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OFFSHORE & AUTONOMOUS

Electrical Digital Twin Architecture for Autonomous and Survey Platforms

System-Level Validation for Mission-Critical Marine & Subsea Electrical Systems

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Autonomous and survey marine platforms - including survey vessels, unmanned surface vehicles (USVs), autonomous underwater vehicles (AUVs), and remotely operated vehicles (ROVs) - operate under electrical design constraints that differ fundamentally from conventional marine systems.

These platforms demand mission-critical power reliability, operate with limited or no onboard personnel, and undergo frequent reconfiguration between mobilizations. Traditional spreadsheet-based electrical design and validation methods are structurally insufficient for managing the lifecycle complexity of these systems.

This paper applies the Electrical Digital Twin Architecture to autonomous and survey platforms, describing how graph-based topology modeling, deterministic constraint evaluation, immutable lifecycle validation, and telemetry binding address the unique electrical engineering challenges of this domain.

SCOPE OF APPLICABILITY

This publication describes an architectural framework applied to electrical systems in autonomous and survey marine platforms. It focuses exclusively on:

- Low-voltage DC and mixed AC/DC electrical systems
- Power distribution architecture
- Redundancy topology
- Mission-critical load modeling
- Lifecycle configuration management

This publication does not describe acoustic positioning systems, calibration algorithms, navigation fusion, sensor fusion, signal processing methods, photogrammetry pose graph logic, or any non- electrical subsystem modeling. AC systems are addressed only as interface boundaries, not as full AC power-flow models.

Application of this architecture to real-world systems must be performed by qualified electrical and marine engineers in accordance with applicable codes, classification society requirements, and flag-state regulations.

COMPLIANCE AND SAFETY NOTICE

This publication is provided for informational purposes only and does not provide engineering advice, installation instructions, or certification evidence. It does not guarantee compliance with ABYC, ISO, IEC, DNV, Lloyds Register, Bureau Veritas, ABS, USCG, MCA, flag-state rules, or classification society requirements. Compliance determinations remain the responsibility of qualified professionals and the relevant authority.

Electrical failures on autonomous and survey platforms can create safety hazards including fire, loss of vessel control, and mission- critical system failure. Any implementation must be independently reviewed, tested, and validated.

No representation is made that use of this architecture ensures safety, regulatory compliance, or fitness for a particular purpose. Readers shall not rely on this document as a substitute for independent engineering analysis, regulatory consultation, or professional design review. Use of the architectural concepts described herein remains at the sole risk of the implementer.

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1. THE OFFSHORE AND AUTONOMOUS ELECTRICAL ENVIRONMENT

Autonomous and survey platforms present electrical design challenges not typically encountered in conventional marine vessels. These challenges arise from the intersection of mission criticality, operational autonomy, environmental exposure, and platform diversity.

1.1 Survey Vessels

Survey vessels carry significant electrical loads driven by mission equipment: multibeam echosounders, sub-bottom profilers, magnetometers, USBL positioning transponders, motion reference units, and associated data acquisition systems. This mission equipment is frequently changed between mobilizations. Each mobilization may add, remove, or reconfigure deck-mounted and hull-mounted systems, altering the electrical load profile, protection requirements, and conductor routing.

Hybrid propulsion architectures - combining diesel generators with battery energy storage - create complex power management requirements. Generator loading, battery state-of-charge, and dynamic load transitions between propulsion and survey modes must all be accounted for in the electrical design.

Dynamic Positioning (DP) systems impose strict redundancy requirements. DP Class 2 and Class 3 vessels require independent power bus architectures with defined fault tolerance. The electrical topology must demonstrate that single-point failures do not compromise positioning capability.

1.2 Unmanned Surface Vehicles (USVs)

USVs are typically battery-dominant platforms with limited onboard energy storage. Electrical system design is constrained by:

- Total energy budget for mission duration
- Propulsion motor peak and continuous loading
- Payload electrical demand
- Shore charging integration and docking power transfer
- Fail-safe redundancy for loss-of-communications scenarios
- Remote monitoring without onboard personnel

The absence of onboard operators means that electrical faults must be detectable, diagnosable, and where possible recoverable through automated or remote intervention. This places elevated requirements on telemetry binding and real-time load monitoring.

1.3 Autonomous Underwater Vehicles (AUVs)

AUVs operate with sealed energy systems - typically lithium battery packs enclosed in pressure housings. Electrical design constraints include:

- Fixed energy capacity per mission
- Thermal management within sealed enclosures
- Load prioritization and shedding logic
- Pressure-compensated connector interfaces
- Limited ability to modify systems between dives without significant intervention

Mission duration is directly coupled to electrical energy management. Conductor sizing, protection coordination, and load scheduling directly affect operational endurance.

1.4 Remotely Operated Vehicles (ROVs)

ROVs receive power through an umbilical from a topside vessel. The electrical design challenge is dominated by:

- Long conductor runs through the umbilical (often hundreds of meters)
- Voltage drop across the tether under full load
- Topside generator capacity and loading constraints
- Power conversion at the vehicle (typically high-voltage AC to low-voltage DC)
- Tool power demand variability (manipulators, cutters, pumps)

The umbilical is both the power delivery mechanism and a single point of vulnerability. Conductor sizing, voltage regulation, and protection coordination across the full topside-to-vehicle path require system-level analysis that spans two physically separate platforms.

1.5 Hybrid Generator/Battery Platforms

Many modern survey and autonomous platforms use hybrid power systems combining:

- Diesel or gas generators
- Battery energy storage systems (BESS)
- Shore power connections

- Solar or fuel cell auxiliary sources

These hybrid architectures create complex power flow scenarios where source priority, load sharing, battery charge/discharge management, and generator run-time optimization must all be captured in the electrical model. The graph-based topology must represent multiple source types, switching configurations, and load allocation paths.

2. WHY TRADITIONAL TOOLS ARE INSUFFICIENT

Conventional marine electrical design relies on:

- Spreadsheet-based load analysis
- Manual cable sizing calculations
- Standalone single-line diagrams
- Protection coordination studies performed as isolated exercises
- Classification society submissions prepared as static documents

These methods share common structural limitations:

- No lifecycle binding: calculations are not linked to specific system revisions or configurations.
- No topology awareness: conductor sizing and protection analysis treat circuits in isolation rather than as an interconnected system.
- No mobilization tracking: configuration changes between survey campaigns are managed through document revisions, not system- level validation.
- No telemetry correlation: operational data from generators, batteries, and loads is not compared against design assumptions.
- No redundancy verification: DP bus separation and fault tolerance are described in narrative documents, not validated against topology.

For autonomous and survey platforms - where configurations change frequently, operational monitoring is essential, and redundancy requirements are strict - these limitations create compounding risk.

3. GRAPH-BASED TOPOLOGY FOR MISSION-CRITICAL SYSTEMS

The Electrical Digital Twin Architecture represents the complete electrical system as a versioned, directed graph:

- Nodes represent electrical entities: power sources (generators, battery banks, fuel cells, shore connections), DC and AC buses, protection devices (fuses, breakers, electronic protection), switching devices, connectors, loads, and grounding points.
- Edges represent conductive relationships: conductors, bus segments, umbilical cores, and ground return paths.
- Attributes encode electrical properties: conductor gauge, insulation rating, voltage rating, current capacity (subject to derating factors), length, environmental classification, and redundancy group assignment.

This graph structure enables:

- System-level voltage drop analysis across complete distribution paths, including long umbilical runs.
- Aggregated thermal loading within conductor bundles and enclosed spaces.
- Protection coordination analysis across cascaded protection devices.
- Redundancy topology verification for DP bus separation.
- Source-to-load path tracing for mission-critical circuits.

The model is deterministic within the bounds of declared model inputs and constraint definitions: given the same topology and attributes, it produces the same evaluation results. No hidden state. No probabilistic behavior. Every evaluation is reproducible and auditable.

4. CONSTRAINT PROFILES FOR OFFSHORE PLATFORMS

Constraint profiles allow domain-specific rules to be applied to the core graph model without modifying the underlying topology structure.

For autonomous and survey platforms, constraint profiles address:

4.1 Survey Vessel Profiles

- Generator loading limits and operating range constraints
- DP bus separation requirements (independent power paths)
- Deck equipment aggregate load budgets
- Shore power transfer switching constraints
- Battery BESS charge/discharge rate limits
- Redundancy group isolation verification

4.2 USV Profiles

- Battery energy budget per mission duration
- Propulsion motor continuous and peak current limits
- Shore charging connector and conductor constraints
- Fail-safe switching requirements for loss-of-comms
- Payload power allocation budgets
- Thermal constraints for battery enclosures

4.3 AUV Profiles

- Sealed battery capacity and discharge constraints
- Pressure housing thermal dissipation limits
- Load priority classification and shedding hierarchy
- Connector pressure-rating constraints
- Mission-duration energy budgeting

4.4 ROV Profiles

- Umbilical conductor voltage drop across full length
- Topside generator loading impact from vehicle demand
- High-voltage to low-voltage conversion constraints
- Tool power variability and peak demand allocation
- Umbilical conductor thermal limits

4.5 Hybrid Power Profiles

- Multi-source load sharing and priority constraints
- Battery state-of-charge boundary conditions
- Generator minimum/maximum loading thresholds
- Source transition switching constraints
- Charging source conflict detection

These profiles are declarative overlays. They are applied to the graph topology without mutating core structure. Multiple profiles can be composed to represent specific platform configurations.

5. REDUNDANCY ARCHITECTURE MODELING

Autonomous and survey platforms frequently require demonstrated electrical redundancy. DP Class 2 systems, for example, require that the electrical system be divided into independent sections such that a single failure does not result in loss of position.

The graph-based topology enables:

- Identification of all source-to-load paths for critical circuits
- Detection of single points of failure in power distribution
- Verification that redundant buses are electrically independent
- Confirmation that switching configurations maintain redundancy under defined failure scenarios

Redundancy analysis is performed against the topology graph, not against narrative descriptions. This means that configuration changes - such as adding a new load to a DP bus - are immediately evaluated against redundancy constraints.

The architecture does not replace classification society review or FMEA (Failure Mode and Effects Analysis). It provides structured topology evidence that can support such reviews.

6. LIFECYCLE CONFIGURATION MANAGEMENT

Survey and autonomous platforms undergo frequent electrical system modifications:

- Mobilization: adding survey equipment, deck sensors, and associated power distribution for a specific campaign.
- Demobilization: removing campaign-specific equipment and restoring baseline configuration.
- Sensor package swaps: replacing one suite of instruments with another, altering load profiles and conductor routing.
- Redundancy switching configuration: reconfiguring bus-tie breakers and transfer switches for different operational modes.
- Generator capacity upgrades: replacing or supplementing generators, altering available power budget.
- Deck equipment additions: installing winches, A-frames, cranes, or other equipment with significant electrical demand.

Each of these modifications changes the electrical topology. In traditional workflows, these changes are captured (if at all) through revised documents. There is no structural guarantee that the revised configuration has been re-validated against all applicable constraints.

The Electrical Digital Twin Architecture addresses this through immutable revisions:

- Every modification creates a new graph revision.
- Constraint evaluation is performed against the new revision.
- Validation results are bound to the specific revision, not to a generic "current state."
- Previous revisions remain accessible for comparison, audit, and rollback assessment.
- Mobilization and demobilization configurations exist as distinct, validated graph states.

This provides lifecycle traceability: the ability to answer, for any point in the platform's history, what the electrical configuration was, what constraints were evaluated, and what the validation outcome was.

7. TELEMETRY BINDING FOR REMOTE AND AUTONOMOUS OPERATIONS

Autonomous and remotely operated platforms generate continuous electrical telemetry:

- Battery voltage and current (per bank or per cell group)
- Generator output voltage, current, and frequency
- Bus voltage at distribution panels
- Individual circuit current draw
- Temperature at critical points (battery housings, motor controllers, enclosed spaces)
- Umbilical voltage at topside and vehicle ends (ROV)

In conventional operations, this telemetry is monitored in real-time but is not correlated with the designed electrical model. The digital twin architecture enables telemetry binding: mapping operational measurements to specific graph entities.

This supports:

- Power budget drift detection: comparison of actual aggregate load against design assumptions for a specific configuration.
- Battery discharge profile comparison: actual discharge curves compared to modeled energy budgets.
- Generator loading assessment: actual generator demand compared to rated capacity and constraint thresholds.
- Thermal anomaly identification: measured temperatures compared against modeled thermal constraints.
- Umbilical performance monitoring: actual voltage drop compared to designed conductor characteristics (ROV).

Telemetry binding is read-only and observational. It does not retroactively alter validated design states. It does not implement autonomous control actions. It provides a structured comparison between as-designed and as-operated states.

For USV and AUV platforms operating without onboard personnel, this telemetry comparison is the primary mechanism for detecting electrical system degradation between missions.

8. STANDARDS AND CLASSIFICATION ALIGNMENT

Autonomous and survey platform electrical systems are subject to multiple overlapping standards and classification frameworks:

- DNV Rules for Classification of Ships (Part 4 Ch.8 Electrical Installations)
- DNV-RU-OU-0512 (Autonomous and Remotely Operated Ships)
- Lloyd's Register Code for Unmanned Marine Systems
- IEC 60092 (Electrical Installations in Ships)
- IEC 61508 / IEC 62443 (Functional Safety / Cybersecurity)
- ABYC E-11 (for applicable smaller survey vessels)
- Flag-state specific regulations and Naval Authority requirements

The architecture does not certify compliance with any standard. It provides a structured framework within which compliance evidence can be captured, validated, and maintained across lifecycle modifications.

Constraint profiles can be parameterized against specific standard requirements (conductor sizing rules, protection coordination requirements, redundancy class definitions). This parameterization describes capability, not certification. Compliance determinations remain the responsibility of qualified naval architects, marine engineers, and the relevant classification society.

9. OPERATIONAL SCENARIOS

The following scenarios illustrate how the architecture applies to typical offshore and autonomous operations. These are conceptual illustrations, not descriptions of specific implementations.

9.1 Survey Vessel Mobilization

A survey vessel is being mobilized for a deep-water campaign. The mobilization adds: a hull-mounted multibeam echosounder, a towed magnetometer winch, a sub-bottom profiler, two USBL transponders, and associated acquisition servers.

The electrical model is revised to include the new loads. Constraint evaluation identifies:

- Aggregate load on the survey equipment bus now exceeds the recommended continuous loading for the bus feeder conductor.

- The addition of the magnetometer winch places a cyclic load on a bus shared with DP-critical navigation equipment.
- Shore power capacity at the planned port of mobilization is insufficient for simultaneous charging and survey equipment testing.

These findings are captured in the validation snapshot for the mobilization revision.

9.2 USV Mission Planning

A USV is being configured for a 72-hour autonomous survey mission. The architecture enables evaluation of:

- Total energy budget based on propulsion profile, payload demand, and hotel load across the mission duration.
- Conductor thermal loading under sustained propulsion at planned survey speed.
- Battery discharge profile against manufacturer-specified limits for cycle count preservation.
- Fail-safe switching configuration validation for loss-of-comms scenarios.

9.3 ROV Umbilical Voltage Drop

An ROV is being deployed with a 3,000-meter umbilical. The architecture enables evaluation of:

- End-to-end voltage drop across the umbilical under maximum tool loading.
- Topside generator loading impact from vehicle demand plus umbilical losses.
- Voltage at the vehicle power converter input under various load combinations.
- Protection coordination between topside breakers and vehicle- side protection.

9.4 AUV Pre-Dive Validation

An AUV is being prepared for a deep-water dive. The architecture enables evaluation of:

- Energy budget adequacy for planned mission duration and profile.
- Battery thermal state within pressure housing constraints.
- Load priority configuration for the planned sensor suite.
- Connector and penetrator current ratings against planned loading.

10. COMPETITIVE CONTEXT

The autonomous and survey sector currently relies on:

- General-purpose marine electrical design spreadsheets
- Classification society submission documents (static PDFs)
- Vendor-specific battery management system interfaces
- Isolated protection coordination studies
- Manual mobilization checklists

These approaches do not provide:

- System-level topology awareness
- Lifecycle-bound validation
- Configuration revision management
- Telemetry-to-design correlation
- Redundancy topology verification

The architecture described here provides a complementary engineering validation and lifecycle layer not typically native to these existing tools and workflows. It does not replace classification society review, vendor battery management systems, or operational procedures. It provides the structured electrical system model against which these activities can be anchored.

11. DEFENSIVE PUBLICATION NOTICE

11.1 Prior Art Disclosure

This whitepaper constitutes a defensive publication. The application of graph-based topology modeling, deterministic constraint evaluation, profile-based rule layering, and lifecycle-bound validation to autonomous and survey platform electrical systems constitutes prior art as of the publication date of this document, including but not limited to implementations in marine, motorsport, off-grid, and industrial low-voltage domains.

Specifically, this publication discloses the architectural concept of:

- Representing mission-critical electrical systems in autonomous and survey platforms as versioned graph structures.
- Applying deterministic constraint evaluation across such graphs, including redundancy topology verification.
- Binding validation states to immutable graph revisions, including mobilization and demobilization configurations.
- Applying domain-specific constraint profiles for survey vessels, USVs, AUVs, ROVs, and hybrid power platforms without modifying core topology.
- Binding operational telemetry to graph entities for lifecycle evaluation in remote and autonomous operations.

This publication discloses the architectural integration of graph-based electrical topology representation, deterministic system-level constraint evaluation, immutable revision binding, domain-profile overlays for autonomous marine platforms, and telemetry-to-topology lifecycle correlation in mission-critical marine and subsea electrical systems. Any claims attempting to patent these combinations or their lifecycle-bound integration in autonomous or survey marine platforms are disclosed herein as prior art.

This disclosure is intended to establish prior art for broad claims covering lifecycle-bound, graph-based electrical validation architectures applied to autonomous, survey, and subsea platform systems.

This disclosure is non-exhaustive and is intended to establish prior art for the general architectural approach described, including variations, extensions, and domain-specific implementations thereof.

11.2 Proprietary Elements

Implementation details, computational methods, optimization techniques, data schemas, and proprietary validation algorithms are not disclosed.

No license, express or implied, is granted by this publication under any patent, trade secret, or other intellectual property rights of Neuronetiq Ltd.

The concepts described herein are illustrative and non-exhaustive. Additional architectural variations and implementations are possible within the disclosed framework.

12. CONCLUSION

Autonomous and survey marine platforms represent one of the most demanding environments for low-voltage electrical engineering. The combination of mission criticality, frequent reconfiguration, operational autonomy, and strict redundancy requirements creates a design and lifecycle management challenge that traditional tools do not adequately address.

A graph-based electrical digital twin architecture provides:

- System-level topology modeling with full path awareness
- Deterministic constraint evaluation across interconnected systems
- Immutable lifecycle revision management for mobilization, demobilization, and modification tracking

- Domain-specific constraint profiles for survey vessels, USVs, AUVs, ROVs, and hybrid platforms
- Telemetry binding for operational comparison against design assumptions
- Redundancy architecture verification against topology, not narrative

No representation is made that use of this architecture ensures conformance with any regulatory or safety standard without independent professional verification.

The operational autonomy of these platforms demands a corresponding autonomy of engineering rigor. The electrical system model must be as reliable as the platform it describes.

REFERENCES

[1] DNV Rules for Classification of Ships, Part 4 Ch.8, Electrical Installations.

[2] DNV-RU-OU-0512, Autonomous and Remotely Operated Ships.

[3] Lloyd's Register, Code for Unmanned Marine Systems.

[4] IEC 60092, Electrical Installations in Ships.

[5] IEC 61508, Functional Safety of Electrical/Electronic/ Programmable Electronic Safety-related Systems.

[6] ABYC E-11, AC and DC Electrical Systems on Boats, American Boat & Yacht Council.

[7] IMCA M 206, Guidance on the Design, Selection and Operation of ROV Systems.

[8] DNV-ST-0412, Safety Assurance of Digitalization.

[9] IEC 62443, Security for Industrial Automation and Control Systems.

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This document constitutes a public disclosure of architectural concepts for graph-based electrical system modeling applied to autonomous and survey marine platforms. Implementation details, algorithms, data models, and internal methods remain proprietary.

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About LoomLab

LoomLab is a structured electrical engineering platform built on a graph-based digital twin architecture. It provides system-level validation, lifecycle management, and operational awareness for low-voltage electrical systems across marine, motorsport, offshore, and industrial domains.

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