Data Acquisition and Control for Marine Energy Devices: Cost Considerations

Robert Raye, Casey Nichols, Aidan Bharath,
Charles Candon, and Elena Baca

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Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

List of Acronyms

AWS	Amazon Web Services
CT	current transducer
DAQ	data acquisition
DMCP	Data Management and Communications Plan
FEED	front-end engineering design
HMI	human-machine interface
IEC	International Electrotechnical Commission
I/O	input/output
M1 or M2	MODAQ version 1.0 or version 2.0
MHKiT	Marine and Hydrokinetic Toolkit
MODAQ	Modular Ocean Data Acquisition
NREL	National Renewable Energy Laboratory
PT	potential transducer
QA	quality assurance
QC	quality control

Executive Summary

This report outlines key considerations for stakeholders in the marine energy sector who are planning a data acquisition campaign to support testing and validation of marine energy devices. Numerous factors must be evaluated to accurately assess the costs associated with such a campaign, and this report provides a foundation for estimating data acquisition project expenses. It highlights the crucial role of front-end engineering design, emphasizing the importance of developing a comprehensive and detailed plan before initiating device testing. Since device validation is a pivotal stage in advancing marine energy technologies through technology readiness levels, delivering a high-quality data acquisition system is essential to maximize return on investment and ensure efficient use of both time and resources.

NREL has developed a data acquisition system design known as the Modular Ocean Data Acquisition System (MODAQ), which has been adopted by marine energy device developers and is available publicly. The MODAQ 1 design is built on National Instruments hardware and software while the MODAQ 2 design uses hardware that is brand-agnostic and leverages free and open-source software. Using a MODAQ system as an example, this report highlights the considerations for data acquisition planning and design. A similar design approach can also be applied to non-MODAQ data acquisition systems. The examples outline cost and labor estimates for implementing a MODAQ system.

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1 Introduction

This report discusses the process to develop a data acquisition (DAQ) system for marine renewable energy technologies; however, much of what is presented is applicable to any applications that require data acquisition. Process details are provided to highlight the requirements and critical steps for a successful measurement campaign and to explain what can impact the overall outcome, cost, and schedule.

The process presented is an amalgamation of best practices, lessons learned, recommendations, and prudent technical project planning and management. DAQ systems may be tightly integrated with the device being measured and often have their own dependencies. Therefore, early consideration for the DAQ system is stressed throughout this document.

1.1 Data Acquisition

In the strictest sense of the term, DAQ refers to the hardware component and associated firmware or software that samples a signal from one or more input channels. The DAQ system (or simply "DAQ," as used in this report to mean a DAQ system) is just one link in a chain of components that might include a controller, logger, communications components, human-machine interface (HMI), and special-purpose input/output (I/O) modules.

A DAQ by itself is fairly limited and depends on a computer or controller to issue instructions and to receive and process the acquired data. There is not a simple, widely accepted term that describes the complete end-to-end chain from sensor to dataset, so DAQ has become synonymous with several data acquisition architectures that might have widely differing features and capabilities. For simplicity, this report uses the term DAQ to describe a complete system that acquires, processes, logs, and communicates data, unless otherwise noted.

For context, these are the major components found in a DAQ and their functions:

- **Input and/or output module**: These modules can have one or more channels (or ports, or lines) that convert a signal from a sensor or instrument into a digital representation that can be processed or manipulated by the controller. I/O modules frequently include filters, amplifiers, and/or other processing circuitry to clean up or enhance the signal, all of which affect the overall cost of a measurement. In the case when the input signal is already digital, the signal is likely in a format or protocol that needs to be decoded or converted by the module to be understandable to the controller. Several standard digital signal formats exist; however, with continuous advances in sensor technology, the form of digital signals and how they need to be handled can vary widely.
- **Controller**: The controller is the brains of the operation, and it may perform many functions depending on the use case, such as:
    - Acquire the digitized data from the input modules
    - Manage timing and synchronization of data from multiple sources
    - Apply signal processing to the data
    - Apply scaling and/or offset values

    - Convert the data to preferred engineering units
    - Apply basic quality control (QC) screening to the data
    - Save the data to a file
    - Plot or display the data in an HMI
    - Accept user input from an HMI
    - Perform control logic
    - Issue email alerts
    - Copy data to/from a remote location
    - Monitor for and handle exceptions.
- **Communications**: Communications hardware allows near-real-time reporting of the measurements or system status. It may also allow for remote access to the controller for operator control or maintenance. A wide variety of communication frameworks exist with their own benefits and limitations. Through the design phase of a DAQ, an appropriate communications framework is chosen to best suit the needs of the user.

DAQs can be configured in three basic architectures:

1. **Tethered**: A computer or laptop executes the DAQ software and serves as the controller. It will often have one or more connected devices that sample the input signals. This configuration is common during bench or in-lab testing. Benefits of this configuration include few or no restrictions to the system footprint, access to power, data storage, a secure location to house equipment, and continual access for configuring and testing system performance. The tethered configuration is ideal for exploratory work with a test article given the level of access and configurability of the DAQ.
2. **Integrated**: A dedicated controller is either packaged with or coupled with the sampling hardware as a complete system. The system is often embedded in/with the test article. This is the most common configuration, particularly for deployed test articles, and it can behave like a tethered system if cabling options are available. Integrated systems tend to require a more rigorous design because they may have specific installation locations or because of how external systems or the test articles interact with the controller. This configuration is well suited for test articles that will be field tested, as they can be designed and built to run without continuous interaction and to operate for a specific length of time.
3. **Distributed**: This is a hybrid configuration that can have one or more controllers and/or sampling hardware devices that work together through interconnections. This modular approach is ideal for instrumenting large devices (moving the sampling closer to the sensor location and reducing the number of wire runs), separating the hardware into distinct zones, and expanding the system to accommodate high channel counts. The distributed configuration provides several benefits to system redundancy and risk, as the data acquisition work is spread across several DAQs. The trade-off is generally greater overall system complexity to achieve communication, synchronization, and interaction between the distributed systems.

1.2 Control, Automation, and Supervision

A DAQ, by definition, acquires a signal, but a DAQ may be configured to issue a signal as well. That output signal may depend on acquired input signals and some programming logic. The DAQ is considered to be "controlling" whatever device is receiving the output signal. This is the basis for a control system.

As discussed later in this report, a control system can range from simple to complex. A simple control system might open a valve when a pressure measurement exceeds some value and close the valve when the pressure drops below another value. A more complex control might try to maintain a steady pressure by continuously controlling how much a valve is opened. The complexity can grow from there and approach automation. Automation may be in the form of a sequence, where a collection of individual control rules are executed in or out of order based on the states or values of one or more parameters.[1] Another type of automation might be in the form of a state machine, where the logic in one state might determine which state is executed next.

Unless the control logic is run at high speed or incorporates complex mathematics or numerical models, even complex rules can be run on modest DAQ controllers. For example, the flight controller on a quadcopter (drone) considers numerous discrete inputs simultaneously, such as rotor speed, accelerometers, gyros, GPS position, and user inputs, to control the speed of each rotor independently to move the drone where the user commands. This operation can be done on a controller that cost less than $50 (not including the sensors). That said, control rules come with a cost: increased development time and effort. With increasing control rules or rule complexity, the likelihood of conflicts or unintended actions increases as well. Therefore, extra effort is necessary to understand how rules might impact the system or other rules.

1.3 MODAQ

The Modular Ocean Data Acquisition (MODAQ) system is a data acquisition solution developed at the National Renewable Energy Laboratory (NREL) to support validation and testing of marine renewable energy technologies in both the laboratory and open water.[2] It is a robust system built on industrial-grade hardware that can acquire high-quality measurements from many sensor and instrument types. MODAQ includes modules to perform real-time QC screening, monitor system health, and issue alerts. MODAQ is the larger data management, processing, visualization, and archiving system.

MODAQ can support a wide range of missions in various marine energy environments (wave, current, tidal, river); it also supports different device archetypes and size scales. Because projects rarely have the same measurement objectives and requirements, MODAQ is designed for flexibility to adapt to individual use-case demands.

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[1] A parameter is an engineering value of interest that is obtained by a sensor or instrument. Parameters can be either direct or derived. For example, a rotary encoder measures the shaft position as a direct parameter in degrees or radians. Revolutions per minute or angular rate are derived parameters that are calculated from the change in position with respect to time.

[2] For more information about MODAQ, visit https://www.nrel.gov/water/open-water-testing.html.

1.3.1 The MODAQ Suite

MODAQ is an end-to-end solution for acquiring, processing, storing, and displaying measurement data.

MODAQ:Field

MODAQ:Field is the sensor and instrumentation system with data acquisition hardware. It is designed to be highly configurable to meet the measurement requirements of a specific project.

MODAQ:Field is the name given to the actual DAQ hardware and software system to distinguish it from the MODAQ internet-based services. For simplicity in this report, the term MODAQ refers to MODAQ:Field.

MODAQ:Cloud

MODAQ:Cloud is hosted on Amazon Web Services (AWS) and provides an ingestion point for the field data as well as quality control, processing and analyses layers, data archives, derived products, and collaboration space. Standardized data processing is accomplished by leveraging the Marine and Hydrokinetic Toolkit (MHKiT™) and the Marine Energy Data Pipeline. With AWS, very large datasets can be processed efficiently and collaboratively. MHKiT is an open-source marine energy data processing software that provides the analysis functions for MODAQ. The ME Data Pipeline is a suite of open-source code for standardizing and applying quality control to data.

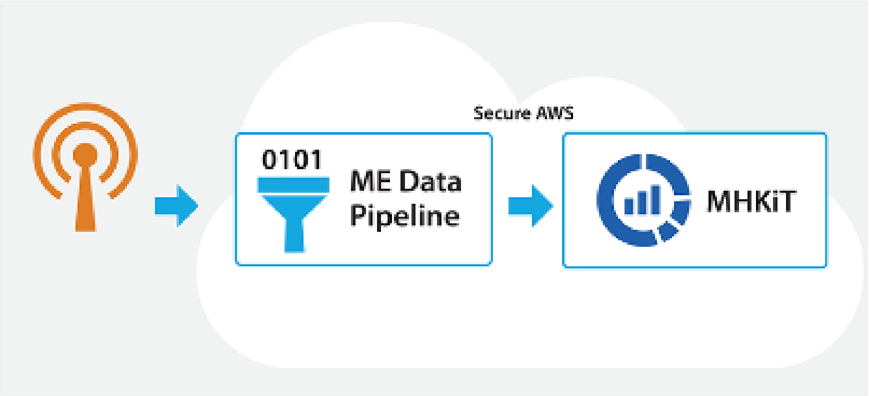

Figure 1. A simple diagram illustrating the data flow for MODAQ:Cloud

MODAQ:Web

MODAQ:Web is a web-based dashboard for near-real-time monitoring of key measurement and health parameters. For bandwidth-sensitive deployments, MODAQ:Web uses summary data generated by MODAQ:Field that are transferred to their own AWS bucket and stored in a SQL database.

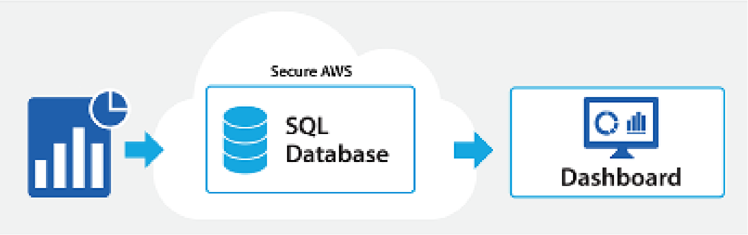

Figure 2. The data flow for MODAQ:Web

The configuration of a MODAQ system is highly flexible and scalable. MODAQ uses a modular approach that allows the system to be easily configured to meet measurement requirements or to be reconfigured as requirements change. MODAQ can be configured to meet the rigorous requirements of International Electrotechnical Commission (IEC) certification-level testing. All MODAQ systems are built for high-quality measurements, reliable operation, and harsh service conditions.

Some of MODAQ's capabilities include:

- Data acquisition: bidirectional analog (current and voltage), and digital (RS-232/RS-422/RS-485, DIO, USB, IP, etc.) channels, including temperature, loads/strains, rotations/positions, and pressures
- High-speed analog sampling where necessary
- Remote management: reconfigure MODAQ and data processing algorithms and monitor/control power to individual components
- Data QC: a range of high-level QC checks to verify sensor, instrument, and DAQ operation
- Data conversion: data are converted from their raw form (i.e., binary, ratiometric) to scaled values/engineering units
- Local data storage
- Internet and/or local area network file transfers
- Configuration utility
- System monitoring and alerts: real-time monitoring of specified parameters, such as position, temperature, power, and others, with tiered email alerts
- IEC-compliant software modules for power performance, power quality, and mechanical loads; other modules include motion, availability, and control
- Control and automation.

MODAQ is highly performant—even with complex designs. Much care goes into assuring data are time-stamped to a reliable reference and samples are tightly synchronized. For very demanding applications, specialized hardware and programming considerations may be necessary to achieve expected performance.

The first generation of MODAQ was built on National Instruments hardware and coded using the LabVIEW Professional Development System. While MODAQ v1.0 (M1, hereafter) has proven itself in both the field and laboratory, several factors have indicated the need for additional solutions that were not well served on the M1 architecture. This led to the development of MODAQ v2.0 (M2). M2 leverages the broad market of industrial controllers and single-board computers, which allows for scaling from tiny, battery-operable designs to powerful systems with nearly limitless expansion. In addition, the M2 code base is written in C++, which has a large user base and support community and does not require expensive licenses and development tools. That said, M2 is an alternative to M1, not a replacement.

Note: Whenever the term DAQ is used in this document, the discussion also applies to MODAQ. However, where the term MODAQ is used, the discussion may be about a unique feature of MODAQ or a feature that is not commonly found on general DAQs.

2 Planning and Design

In an ideal world, the planning and design of a system to acquire measurements and control outputs should be considered in the early stages of the host device's design or in the early stages of project planning for the following reasons:

- It may be necessary to include a sensor or other provision in the general design, such as building a load cell into a shaft assembly to measure torque or providing hull penetrations for cabling. These can be non-starters after the design is finalized or after fabrication.
- Space, weight, and power may need to be allocated for the DAQ and its sensors/instruments and cabling.
- In some cases, permitting or other approvals may need to be secured that have long lead times.
- The DAQ design engineers may offer valuable input to get the most from the measurement effort.

Sufficient time and budget might not be allocated for designing and integrating an effective DAQ solution if it is not considered in the early planning stages, which can lead to significant opportunity loss of data and could negatively affect project objectives. Early engagement with DAQ engineers during the general design process can minimize cost, compromise, and frustration.

2.1 Project Definition

To efficiently execute a data acquisition campaign, it is important to identify project goals, objectives, system requirements, and measurement expectations early in the process so the system design team, deployment team, DAQ engineers, project management and other stakeholders can review what is planned, and a well-defined path of execution can be determined. This section highlights these aspects of project planning and design in greater detail.

2.1.1 Project Goals

At a high level, it is useful for the project technical leads, management, and relevant stakeholders to have a clear set of goals prior to designing a DAQ system. Goals can be driven by project deliverables or milestones, research interests in model validation, device performance optimization, or obtaining device certification for power performance. In some cases—particularly for projects with a high level of scrutiny—review processes and reporting may dramatically affect budgets, timelines, and DAQ objectives. With clear project goals, planning and design can become far simpler.

An example project goal might be to develop a scale prototype of a seawater desalination system that is powered by an onboard wave energy converter. The system will be instrumented and deployed in an oceanic environment to determine performance characteristics and to validate numerical estimations.

2.1.2 System Objectives

System objectives tend to be high-level drivers that guide the data acquisition (and control) design and execution. System objectives are what the DAQ must fulfill to achieve the project goals. If an objective is unmet, it could lead to an unfulfilled project goal, which would disappoint the project sponsors or render the entire project a failure. Therefore, it is important to manage expectations by defining the system objectives through design iteration between the project team and DAQ team to determine if they are practical, realistic, and achievable within the constraints of time, budget, and available technology.

Using the example of a seawater desalination system, a DAQ system objective might be to collect continual measurements of pressure in the line that moves seawater from the wave energy converter to the shore-based desalination system. It is important to distinguish the objectives of the DAQ system from those of the project. In this example, the project goal is to validate numerical analysis, whereas the objective of the DAQ is only to deliver the data required for the numerical analysis.

2.1.3 System Requirements

Requirements are the specific factors that define and/or constrain the design, capability, operating conditions, and overall specification of the system. System requirements describe the constituent parts that support the defined project objective. Some examples of MODAQ requirements might include:

- Specific values to measure
- Measurement quality expectations
- Measurement range of the values
- Standards compliance
- Data management plan
- Deployment location and duration
- Maximum weight, size, and/or power budget.

Requirements can be classified as “shall,” “should,” or “may,” which determines the level of flexibility allowed in meeting the requirements and which requirements can be considered optional or aspirational. The DAQ engineers take all requirements into consideration and develop a strategy to meet those requirements. It is not unusual for two or more requirements to conflict, such as an aggressive sampling strategy for an extended duration powered by batteries. The definition of system requirements begins the design spiral, where alternative solutions or trade-offs are considered to balance conflicting factors, or the requirements are revised to align with fixed constraints. Evaluating requirements for feasibility early in the process is vital to for addressing issues and engineering viable solutions.

Continuing the desalination example, the DAQ system shall be required to measure pressure in the range of 0–150 pounds per square inch at a minimum of 10 Hertz over the course of at least a 2-week deployment on the inflow pipe from the wave energy converter to the shore station.

2.2 Constraints

As mentioned earlier, there are often constraints that shape the design of the DAQ, which may be imposed by limitations of the host platform, costs, environment, or physics. Regardless of their source, constraints often result either in compromises elsewhere in the DAQ design or in clever workarounds.

Known constraints should be communicated to the DAQ engineers along with the general measurement requirements. While it may be difficult to determine which constraints are relevant, it is better to overcommunicate than to face roadblocks or change orders at a critical juncture in the project. For instance, if cable transits are used to pass cables through bulkheads or the hull, and only one position is currently available, that could constrain the DAQ design, especially if additional penetrations are disallowed.

The following is an actual example of a host system with significant constrains and demanding measurement requirements:

> **Objective**: Measure strain on the blades of a marine current turbine while deployed and operational in the water.
>
> **Constraints**:
>
> - Unable to include sliprings to pass power and data communications between the fixed and rotational parts of the turbine because the host was in the final stages of fabrication, and adding sliprings would be a major engineering challenge
> - Hub will be flooded, so DAQ must be self-contained in a submersion-rated enclosure
> - No hotel/host power available for the DAQ
> - Materials must be selected to minimize corrosion or galvanic coupling.
>
> **Outcome**: After considering the constraints and measurement requirements, a self-contained DAQ was proposed that would include sufficient battery power to last the duration of the deployment. This required the concession of a requirement for real-time delivery of the measurement data, as there was insufficient time and budget to engineer a viable solution.

In some cases, such as in the previous example, constraints inform the DAQ design and may limit its capabilities.

2.3 Scheduling and Budget

Schedules and budgets are often set long before the actual time and costs to execute a certain scope are fully known. They are usually based on notional estimates. Unfortunately, these early estimates often become the expectation in the eyes of the sponsor, with little room for renegotiation.

Time and budget may have been earmarked for a DAQ system in the project's master budget without consulting a DAQ engineer or setting the actual measurement requirements in advance. This is common with funding opportunities or requests for proposals or quotations that do not demand detailed cost, time, and resource analysis of the individual tasks in a scope of work. Due to the competitive nature of these opportunities, estimates might be overly optimistic or unrealistic.

A best practice is to attach a probability/confidence level to all time and budget estimates in the form of P*xx*, where *xx* is the percent certainty of the estimate. For instance, a P90 estimate is one with a 90% certainty of the time and costs presented. This would be considered a high confidence estimate and would usually carry a 10% contingency factor.

Creating a P90 estimate requires either a well-defined scope, complete with detailed requirements, constraints, and deliverable timeline, or a substantially similar repeat of a previous project's scope.

A well-defined scope may take time to define. First, a preliminary design needs to be developed. Then, components and suppliers need to be identified and quotes requested. If there are novel or challenging aspects to the scope, it may be necessary to do additional research to formulate an effective solution. Some of the front-end engineering design effort needs to be completed to get to a P90 certainty.

An estimate for a system substantially similar to one previously delivered may have a higher level of certainty because many of the project steps are fairly well known or already complete.

More commonly, estimates are produced on incomplete scopes and limited details. In this case, a confidence-based approach is useful to anticipate costs and time. Depending on the amount of information provided when requesting a quote or estimate for developing a particular DAQ solution, the P-level confidence might be in the range of P50–P75. Budgets should be adjusted with the corresponding contingencies to set expectations. P-levels can be different for costs versus schedule. For instance, the cost estimate may have a confidence level of P50, whereas the schedule could have higher confidence, such as P75. Outliers and surprises can occur in a project, but a conservative P-level can usually absorb unexpected occurrences.

2.4 System Specification

While objectives describe the overall mission in broad strokes, the requirements define the system expectations, and the constraints are special design factors. The system specification is the synthesis of these elements and describes the technical design of the system in fine detail. The system specification is both a prebuild description and final design basis deliverable. A map of some of the key considerations for system specifications is shown in Figure 3.

Figure 3. Map of DAQ system specifications

In its early form, the system specification is a plan written by the DAQ development team in conjunction with the project partner(s). During the design process, the system specification should be considered a living document that gets revised as:

- Hardware is selected and procured
- Per-channel sampling schemes are decided
- Output parameters and their attributes are defined
- General, on-controller functionality is defined
- Control rules are defined
- Schematics, line drawings, and wiring maps are developed.

While the software is being coded, the system specification guides the developer effort and serves as a checklist. The developer will consult the system specification, particularly the channel list spreadsheet (described in a following section), and write the code per the instructions. Similarly, coders responsible for developing the HMI and/or web dashboard will enable the functionality specified in the system specification.

Once the hardware assembly and integration work begins, the integrator will use the system specification as guidance for connecting components and placing each piece, instrument, and/or sensor. The integrator will record the as-built details in the system specification, which might include the wire bundle, wire color, and/or connector pin position of a signal wire; the calibration or scaling factor data for a sensor; and the serial numbers of the components.

2.4.1 Parameters and General Functionality

Marine energy converter designs vary significantly, so there are many possible measurement parameters that may be of interest to system designers. Parameters are the engineering values of interest that when captured and analyzed reveal complex properties of a system's behavior. A key aspect is the validation of numerical models that estimate the performance of a particular device or system. Depending on the complexity of the model, this could include mechanical stresses/strains, flow rates, pressures, position/velocity of degrees of freedom, as well as electrical voltages, currents, impedance, and efficiency. In addition to those used for model validation, there are many other parameters that may be necessary to measure to understand system operations. All of MODAQ's possible measurements should be considered when down-selecting the parameters to collect. Also, if the data acquisition campaign is informing the compliance to an IEC standard, the standard should be reviewed to ensure that all the necessary parameters are selected.

2.4.2 Performance Requirements

The specifications, capabilities, and quality of sensors or instruments available for a measurement campaign can vary considerably and can have a significant impact on the campaign's cost. Generally, the measurement objectives and stated requirements are considered, along with any constraints and environmental challenges, to select acceptable devices. Where standards compliance applies, a particular standard may specify the minimally acceptable specifications for a measurement.

Understanding the intricacies and impacts of specifications listed on a device's data sheet is a dense topic that instrumentation engineers spend years mastering; therefore, this report only provides a brief list of some of the more common specifications to consider:

- Accuracy: how close is the measurement to a reference (or actual)
- Precision: how repeatable is the measurement
- Frequency response and bandwidth: optimal frequency performance for time-varying signals
- Sensitivity: smallest signal detectable by the device
- Signal-to-noise ratio: relative strength of desirable to undesirable signals
- Filtering: rejection of undesirable signals
- Stability: amount of drift

- Settling time: minimum time needed for the device to resolve a measurement
- Update rate: time between successive measurements
- Output delay: difference between the time the measurement is made and when it is available to read by the controller
- Hysteresis: lag between the property measurement and the value experienced by the device
- Mean time between failures: measure of the failure rate of manufacturing samples of the device
- Ingress protection: resistance of the device to dust or water
- Certifications/calibrations.

Subjective qualities to consider include:

- Manufacturer
- Build material
- Subcomponent quality
- Vendor quality
- Documentation quality.

To determine the minimum performance requirements for a sensor, it is essential to understand the physical system and the underlying properties that are of interest. This often requires collaboration between designers, modelers, and DAQ engineers. The designers and modelers know how the system is expected to behave in operation, and the DAQ engineers know which sensors to use and the standard practice for capturing pertinent data. A sensor can be deemed sufficiently performant if the necessary specifications are met to achieve the desired measurement fidelity.

A recommended approach for selecting sensors is to record each sensor’s published specifications in a decision matrix and use a scoring system to identify viable candidates. Although the ideal sensor may not exist or may cost too much, the matrix will highlight alternatives that meet both system requirements and budget constraints.

Along with selecting sensors or instruments that align with measurement objectives and requirements, the sampling strategy for each data channel must be developed. The available performance and settings are governed by the selection of the I/O module. Of most concern are the sampling rate and bit depth (resolution); however, there may be other options for consideration, such as synchronization, filtering, and cutoff frequencies. Higher-end (more expensive) modules can sample their input channels simultaneously as opposed to sequentially. Simultaneous sampling may be a requirement for precise frequency analysis of related inputs, such as the separate channels of a three-phase AC voltage measurement.

2.4.3 Channel List

While there are many ways to document the DAQ design, the recommended tool is a shared spreadsheet. A template is available for MODAQ designs on the MODAQ Reference Design GitHub[3] repository that captures the following information on separate tabs:

1. Bill of materials and associated costs.
2. Diagrams of the DAQ hardware design, including channel allocations.
3. Channel list that maps each active I/O channel to a particular sensor/instrument; this tab includes columns for the following:
    a. Device tag name
    b. Channel description
    c. Which party is responsible for provision of the sensor/instrument
    d. Location and/or mounting position of sensor/instrument on the host device
    e. Measurement range of the sensor/instrument
    f. Power or excitation requirements of the sensor/instrument
    g. The specific controller/chassis, I/O module, and I/O channel to which the sensor is attached
    h. Type of signal the sensor/instrument uses to communicate its data
    i. Manufacturer of the sensor/instrument
    j. Model number of the sensor/instrument
    k. Serial number of the sensor/instrument
    l. Supplier/URL to webpage
    m. Notes/comments/miscellaneous information.
4. Signal list that maps each device tag in the channel list (physical channel) to one or more data tag names (measurement parameter). A device may be multivariate, such as a temperature and humidity sensor, or inertial measurement unit, but it will have only one physical connection (channel) to the DAQ hardware. The signal list tab should include the following:
    a. Corresponding device tag name
    b. Data tag name, which can be the same as the device tag name for single-parameter devices
    c. Parameter description
    d. Sample rate
    e. Scaling factor(s), offsets
    f. Native units delivered from sensor

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[3] https://github.com/NREL/MODAQ

    g. Notes.

5. Output channel list that maps each data tag name to one or more output destinations. This list is used to describe how the raw data are processed on the DAQ into their agreed/deliverable form and saved to a particular format. This tab includes columns for the following:
    a. Corresponding data tag name
    b. Description
    c. Stored sample rate
    d. Stored data type
    e. Precision of data type (mostly for floating point)
    f. Stored units
    g. Type of data file (e.g., TDMS, CSV)
    h. Are data uploaded to the cloud?
    i. Is a summary file generated?
    j. Threshold for alerts (if applicable)
    k. Distribution list or email to send alerts
    l. Whether data item is to appear in the HMI/MODAQ:Web
    m. Notes.
6. Control rules tab (if applicable), which captures the conditions and actions for both simple and complex control logic. Rules are organized into related groups, which can include sequences (chained rules). This tab includes columns for the following:
    a. Rule name
    b. Description
    c. Condition—the "if" part of the if/then relation
    d. Action—the "then" part of the if/then relation
    e. Log event? Does the occurrence get logged to the system event logger?
    f. Email event—whether the occurrence should generate an email and to which distribution list(s) or email addresses.
7. Interconnect wiring map, which is used to document each conductor in a cable, its end points, and the conductor label that maps back to the associated device tag name. Further, it can capture the pinout of terminations and bulkhead connectors. Other details in this tab include the conductor color, wire gauge, length, and miscellaneous data such as whether the wiring is a twisted pair.

The channel list becomes the central reference for the DAQ build and is an important piece of project documentation. Since it is collaborative, the design details can be easily socialized with a team, and other members can add data as they become available. Once the design is finalized, it is used to guide the coding process and inform the hardware integration.

2.4.4 Control Logic and Thresholds

Control systems can vary in complexity from simple if-then cases to elaborate state machines that could have multiple inputs/outputs, feedback loops, and/or algorithm/model-based logic blocks. MODAQ supports control logic integration, including automated tasks and supervisory control. The reuse of previously written code is generally high with acquisition logic, but there is less opportunity to leverage existing code for control logic since control logic tends to be highly project-specific. In addition, as the number of control rules increase, there is a likely increase of issues such as conflicts, co-dependencies, race conditions, and unexpected/unintended behavior that must be resolved.

In practice, it has been found that coordination between the MODAQ controls development team and knowledgeable persons responsible for the device's affected systems is a priority from the point of control rule definition through bench or in situ validity testing of the control logic. It is not unusual for the logic to be tuned multiple times during a project, especially for complex logic.

Thought should be given to exception handling and fail-safe conditions. Although all possible points of failure cannot be predicted, control actions can be planned for when a rule does not result in the desired outcome. The progress of a particular control action should be monitored, and its degree of success should be logged for later evaluation and possibly sent as an email notification to relevant parties.

> **Example**: A control rule is designed to enable battery charging when the device is generating power or connected to shore power. The rule only triggers when the battery is below its low threshold setting, and it turns off the charger when the battery is above the high threshold setting.
>
> **Possible exception handlers**:
>
> 1. Is current flowing into the battery?
> 2. Is the battery's state of charge increasing?
> 3. Has the battery been charging longer than an allowable amount of time?
> 4. Is the battery's temperature within set thresholds?
> 5. Has the supply power dropped below a threshold?

From this example, the complexity of the basic control logic extends well beyond the simple task of turning the battery charger on or off. It also indicates that four additional measurements might be necessary to perform this oversight on the battery charging process: (1) a voltage measurement on the power supplied to the battery charger, (2) a voltage and (3) a current measurement on the power supplied to the battery, and (4) a temperature sensor on the battery. This adds to the overall channel count of the DAQ, but the benefits include better fault protection for a potentially critical component and better overall data intelligence during prototype testing.

The practicality of adding oversight for control logic depends on the consequences of failure and what mitigation measures are in place. The project's risk register is used to outline the frequency and severity of such a risk and the strategies to reduce the risk to an acceptable level.

Most control logic rules depend on states of certain data channels or thresholds of data parameters. While not technically considered control rules, similar coding logic can be used for basic data QC screening and threshold monitoring. For instance, rules can be developed to issue an email if a temperature exceeds a preset value or if a data channel is reporting the same value (flatlining) for longer than a preset period of time.

2.4.5 Identify and Source Hardware

A critical part of the design process is to identify candidate hardware that best meets the project requirements and system specifications and that works within defined constraints. This tends to be an iterative process because selection of one component might influence the selection of others, and vice versa. The iteration often involves engaging with personnel responsible for other aspects of the project. For instance, if a project requirement is to measure the pressure in a pipe, does a port for the pressure sensor already exist, and if it does, what is its type and threading? If it does not exist, who will be responsible for adding the fitting? Provisions will need to be made for the mounting of most sensors and instruments and for providing paths for cabling back to the controller.

It can be difficult to source components that align perfectly with the project requirements or system specifications. In these cases, it may be necessary to modify the measurement requirements or explore alternative solutions.

As hardware is identified, it should be recorded in the channel list spreadsheet, where it is assigned a tag name and a channel on a controller module.

Some items may have availability issues, such as long lead times, or may only be available from vendors that might not pass organizational procurement requirements.

2.4.6 Alignment With Necessary Standards

The need for DAQ design elements to comply with certain standards should be explicitly stated in the requirements. Statements like "should comply with all applicable standards" are nonspecific and should be avoided. The client must inform the DAQ team of which design elements are subject to standards compliance and which standards to use.

In the marine energy industry, data collection is often performed to gain certified or accredited test results against particular technical specification within the IEC 62600 series ("Wave, tidal and other water current converters") [1], [2], [3]. There are certain considerations for sensor/instrument selection and DAQ software programming for accredited testing that increase the cost and effort and are unnecessary for nonaccredited applications.

2.4.7 Permitting

Devices deployed in the field will usually be subject to permitting by one or more regulatory agencies. The permits may concern areas of land use, impacts to the environment or wildlife, discharges (chemical, thermal, and/or acoustic), and maritime hazards. Securing necessary permits is typically the responsibility of the overarching device project, but there could be permitting stipulations that impact DAQ design requirements. For instance, additional sensors or instruments may need to be added to the design to satisfy a permitting requirement.

2.4.8 Line Diagrams and Logic Flowcharts

The overall architecture of the DAQ hardware design should be captured in a one-line or block diagram that describes the physical interconnections between the various components in the DAQ. This is useful for assuring that each sensor or instrument has a suitable input channel on the controller, and for determining how the components are spatially arranged. The diagram should be sufficiently annotated to identify the tag names associated with each wire and useful attributes such as wire gauge and conductor color. The line diagram is referenced during hardware integration and troubleshooting and is a key part of the delivered system specification.

Similarly, the general logic of the DAQ software design should be outlined in a flowchart to indicate the major logic blocks/nodes and their interconnections and dependencies. Where applicable, complex logic blocks—particularly those containing state machines or control logic—should be separately diagrammed. Diagramming logic easily communicates DAQ functions to non-programmer stakeholders and future maintainers of the DAQ and code.

2.4.9 Data Management and Communications Plan

Since a DAQ generates data, and that data needs to be processed, stored, and communicated, the Data Management and Communications Plan (DMCP) is the document for capturing that information.

The DMCP describes the following:

- Parameterization of the data signals, including description; for instance, an analog voltage is converted to a pressure estimate
- Description of onboard processing applied to measurement data, including scaling, filtering, and QC
- Format for data storage, e.g., HDF5, TDMS, CSV
- Units, precision, and final sample rate of stored data
- Location of stored data on the DAQ
- Destinations for stored data that are programmatically pushed from the DAQ to a remote server or the cloud
- Description of any data portals or dashboards that are in scope for the project.

Often, organizations develop their own description of how they expect the collected data to be processed and delivered. If the client's DMCP is to be used, it should be included in the requirements and provided during the request for proposal or request for quotation process. Stringent or obscure requirements in a client-provided DMCP could impact the final cost of the project. For example, the DMCP might specify a data format that is unfamiliar to the developer. Because a client DMCP is often generic or duplicated from another project, it should be reviewed and edited by the client for appropriateness in the current project.

In the absence of a client-provided DMCP, the DAQ team will draft one to describe the as-built management and communications of the measurement data. Decisions by the DAQ team regarding the bulleted list above should be reviewed and approved by the client prior to implementation.

2.4.10 User Interfaces

The MODAQ design is adaptable to many types of device testing, which can result in a complex user interface. Some MODAQ deployments are just measuring system parameters with no need for a user interface. In some deployments, MODAQ operates as a supervisory control and data acquisition system, and a complex user interface or HMI is needed. It is important to determine the need for a user interface early in the planning and design phase of the project and to understand the time and cost implications to the project.

MODAQ:Web is a simple and effective way to monitor the system's operation from anywhere in the world with an internet connection. This is usually an invaluable capability for device developers, as it can be used to check the status of their system from shore and to promote product awareness and outreach. MODAQ:Web is optimized for monitoring system status with updates typically on the order of minutes. It can also provide the MODAQ:Field system with automated updates that can be used for optimized control. These processes typically happen in the range of minutes to hours, but quicker updates are possible with the MODAQ HMI.

The MODAQ HMI is used when a system depends on a user input to instantaneously change the way a system operates. Examples include changing control settings during field deployments, enabling and disabling the system for commissioning and decommissioning, exercising various controls to aid in laboratory testing and validation, and starting/stopping data collection to make data handling easier. Another important aspect of the MODAQ HMI is it allows for instantaneous monitoring of the system parameters while in operation. The MODAQ HMI is a web browser-based application that is hosted on the MODAQ controller and allows personnel located near the hardware or connected via a virtual private network to control and monitor the system in near real time.

Depending on the project, developers may choose to include the MODAQ:Web and/or MODAQ HMI capabilities. Once that is decided, it is important to identify the control and data monitoring functionality early on to improve development efficiency. To aid in this effort, the channel list design spreadsheet includes a column for MODAQ:Web and MODAQ HMI with the type of display required for each. The options are graph, table, numerical indicator, traffic light, and LED Boolean.

2.4.11 Risk Register

It is standard practice to complete a risk assessment in the planning and design phase of a marine energy development project. Funding agencies like the U.S. Department of Energy's Water Power Technologies Office (WPTO) include it as a requirement for awards. Because this is a critical component of a marine energy deployment, WPTO funded NREL to develop the *Marine Energy Technology Development Risk Management Framework* [4], which provides guidance for identifying and managing risks associated with projects. This framework encompasses all aspects of a marine energy project, including but not limited to safety, environmental, technical, and programmatic risks.

The control and data acquisition system design, implementation, and operation are key components in a project risk register, the template for which is provided in the framework report. All risks related to the DAQ system should be identified and documented, along with appropriate risk responses that would reduce the severity of the consequences of the risks.

Risk management can be time-consuming and requires the participation of a large team of technical experts. The complexity of the project should be assessed to determine how many hours and which personnel to allocate to the risk management effort. The sufficient investment of project resources into this process is important and has historically been valuable in the successful completion of a marine energy project.

The risk register should not be viewed as a “box-checking” exercise. Its true value is realized when it is revisited as the project progresses to assure that captured risks are indeed mitigated according to the risk management plan. Aside from the obvious purpose of identifying and managing project risks, the risk register is also a tool to socialize the risks among project stakeholders and sponsors so that they are aware of the risks and agree with the mitigation strategies.

2.5 Other Considerations

2.5.1 Design Spiral

The design spiral is named for the circular path taken to converge on a solution. It is progressively iterative: solutions evolve while the requirements or system specifications are refined.

Although not a defined or required step, the design spiral tends to occur spontaneously and can slow progress towards design finalization. It is not problematic, and it should not be avoided—the design spiral is a healthy process that is hard to set to a schedule. However, it is often indicative of a poorly defined scope or requirements.

Design spiraling can occur early in the design maturity of the host device or when the requestor (client, customer, sponsor) does not have the necessary domain knowledge to clearly define the system requirements. In the former case, progress on the host device design is ongoing, so DAQ system requirements are a moving target. In the latter case, the DAQ engineering team takes on more responsibility for defining the scope and measurement requirements.

Even in cases with solid scoping and well-defined requirements, unexpected discoveries or problems could arise that inhibit faithful fulfillment by the DAQ team. For example, if a solution for a particular measurement could not be found, a component had a long lead time or was priced too high, or the sampling strategy was too aggressive. Regardless of the issue, a solution must be found, which might involve modifying the requirements, deleting the measurement, or making some other concession.

Closely related to the design spiral is the trade-off analysis. This analysis occurs when there is more than one viable solution with potentially different impacts to the project or when a conflict has arisen that requires a decision to resolve. The relative strengths and weaknesses of each option are evaluated, and a compromise solution is selected.

2.5.2 Finalize/Freeze Design

Once the DAQ design has been matured to the point where:

- All requirements and system specifications have been met
- Hardware and suppliers have been fully identified
- A software specification has been created, including applicable flowcharts or pseudo code of unusual logic blocks and/or control logic
- Schematics, wiring diagrams, and flowcharts (where applicable) have been completed
- Any risks identified that pertain to the DAQ design, installation, or commissioning have been mitigated, deviated, or accepted.

A formal statement of design freeze or finalization should be issued and approved by the sponsor, project manager/principal investigator, budget holder, or otherwise accountable person. This signals to all involved that further changes to the DAQ design or capabilities are disallowed without going through a formal change process. It also signals the commencement of the actual DAQ development work and authorizes procurement of required hardware and supplies.

While some progress may be made on the DAQ development prior to the design freeze (such as procuring components with long lead times), best practices indicate that this should be avoided until an approved design freeze is in place.

2.5.3 Management of Change

Even with the best-laid plans, scope creep happens. In addition, there can be a severe underestimation of some work tasks that are not well defined by the existing scope. This usually occurs when the scope and/or requirements are notional at the time of award. However, scope creep is often introduced as the project matures and new needs or features are identified. Recognizing scope creep can be difficult, and what is or is not “in scope” is often left to interpretation.

Modifications to the scope of work, particularly when the changes will impact the project cost or delivery schedule, should be executed through a management-of-change process or change order. Any changes to scope after a design freeze warrant a change order, which is essentially a simplified version of a proposal or quote that captures:

1. The requested change
2. Actions required to address the scope change
3. Impacts of the change to other parts of the existing scope
4. Impacts of the change to cost and/or schedule
5. Approvals/signatures from relevant parties involved.

In most cases, work related to the change should not commence until authorized by the sponsor, project manager/principal investigator, budget holder, or other accountable person.

While less common, the management-of-change process should also be used in cases of scope reduction. This is intended to capture the removal of deliverables, milestones, or work products from the original scope of work or proposal.

2.5.4 Spares Strategy

Deciding on an appropriate strategy to keep spare hardware on hand depends on the project's risk tolerance. For high-value or high-profile projects, there might be justification for having a complete second copy of the primary DAQ system on standby. A less-costly approach might be to only hold spares of long-lead items. Yet another approach is to accept that data may not be collected if certain failures occur. The spares strategy should be captured in the risk register and approved by the accountable and responsible parties.

3 Software Development

Once the design freeze has been authorized, software development typically begins. Estimating the time and effort required to deliver the completed software is not straightforward, especially when there is a large component of new code or complex control logic to be developed.

MODAQ follows a modular approach to software development, which allows significant reuse of code between projects. Much of the base functionality or subsystems carry over into new coding projects with minimal changes. Commonly reused code modules include:

- Precision time keeping
- Event logger
- Email and AWS S3 communications workers
- System health monitoring
- Binary data storage methods.

Similarly, if hardware devices are selected that have been used in previous projects, the existing code modules can likely be reused. The measurement database section of the appendix lists these devices. Any opportunity to leverage existing code will reduce the subsequent development effort and thus help reduce costs.

New hardware and often variants of hardware previously used generally require fresh code, but sometimes pieces of existing code could be repurposed to accelerate the process. Sensors that output analog voltage or current signals usually require little coding effort, while devices with digital outputs can take more effort. Digital signals can be in various protocols and data formats, including proprietary formats. These are typically binary, and if a suitable decoding library does not exist, then one will need to be written. Devices with high development effort include inertial measurement units, acoustic Doppler current profilers, encoders, and most devices classified as instruments.

Bespoke code requires the greatest development effort. Most projects require some degree of unique or custom code, and the time required to create this code will depend on a few factors: scope, complexity, and novelty. Almost all instances of control logic, HMIs, and web portals are bespoke, as are any logic blocks that include custom algorithms or QC screening. Bespoke does not necessarily mean that the code is 100% written from scratch. For instance, in MODAQ, the methods for providing an HMI or web portal have been previously developed. However, the content presented or the functionality required differs between projects and must be customized.

3.1 Debugging and QA

Regardless of the skill of a developer, bugs or unintended operations are likely while the code is under development. Software bugs come in many different forms, but the most insidious are those that occur seemingly at random, give few clues to their source, or are latent. Finding the source and implementing a fix to such issues can take an unknown amount of time and effort. One of the benefits of code reuse is that any bugs or ill behaviors have been previously addressed.

Quality assurance (QA) includes the steps taken *before* deployment/handover to assure the system functions consistently with the requirements and expectations. This is different from QC, which includes validating the system to ensure it meets the requirements and expectations *after* (or even during) deployment. QA is described as preventative or proactive, while QC is corrective or reactive. QA of the complete DAQ code considers:

1. Does the code function as intended?
2. Does the code handle errors gracefully?
3. Do system resources, such as RAM and CPU utilization, remain at acceptable levels?
4. Are data files being written correctly and are time stamps monotonically increasing?
5. Is the code stable and responsive, with no system lockups?

When the code passes the QA screening, a code freeze should be declared, and further changes of the code should not be allowed; otherwise, the QA process must be repeated to assure no new bugs were introduced due to the code change.

3.2 User Documentation

At handover, documentation of the features and general use of the software should be provided to the client and relevant end users. This can either be a stand-alone document or it can be included in the system specification deliverable. The scope and level of detail in this document should be appropriate for the use of the system if the intended operator is someone other than the DAQ team.

4 Hardware Build

During software development, it is often necessary to have some or all of the DAQ hardware components on-hand and available to write interface modules and test code logic. With systems like MODAQ, which have uniformity in frequently used hardware components, a surrogate or development system is often used during the coding process, thus making the code development less dependent on procurement. However, new or more specialized hardware could delay parts of the code development until the pieces are received.

Figure 4. A MODAQ system is packaged in a stainless-steel enclosure for field deployment.

Photo by Mark Murphy, NREL

As mentioned in Section 2.4 System Specification, hardware should be procured after the design freeze is approved. Assuming there is little risk, items that might delay code development or those with long lead times might need to be ordered in advance of the freeze. When it comes to DAQ hardware, it is not unusual for items to be built to order, even for seemingly off-the-shelf components. In addition, some organizations may have policies or restrictions on hardware purchases that can slow down or derail procurement for reasons like cybersecurity, safety certifications, licenses, terms and conditions, and country of origin. Therefore, the schedule should allow for ample time, plus a margin, for the hardware procurement process.

For accredited testing and instances where measurement results may be subject to scrutiny, hardware should be obtained that have tractable certifications and calibration sheets. This might be an added cost or may delay the shipment for some items. Calibrations are usually good for a period, such as one year, after the calibration is performed. If the calibration expires while the device sits unused on a shelf, it must be recalibrated before it is put into use.

A calibration sheet for a sensor may contain one or many “calibration points” that indicate the exact sensor output for a particular measurement value. For instance, a load cell might output exactly 3.10 volts (V) when loaded with a calibrated 1-ton reference weight. Whereas a second, identical load cell made by the same manufacturer might output 3.15 V with the same reference weight. Minor differences in sensors are to be expected and are mitigated through proper calibrations. The calibration values are applied as part of the DAQ processing to correct the measurements.

To prepare the DAQ for the field, the hardware is usually packaged into one or more enclosures suitable for the deployment environment. The ultimate layout or configuration is project-specific, but generally, the controller, data storage, and communications devices are placed together in the enclosure. Internal wiring blocks allow for easy field repairs and fusible power links.

Connections for each sensor, instrument, antenna, and external power source are provided through bulkhead fittings on the enclosure. This allows for easy assembly in the field and teardown for shipping.

Once the hardware has been built, another round of QA functional stability tests should be run. This is the final test before shipping the system to the field. As a best practice, it should be run uninterrupted for several days to a week. This process should not be skipped, since problems caught at this stage are much cheaper and easier to address than attempting field repairs or risking loss of data.

5 Integration

The integration of the DAQ and test article typically involves transferring the hardware and integration team to the test site, where the DAQ, sensors, and instruments are integrated with the various systems they were designed to measure.

While shipping hardware and dispatching personnel to the field might seem trivial, there are often details that must be considered. For example:

1. The shipping weight of a large MODAQ system may exceed 100 pounds, and it is typically bulky and fragile.
2. Depending on the location or jurisdiction at the receiving end of the hardware, there may need to be permits, inspections, duties, or export control restrictions.
3. Personnel may require special training or authorization to enter the location (for example, Transportation Worker Identification Credential or TWIC card).
4. Remote sites may have limited infrastructure, so all tools, supplies, and spares must be brought along.
5. Personnel should bring necessary personal protective equipment, such as hard hats, gloves, eye protection, and personal floatation devices (if working on or near water). Some sites may have strict personal protective equipment requirements, so be sure to check in advance.

The physical act of installing the hardware varies with the project, host device, and DAQ complexity. In most cases, it is expected that the client has allocated sufficient space with a mounting surface for the DAQ hardware and has cleared paths for cable runs, per the planning and design phase. Most integrations involve the following:

1. Securely mounting the DAQ enclosure(s) to the structure
2. Placing sensors and instruments in their designated locations
3. Mounting antennas to topside mast or other securing point
4. Tapping into hotel power system and communications network (if applicable)
5. Running and securing cabling between DAQ enclosure and sensors, instruments, and antennas.

Most sensors and instruments are deeply integrated with the system they are measuring. For instance, measuring voltage or current requires access to the wires or test busses, and measuring pressure in a pipe requires a tap or port. This preparation is generally out of scope for the DAQ and integrator, and it is the client's responsibility to ensure necessary provisions are ready at the time of installation. These details should be agreed upon and settled during the front-end engineering design (FEED) phase. Integrators will not disassemble or modify a client's hardware unless that activity has been clearly captured in the scope.

Once all DAQ hardware is installed, an end-to-end test of each component is performed with the DAQ controller to assure all signals are received and are of sufficient quality. Remedial efforts may be necessary to address any noise introduced to the system due to systems on the host device.

A final functional test is performed with DAQ software running the same version of the code that will be run during deployment. Similar to previous pre-shipment tests, this is an extended QA test of system stability and data quality.

Upon acceptable completion of the stability test, the DAQ is considered commissioned and ready for deployment. In many cases, this also signifies official handover of the DAQ to the client.

6 Operations

Usually, a small percentage (~5%) of the overall DAQ labor budget is allocated for operational support during deployment. This consists of:

- Occasional checks on the DAQ system health and data review
- Remote support for troubleshooting/issues
- Technical assistance to the client for DAQ operation and data access.

In some cases, it might be desirable for the DAQ team to perform or oversee the DAQ operations on behalf of the client. Discussion of scope and budgeting for this level of service will not be included in this document, but costs are usually based on an hourly rate plus travel and expenses.

6.1 Data QC

Data QC broadly applies to the processes used by the MODAQ team to ensure the data produced by a MODAQ system provides quality data consistently throughout its deployment life cycle. This section refers to the methods implemented solely to understand the reasonableness of the data streams being collected. The data streams collected by a MODAQ system are time-stamped numerical values, which can be linearly associated to some type of engineering quantity through some means of calibration. Basic QC screening performed by MODAQ on the incoming data can be enabled to determine if the data are within user-defined thresholds for magnitude, deviation, and rate of change.

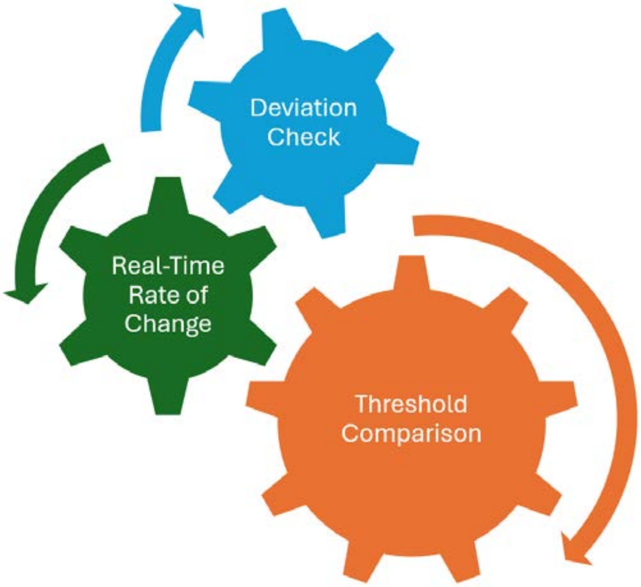

Figure 5. Key components of Data QC

It is an important distinction to recognize the difference between various levels of quality control and how monitoring methods can be used for more than one purpose. The MODAQ development team aims to ensure that the data collected meet the client's requirements by implementing checks to highlight issues with the data streams or DAQ hardware in near real time. Several more sophisticated methods are available for data QC in postprocessing through time-series analysis techniques, but these can be resource-intensive to execute on DAQ hardware and are generally only implemented if requested by the client. QC checks can also be applied to test article health and other details of interest to researchers, but this discussion focuses on the quality of the data stream point by point.

Applying thresholds to a measure quantity and running comparisons as the data are being collected are simple data QC checks that can be accomplished. As an example, assume a MODAQ system is monitoring the temperature of a hardware component that is continuously running and creating heat. In this case, the MODAQ team can refer to the hardware data sheet for expected operating temperature ranges and implement a check in the code to monitor that the data stream falls within the expected range. A MODAQ system can, in near real time, identify that a limit has been exceeded and act on it in several ways. One method that is commonly used is to send out an email alert to operators or software engineers, so they can investigate the issue.

In contrast to a limit check, a deviation check on an incoming data stream monitors a quantity's difference from a set point. The set point used for comparison can vary with time. An example of a deviation QC check is a generator shaft speed measurement compared to a three-phase generator voltage measurement. In this instance, the generator shaft speed and three-phase voltage are known to be directly correlated so a quality issue could be identified by observing a loss of correlation between these parameters. Over the course of the test article's life cycle, the MODAQ team can ensure that the measurement falls within the expected range of known values, identify potential issues, and produce an appropriate response.

When monitoring the rate of change of a measurement on a real-time system, the MODAQ team would compare a point previously collected to a current one. A simple case can compare a measured value to one collected in the previous iteration. This type of QC is used to monitor for excessive change or potentially no change in a measured quantity. Several hardware and software problems can be attributed to excessive or no change in a measured quantity, making this a key piece of near-real-time QC procedures.

Depending on the complexity of the MODAQ system in question, these basic checks can be used in several ways, including health monitoring and control. Their implementation at the software level is straightforward; however, developing the set points, expected values, and alerting strategy can be a time-consuming task. At a fundamental level, these QC checks done in real time on the MODAQ system offer an automated way to ensure the system is functioning as expected and are commonly used to flag the produced datasets as potentially having erroneous data. Correcting any issue requires further intervention from operators, technicians, or engineers.

7 Closeout

At the closeout of a DAQ project, there might be several pieces of information that need to be delivered to the client apart from the data the system was built to collect. If a project used NREL-owned hardware, then there is usually a task to collect and account for all MODAQ hardware and return it to inventory. If the hardware is included in the deliverables, the MODAQ team can produce software and hardware design reports along with post-deployment reports summarizing the data collected. In the case where the MODAQ system was used in an accredited test, there would be an additional analysis phase to produce a final report for the client.

In many projects funded by the U.S. Department of Energy, there is a requirement to make some or all of the data collected through the measurement campaign public via the Marine and Hydrokinetic Data Repository[4] following some further postprocessing QC; this has been carried out by the MODAQ team as necessary for several projects.

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[4] https://mhkdr.openei.org/

8 Costs

Based on the highly variable nature of projects requiring data acquisition systems, cost estimates can be difficult to produce in absolute terms in a general document. Scope and requirements will have the greatest impact on the overall cost. In cases where budget or time (or both) is constrained, there may need to be concessions on the scope or requirements.

Costs are also temporal and tied to quality expectations. Today's prices may be irrelevant months or years from now. Quality can be tuned with associated adjustments to costs. This applies equally to hardware and personnel. Higher quality and performant hardware tend to cost more, as do skilled and experienced personnel.

Schedule is an independent variable when it comes to overall quality. It may be assumed that with skill and experience, a task could be completed quicker. However, individuals with greater skill or experience may be more exacting, careful, and deliberate and not willing to release something until it has been thoroughly tested and validated.

Comprehensive planning early in the project usually pays off in significantly better control as the project matures. When little effort is applied to FEED early in the project, cost and schedule tend to be poorly controlled.

8.1 Cost Breakdown Structure

This section provides some insight into how DAQ development personnel costs might be distributed over the project life cycle. It is not unusual that over a third of the effort may be spent before the first line of code is written or any hardware purchases are made. The FEED process is important to get to the point of a design freeze. It is wasteful to rush into coding and building while the system specification is still in flux.

In the following chart, two estimates for how effort or personnel costs are distributed over the project life cycle are provided. The Low column assumes less FEED effort while the High column assumes more FEED effort. This can be normalized and applied to any budget to indicate the relative costs associated with each phase.

Table 1. Distribution of Effort Estimates Over the DAQ Project Life Cycle

Activities and Milestones	Low	High
FEED • Determine system requirements and constraints • Develop system specification • Develop data management plan • Freeze design	20%	40%
Software • Develop preliminary software architecture • Write and/or repurpose existing code to system specification • Verify intended operation of programming logic • Optimize for memory and CPU utilization	35%	25%
Hardware Design and Integration • Identify hardware and suppliers • Physical design of the hardware system, including schematics and wiring diagrams • Physical build of hardware into cabinet(s) or enclosure(s) • End-to-end testing of hardware components	25%	15%
System Validation • Burn-in period for testing hardware and software stability • Verify that no memory growth (leaks) exists • Verify file writes and communications • Handover on successful completion	5%	5%
Mobilization (Mob) • Transfer hardware (and personnel) to deployment site • Install hardware • In situ end-to-end test of hardware	5%	5%
Operations • Monitor system performance through deployment duration • Verify data quality and file saves • Remote maintenance	5%	5%
Demobilization (Demob) and Closeout • Uninstall/recover hardware • Prepare data for delivery • Issue final report and data	5%	5%
Total	**100%**	**100%**

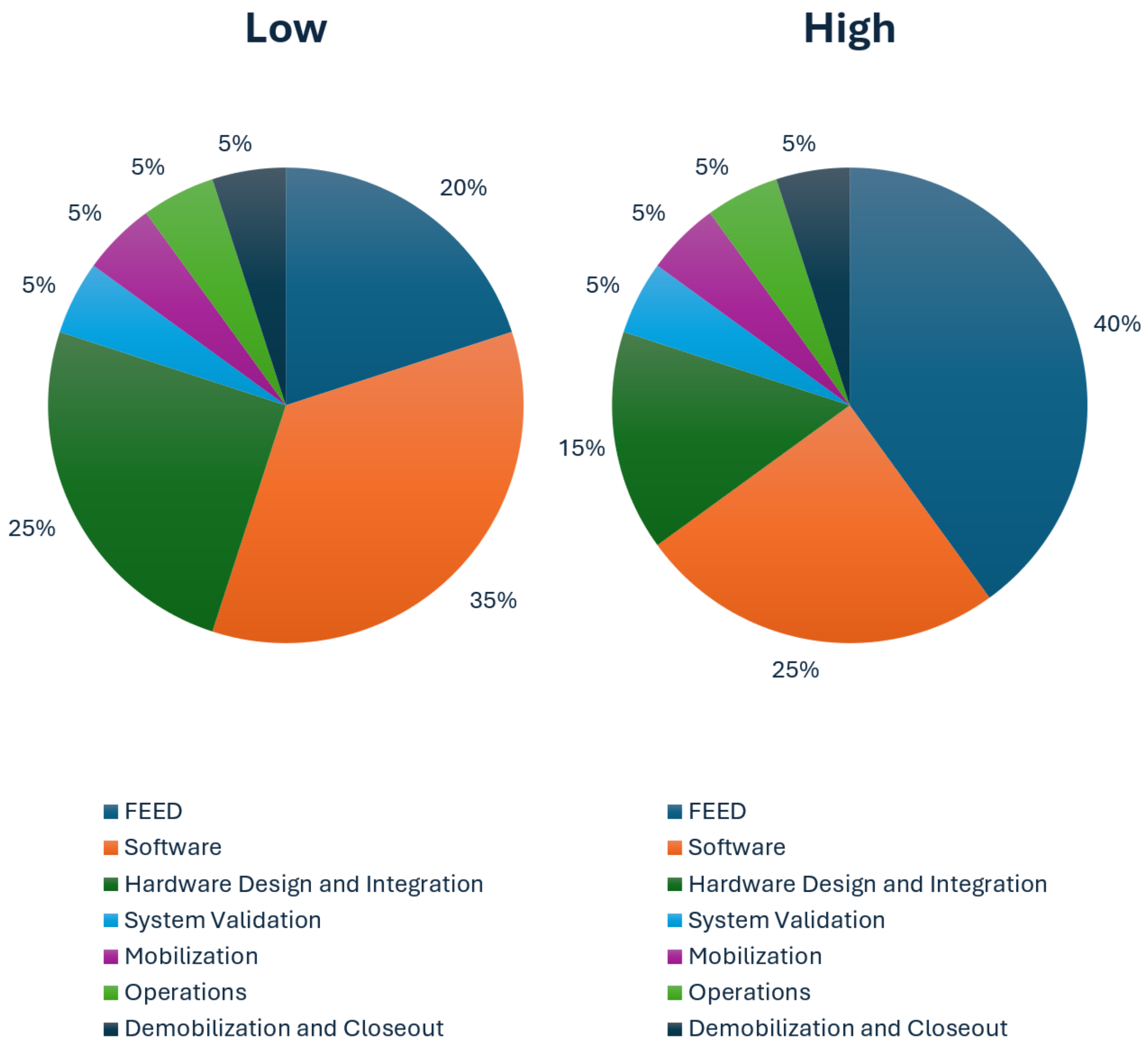

Figure 6. Low- and high-effort estimates over the DAQ project life cycle

While this chart is not universal, and the percentages can be adjusted for different scopes, it illustrates that about 85% of the effort is expended before the system is handed over or shipped. In most cases, the Mobilization, Operations, and Demobilization/Closeout activities should be captured with separate budgets and schedule. For considering these activities in this report, the minimal effort is assumed. Realistically, the mobilization/demobilization activities may involve long-distance travel or extended time in the field or on a ship. So, if the DAQ budget was $100,000 (for example), it is unlikely that the mobilization could be accomplished with $5,000.

No rules of thumb or percent allocation are possible for hardware estimates. These costs are governed strictly by the project requirements and can vary greatly based on the scope and the quality and capability of the hardware selected. While it is possible to set a budget and select the hardware accordingly, if underestimated, this approach will likely be in tension with the requirements and quality expectations. If overestimated, it could (temporarily) tie up funds that might be useful elsewhere in the project.

8.2 Cost Examples

The following examples are provided to illustrate cost estimates for some realistic DAQ designs at different complexity scales, including assumptions. Some of the actual hardware costs are estimated and based on reasonable procurement costs in 2024.

8.2.1 Example 1

Description: Basic DAQ to measure three-phase voltage and current for IEC 62600 – 100, 200, or 30 compliant testing [1], [2], [3]. This estimate includes costs based on either the M1 or M2 architectures. The sensors and integration parts are the same for either MODAQ controller platform (select either MODAQ 1 or MODAQ 2).

Features:

- High-performance ±10 V analog to digital converter with eight available input channels
- Potential and current transducers (PTs and CTs) sized appropriately for the expected voltage and current range coming off the generator
- 2-terabyte (TB) high-speed storage
- Weather and temporary submersion rated build for everything but the PTs and CTs
- System can be expanded as necessary.

Table 2. Bill of Materials for Example 1

Model	Brand	Function	Qty	Unit Cost	Extension
Required components only for MODAQ 1					
cRIO-9042	National Instruments	Primary controller	1	$7,705	$7,705
NI-9239	National Instruments	4 Ch ±10-V analog input	2	$1,992	$3,984
T7	Samsung	2 TB USB solid-state drive (SSD)	1	$170	$170
				Total	**$11,859**
Required components only for MODAQ 2					
H4 Ultra	ODROID	Primary controller	1	$250	$250
T8	LabJack	Multi I/O	1	$1,400	$1,400
970 Evo Plus	Samsung	2 TB NVMe SSD	1	$170	$170
				Total	**$1,820**
Sensors/Instruments/Other					
IsoBlock V-4c	Verivolt	4 Ch PT	1	$1,600	$1,600
IsoBlock I-FG-4c	Verivolt	4 Ch CT	1	$580	$580
G5105	Netgear	5 Port unmanaged switch	1	$35	$35
				Total	**$2,215**
Integration Parts					
WQ-80-02	Polycase	Enclosure (poly, IP67)			$406
		Power supplies/ converters			$200
		Terminations and bulkhead conns			$200
		Wiring blocks			$100
		Wire/cabling			$100
		Brackets/hardware			$100
		Misc.			$250
				Total	**$1,356**
Cost Totals					
				M1	**$15,430**
				M2	**$5,391**

8.2.2 Example 2

Description: Step-up DAQ system to measure three-phase voltage and current for IEC 62600 – 100, 200, or 30 compliant testing [1], [2], [3] . In addition, it includes the following measurements: temperature, platform motions (accelerations and rotations), position, and heading. It also includes full remote management capability through a mobile data carrier. This estimate includes costs based on either the M1 or M2 architectures. The sensors and integration parts are the same for either MODAQ controller platform.

Features:

- High-performance ±10 V analog to digital converter with eight available input channels
- PTs and CTs sized appropriately for the expected voltage and current range coming off the generator
- Inputs or up to 8 PT100 RTDs (temperature sensors), either stick-on or probe style
- Precision 9-degree-of-freedom, GNSS-assisted inertial navigation system; includes tri-axis accelerometers, gyros, and magnetometers
- High-performance GNSS compass for GPS position and heading
- GPS-based precision time protocol (PTP) server and PTP-enabled DAQ controller
- High-speed LTE mobile network data gateway for real-time access to data and remote operation/maintenance
- 2-TB high-speed storage
- Marine-rated cellular and GPS combination antenna
- Remotely operated relay module, for controlling power on up to eight circuits
- Stainless steel corrosion-resistant IP66 industrial enclosure
- System can be expanded as necessary.

Table 3. Bill of Materials for Example 2

Model	Brand	Function	Qty	Unit Cost	Extension
MODAQ 1					
cRIO-9049	National Instruments	Primary controller	1	$12,845	$12.845
NI-9870	National Instruments	4-Port RS-232	1	$1,080	$1,080
NI-9239	National Instruments	4 Ch ±10-V analog input	2	$1,992	$3,984
NI-9216	National Instruments	8 Ch PT100 RTD	1	$2,032	$2,032
T7	Samsung	2 TB USB SSD	1	$170	$170
				Total	**$20,111**
MODAQ 2					
Karbon 410	Onlogic	Primary controller	1	$900	$900
T8	LabJack	Multi I/O	1	$1,400	$1,400
ED-582	Brainboxes	4 Ch PT100 RTD to Ethernet	2	$408	$816
USC-UR202	US Converters	2 Port RS-232 to USB	1	$59	$59
970 Evo Plus	Samsung	2 TB NVMe SSD	1	$170	$170
				Total	**$3,345**
Sensors/Instruments/Other					
GNSS Compass	Advanced Navigation	Compass/GPS/IMU/PTP server	1	$2,500	$2,500
Mti-G-710	Xsens	GNSS INS	1	$5,368	$5,368
IsoBlock V-4c	Verivolt	4 Ch PT	1	$1,600	$1,600
IsoBlock I-FG-4c	Verivolt	4 Ch CT	1	$580	$580
IBR-600c	Cradlepoint	Cell modem	1	$700	$700
IDS-710	Perle	8 port network switch	1	$1,700	$1,700
SA1-RTD	Omega	PT100 RTD (stick on)	8	$105	$840
MA700.W.A.ABC.001	Taoglas	3n1 4G/GPS antenna	2	$183	$366
10 Plus	WebRelay	8 Ch remote relay	1	$550	$550
				Total	**$13,654**
Integration Parts					
75505K24	McMaster-Carr	Enclosure (SS)			$1,700
		Power supplies/ converters			$600
		Terminations and bulkhead conns			$500
		Wiring blocks			$150
		Wire/cabling			$250
		Brackets/hardware			$200

Model	Brand	Function	Qty	Unit Cost	Extension
		Misc.			$500
				Total	**$3,900**
Cost Totals					
				M1	**$37,665**
				M2	**$20,899**

8.2.3 Example 3

Description: Large MODAQ system with outputs for control (supervisory control and data acquisition). This system has a secondary chassis to accommodate the additional input and output modules, and it can be configured as a distributed system, where one chassis is mounted in a different zone. It includes the following measurements: three-phase voltage and current for IEC 62600 – 100, 200, or 30 compliant testing [1], [2], [3], mooring loads, shaft position and speed, fluid pressure, temperature, platform motions (accelerations and rotations), position, and heading. It also includes full remote management capability through a mobile data carrier.

Features:

- High-performance ±10 V analog to digital converter with 32 input channels
- PTs and CTs sized appropriately for the expected voltage and current range coming off the generator
- Up to nine each additional PT/CT measurements elsewhere in the power electronics or supporting systems (18 total inputs)
- Two high-precision shaft absolute encoders
- Four mooring load shackles
- Four pressure transducers
- Four strain gage/load cell measurements (1/4, 1/2, and/or full bridge)
- 32 digital I/O channels for control or state monitoring
- Eight solid state relays for control
- Inputs for up to eight PT100 RTDs (temperature sensors), either stick-on or probe style
- Precision 9-degree-of-freedom, GNSS-assisted inertial navigation system; includes tri-axis accelerometers, gyros, and magnetometers
- High-performance GNSS compass for GPS position and heading
- GPS-based precision time keeping (PTP), including time server and PTP-enabled DAQ controller
- High-speed LTE mobile network data gateway for real-time access to data and remote operation/maintenance
- 4-TB high-speed storage
- Marine-rated cellular and GPS combination antenna
- Remotely operated relay module for controlling power on up to eight circuits
- Stainless steel corrosion-resistant IP66 industrial enclosure
- System can be expanded as necessary.

Table 4. Bill of Materials for Example 3

Model	Brand	Function	Qty	Unit Cost	Extension
MODAQ 1					
cRIO-9049	National Instruments	Primary controller	1	$12,845	$12,845
cDAQ-9189	National Instruments	Secondary Chassis	1	$3,417	$3,417
NI-9870	National Instruments	4-Port RS-232	1	$1,080	$1,080
NI-9239	National Instruments	4 Ch ±10-V analog input	4	$1,992	$7,968
NI-9224	National Instruments	8 Ch ±10-V analog input	2	$2,012	$4,024
NI-9216	National Instruments	8 Ch PT100 RTD	2	$2,031	$4,062
NI-9237	National Instruments	4 Ch strain bridge	2	$2,600	$5,200
SEA-9521	SEA GmbH	3 Ch encoder input	1	$1,527	$1,527
NI-9253	National Instruments	8 Ch ±20-mA current input	1	$1,200	$1,200
NI-9485	National Instruments	8 Ch SS relay	1	$991	$991
NI-9403	National Instruments	32 Ch DIO TTL	1	$1,115	$1,115
T7	Samsung	2 TB USB SSD	2	$170	$340
				Total	**$43,769**
Sensors/Instruments/Other					
GNSS Compass	Advanced Navigation	Compass/GPS/IMU/ PTP	1	$2,500	$2,500
Mti-G-710	Xsens	GNSS INS	1	$5,368	$5,368
IsoBlock V-4c	Verivolt	4 Ch PT	3	$1,600	$4,800
IsoBlock I-FG-4c	Verivolt	4 Ch CT	3	$580	$1,740
INC-3-175-211001-B1	IncOder	Absolute encoder	2	$1,600	$3,200
ISHK-B	Interface	Load shackle (25 MT)	4	$7,500	$30,000
MMF-403112	Vishay	Precision foil strain gauge	4	$65	$260
PX309	Omega	Pressure transducer	4	$375	$1,500
IBR-600c	Cradlepoint	Cell modem	1	$700	$700
IDS-710	Perle	8 port network switch	1	$1,700	$1,700
SA1-RTD	Omega	PT100 RTD (stick on)	8	$105	$840
MA700.W.A.ABC.001	Taoglas	3n1 4G/GPS antenna	2	$183	$366
10 Plus	WebRelay	8 Ch remote relay	1	$550	$550
				Total	**$53,524**
Integration Parts					
75505K24	McMaster-Carr	Enclosure (SS)			$1,700
SDN524100C	Sola	24 VDC power supply	2	$400	$800

Model	Brand	Function	Qty	Unit Cost	Extension
		Terminations and bulkhead conns			$850
		Wiring blocks			$250
		Wire/cabling			$800
		Brackets/hardware			$400
		Misc.			$1,500
				Total	**$6,300**
Cost Totals					
				M1	**$103,593**

References

[1] "IEC TS 62600-100:2012 Marine energy - Wave, tidal and other water current converters - Part 100: Electricity producing wave energy converters - Power performance assessment." Aug. 30, 2012. Accessed: Sep. 12, 2024. [Online]. Available: https://webstore.iec.ch/en/publication/7241

[2] "IEC TS 62600-30:2018 Marine energy - Wave, tidal and other water current converters - Part 30: Electrical power quality requirements." Aug. 29, 2018. Accessed: Sep. 12, 2024. [Online]. Available: https://webstore.iec.ch/en/publication/28781

[3] "IEC TS 62600-200:2013 Marine energy - Wave, tidal and other water current converters - Part 200: Electricity producing tidal energy converters - Power performance assessment." Accessed: Sep. 12, 2024. [Online]. Available: https://webstore.iec.ch/en/publication/7242

[4] D. Snowberg, R. T. Philip, and J. Weber, *Marine Energy Technology Development Risk Management Framework.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-90212. 2024. https://www.nrel.gov/docs/fy24osti/90212.pdf.

Appendix A. Additional Information

A.1 Useful Links

MODAQ v1 Reference Design: https://github.com/NREL/MODAQ
MODAQ v1 RD Documentation: https://nrel.github.io/MODAQ/
MODAQ v2 Reference Design: https://github.com/NREL/MODAQ2
MODAQ v2 RD Documentation: https://nrel.github.io/MODAQ2/
MODAQ:Web (HERO-WEC Portal): https://modaq.nrel.gov/hero-wec-dashboard/

A.2 Measurement Database

The following is a list of sensors and instruments that have been used in MODAQ projects. While the list is not exhaustive and does not account for model variations, it offers a glimpse into the types of measurements that MODAQ typically performs and which devices have available software modules.

Table A-1. Sensors and Instruments Used in MODAQ Projects

Name	Measured Value(s)	Notes	Link
Water Velocity			
Nortek Vector ADV[5]	water velocity	RS232 connection	https://www.nortekgroup.com/products/vector-300-m
Nortek Signature 1000 ADCP[6]	water velocity	Ethernet connection	https://www.nortekgroup.com/products/signature-1000
Blancett flow meter	flowrate	Requires frequency to voltage converter	https://www.instrumart.com/products/18337/blancett-1100-turbine-flow-meter
IFM Magnetic-inductive flow meter	flowrate	Analog output	https://www.digikey.com/en/products/detail/ifm-efector-inc/SM8601/17866646
Flow Technology flow meter	flowrate	Requires frequency to voltage converter	https://ftimeters.com/products/turbine-meters/
Wave/Water Height			
Liquid level sensor	water height	Analog output	https://www.digikey.com/en/products/detail/maxbotix-inc/MB7850-B31/16909597
Akamina Wave Gauge	wave height	Analog output	http://www.akamina.com/AWP-24-3.html
Wavestaff	wave height	RS232 connection	https://www.oceansensorsystems.com/products.htm#WaveStaff:

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[5] Acoustic Doppler Velocimeter
[6] Acoustic Doppler Current Profiler

Name	Measured Value(s)	Notes	Link
Pressure			
Omega general purpose pressure transducer	pressure	Analog output	https://www.omega.com/en-us/pressure-measurement/pressure-transducers/px309/p/PX309-150G10V
Applied Measurements DMP pressure sensor	pressure	Analog output	https://appmeas.co.uk/products/pressure-sensors/high-accuracy-industrial-pressure-sensor-dmp331/
Load/Torque/Strain			
Futek Loadcell	force	mV/V output - requires NI-9237 module	https://www.futek.com/store/load-cells
Applied Measurements Submersible Load Cell	force	Analog output option	https://appmeas.co.uk/products/load-cells-force-sensors/in-line-submersible-load-cell-dden/
IMU/INS/GPS			
Yost 3-Space IMU[7]	IMU	RS232 connection	https://yostlabs.com/product/3-space-watertight-usbrs232/
Xsens MTI 710 INS[8]	IMU/INS/GPS	RS232 connection	https://www.movella.com/products/sensor-modules/xsens-mti-g-710-gnss-ins
Spatial Dual	IMU/INS/GPS	RS232 connection	https://www.advancednavigation.com/wp-content/uploads/2021/11/spatial-dual-datasheet.pdf
LORD AHRS[9]	AHRS	RS232 connection - no LabVIEW module yet	https://www.microstrain.com/inertial-sensors/3dm-gx5-25
Hemisphere V104	GPS	RS232 connection - NMEA	https://www.navtechgps.com/hemisphere-vector-v104n-gps-compass/
Encoders			
Dynapar Analog Encoder - Submersible	shaft position	Analog output	https://ecatalog.dynapar.com/ecatalog/absolute-encoders/en/AR62_AR63
IncOder	shaft position	BISS-C - requires NI-9521 module	https://www.celeramotion.com/zettlex/products/incoder-inductive-encoders/

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[7] Inertial Measurement Unit

[8] Inertial Navigation System

[9] Attitude and Heading Reference System

Name	Measured Value(s)	Notes	Link
Generic Resolver	shaft position	Requires SET-RDK-9316 module	https://www.smart-e-tech.de/wp-content/uploads/2022/06/SET-RDK-9316-Technical-Description.pdf
Generic TTL Encoder	shaft position	Requires NI-9403 TTL card	https://www.ni.com/en-lb/shop/model/ni-9403.html
Voltage/Current			
Verivolt Isoblock V-1c	voltage	Analog output	https://www.verivolt.com/shop/isoblock-v-1c-310
Verivolt Isoblock I-ST-1c	current	Analog output	https://www.verivolt.com/shop/isoblock-i-st-1c-436
Temperature/ Humidity			
Generic PT100	temperature	resistance output - require NI-9216 module	https://www.ni.com/en-us/shop/model/ni-9216.html
Generic PT1000	temperature	resistance output - require NI-9226 module	https://www.ni.com/en-us/shop/model/ni-9226.html
Vaisala Temp and Humidity	temperature/humidity	Analog output	https://www.vaisala.com/en/products/instruments-sensors-and-other-measurement-devices/instruments-industrial-measurements/hmp60
Water Quality			
Conductivity sensor	conductivity	Analog output - 4-20 mA	https://www.streamlinefiltration.com/product/signet-integral-conductivity-sensor-4-20-ma-output-signal-1-0-cell-constant/