept of measuring and monitoring appears to be straight forward. It occurs everywhere in daily life from weighing groceries at the shop, to temperature readings outside. "Monitoring systems" include these types of technology but have additional functionalities that make them more challenging to consider. Measured data are not just shown, but also stored, not only the instantaneous reading is relevant but also its relation to the past, and to other factors, and maybe most relevant, the information is used to for process control by basing decisions on the acquired information. As such, the parts of the systems have to comply to standards for overall confidence, that make it possible to replace parts with similar grade equipment in case of failure etc.

This paragraph briefly overviews the relevant concepts of measuring and how to ensure that the right things are measured,

- How to measure a parameter. Metrology, definitions, standards and vocabulary
- Quality control and making sure to measure the right parameters.

2.1.1 Basic metrology – ISO concepts

A consistent semantic approach is required when discussing something to be measured, sensors, logging systems, measurements, readings, sampled quantities, units of measurement, monitored values, derived parameters, precision, accuracy and uncertainty to name just a few. Standardisation is needed to maximise clarity in documents discussing measurement and monitoring solutions. Different approaches are being used in practice to handle semantics in metrology in more or in less strict ways. "A" possible standard for a shared language relating to measurements is drafted in *"ISO/IER Guide 99:2007(en) International Vocabulary of metrology – Basic and general concepts and associated terms (VIM)".*

An excerpt from the foreword of that code reads:

"The second edition of the International vocabulary of basic and general terms in metrology (VIM) was published in 1993. The need to cover measurements in chemistry and laboratory medicine for the first time, as well as to incorporate concepts such as those that relate to metrological traceability, measurement uncertainty, and nominal properties, led to this third edition. Its title is now International vocabulary of metrology — Basic and general concepts and associated terms (VIM), in order to emphasize the primary role of concepts in developing a vocabulary.

In this Vocabulary, it is taken for granted that there is no fundamental difference in the basic principles of measurement in physics, chemistry, laboratory medicine, biology, or engineering. Furthermore, an attempt has been made to meet conceptual needs of measurement in fields such as biochemistry, food science, forensic science, and molecular biology"

The VIM references its vocabulary to 5 basic concepts which are:

1. Quantities and units
2. Measurement
3. Devices for measurement
4. Properties of measuring devices
5. Measurement standards

The first concept addresses "what" actually is observed by a measurement and the unit of measurement that it is expressed in. The second concept highlights that in reality the true quantity to be observed is usually not measured, but instead something that is somehow closely related to it. The third concept describes the equipment and instruments that are used to take the actual readings. The fourth concept addresses the typical properties that each of these devices may have and that contribute to accuracy, uncertainty, and noise in the observations. The last concept highlights the relevance of standards in metrology that should ascertain that separate measurements on similar quantities will provide compatible results. For example, that a referenced kg in Amsterdam is the same as a kg referenced in Paris.

Quantities and units

The metrology concept "quantity" refers to a specific "something" that has to be measured. The VIM expresses this as a basic "property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed by a combination of a number and a reference". In this definition, a reference can be a measurement unit, a measurement procedure, a reference material, or a combination of such.
Following additional notes are recalled from the VIM to further clarify the quantity concept.

- Quantities as defined are scalars. However, a vector or a tensor, the components of which are quantities, is also considered to be a quantity.
- The concept 'quantity' may be generically divided into, e.g. 'physical quantity', 'chemical quantity', and 'biological quantity', or base quantity and derived quantity.
- Basic quantities are defined in the international system of quantities (ISQ). Proposed symbols for quantities are listed in the ISO 80000 and IEC 80000 series Quantities and units.
- Base quantities are defined in the international system of quantities (ISQ). Each quantity is expressed in a unit. Standardised units are defined in the SI system which is derived from the ISQ. The standard lists seven base quantities with corresponding units as listed in Table 1. Derived quantities can have combined units. Units are then combined and can then have dimensions as for instance force that can be expressed as kg.m.s^-2.

Table 1 Base quantities ISQ

Base quantity Grandeur de base	Base unit Unité de base	
Name Nom	Name Nom	Symbol Symbole
Length Longueur	Meter Metre	m
Mass Masse	Kilogram Kilogramme	kg
Time Temps	Second Seconde	s
Electric current Courant électrique	Ampere Ampère	A
Thermodynamic temperature Temperature thermodynamique	Kelvin Kelvin	K
Amount of substance Quantité de matière	Mole Mole	mol
Luminous intensity Intensité lumineuse	Candela Candela	cd

Note that under this implies that things that cannot be expressed in these 7 base reference quantities do not fit into the standard, or need to be reformulated such that they do.

Measurement

The concept of a measurement is the "process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity". A floating island configuration may have characteristic properties that are not easily or directly measured. The approximation of such properties by combing or interpreting various other measured quantities is also considered a measurement.

Some relevant nomenclature used with respect to measurements is briefly summarised from VIM:

Measurand, measured quantity value	The quantity to be determined, and the measured representation for it
Measurement principle, method and procedure	Describes the principle of a measurement, the type of measurements whether it is direct, indirect, differential etc., and the procedure and calculations that are used to obtain the required quantity value from the measurement results
Accuracy, precision and error	Accuracy and error indicate closeness of measured values to true values. Precision indicates reproducibility of subsequent measurements under similar conditions.
Calibration, Verification	Determining calibration settings for transduces, verifying if items are fit for purpose to required specifications.

Devices for measurement

The equipment or hardware used to take measurements are referred to as device for measurements. Multiple devices can be required in serial or parallel configuration in order to determine a measured value. Following concepts are highlighted in particular.

Measuring-chain, -instrument & -systems	These describe the components for a 1) single signal path from sensor to output, 2) A specific instrument or set of instruments that can be used to take specific measurements, and 3) The combined installed ready to use system to provide specified readings.
Transducers, sensors, detectors	These are the devices that relate to be measured quantities to objective (and typically electronically detectable) quantities. A transducer has a specified relation between input and output quantity, where sensors and detectors formally determine if quantities satisfy conditions as presence or threshold values.

Properties of measuring devices

Measuring device properties are the most diverse part in the metrology vocabulary. This because of the large variation in measurement devices, principles, and quality and the resulting impact on the uncertainty and accuracy of measured quantity values.

Following concepts are highlighted:

Indication	The direct indicated value on the instrument
Calibration curve	The relation between the indicated value, and the measurand quantity value.
Resolution, dead band, sensitivity, range	Smallest detectable steps and the full output range for the indicated values and the measured quantity values
Selectivity	The ability of a measurement system to differentiate the required quantity measurement from contributions by other quantities.
Stability / drift / bias	Describe the variation of metrologic parameters of measurement devices over time.

Measurement standards

Measurement standards or Etalons, as referred in VIM refer to the definition of reference quantity values as used in the setup, calibration, adjustment and output of measurement systems. Reference is made to International Standards that provide a worldwide shared baseline reference, and National standards, primary, secondary and working standards that each should be hierarchically traceable to the International standard.

2.1.2 Managing measurement systems

The VIM outlined in par 2.1.1 defines relevant concepts with respect to metrology but it does not specify how the quality of a measurement as expressed in the listed terms could be ensured. It is useless to measure the wrong parameters perfectly. For a given process, the right parameters should be measured sufficiently accurate. Quality requirements are thus needed when considering monitoring systems for O&M purposes. ISO 10012:2003, “Measurement management systems – Requirements for measurement processes and measurement equipment” provides a standard for a measuring system quality management approach. An excerpt from the introduction reads:

“An effective measurement management system ensures that measuring equipment and measurement processes are fit for their intended use and is important in achieving product quality objectives and managing the risk of incorrect measurement results. The objective of a measurement management system is to manage the risk that measuring equipment and measurement processes could produce incorrect results affecting the quality of an organization’s product. The methods used for the measurement management system range from basic equipment verification to the application of statistical techniques in the measurement process control.”

A flow diagram of the management process loop is shown in Figure 1.

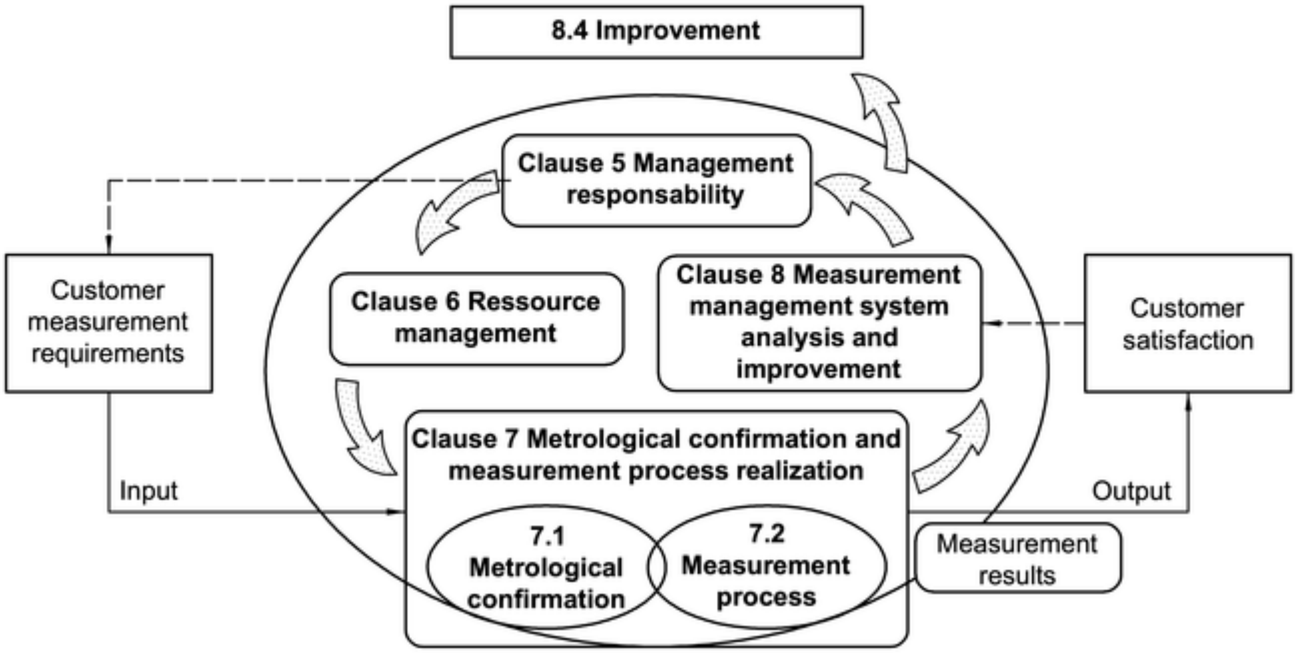


Figure 1 ISO 10012 - Quality management flow diagram for measurement processes

Clear customer defined measurement requirements are an essential input into this process. The actual measurements are realised in steps 7.1 and 7.2 "metrological confirmation and measurements process". The result of measurements is then forwarded to the user. The user satisfaction is the input for the internal evaluation of system performance and definition of any required modifications, maintenance activities or system improvements.

Features of a well-considered monitoring system should thus include

- Functional requirements that must be fulfilled,
- Hardware comprising of sensors, transducers and measuring equipment collecting actual data
- An interface for intuitive feedback of measured information back to users
- An approach to draw right conclusions on the observed processes and quantities
- An approach to recognise break down and anomalies in the measuring chain

Functional requirements to be full filled depend on the specifics of the monitored process. They will be evaluated for floating islands further down in this report. The general specific of measurement systems as they are used on large industrial plants over past decades is briefly reviewed in next paragraphs.

2.2 Process Control and Automation

The definitions in the VIM as for instance for sensors, transducers, measuring chain, measuring instrument, and measurement system illustrated that measurement systems can be complex. In the past a measurement system could be a data logger with a/some dozen sensors connected to a computer, a dial screen or chart plotter. The types, flavours and output flavours of sensors and loggers however have developed extensively. Modern industrial plants rely on extensive data collection and electric actuator networks that are huge both in terms of the number of connected sensors as the area across which they are wired and deployed. Sensors and transducers now also provide their indications in a variety of ways. From classic electric readings in Volt or mA, to digital via Ethernet or serial bus lines, using any communication protocol, web interface, and with data availability varying from asynchronous streaming, polled request, buffered block transfer and many more. The nature of the industrial process plant facility determines the type of required sensors, the type of sensors and their operating environment usually determine the favoured interface. In practice a multitude of sensors, data interfaces, data buffering, timing, storage, visualisation and quality assessment have to be combined in operational systems. These systems do not only comprise of cabling and equipment to take readings, but also rely on combined metadata to indicate what the obtained values refer to, limit states to recognise alert conditions and specialised control functions to make adjustments.

A specialised industrial field of "Process control and Automation" has developed to design, install and maintain such systems for high end industrial applications. Frameworks were developed to maximise efficiency and reusability of solutions across multiple projects. Some of these have turned into industry standards but some are bound to the system architecture of specific companies. Three areas of expertise are mentioned hereby to represent specific technological areas as often referred to in Process Control

DCS	Distributed control systems. The emphasis with DCS systems is on the closed loop infrastructure to continuously acquire data, and control actuator settings. These are complex systems with sensors, acquisition workstations, storage and control actuators that are typically not centrally wired and organised but are truly distributed and networked across a large area to minimise cabling and maximise flexibility.
SCADA	Supervisory Control and data acquisition. The emphasis for SCADA systems is on providing a best possible operator (open loop) point of view onto the underlying process using available data from for instance a DCS. This includes software standards to acquire, exchange and visualise process information to operators and users.
CAMS / ESD	Central Alarm Monitoring System / Emergency Shut Down systems. These are systems to ensure controlled shutdown of critical processes triggered by automatic or manually raised alarms. These systems have configured algorithms to interpret input data and/or trigger alarms or alarms scenarios without operators coming in between

2.2.1 DCS layer

The DCS or Distributed Control System represents the hardware that links sensors, transducers, and actuators to a network of controllers and workstations. The reference to "distributed" refers to a networked architecture where all equipment is no longer wired to a single central server, but where the interconnecting hardware is designed to be modular, and located as close as possible to sensor equipment to minimise cabling, and noise. Multiple I/O servers are installed, each handling smaller groups of sensors and actuators.

The collected data is typically

- Forwarded to permanent storage
- Forwarded to a user feedback layer
- Forwarded to closed loop controllers that can be part of the DCS layer

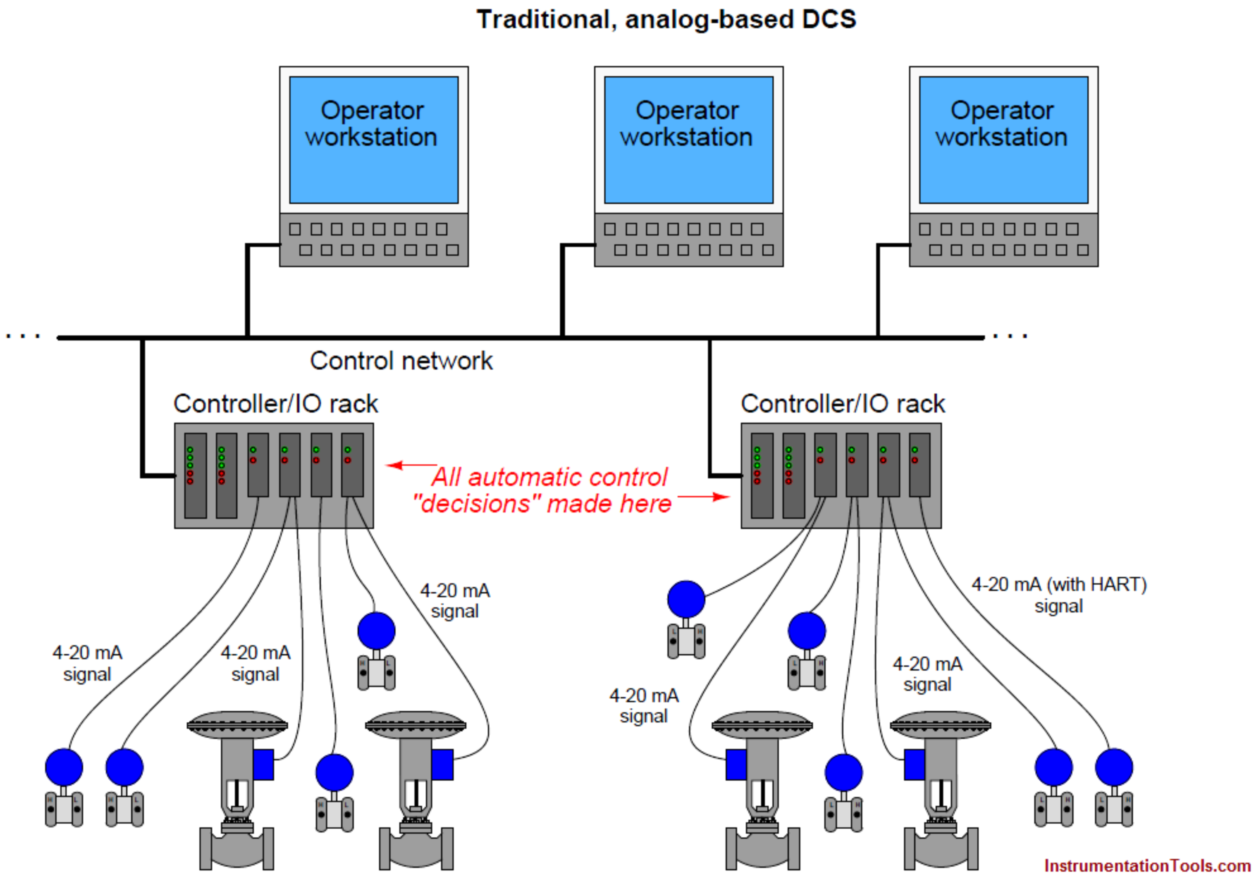


Figure 2 DCS system schematic (https://instrumentationtools.com/distributed-control-systems-dcs/)

2.2.2 CAMS and ESD layers

Central alarm monitoring and emergency shutdown systems are in place for processes that require direct attention and cannot rely on operators that may be focused on other tasks. Both CAMS and ESD systems will trigger specific actions automatically when predefined conditions are recognised from the DCS sensor readings. These can be alarms in case of CAMS, or specific actions being started in case of ESD.

2.2.3 SCADA layer

SCADA or supervisory control and data acquisition refers to the visualisation of the collected information and the interfaces to actuators that are offered to operators. A SCADA system thus requires a data collection infrastructure or DCS to be in place. The operator is the key element in the process. SCADA is typically an open loop process where the operator decides the actions based on the inputs offered by the system.

Collected, pre-processed and possibly combined data is typically presented to the operators in a way that relates to the process that is being controlled or monitored. Typical examples for SCADA screens relating to ship type systems are shown in Figure 3.

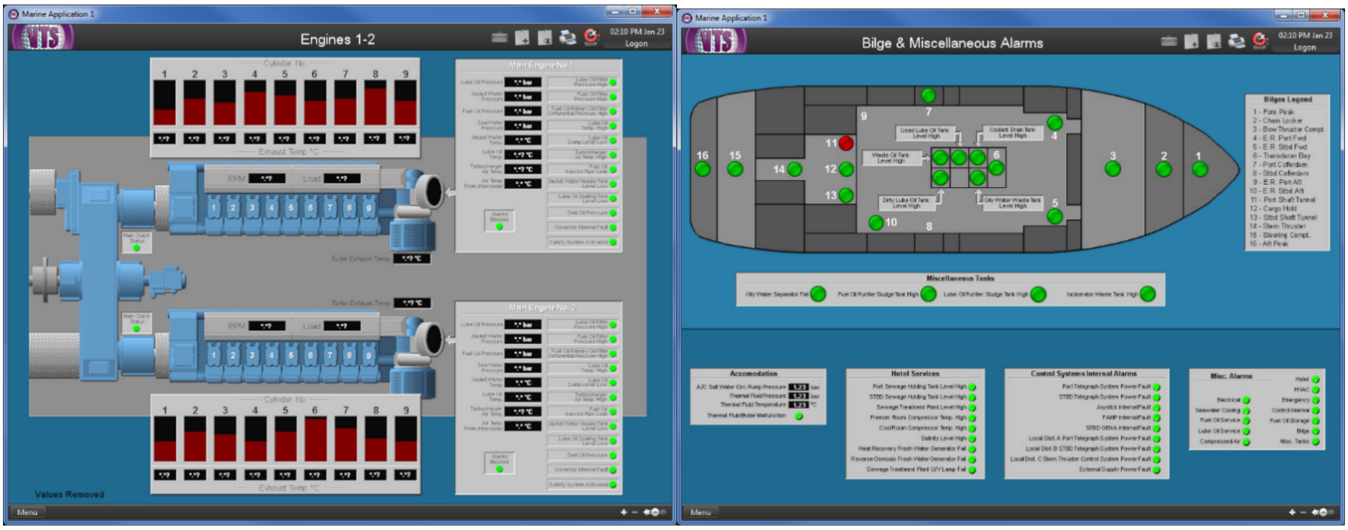


Figure 3 SCADA displays - (www VTscada Canada)

2.2.4 Example: Offshore wind

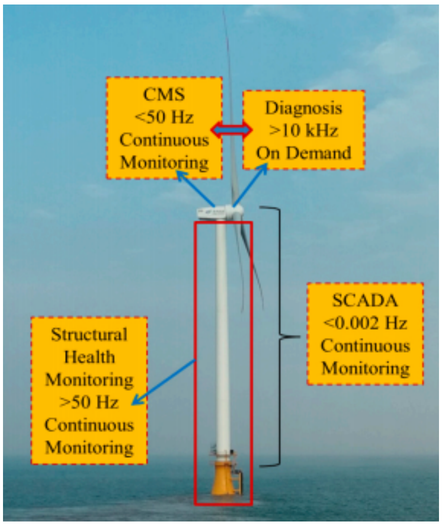
Since offshore wind farms are always far away from the mainland, many remote health monitoring systems have been applied in order to reduce failure risks, identify fault occurrences, and improve the working performance by analysing the data measured from the wind turbine. Supervisory control and data acquisition (SCADA) systems and condition monitoring systems (CMS) are considered as the two most common means of structural health monitoring in the offshore wind.

SCADA systems, with more than 20 variants, are widely approved and deployed to the offshore wind power industry. They are usually used to monitor several parameters related to different wind turbine components (e.g., structural vibration levels, temperature, bearings, tower, and drive train acceleration). In addition, SCADA systems are also utilised to obtain different factors as inputs of the wind turbine (e.g., wind speed, wind deviations, and wind direction angle) or outputs (e.g., rotor speed, blade angle, output active, and reactive power). The measured signals, recorded at a low sampling frequency (usually at 10 min intervals and smaller than 0.002 Hz), can be processed in a timely manner by many data analysis tools to detect the fault location and degree, explain problem causes, and automatically provide the operators and managers with real-time online feedback and useful suggestions.

Simultaneously, the researchers, on one hand, make full use of the data collected by the SCADA systems for further analysis of the parameter identification, fault diagnosis, and risk prediction. On the other hand, the traditional SCADA system and monitoring data are also combined with new analysis and process techniques to perfect and update the system so that they can show a more efficient and reliable performance.

CMS are considered as another important tool to monitor and measure data such as the vibration, load, wind speed, and temperature of the offshore wind turbine (OWT) structure continuously at a higher frequency (usually more than 50 Hz) in order to examine whether the wind turbine is operating correctly. When a fault or damage has been detected based on an alarm signal from the CMS, a diagnosis system, which obtains data at a sampling frequency greater than 10 kHz, could be activated to determine the degree and location of the potential fault either automatically or artificially. This kind of system can usually be implemented for the operators, indicating the health condition, obtaining the reliable alarm, and taking essential actions on the OWT by many analysis techniques including vibration analysis, motor current signature analysis, operational modal analysis, and acoustic emission technique.

For example, the ADAPT wind system designed by GE Energy Company can monitor 150 static variables on the bearing, gearbox, and generator, and achieve the aims of detecting the gear tooth damage and fault diagnostic and reporting the alarm based on the time and frequency domain analysis. Nowadays, most CMS were attempted to be integrated into the SCADA systems, because CMS can only focus on the vibration data explanation and are still not standardised, in contrast to the SCADA system. It is a good phenomenon that CMSs can either collect data from the SCADA system or allow its results to be integrated into the SCADA display. Furthermore, as CMS and SCADA systems continue to merge, they will eventually produce one comprehensive system able to significantly improve the efficiency and accuracy of the structural health monitoring of the OWT. The general layout of structural health and condition monitoring systems for OWTs is shown in below figure.



In simple terms, a SCADA system is a collection of software and hardware components that allow offshore operator to perform a series of specific functions. These functions include:

- Monitoring and gathering process data (real time monitoring)
- Interacting with field devices and control stations like sensors and motors via an HMI (Human Machine Interface) display
- Recording system events in a log file
- Controlling the specific processes locally, or from an off-site location (remote processing)

The information that is gathered is analysed in order to identify opportunities for improved efficiency and to expedite the communication of issues within the system to reduce the amount of time required to repair key parts of the offshore assets as described above.

Typically, SCADA systems are centralised systems that provide monitoring and control functionality for a specific area. The simplest way to conceptualise the architecture of a SCADA system is to envision a software package that works hand in hand with the devices on the floating island.

Sensors and/or manual operator-activated inputs are positioned throughout the system, gather data and transmit it to the programmable logic controller (PLC). The PLCs in turn transmit that data to the HMI via a wired or wireless network, where it can be viewed graphically and analysed by an operator situated in the control room. In the case of Space@Sea, it means that the PLC will transfer its data to the HMI via a wireless network and on its turn the HMI will process the data and makes it viewable for technicians, allowing them to visually locate the problem areas within the given system and/or provide the technician the operational control to a specific asset on the floating island to control the situation. Additionally, equipment status is also easy to monitor for each asset by means of an alarm notification if the retrieved data exceeds a certain pre-defined limit.

2.3 Developments in Process control and automation

Over the past 30 years, large players in Process Control industry have developed their own proprietary architecture to optimise their corporate efficiency. For example Siemens, ABB, Honeywell and Yokogawa. The possibilities offered by these individual frameworks are quite versatile. Interchanging parts of completed systems with other corporate framework solutions however is not as easy. Process Control and Automation solutions for specific industrial projects are usually contracted to a partner that efficiently implements its own underlying framework. The cooperation between the industrial plant and the Process Control partner is from that point on practically exclusive, because it is too costly to change the fundamental measurement and visualisation frameworks that are entwined in the underlying industrial process. Modifications and extensions are thus typically implemented by the original manufacturer of the monitoring system.

New developments in sensor technology, analytics and user interface technology did however raise a growing interest with industry end users to modify and interconnect existing systems during their lifetime. The introduction of the internet and cloud based solutions have speeded this up further. The automation industry recognised this as a next industrial revolution that is now taking place and which is referred to as Industry 4, or the Smart Industry network.

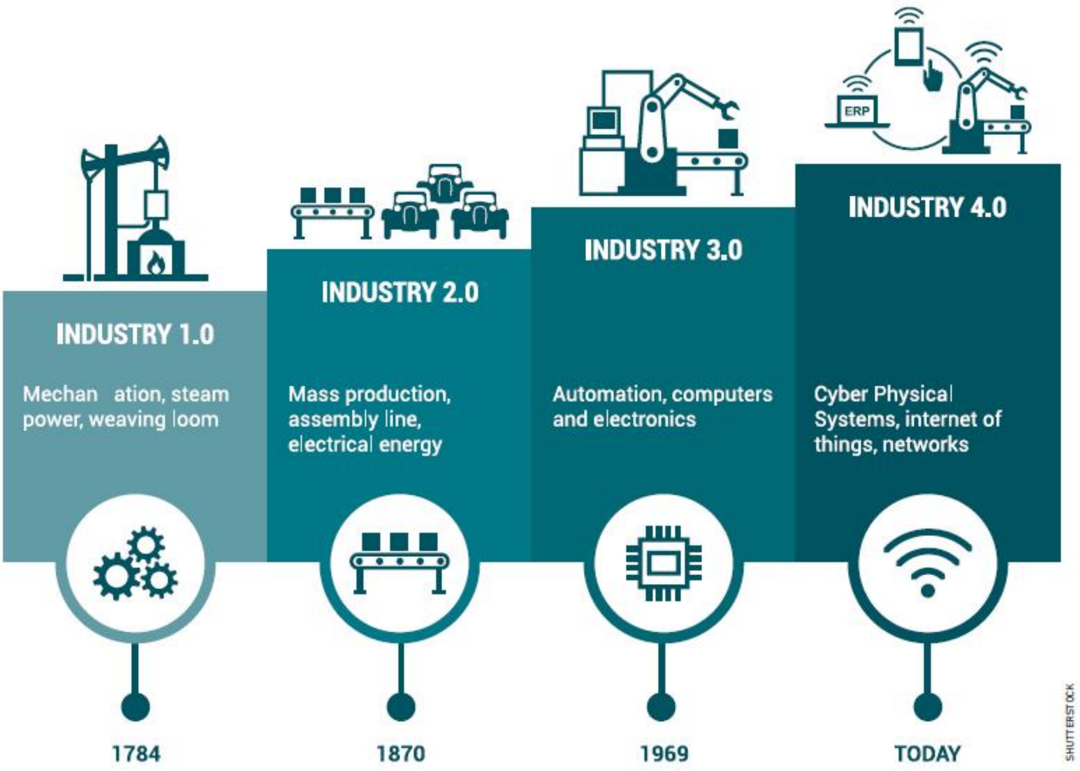


Figure 4 Industry 4.0 - An industrial revolution occurring today

Fast times to market, and changing use of existing facilities raised tendency in the industry to move towards higher level "open architecture" frameworks where systems from individual PCA partners would be more easily interconnectable or interchangeable. This is driven from end user side by additional versatility and market competition, and by academic and techno consortia that do not already have an established link in the PCA world but aim for software middle ware solutions.

Developments are occurring throughout the chain from sensor side, DCS, storage and user feedback side.

2.3.1 Sensor interaction

Development of electronic components has become so cost efficient and relatively easy that huge amounts of sensor solutions are being made available for a variety of things at fractions of the cost of what they used to be. Large scale introduction of acceleration and navigation sensors in cars has triggered development of low cost motion sensors with reasonably high performance at extremely low cost. Similar developments have taken place in telecommunications with fibre optics, laser technology and telemetry. These basic low cost OEM modules are combined into versatile sensor equipment in proper housing and with suitable interfacing by specialised companies. This has increased the number of sensors that are now available on the market substantially. And it also enables the development of new sensory approaches for future applications.

It is however not straight forward to just plug in such a new type of equipment into an existing DCS or SCADA framework. An example of a development aimed at open standard for sensor data collection at DCS end is the MTP or module type package. This development is supported by end users of process control and automation systems in the chemical industry as represented by NAMUR, the Standardisation Association for Measurement and Control in Chemical Industries. NAMUR supports development of a middle layer between classic DCS systems design and their implementations via MTP or Module Type Package descriptions that uncouple actual hardware from its functionality via driver services with specified interfaces that are implemented under the hood inside the driver by the equipment manufacturer. The interface layer where this is implemented is called the Orchestration Layer. The generated data is forwarded to existing industrial frameworks.

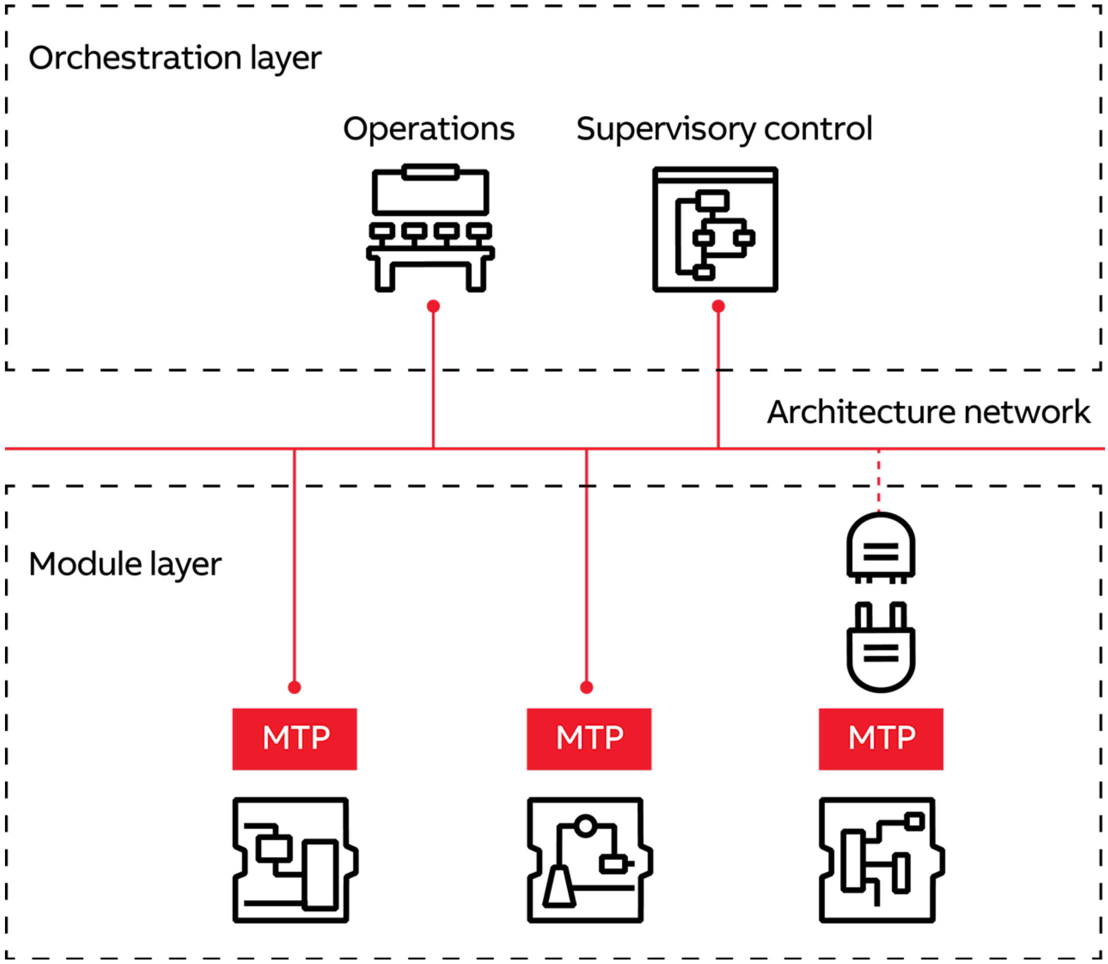


Figure 5 Open architecture framework

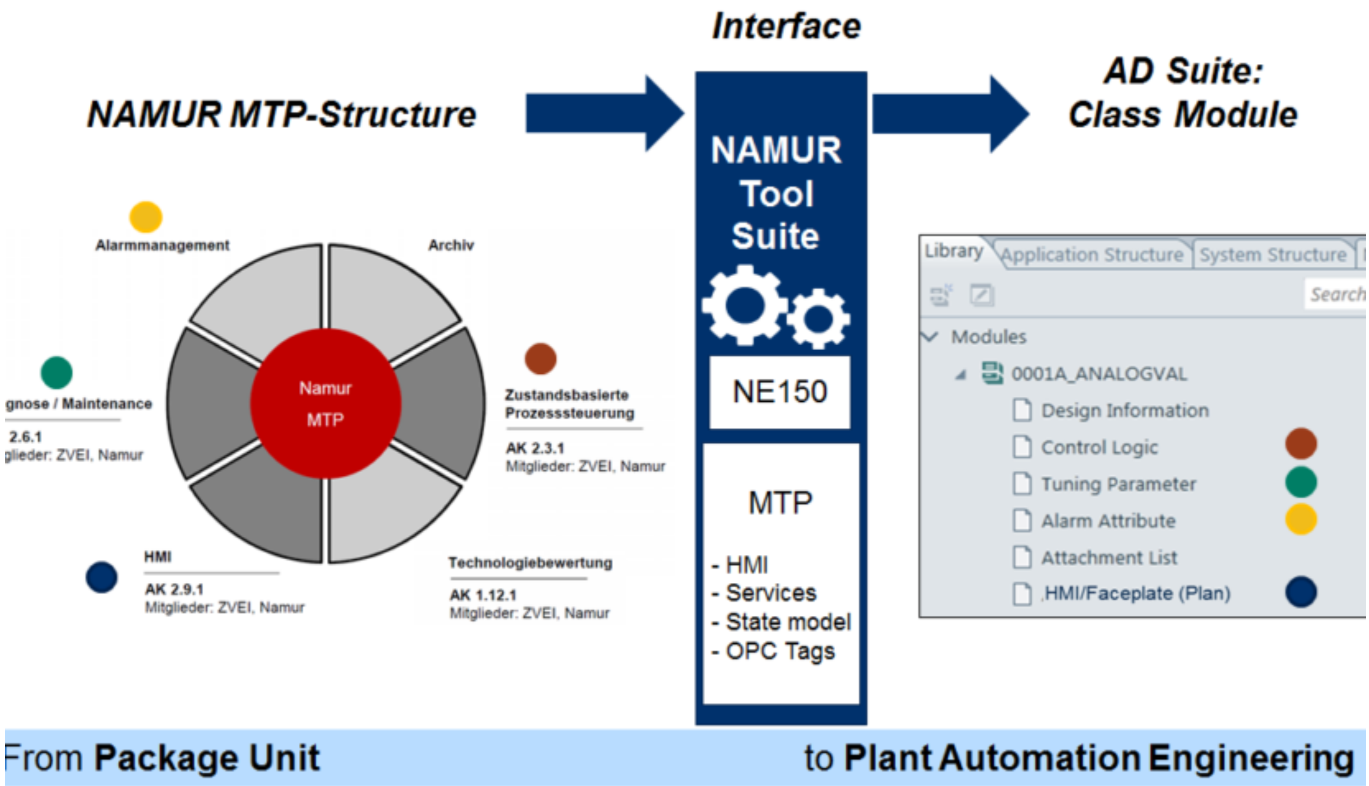


Figure 6 Structure of a Module Type Package

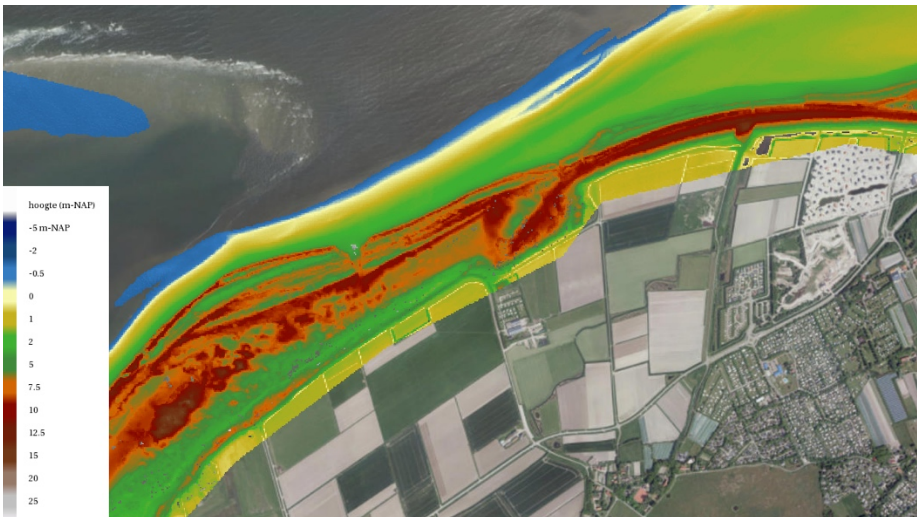
2.3.2 Data standardisation

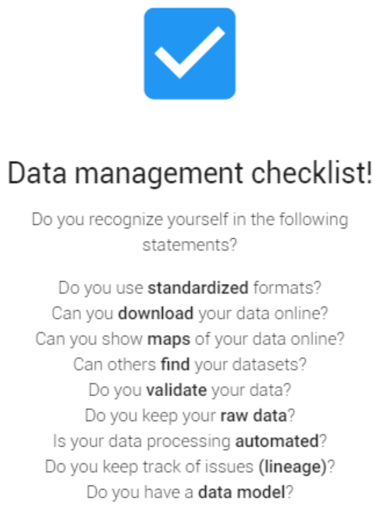
Many types of data can be visualised with standardised tools depending on the nature of the data. Time series can be visualised in charts, correlations in X-Y plots, and geographical information can be shown on a map. Some user groups are developing frameworks that link measured data to its inherent nature or type. The objective is that this will allow to make use of standardised tools for processing, analytics and visualisation of the collected data.

Examples for these are:

The Open Earth framework that was developed by a mix of industrial end users and academic partners with a focus on geographic and bathymetric information. The introduction on the open Earth website reads:

(https://publicwiki.deltares.nl/display/OET/OpenEarth*): "OpenEarth is a free and open source initiative to deal with Data, Models and Tools in earth science & engineering projects, currently mainly marine & coastal. In current practice, research, consultancy and construction projects commonly spend a significant part of their budget to setup some basic infrastructure for data and knowledge management. Most of these efforts disappear again once the project is finished. As an alternative to these ad-hoc approaches, OpenEarth aims for a more continuous approach to data & knowledge management. It provides a platform to archive, host and disseminate high quality data, state-of-the-art model systems and well-tested tools for practical analysis. Through this project-superseding approach, marine & coastal engineers and scientists can learn from experiences in previous projects and each other. This may lead to considerable efficiency gains, both in terms of budget and time. "*





Another initiative is by Open Geospatial Consortium (OGC), and subgroups operating under that umbrella as SOS or Sensor Observation Service. *"The SOS standard is applicable to use cases in which sensor data needs to be managed in an interoperable way. This standard defines a Web service interface which allows querying observations, sensor metadata, as well as representations of observed features. Further, this standard defines means to register new sensors and to remove existing ones. Also, it defines operations to insert new sensor observations. This standard defines this functionality in a binding independent way; two bindings are specified in this document: a KVP binding and a SOAP binding."*

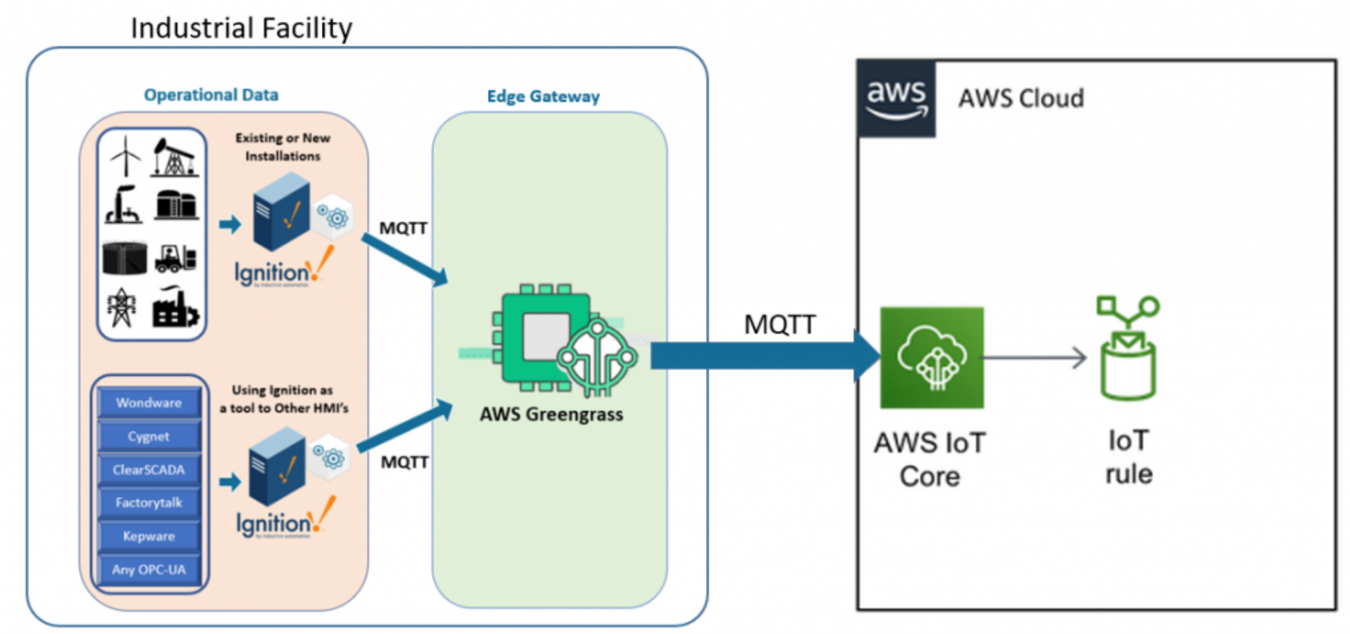
Focus of these developments is not on the acquisition of measured data, but on standardising its representation such that it meets the standardised input requirements of existing processing analytics and reporting or visualisation tools.

2.3.3 Data science

Quite another type of developments is occurring from the side of data scientists that are not classically involved in process control and automation and who are not constrained to industrial SCADA alike environments. This field of industry has developed in business software and solutions and is now starting to enter into industrial process control and automation as well. Solutions are being developed around high level (cloud) frameworks as e.g. AWS, google Cloud and Azure. These run a variety of big data software as Apache Hadoop, Apache Kafka for data organisation, storage, processing and analytics.

Solutions offered by data science are not rooted in an a priori understanding of the underlying process, but in the assumption that an underlying process can be described and understood by a (large) set of parameters, and that good or unfavourable behaviour of the process can be recognised from these parameters by trained algorithms.

This field is developing fast and the options that are offered today might already be outdated in 10 years.



The technological domains for Process Control and Automation, and ICT – cloud technology are different but may be complimentary. Classic industrial closed loop and open loop systems however were built along hardwired overseeable installations. Applications for monitoring and diagnostics may be well possible. Dealing with plant exceeding and possibly ICT vulnerable technology for primary process control however may still be a step too far at the moment.

2.4 Statutory requirements and class rules

Industrial facilities are essential for modern economy and society but their reason of existence in the end are the private interests of their stakeholders. Statutory requirements to its operation are (usually) in place to safeguard public interests as personnel safety and environmental impact. Shore based industry in this aspect has to comply with the national legislation of the particular country. Industrial facilities at sea however operate outside the boundary of a single nation and should comply with internationally agreed regulations.

Regulations at sea for safety and well-being of crew and environment are defined in IMO SOLAS (Safety Of Life At Sea) and MARPOL (MARitime POLlution) codes. IMO, the International Maritime Organisation, is the association of flag states that together specify, agree and enforce these codes. Specification and agreeing is done inside the IMO meetings. The individual member states of IMO agreed by membership to the obligation to include the IMO codes in national legislation and enforce compliance of their own fleet, and check compliance of foreign ships visiting national ports.

In practice the compliance to IMO rules is often implemented by specific class notations. Existing high value marine structures as ships and offshore plants are usual implemented and operated under class rules in order to be accepted for insurance coverage. Class rules are supposed to impose the requirements as needed to ensure the structure to be fit for purpose and safe operation. Both the industry, class authorities and insurance sector have developed extensive historic experience with these rules over decades and centuries of maritime innovations.

It is unknown to the authors of this report if there are existing standards and mandatory requirements to monitoring systems in specific.

Safety considerations for crew, passengers and marine environment have driven rule developments under class referring to IMO. These include requirements to structures, equipment, monitoring systems, its components, its functionality, documentation and certification, how they are operated and how staff has to be trained and certified. Class rules are continuously being adapted and improved to match ongoing developments. They are the result of decades of continued developments, experience and evolving insights. Examples of class approved systems are ship structures itself, bridge and navigation systems, DP control systems, engine management and ballast control systems, hoisting equipment and the bilge, fire and gas alarm systems.

Individual key system parts as sensors etc. can be class approved. This usually refers to quality statements on production process, documentation, and compliance with relevant industry standards. It is not clear if there are explicit requirements to generic “monitoring systems”.

It is noted though that Statutory and Class rules rely on technical understanding in combination with extensive experience with structural dimensions as function of ship type and sailing areas. Experience that in the case of floating islands is missing for a large part. Both overall structures, structural details, exposure to environment and docking regime of floating offshore islands may be different from existing ships. Class rules for floating islands may thus be different from existing rules, and more extensive requirements may be imposed to monitoring systems to demonstrate compliance of the “as built” structure with its anticipated behaviour.

2.5 Concluding

Monitoring infrastructure on industrial setups is needed to assess

- How the entirety of the structure is behaving at this moment
- Whether the actual behaviour is in line with expected
- Which trends are showing in longer term to trigger actions

The industrial specialisation of “Process Control and Automation” addresses monitoring systems for industrial applications. Such systems generally comprise of

- A data collection layer with hardwired sensors, I/O modules and closed loop controllers for local processes. This layer is on larger structures often referred to as the DCS or Distributed Control System.
- A visualisation and data sharing and collection layer where sensor and controller state information is used to provide intuitive feedback to operators that can adjust control parameters in typical open loop applications.
- Automated CAMS and ESD services that are configured to trigger specific actions when monitored behaviour exceeds predefined limits.

Industrial systems are usually required to meet standards and certifications as required by insurances and authorities to safeguard private (financial) and public (safety) interests.

Relevant standards vary from national to international, application industry standards, and classification rules. E.g. DIN, NEN, IEC, ISO, DNV/GL, ABS, LR, BV

Standards and class rules include years of experience with similar structures. For new type of structures, it may be expected that extended monitoring is performed to check compliance with the design assumptions.

The introduction of internet, cyber technology, cloud computing and data science have triggered new developments that are now entering into the classic world of Process Control and Automation.

3 Floating island – Monitoring system

The concept of floating multi modular islands is a new extension to maritime technology. Floating islands may comprise of many modules from various manufacturers each using different and new types of technology. They most likely shall be in continuous use for a long time period without classic possibilities for recurring dry dockings but relying to on site (preventive) maintenance. It is expected that new rules will be required for specific details of floating islands, and also a new approach to deal with O&M aspects given the new equipment, and less frequent or impossibility for docking.

The introduction of this new technology and its operation requires careful validation of the design assumptions. The first actually built units have to be equipped with monitoring systems to validate design assumptions against the in operation reality. Both for short term and long term behaviour. As explained in the chapter 1, validation, trending and correlation of specific phenomena rely on "quantity" value indicators.

As shown in previous paragraphs, a concept monitoring system for a floating island can be elaborated based on functional requirements, specifics for the data collection layer or DCS, specifics for the controller feedback or SCADA, and considerations that are relevant to alarms and predefined responsive scenarios as in CAMS and ESD services. These are outline in following chapters.

Each floater may be expected to be outfitted with many sensors already. And with a large number of floaters, and additional measured inputs from the mooring and surrounding environment as indicated in Figure 7, the number of available measured parameters is quickly too much to be intuitively manageable and comprehensible.

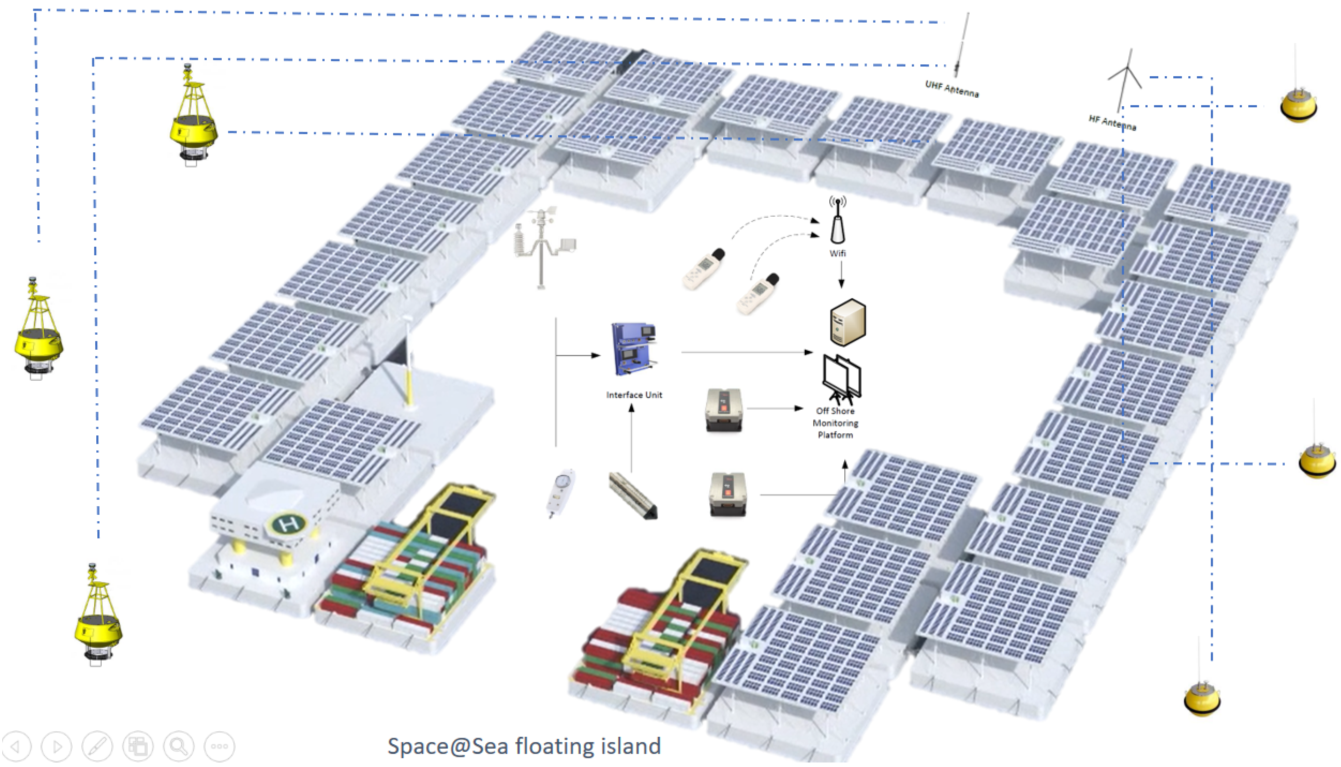


Figure 7 Distributed monitoring inputs for a floating island.

New approaches need to be developed to feedback collected information from the DCS/SCADA layers to operators. The key question for O&M consideration is to determine if present and future projected conditions are in line with expectations, or if/when flags or alarms need to be raised for direct actions, or for long term (preventive) maintenance efforts. This may require new reference models or algorithms to estimate expected behaviour under given now state conditions. Options that may be considered for this are handled in this report under the Digital Twin chapter that represents the state of the true structure as a virtual or "digital twin" that is matched thru its sensory DCS system.

Even so it is questionable if the O&M challenge for the island configuration has a time scale and operational characteristic that calls for short lines on site operator evaluation. Trends in behaviour will develop over longer time and may not justify daily operator involvement. Operator control options in case of extreme events in severe weather are also limited. Remote operator assistance on shore may be called for. This requires data links to the infrastructure of island from shore via direct cabling, satellite or cellular network as illustrated in Figure 8.

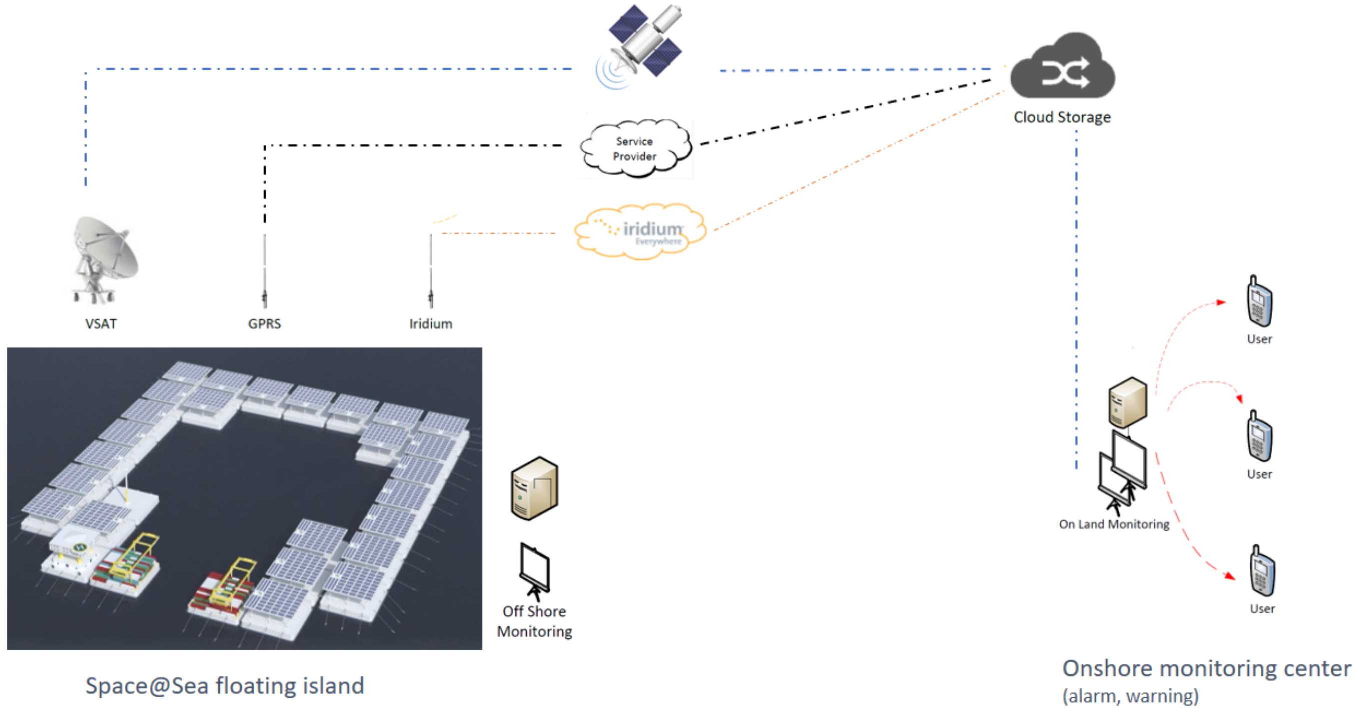


Figure 8 Remote connected floating island configuration

3.1 Functional requirements and user stories

Remote monitoring is an essential aspect of O&M inspection process. The objective of remote monitoring is to provide feedback which allows to relate the in-service state of "a" process or structure to an assumed or expected state.

Space@Sea report D5.3 – O&M and life cycle scenarios highlighted principal O&M processes in relation to five specific principal functions of floating islands. O&M inspections and monitoring were found to be essential in providing feedback for the functionalities of:

- Providing stable and buoyant platform space
- Ensuring station keeping
- Assist with operational processes related to modularity of floating island concept
- Long term structure integrity of modules and moorings
- Monitoring and controlling traffic of goods, personnel, energy

For the monitoring system in particular this implies many different aspects. Following are highlighted:

- The quasi-stationary condition in terms of draughts, heel and trim of the island and individual floaters
- Global response aspects of the island and dynamics in joints and moorings, motions, relative motions, internal forces, mooring forces
- External loads that are acting on, or are anticipated to act on, the island, waves, wind, current, ship traffic,
- Structural condition of the floating island platform and its moorings. E.g. integrity, wall/chain thicknesses & corrosion, wear/tear joints, crack initiation, hull/mooring marine growth,

- Alarms for extraordinary occurring conditions. E.g. Fire, water ingress, gas concentration levels, joint and mooring failures
- Impact of the island on the surrounding environment. E.g. exhaust gases, waste water circulated back into the ocean, above and under water emitted noise, effect on marine environment underneath and in near vicinity
- Process information for the equipment and systems installed on the super structure.

Each of these aspects requires different parameters to be inspected, measured or described at varying intervals. Some may be continuously captured using permanent installed straight forward sensors, while some may be captured using more complicated data collection that is based on processing of high resolution camera or audio inputs from fixed setups or even remote operated (under water) vehicles.

Not all of these parameters will however be relevant to every floater module in the island configuration, and due to the modular nature of the floaters, it is very unlikely that the actually installed data collection systems per floater will even be the same. The objective is that sufficient information is collected to determine answers to the relevant questions for operation and maintenance of the structure. The "user stories" concept is used to further clarify relevant requirements.

User stories are short sentences in a format that defines why someone would want a particular action as in: 'Who, I want what, so that why'. These statements can then be used to set up and check the general architecture of the system to ensure that the system measures what is needed for the O&M of the modular island. It can then help to sharpen what needs to be distilled from the combined measurements, when alarms should be raised, and if and what predefined action scenarios are needed.

Examples of user stories, in this case from an operator side are:

I am an operator and I want to know:

- Any alarms that need to be responded to so that I can take required action
- Are things behaving in accordance with expectations or do I need to worry even though things are not exceeding limits
- What was, is and will be the weather so that I can correlate with the measured behaviour, or prepare for bad weather
- What is the traffic around and below the island (ships, uuv drones) so that I can prepare or warn shore teams to assist with routing and mooring alongside
- Are relative motions between modules inside safe limits or do we have to change fender pretension, ballast configuration.
- Has marine growth increased to a point where cleaning is required
- What is the islands impact on marine environment, regarding above and under water emissions and noise, so that we can report to nature scientists
- Status of ballast tank and handling arrangements per floater, so that we know what can be adjusted,
- Status of load lines and changes of individual modules. So that can be decided when ballast shifting is needed.
- Module motions in general as this is needed to estimate fatigue consumption, and wear and tear.
- Status overview of power, water, waste and data grid, because this is an operational process that should not be interrupted.
- What is the structural condition of individual floaters so that preventive maintenance can be scheduled well before actual failure starts to occur
- What is structural condition of link joints, moorings and anchors such that preventive maintenance can be scheduled well before failure starts to occur.
- Is remaining mooring capacity sufficient for imminent worst-case weather conditions. Because if not than direct need arises for stand by tug boat support

It is noted that the final design of a floating island is not yet done. The concept design however already includes new type and scale of structural solutions that are different from existing maritime practice. This suggests that new types of measurement devices, systems, processing and visualisation may be needed to capture relevant information on quantities that are specific to behaviour of floating islands.

It is also noted that operators can track structural health over time, and schedule preventive maintenance activities. Options to mitigate extreme behaviour, as for instance in severe weather, however may be limited.

3.2 Monitoring system topology

Floating islands and in particular multi modular floaters are anticipated to impose specific challenges to monitoring system infra structures. In particular for reasons of modularity, scale and autonomy. The monitoring and control system will be comprised of interconnected servers and workstations that provide I/O to sensors and actuators via a DCS layer, that is controlled via operator workstations in a SCADA layer and supervised by an Alarm and emergency procedures system running alongside.

The system will be deployed across multiple floater modules. The topology and hierarchy of the measurement and control system network will be a deciding parameter for its complexity and flexibility.

The aspect of big data needs to be taken into account. The modular island will produce a vast amount of data fitting all the 5Vs of big data (Volume, Velocity, Variety, Veracity, Value). The key is not to measure 'everything', but to constrain to a relevant set of parameters by defining risks and specific questions that need to be answered to control these risks. Only data that adds value on these points (resulting from the user stories) is necessary. Besides, failure risks need to be incorporated (risk = chance times impact).

The measurement system and its management system should be flexible and scalable. In time, sensors, hardware and software need to be added, updated or changed without much effect on total the system. Also, in time questions and user stories will change inevitably, due to new insights. This asks for a modular set up of the system, with clear in- and output and a clear release plan. Also, a general open framework will be desired instead of a closed (one company) framework, such that data is easily accessible and created in a FAIR way. FAIR stands for Findable, Accessible, Interoperable and Reusable. The FAIR principles concept originates in data management and are meant to promote good data management practices.

Data generated from sensors can be transported to local acquisition units and from there either to a collection point on the module or straight to a global collection point for the whole island. That global island centre can be placed on the island itself or onshore / in the cloud

Following considerations are listed:

Onshore or on Island

- Connection local → global (telemetry cable, satellite, new method required)
- Connection stability (is connection downtime acceptable, and how much)
- Cyber security → less change of hacking when it stays on the island
- Accessibility → easier sharing of data if it is onshore unless there is an easy way to connect to island data centre
- Needed space available on island (how much data do you build up over time, how long should it be stored, how easy should it be to access (cold storage)

Data processed on individual modules or all together

- Space locally available on modules or on island
- Version control between different locations
- Facility needed in case of failure to stream/transport data
- What data is needed in global storage and what can be hosted on the modules (needed bandwidth)
- Local changes (e.g. new sensor) need to be known in global location or only on module

Interface requirements

- Kind of data to global storage
    - Raw

  - quality control
  - logging
  - meta data (data type, sensor type, calibration, etc.)
  - processed data
- Time
  - all data should be time synchronised before sending over
  - always streaming or specified time frames to send data or connection dependent
- Data format
  - All data in same format to global storage (choice made per project? Or overall, e.g. HDF5)
- Access
  - Who has access to data (clients, office, other modules/other local storages, cloud computing, team viewer)
  - access via e.g. SQL or API
- security
  - needed level of security (password or more needed)
  - impact if data is accessed by non-authorised people
  - impact if system gets hacked / changed / taken over

Combining data:

- Real time or slower
- Data level: Input raw / checked and output: level 2 or higher (i.e. at least partly processed and checked for errors. Also in standard format)
- Follow up needed, is there another process waiting for the output data?
- Forwards and backwards compatibility of software
- Is there a combination with simulations (needed output format or speed)

Data from different modules needs to be combined, processed and stored at some point. This requires data from various sensors on possibly different modules to be exchanged and combined. The flow of data from sensor to the processor that performs the actual combination algorithm can be organised in different ways. Following options are recalled:

1. Sensor data processed and stored on floater local servers, then data forwarded (partly) to island main control server location across data network infra structure
2. Sensor data processed and stored on floater local units, and each floater connected to a remote onshore control server without a central control server on the island
3. From local sensors straight to large control centre or data server on the island
4. From local units straight to large control centre or data centre on shore

The preferred organisation depends on a lot of factors and affects the software and hardware architecture of the modular island.

It is first distinguished in Figure 9 between wiring individual sensors to a data server per floater module and wiring all sensors to a central data servers on the island.

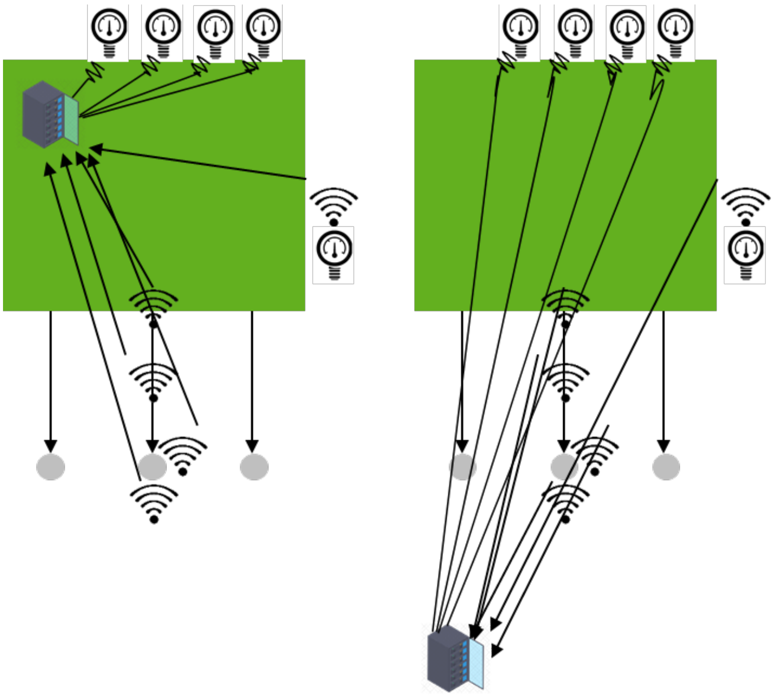


Figure 9 Options for storage per module. Left local storage, right global storage

Pros and cons of the two concepts are listed as follows.

	Each floater outfitted with data server for local sensors	**All sensors wired to central server on the island**
cabling	Cabling on floater. Only network cabling to cross link joint. (++)	Extreme cabling across joints. High cable cost (--)
interfacing	Responsibility for sensors metadata with the floater where sensors actually are installed. -> preferred (++)	Extensive administration on remote sensors has to be exchanged and maintained (--)
Software complexity	Software infrastructure has to be more flexible to interrogate remote sensor data base for metadata (--)	Sensor descriptions have to be filled out manually, but would be one time only effort or when changes occurred.
Flexibility	New sensor types can be installed locally and can then “pop up” at the control server side. (++)	Mismatch between local and central sensor configuration may go unnoticed causing unavailability, or even mistakes. (--)
reliability	Damage to network cable loses all communication. But can be implemented ruggedized and double (+)	Unlikely to lose all contact at once, but likely to lose several, too expensive to run doubles.

It is concluded that the concept of local data servers per floater module is the most favourable way forward. A review of the interfacing options for data servers on individual islands is illustrated in Figure 10.

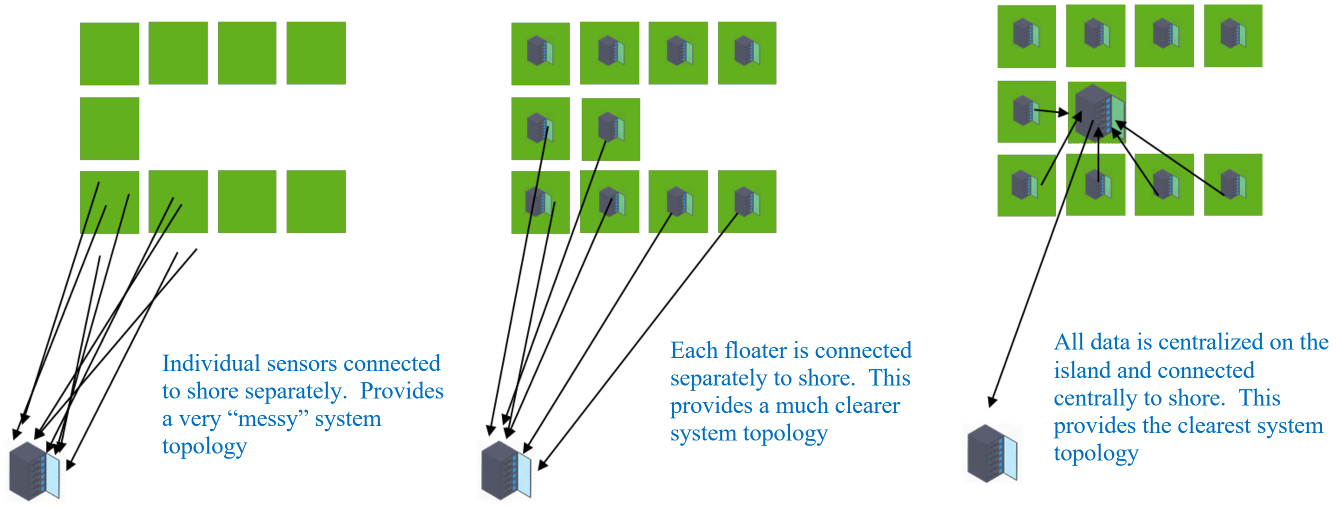


Figure 10: Whole island interface options.

1. Multiple sensor I/O modules per floater can be interfaced individually to a shore side control server.
2. All sensors per floater are interfaced to a floater data server that is connected to a shore side control server
3. All local floater data servers are connected to a local control server which in turn is connected to shore

The benefits are briefly reviewed below

	Sensors direct to shore server	Module servers to shore	Modules to local control server in touch with shore
cabling	Minimal	More cabling to run all sensors to a central data server	More cabling to run all sensors to a central data server
interfacing	Each sensor data link will require an industrial accepted network interface	Regular industrial network	Regular industrial network
Software complexity	Direct related to complexity of sensor network and types. Complication is on shore	Complexity is in local data servers to correspond with sensor networks	Complexity is in local data servers to correspond with sensor networks, And in ability of central server to interface with local servers
Flexibility	Not very	All data related to combined inputs from different floaters has to be forwarded to shore (expensive) before processing. (--)	Data combinations and corresponding aggregation can be done already on the island so much more data efficient. (++)
reliability	Communication downtime interrupts sensor data. All control is interrupted	Data can be buffered locally but processing and open loop control is interrupted	Local control loops can continue if shore link is interrupted

It is expected that the preferred configuration for all floater – island configurations will be to wire all sensor data to local data servers per floater, and interconnect all module data centres on a network that includes a centralized control centre with data uplink to shore. Various options exist for the actual data link from sea to shore side. Some options as available in 2020 are shown in Figure 11. The rise of internet of things technology in Industry 4.0 may well lead to new means for data interfacing. Still it is expected that direct uplink per individual floater will not be practical except for simple islands with limited number and complexity of modules.

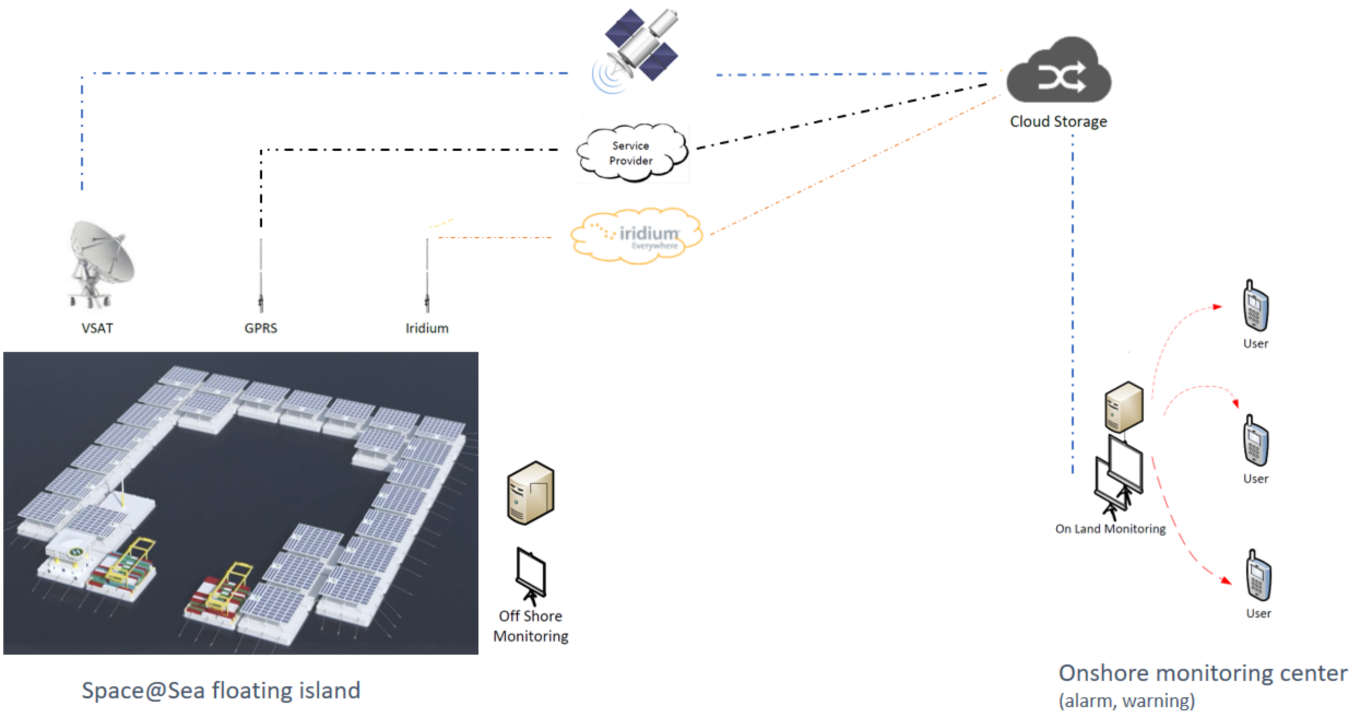


Figure 11 Sea – shore interface options

3.3 DCS layer

As outlined in previous paragraphs it is assumed that each separate floater module will be outfitted with a local DCS system. The DCS system is responsible to collect and forward data from connected measurement devices, interface control data to local actuators, perform basic local closed loop control functions if needed and store logged information for post time reference.

The sensors and actuators in a DCS will very likely vary across different floater modules. The DCS should have an interface that describes to higher level SCADA systems what sensors are connected, and what type of data these provide and require. This "meta data" is typically maintained in a data base representing all connected measurement device input and control output quantities including

- the relevant measurement device properties on the sensor end with sensor details, serial number, electrical connection details etc.
- the measured quantity description, reference type,
- installed location
- history of any changes to sensor details

The meta data is configured and updated with installation or modifications to the DCS hardware. The meta data can be queried by higher level SCADA layers to decide what sensor data is actually to be requested.

The running DCS service during operation ensures that the measured values for each quantity match with the indicated value from the corresponding sensor, that control actuators are matched with corresponding set point values, and that logs are updated at configure intervals.

3.3.1 Time base and resolution

A critical aspect for distributed data collection systems is reliable timing. The various logging systems on individual floaters are referred to as nodes in the network around the island. Each node will collect data that may need to be combined with data from other floaters to estimate a relevant quantity at the same time. The relative motion between two floaters as an example is determined by the difference in vertical displacement at a given time. Since the displacements are determined by separate modules they can only be related if they are time stamped to a mutually shared time base. The same consideration applies to load summations across moorings and link joints. Forces are only compatible at the same moment in time therefor combinations of data through network server links have to include reliable and relevant time stamps with proper resolution.

Synchronised time bases are achieved by disciplining local time servers to a shared reference time base. Time bases can be related hierarchically from higher level time bases. Each derived time base is referred to a lesser accuracy as indicated by so called Strata. The highest possible time accuracy is referred as Stratum 0 which is generally directly linked to a nano second accurate GPS related reference. Clock servers synchronised to that are Stratum 1 etc.

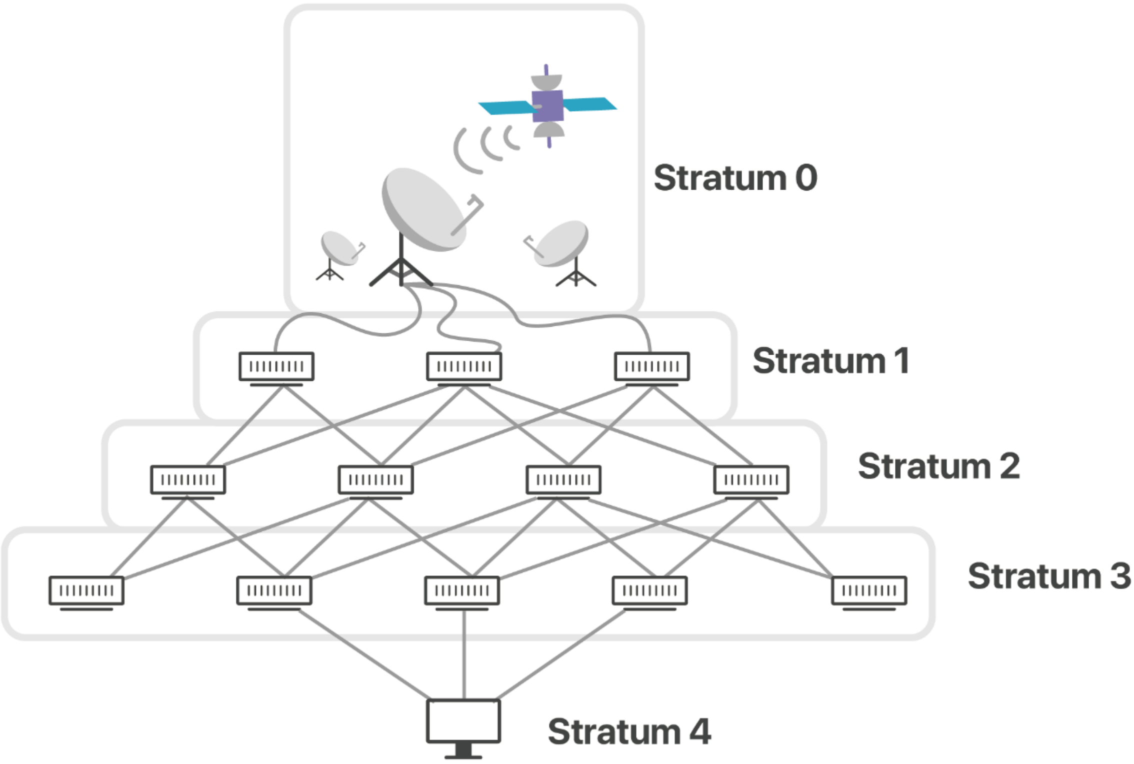


Figure 12 Time server reference

The accuracy and resolution of the time base are equally important. The accuracy of a time tick indicates the largest difference that can occur in the reading compared to the true value of time.

The resolution of the time reference is the smallest time increment that can be represented by successive time ticks. This thus also indicates the smallest possible time that can be distinguished between successive time stamped measurements. Note that accuracy cannot be less than resolution, but resolution can be higher than accuracy.

Both resolution and accuracy should be less than half of the smallest period of change that is ever expected in a data signal connected to the DCS system. Process plant data collection systems often have resolution of 1s. Part of the challenge in floating islands however lies in the dynamics between floater modules. These local dynamics are anticipated to occur with sub second motion periods which calls for higher resolution of the time base. ISO recommended higher resolutions then are ms, or microsecond resolution. For motion and force registrations a resolution and accuracy of 1 millisecond is considered to be required. For sake of consistency and future flexibility it is recommended to adopt microsecond resolution at data server level.

For sake of standardisation it is further recommended to adopt a recognised time standard as microseconds since 1970, or similar.

3.3.2 DCS inputs

Each input into the DCS produces "data" which can be anything from sensor reading to camera frames. There have to be requirements to facilitate some standardisation at DCS level.

Functionality:

Data collection components are responsible to capture information on a specified parameter and forward it into the monitoring system in a documented way.

Considerations:

The type of parameter that is referred to, determines what level of pre-processing and storage is needed.

Meta data is needed to link every collected sample to the logged parameter, the sensor that captured it, and the time and place where the sample was taken. The majority of sensors will be mounted on a particular location somewhere on a floater, but sensors might also be located on support boats, in drones or AUV's.

All the measured data needs to lead to a good overview of how the platform as a total is functioning, data is not measured for itself but e.g. to feed a digital twin or other advisory/maintenance system to support the operation and maintenance.

A reference to measured values and control set points typically involves reading / writing the interface value of an I/O module. DCS systems however have to interface to a wide variety of sensors and actuator controls that each have their own different electric connection specifics. Common interfaces for measurement type of devices are:

- Direct loop connected analogue inputs / outputs
  - mA inputs 4-20 mA,
  - mV and V inputs (+/- 10V, 0-1V)
  - ICP (imposed current protocol)
- Bus connected and serial interface inputs
  - MODBUS, OPC, CANBUS, PROFIBUS, Ethernet, EtherCat, TCP/IP, UDP
  - RS422, RS485, RS232
  - Web HTML, REST-API,
- Data base SQL / NO-SQL

Other data than classic measurements that can be expressed in sense of scalar type quantity values are:

- Imaging data. These including
  - camera still's,
  - video,
  - high speed video
  - radar
- Audio information
- Document type of information
  - Wave data reports
  - Load condition reports
  - HTML / XML / etc.

3.3.3 Measurement device properties

Based on the needed information in e.g. a digital twin of the island, key information can be connected to the user stories. Measured sensor data can measure this often only indirectly, i.e. the data needs to be processed and combined to come to the needed information.

User requirements can be set for the whole island or per module, with the main goal to support O&M and keep risks below an accepted limit. Errors and warnings will inform the operator about possible issues, next to the general quality checks.

Many sensors will be incorporated, per sensor (set) the following aspects need to be considered:

1.001	Choose data type	a. Scalar b. Vector c. Matrix d. Pictures e. time series (in sync vs. asynchronous) f. spectra 2D/3D g. flexibility to add new types
1.002	Time	a. Needed sample rate b. Needed Accuracy c. Time from local sensor / external d. Synchronisation e. Time protocol (ISO, local time, …)
1.003	lifetime	How many days/ months/ years needed
1.004	filtering	Needed and if yes at sensor or later in chain
1.005	output	Disk space/ Output format / build up, meta data
1.006	Operating environment	Temperature, humidity, ATEX, available
1.007	Connection for input from other sensors	Like GPS, clock, trigger sensor, pressure, temperature
1.008	What to measure	One sensor per task, multiple sensors in 1 device (examples: 1accelerometer or tri-ax or MRU)
1.009	Sensor accuracy	a. Accuracy b. Accuracy over time c. Accuracy in specific environment
1.010	Need for redundancy	Yes/ no

Next to the sensors itself, there are also requirements to the measurement management system and the energy provision. For the measurement management system one can think of

- Version control
- Clear rules on who is responsible and takes actions in case of warnings, errors and calamities
- Maintenance
- Architecture
- Speed (e.g. from measured data – processing – advise/warnings)
- Redundancy

The energy provision of the measurement system will need its own architecture and maintenance, taking into account

- Power consumption (sensors, management system, storage etc.) both in active and standby mode
- Duration of power requirement
- Distance to power source
- Type of power source(s)

3.3.4 Data Storage

A large island configuration can be expected to produce a vast amount of data. It will be challenging to store, manage and retrieve incoming sensor data, processed information. Therefore, it is important to have an archiving strategy for the floating island, including what data or software needs to be archived for direct access and for how long, identify data that is not directly used but can be moved to cold storage for later off line research.

To be able to use older data the data format is very important. A widely used, open source format will ensure that the data will be easy to access.

The security level will depend on who has access and what the risks would be of cyber criminality or access without permit.

1	Storage system	a. file-based, object-based or database storage b. Organisation of version control (forwards and backwards compatible) c. Distributed processing, in memory processing d. sharding – partitioning – replication
2	Event triggered	e. Option to only store data based on trigger, including ring buffer for latest data in post trigger mode f. Option to vary storage frequency based on trigger
3	Data space	a. How long is data kept in local storage b. How much space is needed for all sensor-data for the needed time c. How much space is needed for processed data for the needed time d. Archiving local or global e. Is separate slower cold storage space interesting
4	Physical drive replacement / expansion	Hot swappable disk drives can be used to expand drive space if needed
5	Access	Access from shore/other modules.
6	Data partitioning	Data can be stored in a single data server, or may be kept at the location of origin if the data cluster knows how to find it.

Figure 13 Conderations with respect to data storage

Before data can be stored, data checks are needed. Data checks requirements consider amongst others:

1	Data kind	a. Time trace b. Snapshot data fixed times c. Snapshots data event triggered d. Streaming / files (incl. file frequency)
2	Filtering	See sensor requirements
3	Warning controls	a. Detect in range/out of range / time outs / trend /flat lining b. Maintain warning and alarm logs
4	processing	e. Calculate various statistics on streaming data (min, mean, max, rms etc.) f. Distributed processing, in memory processing, columnar indexing g. Option to output statistics on different time windows at the same time h. Real time or slower
5	Version control	How is version control arranged (actually over whole system)

Figure 14 Checks for data integrity

3.3.5 Interface framework to individual floater servers

It is noted that the concept of uniform modular floaters enables the assembly of a large island, built together with floaters from different manufacturers. Each floater in that case can then be outfitted with heavy equipment, sensory and I/O infrastructure as installed by its original builder. In that case it is unlikely that equipment from one floater can be directly connected to and controlled via the same network as other modules.

It is anticipated that individual floaters will be outfitted with vendor specific DCS systems. Combining these systems with a higher level control server is expected to pose a challenge. A data combination framework may be needed in between the operator feedback or SCADA layer and the individual DCS systems installed on the different floaters.

User stories from a controller point of view are used to identify a shortlist of requirements with respect to the interfaces to the DCS systems on local floaters.

- I want to rely on absolute time stamps of data received from remote floaters so that I can relate results to data captured at same time on other floaters. For instance relative motions and link joint forces.
- I want to be able to question a remote floater for its installed sensors, their properties and configuration and be able to adjust these if needed. For instance do your measure mooring loads, what mooring line id, what are the reference units, what is the accuracy, sampling rate.
- I want to be able to request the data from sensors installed on a remote floater. Give me the load for mooring line 4 on floater 23.
- I want to be able to request older data from sensors for a given time period. Show me a history of mooring line 4 on floater 23, for July 20, 2020 between 1300 and 1400 in 1s increments.
- I want to be able to change actuator settings as pumps, valves, camera angles etc. in order to “operate” the island. Close all ballast valves on floater 7. Open ballast manifold valve tank #3 on floater 7, Start ballast pump. Check status accordingly
- I want to be notified of unexpected events as fire, water ingress etc. by means of remotely triggered alarms
- I want to be able to set off a remote alarm in case of fire or emergency somewhere else

The following functionality of individual modules is listed to achieve this

- Sharing and setting time base from central time server
- Local data base characterizing all connected sensors, the so-called metadata.
- Local storage and pre-processing of collected data from sensors
- Respond to request for downstream meta data transfer
- Respond to request for downstream sensor data transfer
    - Single value
    - Streaming in now time
    - Blockwise in post time
- React and confirm to upstream actuator set point transfer
- Raise a downstream alarm status flag autonomously
- React and confirm to upstream alarm status set point

These aspects are further outlined in following paragraphs.

3.4 SCADA layer – Situation awareness

The SCADA layer provides the functionality to operators and controller as needed to run and maintain the structure. For an approach to define the functionalities of a floating island SCADA interface, the island concept is compared with a biological system or a person. The SCADA interface in combination with the operators are the consciousness and decision processes of the island not unlike the brains and consciousness of an animal or a person. Such decision making is based on perception of what is referred to as “Situation Awareness” or SA. A framework model representing key elements in SA is proposed by the “Endsley model” and is outlined in Figure 15.

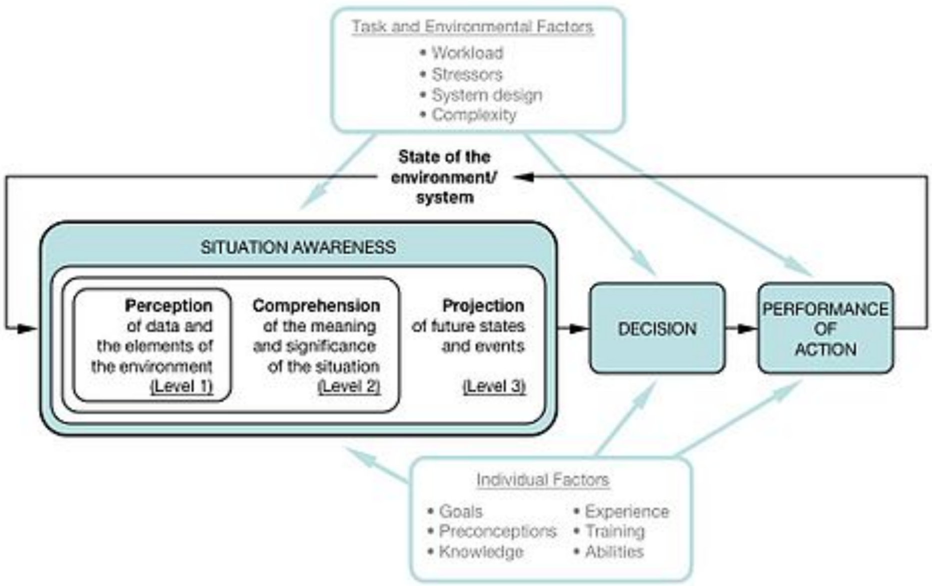


Figure 15 Endsleys model of Situation Awareness – (by Dr Lankton, May 2007)

The “Task and Environmental factors” represent the type of process to be controlled, the environment that it operates in, the tasks to be performed, and factors that complicate these tasks.

Situation awareness represents the

- “Perception” of the actual state of the process itself as well as the environment that it operates in.
- “Comprehension” as the severity of that now state. Typically in relation to experience from the past.
- “Projection” meaning the expectation for a future state that could be negative and thus should be avoided, or positive in which case the process should be steered towards it.

The combination of the stages of Situation Awareness can trigger the need for a decision. Once the decision is taken, the actual actions are performed.

The weighing of now state situation, choosing for a decision and the selected action is based on the "Individual factors". It is as such not guaranteed or even unlikely that successive events with the same process under identical environmental conditions will lead to the same decisions and actions.

On a floating island, the process above is controlled by operators based on their perception of reality as provided through the SCADA system in combination with historic data as previously logged and their own experience.

Factors and stressors that are relevant to the process state now or in the future have to be brought to the attention of the operators and be related (comprehension) to acceptable limits now, or in the future (Projection). Relevant factors that are not represented by the SCADA system will likely go unnoticed, and may raise unexpected and unwanted extreme events.

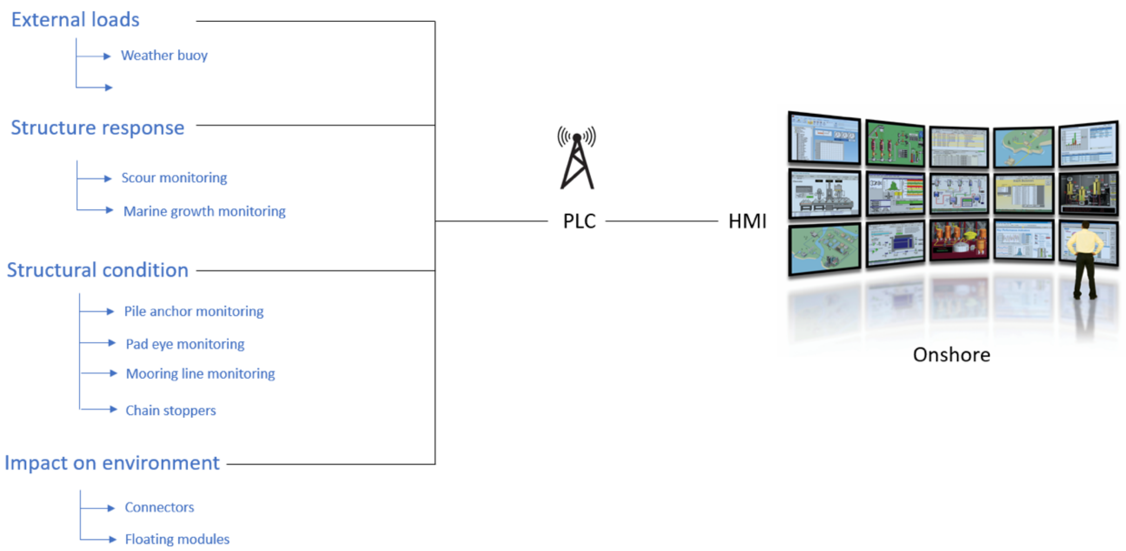


Figure 16 SCADA interface as workstation views into the Floating Island state

Functionality of the SCADA layer is broken in three aspects. These include:

- Relevant views on the now state of system and environment,
- Historian providing relevant views on the past for experience and reference
- Future projection tools to assist in decision making process steering now state away from negative or towards positive scenarios

3.4.1 Now state process view & digital twin

The now state should represent all relevant aspects of the structure as needed to recognise a favoured and non-favoured condition. The relevant aspects are related to the principal O&M functional requirements as listed in Space@Sea report D5.3 O&M procedures and lifecycle scenarios, along with questions raised by the "new" status floating island concepts, their impact on environment, and validity of design approaches. Following aspects are listed:

I am an operator and I want to be able to:

- Check ballast configuration and adjust ballast management system such that the island is operated safely at proper load lines.
- Visualise general motions, relative motions and loads in the island such that staff and operations can be coordinated if needed. For instance when hooking up new modules, adding or adjusting moorings etc.
- Visualise offset position in mooring, mooring loads and status
- The surrounding environment in terms of weather, waves, current, ship and aircraft traffic

- Check status of infrastructure flows for energy, water, data, etc.
- Assess the impact of the island on the environment
- Check (comprehend) agreement of observed behaviour with expectations

The abstract nature of listed considerations, the amount of inputs that need to be considered, the various types that these inputs can have and different ways that they can be combined calls for an intermediate step to be considered.

Instead of, or in addition to, merely representing output values from connected sensors, the complex and various data is used to determine well defined state quantities as indicators for specific functional requirements. The state quantities should be defined in line with the metrological definition as listed in this report 2.1.1 in scalar type quantity and specified reference unit. The benefit of such quantities is that they can be used for standardised representation and input into dials, gauges, strip charts, trend lines, historians etc. and also allow for straight forward comparison with reference values as needed for comprehension. The combination of these state indicators and the required algorithms to determine them from input data is referred to as a digital twin.

3.4.2 Historian

A functionality of a historian is to store and provide access to data. A SCADA layer for a floating island configuration should provide access to historic sensor input data as collected from the DCS, as well as the state indicators that were derived from them and used to assess and comprehend the now state at the time they were recorded.

Three aspects are recalled:

1. The SCADA layer should enable visualisation of historic state parameters. State parameters for a digital twin that are true quantities can be used to produce trends lines, perform correlation studies and other numerical analytics. These can be used to produce overview in time, find interesting events, and learn how to assess new conditions in relation to the past as needed for the comprehension stage. It should be possible to select events to be evaluated in further detail. Considered options are:
    a. Y-t plots representing trends over time
    b. Scatter plots representing correlation of parameters with other parameters
    c. Probability distributions
2. The SCADA layer should have the option to provide a now state views but from a viewpoint perspective in the past. The process details during a particular historic state condition are defined by the sensor inputs from the DCS that were collected at the time. In order to understand underlying process details that related to state indicated values, it must be possible to reconstruct detailed conditions at that selected time. These are the data as logged by the DCS infrastructure. The SCADA layer thus should provide functionality to bring up a Now State view based on user indicated time period.
3. Export selected detailed data from the system. It is very likely that the evaluation of detailed information from the DCS will require tools and analytics that exceed the features provided by a regular SCADA system. In particular validation of design models using long term monitoring results would require direct access to specific DCS logged information over a selected time interval, instead of accessing “all” now state information for a given moment as in option 2.

3.4.3 Future projection – forecast and simulation

Large scale and time wise slow responding systems are quite sensitive to wrong decisions. It takes time for negative effects to show up in actual readings, but it takes even more time to turn back the situation after control actions are adjusted. In order to maximise certainty of proper decisions, fast time simulation tools are needed to project the effect of control actions.

3.5 CAMS & ESD layer

Where the SCADA layer as outlined in section 3.4 is a part of the conscious awareness of a process control and automation installation, the CAMS and ESD layers, represent the subconscious and reflex type of behaviour. CAMS system will raise alarm states without conscious operator intervention. ESD type of systems can be implemented to react to alarm states in a predefined way.

For a floating island these alarm states are anticipated similar to other floating structures and should include:

- Bilge alarms
- Position offset alarms
- Motion and relative motion alarms
- Mooring and link joint integrity alarms
- Structural integrity alarms
- Fire, gas, smoke alarms

3.6 Island interface to shore/cloud

As highlighted in section 3.2, the topology of the sensors, I/O modules, data servers, control servers and workstations will be distributed across the floating island, and may also include storage and workstations on shore. Remote monitoring can refer to data collection and control across numbers of floaters, but it can also refer to monitoring and control of the island from shore. Following considerations are listed.

3.6.1 Communication options

Remote monitoring at Sea consists of the design of a complete eco system to guarantee the update and availability of relevant data to the end user. An equilibrium needs to be found between all of the above parameters to cover the needs of the monitoring system. Because of the remoteness caution is needed to keep costs under control. This can be done by combining different types of communication.

Prioritisation of the data stream is key in the eco system. In the data stream some sensors have a higher priority on results being at all time in real-time available, this is for operational critical data. For critical data the cost of making the data available is less of an importance.

Obviously hardwired data connections will be preferred because of their reliability and bandwidth. It is expected that hardwired (fibre optic) connections will be possible for many near shore floating islands. Even these however may break down unexpectedly and for remote locations they may not be feasible. Critical data therefore needs to have additional paths to reach the end user. E.g. standard all data goes via GPRS but if there is a failure in the system, only the critical data will be sent through iridium. Transmitting all data via Iridium is too expensive and therefore not to be considered.

Non critical data must be considered as a nice to have and will be made according to the needs. E.g. a general synchronisation is done every hour. Data is collected on the island, will be filtered and pre-processed and is waiting in the hot folder to be synchronised as soon as the data link is active. If the system is down, the data will stay stored on the island till the next time the link is active.

Type of communication

Different ways of communication between sensors and the monitoring platform need to be considered. Since monitoring is of great importance to guarantee the integrity of the setup, one type of communication can act as a redundant solution if the primary one drops out.

Wired Communication:

Wired communication is labour intensive during design and construction. Cable routes have to be planned and installed. The advantage is a guaranteed data communication. Some types of cables can also provide power towards the sensor. For indoor applications (like inside the offshore construction) it is the only way to go. Steel constructions at sea suffer from a lot of humidity. Therefor good quality of connectors is crucial to minimise maintenance cost. 3 different types are to be considered:

- Ethernet:
    - Bandwidth is high (100Mbps)
    - Low cost
    - High volume of sensors
    - Can provide power

- Serial (RS232 or RS485)
    - Bandwidth is limited (250kbps)
    - Low cost
    - Limited amount of sensors
    - Not intended for power transmission
- CAN
    - Controller Area Network allows devices to communicate without a host computer. It is designed for electromagnetic environments.
    - Data throughput is reasonable (1 mbps)
    - Low cost
    - Provides power

<u>Wireless Communication:</u>

Wireless communications need to be considered where the cost of cabling is too high. Different types can be used and are subject to the required throughput, the distance to cover and the interference in the area. Wireless communication does not automatically mean that these sensors cannot be linked to an external power supply.

When a lot of wireless data communication is required the introduction of time slots can solve data congestions. Typical, each sensor will send its information at the same time. The receiver is not able to receive all data at once resulting in a loss of vital data. This can be solved by introducing a time slot for each sensor. Only in that specific slot the sensor will send data. It allows more traffic on the same frequency/channel.

For the eco system of a floating island following wireless interface concepts are highlighted:

- Wi-Fi:
    - Limited reach
    - Limited sensors
    - High bandwidth
    - Can be affected by obstacles
    - Can work on sensor level and on general data synchronisation
- UHF:
    - Ultra High Frequency
    - Relatively real-time
    - Not affected by IT or internet connection problems
    - Can be affected by obstacles
    - Low bandwidth
    - On sensor level, cannot work on general data synchronisation
- HF:
    - High Frequency
    - Relatively real-time
    - Not affected by IT or internet connection problems
    - Can be affected by obstacles
    - Low bandwidth
    - On sensor level, cannot work on general data synchronisation

- GPRS:
  - General Packet Radio Service
  - Public network, availability on sea depends on the location
  - Private network could be with 5G
  - Bandwidth up to 118.4 kbps
  - Can be expensive, optimisation in operating cost is possible (depends on subscription + data sent)
  - Can work on sensor level and on general data synchronisation
- V-sat:
  - Very Small Aperture Terminal – Satellite network
  - Bandwidth up to 16Mbps
  - Stabilised antenna for maritime application is available
  - Can be expensive but depends on type of subscription
  - Not on sensor level, only on general data synchronisation
- Iridium
  - Network of 66 geostationary satellites (+10 spare)
  - Bandwidth up to 1.4Mbps
  - Expensive solution
  - Can serve in case of an emergency
  - Not on sensor level, only on general data synchronisation

3.6.2 Bandwidth, data transfer volume, downtime

Requirements for a data link include the bandwidth that is available to transfer operational process information to the operators, and return the control commands to adjust settings. If data storage and SCADA functionality can be handled on servers on board the floating island, then required bandwidth can be low. Only workstation screen output and control settings have to be exchanged. Raw DCS data will stay on the floating island, unless explicitly requested for download from the historian.

Downtime of the data link however will interrupt process control. Open loop process control involving operators via a SCADA layer may therefore be unrealistic if essential controls has to be operated without redundant hardwired data links. Active (remote) controls of the base floater structures however are expected to be limited to the ballasting arrangement and bilge and fire/smoke/gas alarms systems. Operators may not have a lot to do in terms of control.

Still the amount of data that is captured and needs to be evaluated for processing, transmission and storage may be quite high. Some very rough estimates are listed below:

Each floater module to be equipped with sensors providing raw input into the DCS expected as:

	npars	Rate	Data / mth
Acceleration / motion sensors operating capture platform behaviour and inertia loads	~12	20 hz	2.5 GB
Internal strains, mooring and connector forces	~16	5 hz	0.8 GB
GPS	~10	1 hz	0.1 GB
Ballast and alarms state and control params	~50	On change	10 MB

Each floater then expected to produce: 3.5 GB / month. This summed over 30 floaters produces around ~100 GB / month in total in raw data.

For the island assembly further information is expected to be acquired from radar, underwater (automated) ROV inspections, CCTV camera images. Continuous CCTV camera surveillance can produce around 60 GB/month **'per camera'** which makes camera data potentially more constraining then the sensor data.

Radar and underwater camera data are anticipated to generate similar amounts of data of their raw inputs are to be stored.

At present state of the art it is unrealistic to transfer 100 GB order of magnitude data across wireless links due to bandwidth and cost restrictions for 4G/5G and satellite solutions.

If measured data is processed and aggregated on a local server on the island then the resulting aggregated data can be forwarded at far less extensive bandwidth. Under that practical assumption it is expected that data exchange for the platform status can be operated inside the constraints of "normal" data bundle rates as offered by service providers. (10 GB / mth)

3.6.3 Cost estimates

Only a very rough outline estimate can be provided for the cost involved with O&M monitoring systems. These costs are based on experience with measurement systems installed by MARIN and DEME for building stage, and retrofitted measurement systems.

CAPEX

Basic infrastructure data monitoring system (DCS) per floater around 50-100 kEuro including specification, design, preparation, testing, and installation on board

Cost for standardised sensors are expected between 1000 and 3000 Euros including sensor, sensor installation, and cabling from sensor to DCS I/O input.

Per floater motion and GPS solutions are expected to be sufficient based on modern IoT type solutions. Around 3000 Euros including (GPS) antenna, cabling and installation.

Wave / current / environment sensor being it a buoy or remote sensing solutions ~50 – 100 kEuro.

OPEX:

Operation and support monitoring system	30.000 / year
Iridium communication	25.000 / year

4 Data collection parameters and state representation

A huge number of sensor solutions is available to capture pretty much any type of individual quantity that can be considered. The challenge in defining efficient measurement systems is to determine how to capture relevant phenomena, including these that cannot be directly captured in measurable quantities, by combinations of multiple direct and indirect measurements.

Below chapter reviews inputs that can be observed or captured to estimate particular phenomena and quantities related to floating island O&M.

4.1 Highlighted state parameters floating islands

The remote monitoring infrastructure is divided into different groups of parameters that are focused onto specific quantities representing island state factors, stressors, and impact. For each of the groups a variety of measurement and observation inputs are available that can provide various types on input. State representation in a well-defined quantity as defined in section 2.1.1 is required to allow for long term trending, relate and compare effects against historic data, and against other factors. State indicating parameters are proposed in following section for each of the listed groups of factors.

4.1.1 External loads

The external load parameters consist of external parameters which have a direct impact on the behaviour and structural health of the floating island. Presently identified loads may include these from:

- Wind
- Waves
- Current
- Ship and air traffic above and below water.

The offshore weather conditions may cause heavy loads affecting the operability, structural integrity and safety of the floating island. Conditions such as wind, waves and current should be real time monitored in order to justify downtime, any damages and/or failures imposed by the weather. Data as needed to project or anticipate weather related effects can be obtained from forecasts. Measuring the weather data can be done on several ways and will be further discussed in section 4.2.1.

Following selected target state representations indicators are proposed to be determined from the available inputs

Wind:	Mean wind speed at 10m height	m/s
	Gust speed	m/s
	Dominant wind direction at 10m height	deg – true North
Waves:	Significant wave height	m
	Peak period	s
	Dominant direction	deg – true North
Current:	Mean current velocity	m/s
	Current peak velocity	m/s
	Current direction	deg – true North
Traffic		
	Traffic density indicator	ratio - percentage

4.1.2 Stationary condition

The stationary condition is what can be actively controlled by operators. Such is ballast condition, mooring system pretensions, settings of wave energy converters, etc. The ballast conditions of each individual floater modules will have to be matched with its neighbours and the overall island load lines. Monitoring and control of the ballast condition and mooring tensions requires insight in

- floater draught [m]
- trim and heel angles, [deg]
- ballast tank readings [content in m^3, level in m, or fill ratio in %]
- mooring line pretensions (static) [load in t]
- control options for valve and pump arrangements [% of max rating, or flow rate m^3.s^-1]

Representation of state parameters of listed factors can be in their own units, or as ratio of their value to design reference values.

4.1.3 Dynamic response

Dynamic response is related to how the floating island is reacting at a particular moment to the external environment in terms of displacement, motions, loads in joints and mooring lines, and stress and strains inside the floater structures. This topic is related to the motion and force measurements on the connectors between the floating modules, as well as the strains and deflections on the mooring system. It is expected that for the majority of time, these loads will be related to, or dominated by, the previously mentioned external loads.

Dynamic response is a phenomenon that can be characterised:

1. deterministically by means of the short term behaviour of continuously changing motions and forces as function of time.
2. Statistically by describing the character of the deterministic behaviour during a specified period of time.

Dynamic response is typically evaluated by monitoring the deterministic behaviour which is then represented by statistical indicators for selected periods of time during which the behaviour is considered to be statistically stationary. The deterministic process is typically described by observed parameters as function of time. The character of the observed process during that period of time can then be described by factors as:

- Mean, rms, minimal, maximal value,
- Mean zero upcrossing period
- Most probable extreme value in selected interval
- And many more.

For monitoring of dynamic response this approach is also followed.

- The intended deterministic behaviour is captured by the DCS measurements and stored to data files for later reference. Sampling rates to be determined by the dynamics as predicted by detailed design studies but anticipated in order of 5 to 10 Hz.
- The DCS also performs data aggregation of captured data into listed descriptive statistics over periods of 15 to 30 minutes. This will allow long term trending and correlation of parameters based on mean, RMS, and extremes.

Following input and state parameters are proposed to be included in relation to dynamic response

- Individual floater motions. Inputs are typically 6 degree of freedom per floater. This input directly enables quantification of motion and acceleration levels for super structure payload considerations
- Global motion patterns that can be identified in the combined behaviour of individual joined floaters. For operational evaluation of the island response an integral representation of the whole island behaviour and its deflection and deformation, is much more informative that the unstructured heap of data from individual islands together. This approach is further elaborated in chapter 5. The global deformation state can be represented by the combination of derived parameters.

    - 6 degree of freedom displacements for the entire floating island (translations and rotations)
    - Flexural deformation as the contribution of selected principal deformation modes of the entire floating island. This is expected to be represented by an additional order of 5-10 degrees of freedom.
    - The deviation of local floater motions from the reconstructed motion pattern expressed by the combined global motions and deflections. This can be a single degree of freedom per floater and will indicate how well defined and well behaved the island is, and where deviations are highest.
- Measured mooring loads and link joint forces. These can be 3 degree of freedom forces per individual mooring or joint. With the complexity of the envisaged island, this will be too much to monitor integrally. So only limited amount of mooring and link joint loads are likely to be captured in practice.
- Estimated mooring loads and link joint forces. These may be estimated by combining observed weather parameters and measured global motions with numerical prior calculated results or with results from trained black box models.
- Deviation of actually measured loads in moorings and link joints from calculated or estimated values. This could be expressed as a single degree of freedom per measured load. The parameter enables the comprehension of the loads and forces data. Deviations can occur both in amplitudes of observed loads and in the frequency bandwidth of dynamic content. The first would suggest higher response levels in comparison to assumptions, the latter would suggest a different response mechanism to external loads in general.
- Local structure deformations and stresses. These are the deflections that occur in the individual floaters under the combined loads from the moorings, the connectors, the external forces, and the (quasi-stationary) ballasting loads. The amount of structure locations that may be considered for stress levels is infinite and thus impossible to keep track of directly. The most common adopted approach to deal with this is by identifying selected primary load carrying structure locations with low stress gradients (cold spots) in combination with selected high strain / high gradient areas (hot spots) where problems and cracking are anticipated. Measured dynamic response in cold spots is then usually related to anticipated behaviour in actual environmental conditions. Measured hot spot behaviour can be related to corresponding measured cold spot behaviour.

4.1.4 Structural condition

Structural condition is related to the accumulated effects of structural behaviour on wear and tear and on the effects of corrosion and marine growth over time. Different from "normal" marine structures, the floating island configurations may not be easily dry docked. Design life times are expected to be longer than for regular ships and it will be essential to monitor proper alignment between designed and actual lifetime consumption and decide appropriate actions when needed. Monitoring the condition requires structural health monitoring of the actual state and long term changes or deterioration of the structure and mooring conditions. Effects such as marine growth and scour will gradually build up during a certain period of time and will gradually have an impact on the structural health of the floating island.

Following quantitative parameters are proposed to define structural condition

- Floater condition
    - Fatigue consumption lifetime indicator 0 = new, 1=end of life.
        - According to design assumptions straight function of time
        - Calculated using design model in combination with measured environmental factors
        - Estimated from measured structural responses
    - Marine growth indicator around the exterior (Ref: Assessing and modelling the thickness and roughness of marine growth for load computation on mooring lines. Schoefs et al., 2019.
        - Weight [t]
        - Roughness ratio with smooth drag coefficient Cd [unity reference]
        - Thickness [cm]

The effects of marine growth and scour will be further described in section 4.2.8 and the effects of fatigue, wear and tear on the mooring lines in section 4.2.7.

4.1.5 Impact on environment

Floating islands are new to the marine environment and their impact on that environment may be subjected to much criticism. They are likely to have larger projections on the sea surface in comparison with existing ships structure and will stay in place for longer time. As such they may be expected to have “a” footprint on the marine environment around and underneath them.

Part of the monitoring system should be aimed to represent the impact of the structure on the marine environment. Proposed factors to be to included are:

- Marine growth on the floaters and mooring arrangement. (ref also 4.1.4)
- Emitted noise above and under water
  - SLP recalculated at 1m in dB ref 1 muPa under water.
  - SLP recalculated at 1m in dB ref 20 muPa above water.
- Water quality around the island in terms of temperature, waste,
  - Ambient temperature seawater [deg]
  - Temperature waste water flow [deg]
  - Volume flow of waste water [m^3.s^-1]
- Effects on the marine life in the water column underneath the platform
  - Estimated density of bio mass in the water around the structure [t / m^3]

4.2 Measurement devices

4.2.1 Wind waves and weather

Obtaining adequate marine environmental observations from the ocean areas of the world has long presented a serious challenge. Observations of synoptic weather and sea conditions are considered sufficient only along major shipping routes. Marine forecast accuracy will be optimised by a balanced, well-conceived observation network that can provide input to numerical models and operational forecasters. In addition to ship reports, observations in the offshore and coastal areas are provided by satellites, radars, buoys, and other Ocean Data Acquisition Systems (ODAS). Each observing system has strengths and weaknesses, and each tends to complement the others.

All of the above mentioned systems are valuable. Ship observations are absolutely essential to the World Weather Watch (WWW), the World Climate Research Programme (WCRP), and other programmes. However, it is becoming increasingly difficult for individual ships' personnel (whose numbers are decreasing) to maintain meteorological observation schedules. Ship reports tend to be concentrated along shipping lanes, which leads to data-sparse areas outside these routes. The quality of **ship observations** varies considerably from ship to ship. This is probably caused by differences in individual instrument exposure, sensor maintenance, and differences in the level of training of personnel. Finally, ships tend to avoid areas of rough weather and seas, where observations usually are most needed.

Satellite imagery gives an unparalleled, broad view of weather patterns. Its utility, however, is dictated by satellite type and location of the weather with regard to the satellite position. Satellites with all-weather microwave instrument capability and the ability to provide global observations of many marine environmental parameters are becoming operational, but there will still be shortcomings in data coverage and timeliness. The data however is often used to feed and tune numerical weather models with continuous spatial and temporal coverage. Example services that provide satellite based wave and weather data are NOAA, Copernicus, ERA5.

Coastal radar is a very useful tool for detecting precipitation and severe weather approaching land. However, its value is limited by range and, in some places, by topography.

Drifting and moored wave buoys have been found to be very effective in improving weather analysis and forecasting in data-sparse marine areas. It offers the only means of obtaining real-time, continuous, frequent, and accurate observations of marine conditions from the same deep-water location. Often, the first indications that forecasters have of rapid intensification or change in movement of storms come from buoys.

Buoy data are also an important source of observations for research studies, since they are usually the most accurate marine data available and normally one of the few long-time-series data sets from fixed locations. Research programmes on the marine boundary layer, wave generation and propagation, climate, pollution, etc., frequently use buoy data.

Weather buoys are often also equipped with combined sensors for wind speed, barometric pressure, wind direction and air temperature etc. Raw data is processed and can be logged on board the buoy and then transmitted to meteorological centres onshore or in this case to one of the control rooms at the Space@Sea floating island.

Figure 17 Moored wave + weather buoy

An operational downside to prolonged operation of wave and weather buoys is the sensitivity of the mooring to mechanical damage. Buoys often are lost, in particular in areas with dense traffic.

Remote sensing wave radar

Many developments occurred over past decades in field of objective wave surface measurements using marine X-band radar. Since the introduction of radar in mid previous century already it was clear that wave crests could produce reflections in the radar image. This noise or sea clutter was typically filtered off. Since mid-1980 this clutter has been investigated for its merits to estimate wave conditions. Commercial systems are presently available that can capture the directional wave spectrum from radar observations up to 2 nautical miles away. Wave directions, envelopes of wave trains and wave groups can be predicted from the observed data (NextOcean).

More recent developments of past 5 years using FMCW Doppler radars in X-band range enabled capturing of direct wave heights from observed Doppler velocity readings (Radac – MARIN) with a solid state phased array radar.

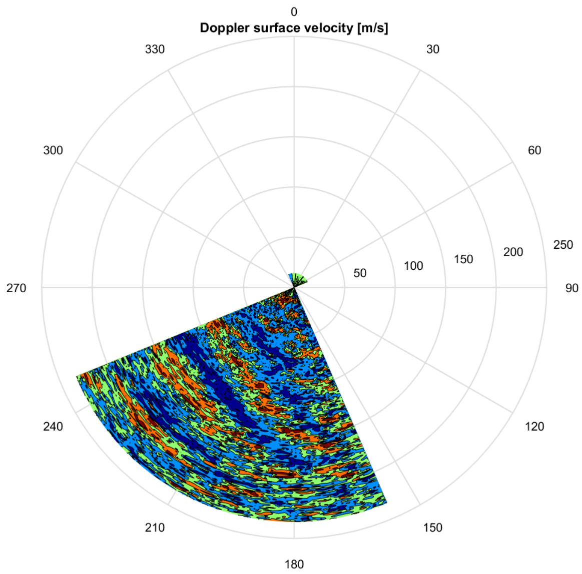


Figure 18 Remote sensing (0-300m near range) FMCW wave radar

Developments in remote sensing wave observations are expected to mature into commercial off the shelf wave sensors that can be operated of stationary moored structures as well as (fast) sailing ships over coming 3 to 5 years.

Output parameters of wave sensor devices can vary from:

- Time series (buoys)
- 1D and 2D energy and directional spectra (buoys and radar)
- Scalar parameters for descriptive quantities as for instance: Hs, Tp, Direction, Spreading, wind sea, swell

Wind loads

Classic wind measurements are performed using Anemometers. These provide time series of wind and direction as function of time at the sensor location. Results are typically corrected to account for effects of the mounting location as upwash or blocking. The measured data can then be further processed to reference values as mean values, gust velocities, etc.

Figure 19 Classic and ultra-sonic Doppler velocity anemometers

Classic anemometers have moving parts. Modern variations based on ultrasonic Doppler velocity sensors provide solid state solutions. Three typical concepts are shown in Figure 19. Newer sensor concepts are developed for remote sensing of wind fields. These include LIDAR wind profiler systems that can capture wind velocity up to kilometres away. These can be used to profile wind velocity as function of height, spatial distribution and possibly anticipate approaching gust or line squalls.

Figure 20 LIDAR based 3D wind scanner

The output from a LIDAR scanner has to be processed to provide a true wind field. The output is highly detailed. Further processing is needed to isolate scalar type quantity parameters that allow for state representation and long term trending.

Current sensors - ADCP

Current is typically observed by means of Doppler based ADCP or acoustic Doppler current profiler.

The measurement device adopts typically 4 or more acoustic transducers to observe the velocity in line with the beam at varying distance and range cell distribution. The combination of the results from the differently aligned beams provides estimates for the 3D current velocity vector as function of depth / range under the sensor in case of ship mount, or above the sensor in case of bottom mounted.

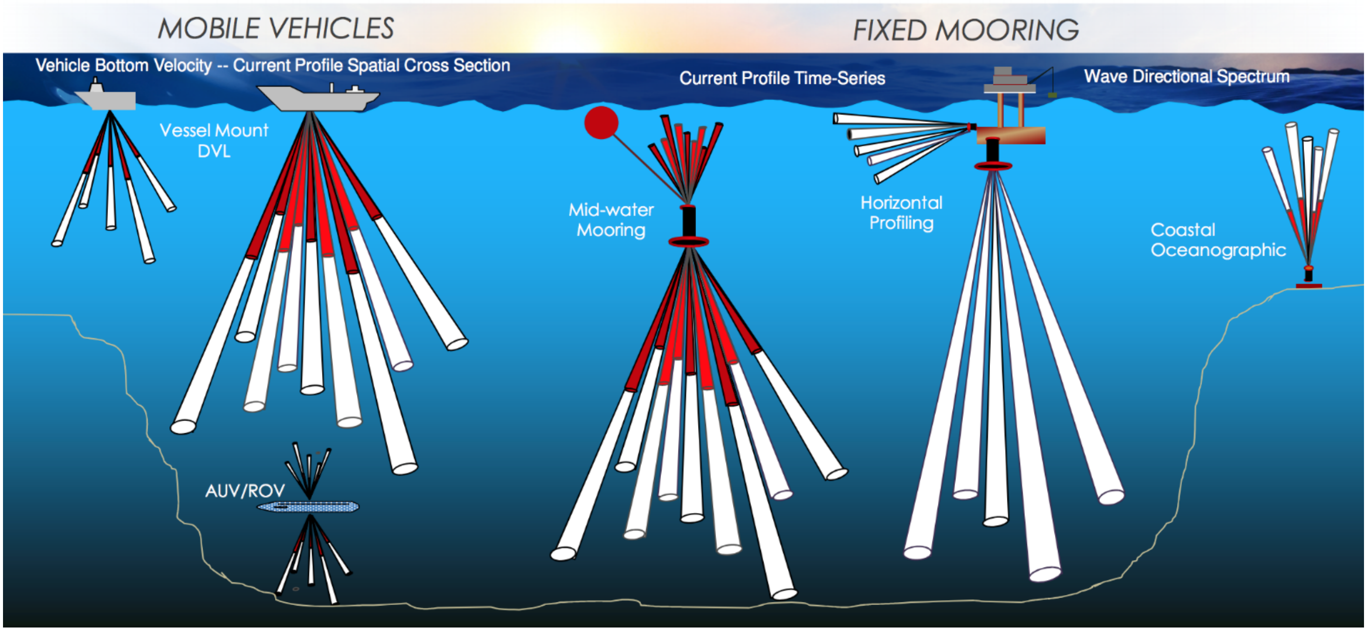


Figure 21 ADCP concepts - Rowe Technologies

A floating island would in principle only require a single weather data input to retrieve environmental data for the entire Space@Sea floating island. Weather buoys, like other types of weather stations, measure parameters such as the wave height, dominant wave period, water temperature, wave directions but also water temperature, water quality,

4.2.2 Traffic by ships and aircraft

Typical traffic monitoring above water is achieved by marine radar. Referred is to regular short and long range navigation radars and AIS receivers. The output of these equipment includes high resolution video, in combination with metadata as tracked AIS contacts, highlighted markers, radar settings etc. Data volumes can be high.

In addition to traffic from surface ships and aircraft, floating island O&M is anticipated to involve with regular deployment of ROV and UUV equipment. Keeping track of deployed equipment may become of interest at some point. Acoustic underwater trackers and transponder technology is available in the market to determine location of actively pinging targets. Side scan sonar equipment may be used to track for under water vehicles in known areas. It is not known if wide area equipment exists for non-defence application.

4.2.3 Floater ballast condition state and control

It is anticipated that a ballast monitoring and management system will have to be in place because of safety considerations and the fact that the structure could be too large to oversee without “control and automation” assistance. This is expected to include at least:

- Draught monitoring
- Ballast tank monitoring

- Pump and valve actuators.

Draught monitoring can be done with pressure transducers, or ultrasonic range measurements. Typical installation is hooked up with a pressure transducer through a valve in the shell, or by means of a vertical range or sounding pipe with an ultra-sonic range transducer looking down through the pipe. The sounding pipe can be located outside the shell, or inside in which case it has to be fitted through the shell with a valve.

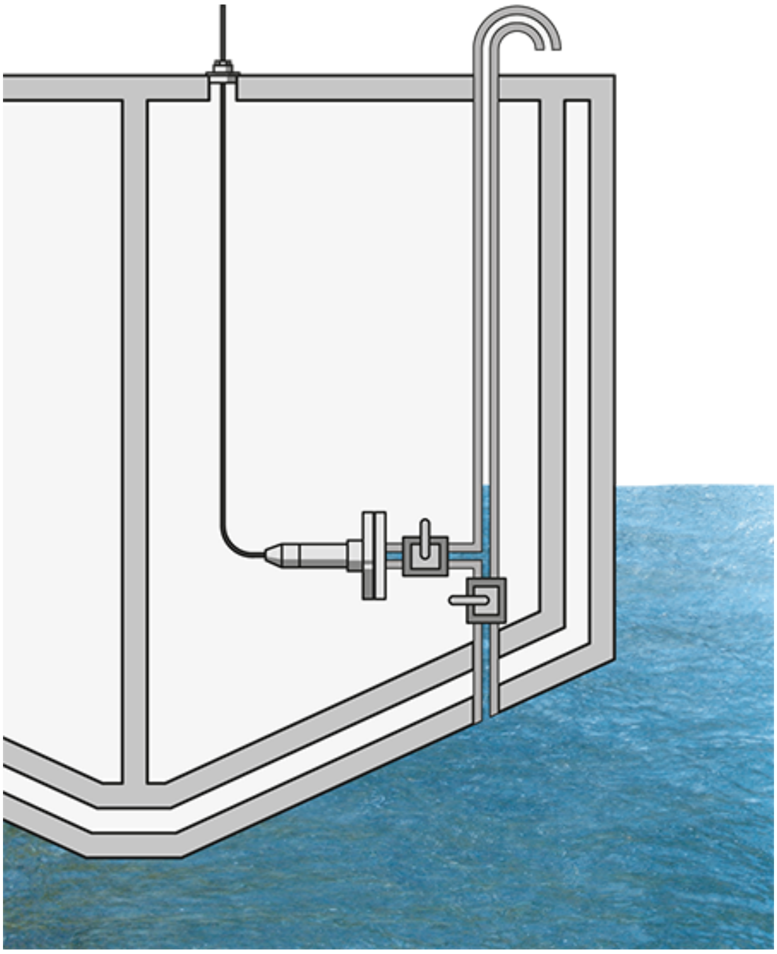


Figure 22 Internally mounted draught sensor

In order to represent the draught and inclination of a module each floater module should be outfitted at least with a draught sensor in combination with accurate list and trim indication, or with three draught sensors if no list and trim are captured. Because of redundancy, cost of draught sensors and low cost of tilt sensors, it is expected that a solution with two draught sensors in combination with redundant inclination measurements will be favourable.

Ballast actions in response to decision to change load lines can be manual or remote operated. In case of manual operation the ballast pumps, valves and water ballast tank soundings may be done locally manually.

In case of remote operation, the DCS should be outfitted with tank gauges in each water ballast tank, and control and feedback of status to valves and pumps.

The ballast management system arrangement includes piping, pumping and control system similar to regular ship installations and is not further elaborated in this report.

4.2.4 Floater motions

When deformation of a floater is small, individual floater motions can be represented by 6 degrees of freedom for a specified reference point. These are 3 translations in x, y and z direction, combined with heel, trim and yawing angles around the same x, y and z direction. The translations and rotations together define the overall position and attitude of the entire domain of the specific floater. So when motions are known in a single reference point, then motions in a remote point assuming a rigid body can be calculated by linear extrapolation under small rotations, or by full 3D transformation using a Direct Cosine Matrix or a quaternion transformation. The latter is simple math. The challenge is to capture the motions in the reference point to required accuracy.

It is further noted that motions, velocities and accelerations are directly related as they are time derivatives of each other. Measurements of motion measurements can thus be grouped in 3 types focused on displacements, velocities or accelerations.

There are different concepts to capture motions of a floating object. Following are recalled here:

- Inertial measurement using spring supported mass. Inertial loads due to motions and motion periods result in changes of the load and displacement of the spring. Either the load in the spring or the displacement is electrically measured by the acceleration transducer and forwarded to the measuring device.
- Inertial measurement of the rate of turning or turning velocity. These are based on gyroscopic precession. Classic solutions used (expensive) rotating gyroscopes but modern bulk produced sensors are based on oscillating cantilevers. Turning rates along the longitudinal axis of the cantilever beam result in out of plane bending of the beam which is electrically measured and forwarded to the measuring device.
- Laser ring gyro and fibre optic gyro turning rate measurements. The measurement principle is based on changing propagation speed of light along a loop that rotates in global coordinates. The optic interference pattern between input and output signals is detectable with common data communication grade optical sensors and provides highly sensitive output with extremely low drift and bias error. Both laser ring and FOG based sensors can be sufficiently accurate to detect the earth rotation rate of 15 deg/hr and thus enabling to find true North indication. The principle of measurement however is focused on turning velocity.
- GPS position measurement. The absolute position of a GPS receiver in earth fixed coordinates can be obtained to ~1 metre accuracy using reference signals from series of Satellites orbiting the earth. By combination of multiple receivers, also rotations may be obtained. GPS systems provide absolute position output, and can in addition provide absolute velocity indications from Doppler shifts in the carrier waves received from the satellites.
- Magnetic compass heading measurement. Where heading alignment is related to the projection of the earth magnetic field vector onto the horizontal plane. Magnetic compass output provides a direct rotation indication which can be affected by local factors as magnetic inclination, deviation and electromagnetic interference soft iron magnetic bias. On large steel structures the signal to noise ratio for magnetic compass operation is often poor.
- Velocity indications from speed log, or propeller RPM

Over the past 10 years, inertial based sensors have been included in standard low grade personal equipment as phones, cars, computer games and toys. The bulk production and R&D around IC chip silicon based MEMS sensors has boosted their performance. Rugged and extremely low cost sensors are now commercially available with OEM sensor parts costing under 10 Euros. Performance of these sensors has increased by the possibility to operate them with smart noise cancelling algorithms, and by combining multiple units to further maximise signal/noise ratio.

Part #	Gyro Full Scale Range	Gyro Sensitivity	Accel Full Scale Range	Accel Sensitivity	Digital Output	Logic Supply Voltage	Operating Voltage Supply	Package Size
UNITS:	(°/sec)	(LSB/°/sec)	(g)	LSB/g		(V)	(V +/-5%)	(mm)
 ICM-20948	±250 ±500 ±1000 ±2000	131 65.5 32.8 16.4	±2 ±4 ±8 ±16	16384 8192 4096 2048	I²C or SPI	1.7 - 1.9	1.71 - 3.6	3x3x1

Figure 23 Consumer electronic 9 DOF MEMS sensor for 3D acc, gyro and magnetic.

The challenge for inertial based motion and attitude measurements always remains in the decreasing signal to noise ratio of velocities and accelerations with lower motion levels and long motion periods. This is because for quasi-stationary displacement, the motion period increases to infinity and corresponding velocities and accelerations drop to zero. There will always be some level of electronic noise and on ships and offshore floating structures there will be further noise levels by vibrations and operations that can be substantial while motion induced acceleration and velocity levels are extremely low.

Dynamic motions around known equilibrium positions can generally be captured well with inertial based instruments. But quasi-stationary motions with long periods require absolute motion or rotation reference measurements.

Other or additional measurement input are used to determine motions with quasi-static character. Most common approach is by combining inertial measurements with quasi-static inputs for heading, vertical reference, and absolute position. Quasi-static references are obtained:

- GPS position updates in 3D providing quasi-stationary position
- Depth or altitude sensors providing vertical coordinate to reference sea level
- Earth gravity true vertical which is included in the 3D acceleration results for heel and trim.
- Magnetic or true heading reference from (fibre optic gyro compass, magnetic compass, or GPS reference.

Figure 24 Various grades inertial navigation systems - IXsea PHINS / Xsense MTi series

Data fusion algorithms are used to determine motion parameters that match the quasi-stationary measurements as provided by the absolute motions reference for longer term, and the usually much more high frequent inputs from the inertial measurements for the short term. Various more and less complex data fusion algorithms are used.

Common algorithms in use are (extended) Kalman filters for higher end sensors and complementary filters for low cost solutions.

Prices for integrated solutions vary from

- low cost ~1500 Euro for high signal to noise ratio applications as in small boats, cars and drones,
- medium cost 10 kEuro for marine applications including accurate heave compensation.
- high end 100 kEuro for high precision attitude, north seeking, and even under water operation

It is expected that the low cost of MEMS type of sensors may be a favoured solution in combination with low cost GPS. The large number of floater modules to be instrumented calls for low CAPEX solution, and the expected short motion periods suggest that signal to noise ratios will be fair

4.2.5 Loads in structure, chain stoppers and connectors

The interaction between the various parts in the island and the floaters are transferred as loads. As such they are an important aspect of the evaluation of the now state of the island, and how that relates to the design. That is necessary for structural health monitoring of

- Floater structures internally
- Linking joint connectors
- Mooring lines.

A distinction is made between direct and indirect load measurements.

Direct Measurements

These appear to be the most common sense approach to measure loads by inserting calibrated load cells between the interface where the forces and loads are to be monitored. This can provide a “direct” measurement of the load quantity via a calibrated load cell. The size and the operational procedures to build and hook-up marine floating structures to each other and to mooring arrangements however impose constraints.

- Direct measurement of internal structural loads is general not possible as continuous structures cannot be interrupted to insert calibrated load cells.
- The design of linking joints is challenging in terms of transferring the expected loads, constraining unfavourable relative motions and trying to allow for some flexibility to share loads between the statically over determined spread of connectors. Inserting calibrated load cells will thus require custom designed sensors to be sensitive to exactly the load components that are of interest. Measurement Device Properties as selectivity, sensitivity, will be determining feasibility.
- Direct measurement of mooring line loads is complicated by their installation procedure. The bottom end is fixed to the anchor point. A load sensor could be installed prior to installation there. In case of the Space@Sea Mediterranean concept the sensors will be piled underneath the sediment layer and will likely not survive. The top end of the mooring line is tightened to the mooring line connector during installation. Options to perform direct measurements might be considered with shear pin type solutions, or wire rope load cells. Shear pin solution are in line with the load path. They have to be installed prior to hook-up and cannot be easily maintained or replaced. Wire rope solutions might be possible to consider as they can be retrofitted but they are complicated from a mechanical point of view and are not easily adopted to operation with heavy load chain moorings.

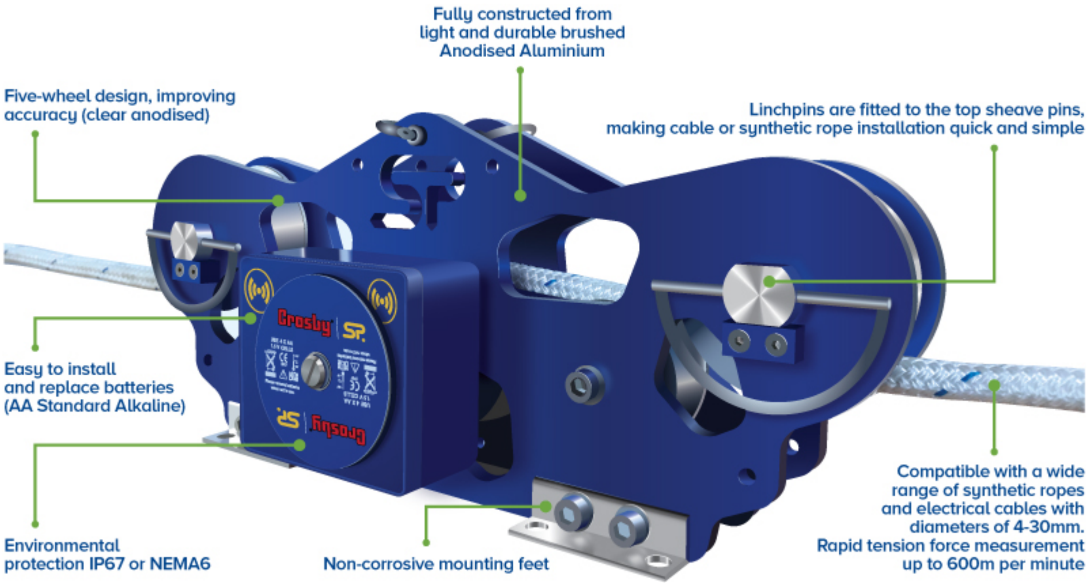


Figure 25 Wire rope loadcell for retrofit direct line load measurement

Indirect measurements

The deformation of the load carrying construction is often used as an indirect measurement of the transferred load. This approach can be used for measurements of structure internal loads, as well as mooring loads and connector loads.

The principle is that applied loads to a structure will induce a given deflection or deformation pattern in the structure that can be measured. If the deformations are a continuous and preferably linear function of the applied load, then the load can be determined from observed deformations if the observed deformations are selected properly.

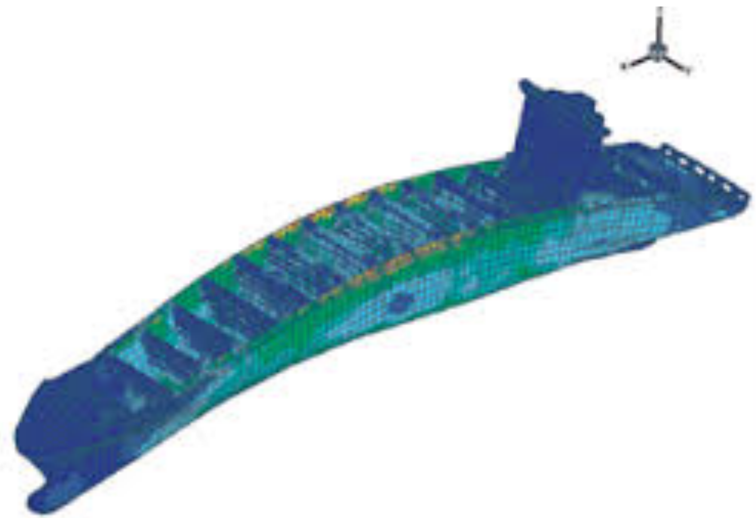


Figure 26 Calculated structure strains as function of applied (wave) load

Hull monitoring and advisory systems are becoming normal practice in shipping and offshore industry. Structural loads as bending moments, torsion moments and axial loads may be related to measured strain or stresses by combining measured results with transfer functions as can be calculated using design tools as FEM, hydro dynamic diffraction and CFD codes.

The detailed design of the floater modules suggests solutions in steel or concrete. Hot spot and cold spot stresses and strains should be measured in the floater structure to measure internal loads, but also to check internal stress levels and loading against material specifications. Strain sensors are commercially available on the market to be casted inside concrete structures or retrofitted to any structure.

Following, approaches are listed as indirect measurement for structure loads:

- Material strains and stresses in structures using strain and displacement sensors. Strain sensors can be regular foil type strain gauges that are glued, wired and protected, but also (spot) weldable strainguages, long base straingauges, fibre optic strain sensors and vibrating wire sensors.
- Deflection measurements using digital image processing

Classic hot spot and cold spot strain measurements are the most common approach to do strain and stress measurements. Two principal challenges are listed for indirect load and in particular strain measurements. These are:

- Cabling efforts that increase very fast with increasing sensor numbers, installation area and vessel compartmentation.
- Protection of the strain sensor and the mother material that is observed against electrical noise (moisture) and in particular corrosion of the motion material that will have a dramatic effect on sensor performance over long term.

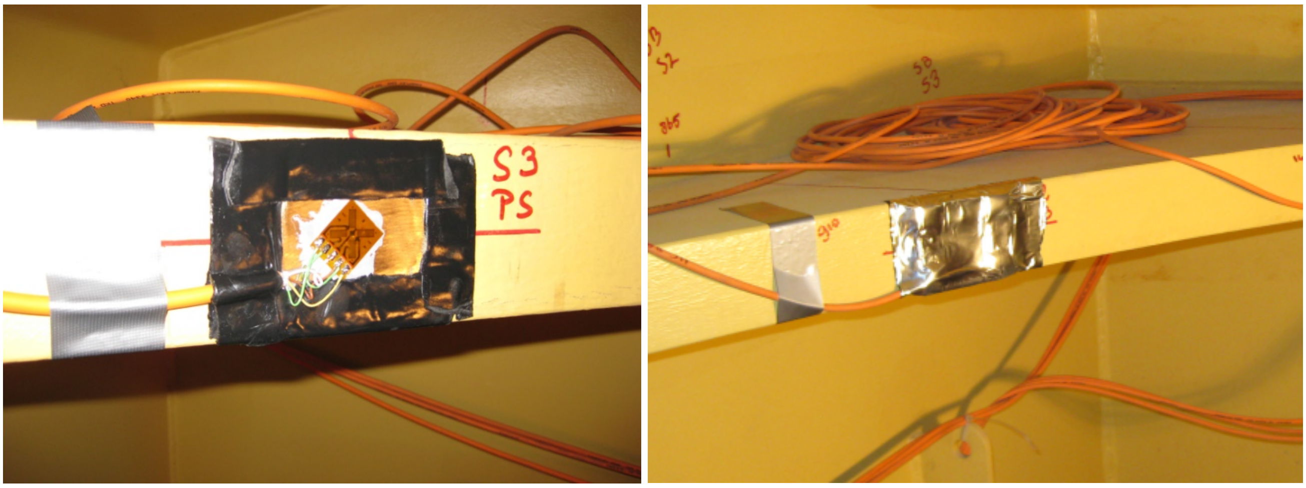


Figure 27 Regular bondable strain gauge requiring extensive protection against moisture and corrosion