Safety & Reliability Capabilities of Lithium-Ion Battery Systems for Subsea Applications That Use Autonomous Lithium-Ion Battery Modules

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Abstract— **Medium and Large Lithium-Ion battery systems constructed from fully autonomous battery modules and configured using distributed system architecture can provide unsurpassed capability for safety and reliability required in subsea applications. These capabilities are described and multiple system examples are provided showing the flexibility of this unique battery system construct. Photos of a recently fielded subsea battery system using autonomous battery modules in a distributed system architecture are provided.**

Keywords—Battery; Subsea Battery; Battery Module; Autonomous Battery Module; Battery System; Battery System Architecture; Distributed Battery System Architecture, Lithium-Ion; BMS

I. Introduction

Medium and large Lithium-Ion Battery Systems used in difficult subsea environments are being challenged to deliver safety and reliability superior to older battery solutions without compromising Lithium-Ion's unrivaled energy density. Unfortunately the road to Lithium-Ion battery safety and reliability has been an especially difficult one filled with missteps that have been widely publicized. Medium sized battery systems such as those on the Boeing 787 [1] and extremely large battery systems such as those on the Navy's ASDS submarine [2] are examples of these widely publicized missteps. Not so widely publicized are requirements for reliability that, if not met, can result in the loss of expensive vehicles or that can even endanger life.

This paper describes the safety and reliability features of a unique architecture Lithium-Ion battery system constructed of fully autonomous battery modules utilizing pressure tolerant Lithium-Polymer cells. The autonomous modules have the flexibility to be configured into medium or large battery systems suitable for use in small to very large AUVs, hybrid ROVs, MUVs, and subsea platforms. Each autonomous battery module contains advanced battery management system (BMS) safety and architectural construct reliability features that are a compendium of continuous improvements learned over the past 15 years.

The BMS safety features are divided into two categories: 1) Industry common and 2) Advanced. Some of the advanced features are covered by patents or pending patents that are owned by Southwest Electronic Energy Group ("SWE"). Each of the features is fully described including their purpose and benefits.

Multiple levels of problem mitigation to improve safety and reliability are described. The list of safety features can be used as a shopping list for safety and reliability that conscientious developers of Lithium-Ion Battery Systems can use to understand what is, or is not, included in the capabilities of a BMS being considered for subsea use.

Battery system architecture is a subject that is almost never covered in battery system papers. This is surprising since the architecture of a battery system is critical to the battery system's ability to tolerate cell or module faults without loss of battery power and potential resultant loss of expensive underwater vehicles, a critical mission, or even life. A battery system's architecture is also critical to the flexibility of constructing multiple vehicle batteries of different voltage and amp-hour capacity using identical battery modules. An advanced 'distributed' battery system architecture interconnecting autonomous battery modules that is redundant in both BMS safety and in failure-tolerant reliability is described in this paper with examples. This advanced architectural concept is extremely flexible allowing fast and easy construction of custom, safe, reliable, and robust battery systems using common, smart, autonomous, battery modules. The brain of the autonomous battery module is the Host BMS electronics that can be fully contained within each autonomous battery module. The small size of a 10 cell Host BMS board is illustrated in Figure 1.

Recent photos of a fielded subsea Lithium-Ion battery system used to power a hybrid ROV built by Woods Hole Oceanographic Institute demonstrate how a distributed architecture battery system using autonomous modules is currently being used in a subsea environment. Other examples of proposed battery system solutions of different voltage and power are also provided.

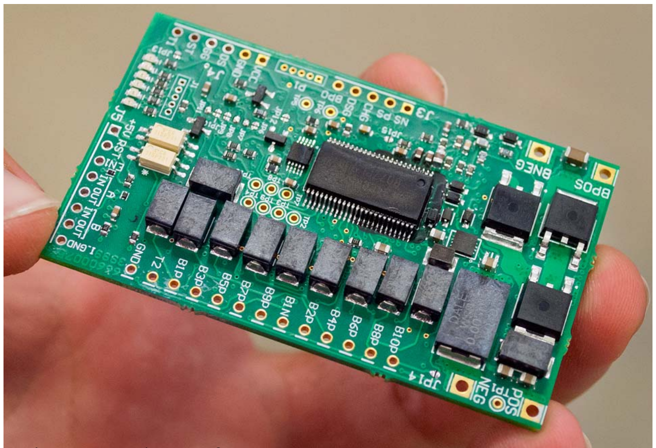


Figure 1. Photo of Host BMS Assy

II. Best BMS Design Practice - Safety & Reliability

Batteries containing Li-Ion cells almost always require a BMS. The BMS's function is dual purpose - safety and reliability. Safety involves prevention of a sudden release of battery's energy to avoid harm to people or property. BMS features' reliability involves prevention of damage to battery cells to maximize battery life and allow the available energy to be utilized when needed. Features have been added to BMS electronics as Li-Ion failure modes and their mitigation have become better understood over the past 15 years or so. Architectural reliability is discussed in section IV and involves redundancy. Both BMS and Architectural Reliability can be as important as safety in applications where battery energy is needed to complete a critical life-or-death mission.

A. *Best BMS Design Practice Overview*

The details for the best BMS design practice are arranged in a series of tables. The tables list the features summarized in Table 1 providing the purpose of each feature, the feature benefits, and, typically, two levels of mitigation associated with the feature purpose. The stronger mitigation level, if available from a BMS supplier, would be appropriate for an application requiring an increased level of safety and reliability.

B. *Best BMS Desigh Practice Details – Tables' Overview*

The tables contain features' details sufficient for a general understanding of the benefits and mitigation levels. The purposes listed in the best BMS design practice details tables are summaries that assume knowledge of how Lithium-Ion cells can fail. A very good tutorial review of this knowledge can be found in [3] whose reading is highly recommended for those who desire a more in-depth understanding of the various BMS features' purposes. Engineering design details associated with features' implementations are beyond the scope of this paper.

The Best BMS Design Practice Details are intended to provide a shopping list of desirable BMS features for either the battery system designer or the engineer who needs to specify battery system BMS requirements for a particular vehicle, application, or mission.

INDUSTRY COMMON FEATURES	ADVANCED FEATURES
1. Cell Over Voltage/Over Charge detection/prevention	*Internal Charge Control/Pulse Charging*
2. Cell Under Voltage detection/prevention	*Copper dissolution shorts prevention*
3. Charge & discharge allowance only within a defined temperature window	*Battery Module environmental controls*
4. Short Circuit detection/prevention	*Internal cell shorts detection*
5. High Current Pulse discharge allowance	*Redundant short circuit fuse*
6. Charge Mode only intra-module cell balancing & Balance error detection	*Continuous intra-module cell balancing*
7.	*Inter-module balancing & High speed module replacement balancing*
8. SMB bus communication port	*MODBUS/CAN bus communication port*
9. Relative Capacity Gas Gauge	*Coulomb Counting Gas Gauge w/auto calibration*

Table 1. Best BMS Practice – Safety and Reliability Overview

C. *Best BMS Design Practice Details – Tables*

- Table 2 provides details on the common and advanced features associated with charging and prevention of over charge stress.

FEATURES	BENEFITS/MITIGATION
1. Cell Over Voltage/Over Chargedetection/prevention (industry common) **Purpose:** Cell damage & thermal run away prevention.	Detection allows BMS to communicate with charger to take collective action to reduce or stop charge current into cells. **Stronger mitigation:** BMS autonomously disconnects battery module from charge current.
Internal Charge Control/Pulse Charging (advanced) **Purpose:** Cell damage & thermal run away prevention and increased cell longevity.	Battery Module, connected to a voltage limited/current limited charging source, autonomously connects and disconnects itself from charging source to charge battery module cells to no more than 100% State Of Charge (SOC). **Stronger mitigation:** is for SOC to be programmable below 100% to reduce stress on module cells and increase module longevity.

Table 2. Over Charge Stress Prevention.

- Table 3 provides details on the common and advanced features associated with discharging, i.e., under voltage detection and copper dissolution shorts prevention

FEATURES	BENEFITS/MITIGATION
2. Cell Under Voltage detection/prevention (industry common) **Purpose:** Cell damage prevention.	Detection allows BMS to take action to disconnect cells from discharge into an external load. **Stronger mitigation:** BMS additionally goes into low power mode to decrease self discharge of battery module.
Copper Dissolution shorts prevention (advanced) **Purpose:** Prevention of Internal shorts due to Lithium dendrite formation after copper dissolution & Thermal runaway prevention.	Detection of any cell reaching low copper dissolution voltage threshold for a defined period of time allows BMS to take collective action to permanently stop charge current into cell. **Stronger mitigation:** Above detection results in BMS autonomously, permanently disconnecting Battery Module from charge current.

Table 3. Over Discharge Stress Prevention.

- Table 4 provides details on the common and advanced features associated with temperature restrictions during charging & discharging and associated with controls on battery temperature environment.

FEATURES	BENEFITS/MITIGATION
3. Charge & discharge allowance only within a defined temperature window (industry common) **Purpose:** Cell damage prevention. Internal shorts prevention. Thermal runaway prevention.	Detection allows BMS to communicate with charger and take collective action to reduce or stop charge/discharge current into/out of cell. **Stronger mitigation:** BMS autonomously disconnects battery module from charger/load outside of a defined temperature window.
Battery Module environmental controls (advanced) **Purpose:** Cell damage prevention. Internal shorts prevention. Thermal runaway prevention. Thermal runaway chain reaction prevention.	Various means to passively and/or actively remove heat from battery module cells and/or thermally isolate cells from one another. **Stronger mitigation:** Means to heat battery cells when temperature is below a threshold that can allow Lithium dendrite formation during charging.

Table 4. Temperature Stress Prevention.

- Table 5 provides details on the common and advanced features associated with external short circuit detection and internal short shorts detection.

NOTE: Internal shorts detection is a current active field of research and development. It is not available with most BMS's – even otherwise advanced BMS's. The advanced internal shorts detection methods used by SWE require data provided by the continuous intra-module balancing feature that will be described later.

FEATURES	BENEFITS/MITIGATION
4. Short Circuit detection/prevention (industry common) **Purpose:** Cell damage prevention. Thermal runaway prevention.	Detection of external short circuit allows BMS to take action to disconnect battery module(s) from the load. **Stronger mitigation:** BMS autonomously disconnects battery module from the load.
Internal shorts detection (advanced) **Purpose:** Thermal runaway prevention.	Detection of internal cell shorts allows BMS to request maintenance action. **Stronger mitigation:** BMS detects cell shorts, autonomously disconnects battery module from charger/load, and autonomously discharges energy from battery module.

Table 5. External & Internal Shorts Detection.

- Table 6 provides details on the common and advanced features associated with high current pulse discharging and short circuit safety fuses.

FEATURES	BENEFITS/MITIGATION
5. High Current Pulse Discharge allowance (industry common) **Purpose:** Prevent disruptive power interruptions.	High currents and resulting Voltage depression for well defined short time periods are allowed to prevent disruptive power interruptions. **Stronger mitigation:** Multiple current and pulse width levels can provide greater load variation flexibility.
Redundant Short Circuit Fuse (advanced) **Purpose:** Thermal runaway prevention.	A safety fuse between cells and battery module/system power path prevents uncontrolled high heat generation in cells should components fail or shorts occur for any reason external to the cells. **Stronger mitigation:** Safety fuse in each autonomous battery module.

Table 6. High Current & Short Circuit Discharge Prevention.

- Table 7 provides details on the common and advanced features associated with intra-module balancing. Intra-module balancing refers to balancing of series connected cells within a battery module.

NOTE: Advanced continuous intra-module balancing is a SWE unique capability covered by US patents.

FEATURES	BENEFITS/MITIGATION
6. Charge mode only intra-module cell balancing & balance error detection (industry common) **Purpose:** Prevent cell damage. Maximize available energy. Maximize cell & Module life. Prevent unequal cell stress.	Discharge balancing (typical) of cells within a module is controlled by the BMS. Balancing resistors are typically within each battery module. **Stronger mitigation:** Intra-module Cell Balancing control within autonomous modules increases balancing accuracy.
Continuous intra-module cell balancing (advanced) **Purpose:** Prevent cell damage. Maximize available energy. Maximize cell & Module life. Prevent unequal cell stress.	Ability to balance cells within a battery module in any mode - charge, discharge, quiescence, or storage allows more balancing time, reduces balancing heat generation, and provides data input to an internal shorts detection algorithm. **Stronger mitigation:** Intra-module Cell Balancing control within autonomous modules increases balancing accuracy.

Table 7. Intra-Module Cell Balancing.

- Table 8 provides details on the common and advanced features associated with inter-module balancing and high speed module replacement balancing.

NOTE: Inter-module balancing of autonomous battery modules and high speed module replacement balancing are features unique to SWE that are covered by US and International Patents awarded or applied for.

FEATURES	BENEFITS/MITIGATION
7. Inter-module balancing (advanced) **Purpose:** Maximize available energy. Prevent unequal cell stress.	Occurring at end of charge, this equalizes State Of Charge among all series connected battery modules. **Stronger mitigation:** Inter-module Cell Balancing control within autonomous modules increases balancing accuracy.
High speed module replacement balancing (advanced) **Purpose:** Maximize available energy. Prevent unequal cell stress. Minimize Time-To-Repair associated with battery module replacement.	Only available with autonomous modules. Inter-module balancing occurs during charging after module replacement. Effective differential inter-module balancing current is equal to fast charge current. No heat generation. Balancing time, even when modules are grossly out of balance, is equal to a normal fast charge cycle.

Table 8. Inter-Module Balancing.

- Table 9 provides details on the common and advanced features associated with battery communication.

FEATURES	BENEFITS/MITIGATION
8. SMB bus communication port (industry common) **Purpose:** Provide battery status/control to charger. Provide battery status/control to host system.	I^2C communication hardware is best for short bus length. Well defined SMB bus protocol. Fixed, single battery address. Provides a means for battery module to inform charger and host system of status. Multiple battery modules require multiple bus ports.
MODBUS/CAN bus communication port (advanced) **Purpose:** Provide battery status/control to charger. Provide battery status/control to system.	Robust RS-485 or CAN communication hardware provides kilometer bus length capability. Flexible bus data definition directory supports custom battery designs. Multiple addresses on one port. **Stronger mitigation:** Autonomous BMS in each battery module allows individual modules status/control communication.

Table 9. Battery System Communication.

- Table 10 provides details on the common and advanced features associated with battery and battery module gas gauging.

NOTE: The Impedance tracking algorithm is patented by Texas Instruments, Inc.

FEATURES	BENEFITS/MITIGATION
9. Relative Capacity Gas Gauge (industry common) **Purpose:** Provides Relative remaining Battery Capacity to host.	Simple gas gauge uses cell Voltage to determine relative State Of Charge in %. Accuracy is only approximate and is best an hour or so after minimum or no battery current. Five element bar graph display is common resulting in max +/-10% relative measurement accuracy.
Coulomb Counting Gas Gauge w/auto calibration (advanced) **Purpose:** Provides Absolute remaining Battery Capacity to host.	Complex gas gauge provides most useful measurement of Ah capacity. Accuracy can be as good as +/-1%. **Stronger mitigation:** Autonomous BMS in each battery module can provide more accurate worst case measurement. Increased accuracy can be obtained using an algorithm to track cell impedance with temperature and age.

Table 10. Battery Gas Gauging.

III. Modular Lithium-Ion Battery Systems

Some medium size and almost all large size Lithium-Ion battery systems claim to be constructed using battery modules. Modularity in a battery system design; however, is broadly interpreted by different battery system suppliers and its meaning has become fuzzy. For this reason a definition of a modular Lithium-Ion battery system is provided as follows:

A modular Lithium-Ion battery system is a Lithium-Ion battery system where modules are configured in series to achieve voltage and in parallel to achieve amp-hour capacity. Each module is or has:

- Battery Cells
- Local Battery Management System (BMS) functions
- Physically Identical
- Identical Connections
- Replaceable
- Relatively Small
- Reasonable Cost
- Individually Transportation Safety Test Qualified

The key features provided by this definition can be addressed one at a time. It is obvious that a battery module will have battery cells in it. What is not obvious is that the cells within a battery module may contain series and parallel combinations of these cells. When this is done, it is usually to increase the Amp-hour rating of the module by paralleling cells prior to series connecting them within the module. These paralleled cells are monitored as if they were a single large cell. A good question to ask the module designer is whether there were any means employed to limit current of paralleled cells from discharging into an internally shorted cell.

By the definition, a Lithium-Ion battery module will contain some local (within the module) BMS functions. Which functions are contained within the battery module will be a differentiator among various battery system suppliers that provide modular Lithium-Ion battery systems. As will be seen, the functionality and reliability of a modular Lithium-Ion battery system will be highly affected by which BMS functions are incorporated within each battery module.

The definition specifies that battery modules are physically identical, including connections. It becomes obvious why this is a requirement when module replacement is considered.

This brings one to the key feature of the Lithium-Ion battery module which is: it is replaceable. It is much cheaper to replace a defective battery module than it is to replace the whole battery system (one of the main reasons for modular battery system design). Similarly, transporting and storing spare modules requires much less logistical support than storing and transporting the whole battery system (another reason for modular battery system design). Lastly, inventory costs for maintaining a modular battery system are significantly reduced when one needs to only keep a few battery modules in spares inventory rather than a whole battery system consisting of dozens or hundreds of equivalent battery modules.

Being relatively small and having a reasonable cost is desirable to keep replacement inventory costs down and, possibly, for improved safety. However, there is usually a trade-off between module size & cost and system size & cost. For a very large battery system, construction using hundreds of very small, cheap battery modules could be more expensive than if one used an order of magnitude of fewer, larger and somewhat more expensive, modules.

The last feature of a Lithium-Ion battery module should not be overlooked. If one expects to repair a battery system using replaceable battery modules this invariably means that the replacement battery module will need to be shipped separate from the battery system. This means that the Lithium-Ion battery module must have individually passed all the UN Transportation Safety Tests (UN 38.3) or it cannot be legally shipped in many countries.

IV. Modular Lithium-Ion Battery Architectures

Almost never is there a discussion of modular Lithium-Ion battery system architectures yet they can have a huge effect on battery system safety and reliability. In this paper, two different battery system architectures will be described that incorporate battery modules: a centralized architecture and a distributed architecture. Architectural differences that can lead to differences in system functionality, safety, and reliability will be discussed.

A. The Centralized Modular Lithium-Ion Battery System Architecture

Since there is already much information about various centralized battery system structures & capability and very little information about distributed battery system structures & capability, this paper will provide only an overview of the centralized architecture so that it can be compared with the distributed architecture. For a more detailed discussion of the centralized architecture see [4].

Figure 2 is a block diagram of an example centralized architecture modular Lithium-Ion battery system. Figure 2 is not a description of any one centralized battery system in particular but contains typical or general characteristics that are provided for illustrative purposes.

What is shown in Figure 2 is a battery system that contains 8 strings of series connected 30 Volt, 30 Amp-hour battery modules. The series connections of 8, 30 Volt modules are done to achieve a nominal battery system voltage of 240 Volts. The parallel connections of 8, 240 Volt, 30 Amp-hour strings of modules are done to achieve a total battery system of 240 Amp-hours and to achieve high output power capability. The diodes shown separating the series strings of modules are there for reliability purposes to prevent failure of one string of modules from causing other strings of modules to fail or have their capacity reduced.

Observe in Figure 2 that, in this centralized architecture, only a portion of the BMS functionality (shown by the colored shapes) is contained within the battery module. The rest of the BMS functionality is contained either in external string controllers or in the external central battery system controller. The specific division of BMS functionality in the various external controllers is what differentiates one specific centralized battery system from another. The common characteristic, however, is that there is at least one external controller and that critical BMS functions are obtained by communication of the battery modules to the external controller or controllers.

A very typical feature of the centralized architecture is that there is only one set of charge and discharge disconnect switches that are located within the external central battery system controller. Sometimes there is only one disconnect switch that does not differentiate between charge current and discharge current. It is common that the disconnect switches are high current normally closed contactors.

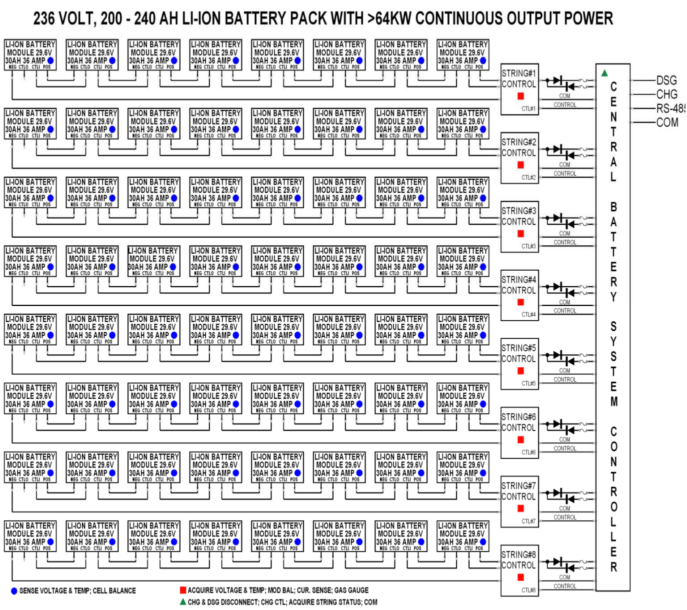


Figure 2. Example Centralized Architecture Lithium-Ion Battery System

B. The Distributed Modular Lithium-Ion Battery System Architecture

Figure 3 is a block diagram of an example distributed battery system architecture used by SWE. Each of the battery modules in the example are fully autonomous; meaning that no communication to, from, or among the modules is required for implementation of BMS safety or reliability functions. For comparison purposes the Figure 3 example is a battery system of the same voltage and Amp-hour capacity as the Figure 2 example. This is only one example of a specific distributed battery system. Other battery systems could be constructed using identical battery modules with different sized cells or more or less number of series cells within each module and using more or less series connected modules within a string and more or less parallel connected strings of modules within the whole battery system. The power of the distributed architecture using identical autonomous battery modules is the flexibility of how the modules can be interconnected to create an almost endless variety of unique battery systems.

As in Figure 2, Figure 3 is a battery system that contains 8 strings of series connected 30 Volt, 30 Amp-hour battery modules. The series connection of 8, 30 Volt modules is done to achieve a nominal battery system voltage of 240 Volts. The parallel connection of 8, 240 Volt, 30 Amp-hour strings of modules is done to achieve a total battery system of 240 Amp-hours and to achieve high output power capability.

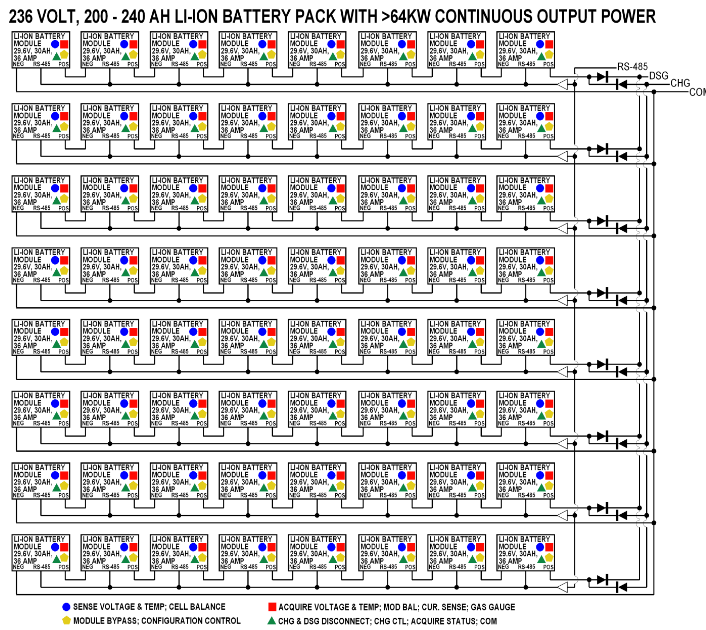


Figure 3. Example Distributed Architecture Lithium-Ion Battery System

In the Distributed Architecture, Charge and Discharge disconnects are contained within each battery module. This is a major difference between the centralized and distributed architecture. Also in the distributed architecture, all of the BMS functionality (shown by the colored shapes) is contained within each battery module. This even includes charge control which some centralized battery systems do not have but leave to an external intelligent charger. Unlike the centralized battery system architecture, there is no need for internal module controllers along with one or more large BMS control boards in the battery system. For the distributed Architecture, the sole intra-module BMS battery module controller is all that is required. The BMS module controller, while having to be functionally robust, does not have to be large. Figure 1 is a photo of a distributed system battery module controller that contains all the best design practice electronic BMS functions previously described within a very small circuit. The circuit in Figure 1 has a 9 Amp continuous current capability. Small booster circuits (not shown) can be connected to this circuit to increase module current capability to more than 80 Amps continuously.

An additional set of BMS functions not normally found in the centralized battery system architecture is the module bypass function and module configuration control function illustrated by the yellow pentagon shape. These will be described later.

There is still a need for external diodes to isolate series strings of modules from one another. These diodes are best implemented using ideal diode circuits that generate minimal heat during charge and discharge of the battery system.

Observe in Figure 3 that each battery module communicates on a common communication bus (RS485, MODBUS in this instance). This communication is not required for BMS functionality but is provided to allow visibility into battery modules' status for use by the system being powered by the battery.

It can be seen from this simple example that the distributed architecture contains an inherently generous amount of redundancy of the BMS functions. For instance, in the Figure 3 example, if there is a short on the output of one of the battery strings all 8 modules are monitoring the shorting current and all 8 modules have an opportunity to disconnect (open) their discharge switches (FETs) in response to the short. Once any of the 8 modules disconnects its discharge switches in response to the short the whole series string is disconnected. If there is a failure in any one of the 8 series connected modules to disconnect its discharge switches/FETs there are 7 redundant opportunities for one of the other series connected modules to do this. Several other BMS functions are similarly redundant.

C. *Distributed Modular Lithium-Ion Battery System Architecture Capabilities*

Table 11 details some of the features and benefits possible with a distributed architecture Lithium-Ion battery system like that developed by SWE. Several of these features are unique to the distributed architecture i.e., they are not available with centralized architecture Lithium-Ion battery systems.

Figure 4 is an example of a thorough but simple Operator Interface that can be constructed from real time monitored data from each battery module via an RS485 MODBUS computer interface. This example is an illustration of how one can use module status data to display the following whole battery system status: System Voltage; Capacity; Current; Temperature; and Faults (status light turns yellow or red when faults are present). A more detailed display of individual module and even cell status can be provided as needed for maintenance purposes by clicking on the SHOW ALL box. Less detail (just the status light for instance) can be provided to simplify battery monitoring for inclusion in a complex operator's panel. Logging of all module status and faults can also automatically be performed for post mission analysis purposes.

All battery systems require periodic maintenance to maintain safety and reliability characteristics. Table 12 contains Maintenance Features and Benefits that can be obtained from an exemplary distributed architecture Lithium-Ion battery system. The maintenance capabilities provide a means for keeping the battery modules and, thus, the whole battery system at a constant state of readiness and safety.

FEATURES	BENEFITS
1. Autonomous Battery Modules	Inherent Safety & Reliability Redundancy
2. Internal Charge Control	Increased Safety & Battery System Longevity
3. Continuous Cell Balancing	Improved Safety & Longevity
4. Fine Inter-Module Balancing & 5. Module Replacement Balancing During Charge	Improved System Capacity, Discharge Current Sharing, & Minimization of MTTR
6. Configurable Safety & Reliability Functions	Cell Chemistry Agnostic & Mission Customization
7. Non-Critical Isolated Communication Port	Improved Reliability & Safety
8. Real Time Monitoring from each Battery Module	Mission Data Record and Operator Interface with System & Module Status

Table 11. Features Available with a Distributed Architecture Lithium-Ion Battery System

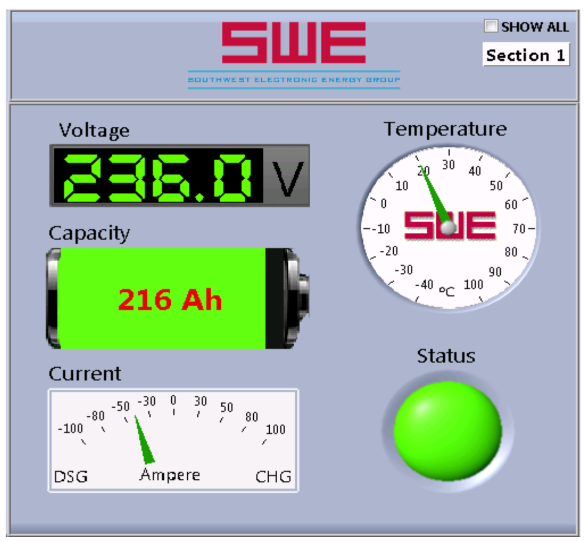


Figure 4. Operator Interface Example

D. *Use Criticality Recommendations between Distributed and Centralized Architectures*

Table 13 provides comparisons of which architecture has an advantage based on use criticality. The division is fairly clear. If the mission is critical or failure and fire can result in loss of life or high value property, the superiority in safety and reliability of the distributed architecture has the highest value. This use criticality is typical of most subsea application.

For non-critical uses the less redundant centralized battery system architecture is generally less costly if the extra custom design effort can be amortized across a large number of identical centralized battery systems. Also, high voltage requirements may favor the centralized architecture because high voltage disconnects are required only for the central disconnect contactor(s).

FEATURES	BENEFITS
1. Identification of Weak Module – i.e. State Of Health (SOH)	Allows Planned Module Replacement at a Convenient Time
2. Identification of Failing or Failed Module	Allows Removal & Replacement of Potentially Dangerous Module(s)
3. No Hassle Module Replacement	Fast, Error Free Module Replacement Without the Need for Extensive Maintenance Balancing Prep.
4. Ultra-Fast Module Balancing During Charge Using Module Bypass Circuits	Balances Modules After Module Replacement Autonomous - No External Communication Control is Req'd Little or No Heat >50% Module Balance Correction in One Charge Cycle (100s Times Faster)

Table 12. Maintenance Features of an Exemplary Lithium-Ion Battery System

USE CRITICALITY	DIST. ARCHITECTURE	CENT. ARCHITECTURE
Where Mission Completion is Critical	Best due to inherent Redundancy & Reliability	
Where a Battery Fire Can Endanger Life	Best due to inherent Safety Superiority & Redundancy	
Where Battery Failure Can Endanger Life	Best due to inherent Redundancy & Reliability	
Where failure/fire will not Endanger Life		Best because less redundancy is less costly
Where Battery Voltage Exceeds 450V		Best as High voltage design is req'd for only one contactor.
Where failure/fire => high value property loss	Best due to inherent Safety Superiority & Redundancy	

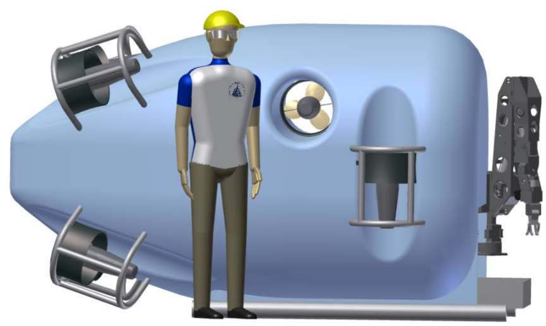
Table 13. Use Criticality Comparisons of Distributed and Centralized Architectures

V. Typical Subsea Applications

This paper will conclude with two real world subsea application examples. One is a hybrid Under Ice Arctic ROV proposed by Woods Hole Oceanographic Institute ("WHOI") and the other is a hybrid High Definition 3D Cinematography ROV that was fielded in 2012 by WHOI.

A. Hybrid Under Ice Arctic ROV Proposal

Figure 5 is a sketch of the proposed WHOI hybrid Under Ice Arctic ROV overlaid both with WHOI's requirements and with how those requirements can be met or exceeded using an SWE designed distributed modular Lithium-Ion battery system.



WHOI Battery Requirements	SWE Autonomous Li-Ion Module Delivers
• Safe, Reliable Operation	• Safe, Reliable, Autonomous BMS
• 2000 m depth	• ≥ 6000 m depth battery modules
• 88 Volts	• 3 Series, 29V/28Ah Modules = 87V
• 100 recharge cycles	• 1000+ recharge cycles
• -20°C to +50°C Range	• -40°C to +85°C discharge Temp Range
• >15kWh in 36" x 24" x 12"	• > 22kWh in ≤ 36" x 24" x 12" using 3S9P modules @90% SOC
• 12 hours recharge time	• < 12 hours recharge
• Internal protection and balancing	• SWE SeaSafe BMS: Internal protection and balancing
• External Battery Data Logging	• SWE SeaSafe BMS: Modbus access to battery status on demand, log external

Figure 5. Proposed Hybrid Under Ice Arctic ROV with Battery Requirements

Figure 6 is a sketch of the Battery system architecture that meets both the WHOI requirements and the SWE delivery specifications of Figure 5. Notice the similarity of this system with the prior example in figure 3. The difference is that Figure 3 uses 8S8P autonomous modules and Figure 6 uses 3S9P autonomous modules. The ease of constructing a custom battery system from common autonomous battery modules is obvious.

B. WHOI Hybrid High Definition 3D Cinematography ROV Battery System

In order to gain some experience with the autonomous battery modules expected to be used in the proposed hybrid Under Ice Arctic ROV, WHOI fielded a smaller hybrid High Definition 3D Cinematography ROV that utilized just 6 of the SWE autonomous battery modules in a 3S2P distributed battery system configuration. A photograph of the inside of the battery system WHOI constructed is shown in Figure 7. The battery system was housed in a pressure equalized plastic box filled with silicon oil.

Figure 8 is a photograph of WHOI's hybrid High Definition 3D Cinematography ROV being readied for deployment in the ocean. The distributed battery system is housed in the white box in the center of the photo. WHOI pressure tested the modules used in this system to 6,000 psi and used the system at depths where the pressure was somewhat less than that. The autonomous battery modules were prototypes constructed by SWE. Subsequent to this field test, pre-production modules have been constructed by SWE that have been pressure validated to 10,000 psi. These modules are rated for use down to 6,000 meters ocean depth.

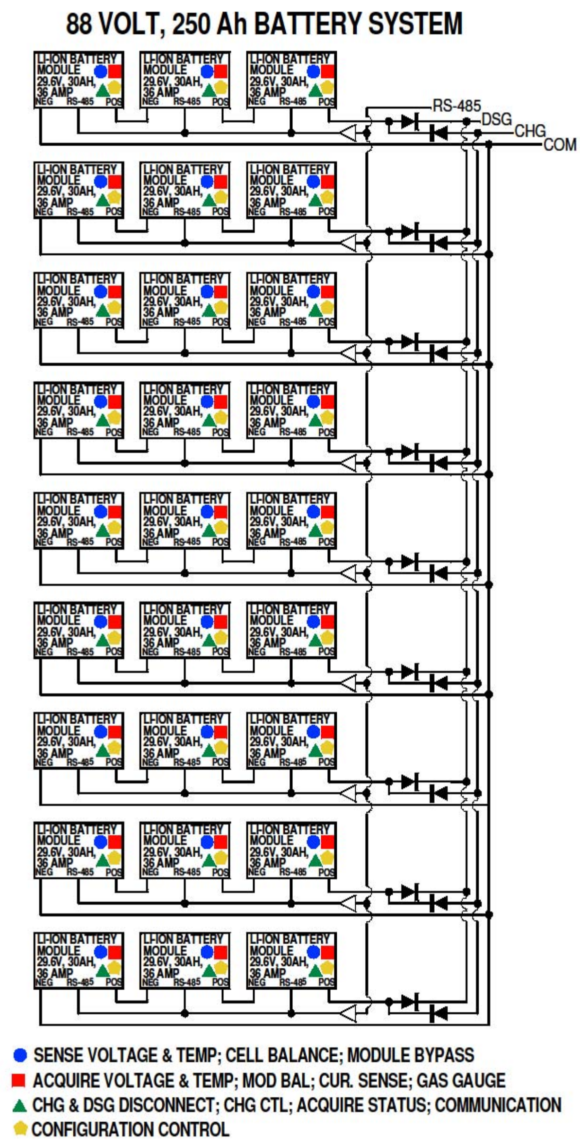


Figure 6. 3S9P Autonomous Battery Modules

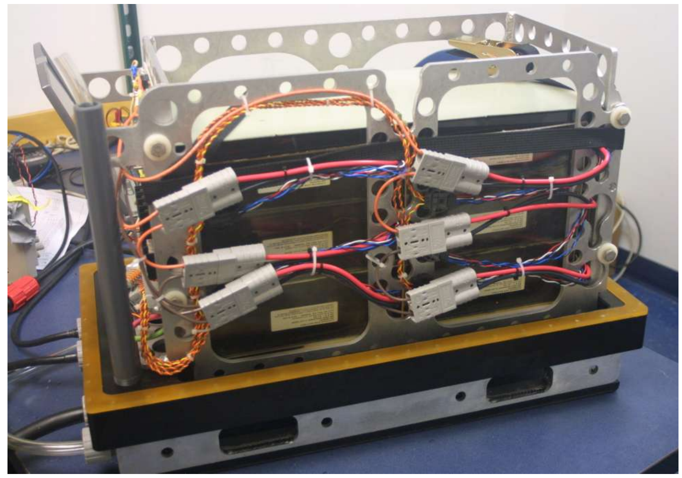


Figure 7. Inside View of a 3S2P Battery System That Uses Autonomous Battery Modules

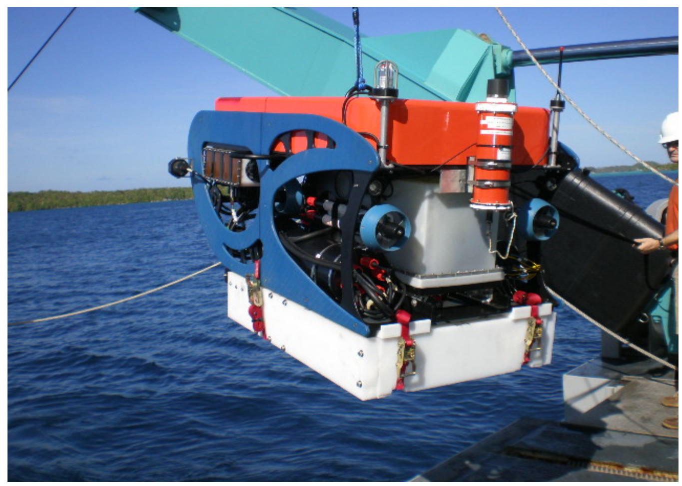


Figure 8. WHOI Hybrid High Definition 3D Cinematography ROV

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