Design of robust shipboard power automation systems

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Abstract

Emergent power and automation technologies provide new opportunities and challenges for multi-disciplinary ship design. In particular, these dynamically interdependent systems require dependable, fault-tolerant control to efficiently manage limited resources and to respond to casualty conditions. Design of an electric warship engineering and damage control system of systems is considered as an illustrative example. In this context, cost and survivability can be considered as either deterministic or probabilistic independent variables. In the stochastic formulation, design robustness is defined with respect to uncertainties including technology readiness, mission creep, and operational environment.

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1. Introduction

Effective ship design is an intrinsically multi-disciplinary design challenge, which continues to grow in complexity as marine technologies become ever more sophisticated. Fig. 1 presents the traditional ship design spiral and primary design drivers.

More specifically, the manning and automation of Hull, Mechanical and Electrical plus Damage Control (HM&E + DC) systems is considered herein. Primary design objectives include ship utility, affordability, and survivability. Of particular interest is the continuity of vital services under disruptive conditions.

2. Background

As noted in the United States 2001, Quadrennial Defense Review, “transformation is not a goal for tomorrow, but an endeavor that must be embraced in earnest today”. Future electric warships must provide mobility, power, and cooling management to sophisticated combat systems. These mission critical services must be continuously available despite natural and hostile disruptions. Existing U.S. Navy monitoring and control systems provide centralized, remote control with manual, crew intensive local backup systems. Intelligence resides in the human operators, not the control system. As ships become more complex, are manned more austerely, and are expected to continue to fight despite battle damage, existing control strategies will no longer be adequate.

The Naval Research Advisory Committee (NRAC, 2000) Roadmap to an Electric Naval Force identified four motivations for an electric warship:

1. electric weapons and advanced sensors for superior firepower range and resolution;
2. electric propulsion and auxiliaries for superior mobility stealth and endurance;
3. common electric power system for real-time power allocation, reconfigurability, and superior survivability;
4. support for offboard weapons and sensors for superior reach and warfighter sustainment.

The ability to field highly available mission and life critical control systems has been demonstrated by a variety of military and commercial fly-by-wire vehicle control applications. The remaining obstacle involves system engineering cost-effective, survivable automation for a distributed and dynamically interdependent naval integrated power system (IPS). The Naval Research Advisory Committee Automation of Ship Systems and Equipment study (NRAC, 1989) conclusions included the following observations:

1. Automation will be essential to ensure survivable and effective surface combatants in the warfare environment of the next century.
(2) High payoff automation technologies are available and reliable. They can enhance combat effectiveness, reduce manpower costs, and reduce manpower skill requirements. At the same time, they can increase systems availability, and may be introduced in a phased manner.

(3) Simplification and rationalization of shipboard processes and functions are prerequisites to efficient automation. The systems engineering discipline is essential to the selection of processes and functions to be automated.

(4) Models and other analytical tools to adequately assess the cost and warfighting benefits of automation do not now exist.

More recently, the Naval Research Advisory Committee Automation Optimizing Surface Ship Manning (NRAC, 2000) observed that since personnel costs comprise over 50% of operating and support costs, it is imperative to reduce the number of people necessary to crew warships. A new political/military/social environment was also noted, where career alternatives, quality of life issues, and family responsibilities make optimizing manning more urgent. Smart Ship was identified as a significant demonstration example:

- labor intensive “trial and error” sequential design iterations;
- lack of insight regarding interaction of multi-disciplinary design parameters;
- limited ability to analyze the dynamic interdependence of engineering plant, automation, mobility, weapon systems and casualty response;
- inability to systematically search and optimize the ship design space.

Compared to traditional ship design disciplines including hydrodynamics, structures, and signatures, a modest HM&E + DC automation research program could achieve a disproportionately high return on R&D investment. This high research payoff potential leverages concurrent innovations in machinery systems, automation technologies and system design methodologies to produce a leaner, more agile and effective naval force. Exploration of new survivable distributed automation concepts and technologies using state-of-the-art physics-based modelling and computational design tools can support early design tradeoffs and decisions within a systematic and automated design environment. In particular, an integrated engineering plant offers new ship design flexibility, which requires a more sophisticated ship design process. The integration of dynamically interdependent HM&E + DC systems presents new challenges for the ship design agent which existing design tools are not equipped to handle. For example:

- How should integrated engineering plant components be distributed throughout the ship?
- What network topologies and spatial arrangements should be used to interconnect dynamically interdependent energy, fluid flow, information, command, and control subsystems?
- How should command, control, situational awareness, maintenance, and casualty intervention tasks be allocated between man and machine?
- Can self-healing automation provide continuity of situational awareness, command, and control authority during combat-induced disruptions and cascading failures?
- Can mission essential engineering and damage control continuity of service be provided despite combat-induced disruptions and cascading failures?

A number of initiatives are underway to address the aforementioned ship design limitations. New ship acquisition
strategies, which give ship builders and systems integrators more flexibility are currently being incorporated in the procurement process. The Center for Innovative Ship Design has been established at the Naval Surface Warfare Center in Carderock, Maryland. This and other initiatives include incorporating aerospace systems of systems design expertise including methods and tools developed by the Aerospace Systems Design Laboratory (ASDL) associated with the Georgia Institute of Technology Aerospace Department.

3. U.S. Naval perspective

3.1. U.S. Navy control system background

The replacement of steam propulsion plants with aeroderivative gas turbines in the 1970s marked the first time a Naval Propulsion Plant could not be satisfactorily controlled without automation. Period FFG-7 frigates, DD-963 destroyers, and CG-47 cruisers all use dedicated hybrid analog/digital automation for gas turbine inner loop control and sequencing. Propulsion supervisory control, along with coordination of controllable pitch propellers provides single lever bridge propulsion control. These systems employ point-to-point wiring augmented by a serial data bus for non-essential machinery monitoring.

The 1980s continued the earlier emphasis on acquisition cost over life cycle cost with few advances in propulsion automation. The representative DDG-51 Machinery Control System was marked by a strong push towards Tactical Digital Standards (TADSTANDS) including: navy standard computers, navy standard computer CMS-2 software, navy standard power supplies, navy standard electronic modules (SEMs), militarized computer peripherals, and a military data multiplexing system (DMS) system. The primary innovation involved the replacement of mission critical point-to-point wiring with the highly redundant data multiplex system.

The conventional U.S. Navy electrical power distribution is presented in Fig. 2. This figure indicates that a single casualty can disable both the normal and alternate power distribution paths. The flight IIA variant of the DDG-51 class ships avoids this vulnerability using a zonal distribution topology with segregated port and starboard distribution buses. Zonal distribution systems will be discussed in the following section.

The Standard Monitoring and Control System (SMCS) marked the early 1990s transition to open architecture standards based primarily on commercial technology. The primary innovations involved: standardized color, multi-watchstation consoles, a distributed digital architecture, a hierarchy of supervisory, zonal, and local controls, separation of mission/non-mission critical components, and a low line replaceable unit (LRU) count. A variant of the SMCS system is being installed on the LPD 17 class amphibious assault ships. The SMCS architecture is presented in Fig. 3.

3.2. Integrated power system introduction

As shown in Figs. 4 and 5, the integrated power system combines propulsion and ship’s service power generation, distribution and conversion. Compared to the conventional segregated system, the integrated power system provides:

- the ability to redirect propulsion power to pulsed loads;
- improved survivability;
- improved efficiency;
- greater operational flexibility.

3.3. U.S. Navy DD(X) new ship design

The transition to the new DD(X) surface combatant, which is currently under contract design lead by Northrop Grumman Ship Systems, is illustrated in Fig. 6. The fundamental engineering plant change involves an integrated power system providing both electric propulsion and ship’s service power. A fundamental operational change involves a significant reduction in crew size. The DD(X) surface ships involve fundamental automation innovations including:

- a reduction in crew size of 40–70%;
- control of an advanced integrated power system;
- the ability to “fight through” combat damage.

4. Problem statement preliminaries

There is an urgent need for innovative methods and tools to formulate, design, validate, operate, and maintain dependable control systems for mission/life critical, complex, interdependent systems (Zivi, 2002; Zivi & McCoy, 1999). This research initiative emphasizes continuity of services in lieu of traditional reliability and availability metrics. Traditional error recovery and error masking techniques are poorly suited to complex, interactive, hard real-time systems. Furthermore, the increasing dependence on complex, commercial-off-the-shelf electronic and software technology requires algorithms that minimize the susceptibility to catastrophic, common mode failures. Analogously, computer and communication systems often employ error-correcting codes to detect and correct single and multi-bit
errors. Conceptually, the control system equivalent of an error-correcting code is sought (Hadjicostis, 2001). The desired system must maintain situational awareness and control authority despite a variety of component failures, internal errors, and exogenous disturbances.

4.1. Control system background

Control theorists and practitioners have well developed methods and tools for the design and implementation of crisp, linear control systems. In the simplest context, consider the linear time invariant feedback control problem shown in Fig. 7. Given a nominal plant model, \( g(t) \), well-known techniques can be used to design and implement the feedback controller \( h(t) \) to attain specified stability, performance, and robustness requirements. These techniques have been extended to accommodate certain classes of non-linearities, uncertainties, and disruptions shown notionally in Fig. 8. Insufficient theory and practice exist to dependably control complex, interdependent systems subjected to hostile disruption.

Consider what happens if the physical equipment, \( g(t) \), is damaged through some unpredictable means. What is the appropriate change to \( h(t) \) such that the closed loop system remains stable? What if control system sensors and communication links are also simultaneously damaged? Can the system distinguish between physical equipment failures, sensor
failures, and software errors? How can computer-controlled systems be made less susceptible to catastrophic common mode failures? Can disruptions be detected and isolated to obtain graceful degradation instead of system failure? An important related program, the DoD/AFOSR Architectures for Secure and Robust Distributed Infrastructures initiative explains (Lall, 2002):

“The major barrier constraining the successful management and design of large-scale distributed infrastructures is the conspicuous lack of knowledge about their dynamical features and behaviours. Up until very recently analysis of systems, such as the Internet, or the national air traffic system, have primarily relied on the use of non-dynamical models, which neglect their complex, and frequently subtle, inherent dynamical properties. These traditional approaches have enjoyed considerable success, while systems are run in predominantly cooperative and “friendly” environments, and provided that their performance boundaries are not approached. With the current proliferation of applications using and relying on such infrastructures, these infrastructures are becoming increasingly stressed, and as a result the incentives for malicious attacks are heightening. The stunning fact is that the fundamental assumptions under which all significant large-scale distributed infrastructures have been constructed and analyzed no longer hold; the invalidity of these non-dynamical assumptions is witnessed with the greater frequency of catastrophic failures in major infrastructures, such as the Internet, the power grid, the air traffic system, and national-scale telecommunication systems.”

4.2. Dependable systems

Dependable systems must continue to operate despite component failures, internal errors, and exogenous disruptions. System reliability is the standard metric for measuring the effect of component failures and internal errors via component mean time to failure (MTTF) statistics and static dependency analysis. By extension, system availability adds consideration of the mean time to repair (MTTR) statistics. This initiative focuses on the ability to provide continuity of service despite significant disruptions due to natural (earthquake, tornado, hurricane, etc.) or hostile (terrorist or military) action. Continuity of service is critical because exogenous natural and hostile disturbances are typified by multiple simultaneous or near-simultaneous failures in the controlled plant as well as the control system. Control system failure modes include damaged hardware, inadequate control/reconfiguration algorithms, software errors, communication failures, and sensor failures. These temporal and spatially clustered “bursts” of events are much more disruptive than random failures. Moreover, the consequences of outages under hostile conditions may be disastrous.

4.3. Survivable systems

While survivability is a well-known and often studied metric in military systems, until recently, little attention has been paid to this metric in the civilian sector. Historical methods for improving survivability include redundancy, spatial separation, and manual backup systems. Traditionally, cost and technical
challenges have restricted the use of high integrity, fault-tolerant systems to a limited set of high-risk systems. Examples include aero vehicle control and nuclear applications. In naval application, the primary objective is continuity of vital services during the major disruptions associated with battle and damage control operations.

The ability to fight through combat damage, such as an anti-ship missile detonation requires systems, which can sense, isolate, and quickly compensate for major disruptions. In this context, the system includes a spatially distributed, non-linear, variable structure physical plant, and the associated hybrid sensing, communication, control, and actuation facilities (Zivi, 2001). Damage is assumed to be clustered spatially and temporally resulting in concurrent disruption of both the physical plant and the control system. An Integrated Engineering Plant must be able to tolerate simultaneous disturbances to both the machinery and the control architecture system. Representative control system disruptions include loss of sensors, actuators, communication links, algorithms, or software failures. The ultimate objective is to maximize system integrity and fault tolerance, while minimizing interdependencies. Time domain continuity of service subject to characteristic damage scenarios will be used to quantify success.

Traditional methods for improving shipboard survivability include redundancy, spatial separation, and manual intervention. In particular, crew intensive manual intervention is no longer economically viable. Furthermore, the introduction of complex, dynamically interdependent systems exceeds human-in-the-loop control capabilities. This is because the dynamic response of the controlled equipment occurs too rapidly for the normal human reaction times and the non-linear system interdependencies are too complex for even a well-trained human operator to comprehend and react to in real-time. This conclusion is consistent with the Fitts’ law and functional allocation human systems integration techniques (NATO, 1999). The three level hierarchical control system presented in Figs. 9–11 correspond to the conventional shipboard command and control structure.

4.4. Information technology infrastructure

One of the many shipboard control system challenges involves the wide variation in product lifecycles. In particular, typical information technology product cycles of 18 months are less than 1/10th of the nominal ship lifetime of 25 years. Fig. 12 presents the information infrastructure aboard the DDG-51 and LPD-17 class ships. This local area network (LAN) includes:

- industry/dual use standards and technology;
- issues include hierarchy, protocols and connectivity;
- monolithic programs with separate processing, information, and redundancy management.

The DD(X) Total Ship Computing Environment (TSCE) is expected to provide an open architecture, survivable, network centric integrated total ship command, control, and automated
decision infrastructure. Fig. 13 presents a schematic of a mesh-oriented information technology infrastructure as envisioned for DD(X). This computing mesh includes:

- higher redundancy and integration;
- self-healing for dependable performance under disruptive conditions;
- modular programs with a more standard interface and infrastructure.

A notional computing network fabric for future ships is provided in Fig. 14. This computing fabric provides:

- the highest redundancy and integration with global information and redundancy management;
- ubiquitous, transparent performance;
- smaller more modular programs with common, transparent interfaces.

5. Power and automation requirements

The Office of Naval Research (ONR) control challenge problem (Zivi, 2001; Zivi & McCoy, 2003) identified the following technology shortfalls:

1. limited ability to efficiently model and simulate complex, distributed, multi-disciplinary, interactive energy, communication, and control systems;
2. incomplete theoretical basis for the robust, fault-tolerant control of complex, interactive energy, sensing, and communication systems;
3. susceptibility to catastrophic common mode and common cause errors, damage, and failures;
4. limited ability to maintain situational awareness during major casualty conditions;
5. limitations in existing non-linear stabilizing control methodologies.

Automation of shipboard systems is driven by cost and performance constraints (Zivi & McCoy, 1999), which may be summarized as:

- the need to shift functions from humans to machines to reduce operational costs;
- control law complexity and time constraints which exceed human capabilities.

Most existing automation systems exhibit “brittle” behaviour in response to non-trivial faults and failures. When subjected to significant failures or damage, brittle systems typically shut down inappropriately and/or lose stability. Conversely, dependable systems provide resilient, non-stop operation of mission/safety critical systems with provable system integrity and fault tolerance.

The control challenge objective is cost-effective, innovative control strategies, which enable pervasive, industrial automation technologies to be applied to the dependable automation problem. Dependable automation strategies include:

- extensions to stabilizing non-linear control theory;
- generalization of analytic redundancy;
- integrating component level intelligent distributed control into robust networks;
- model-based and non-parametric estimation and fore-casting,
- robust sensing and situational awareness;
- analysis, design, and control algorithms for complex, interdependent systems.

Traditionally, reliable systems utilize hardware redundancy to protect against hardware-based failures. This approach is not valid for complex interactive networks and systems, is vulnerable to common mode and common cause failures, and is not affordable. A key aspect of complex dependable systems may involve the hierarchical/functional decomposition into trusted subsystems, which cooperate via implicit and/or explicit communication. Modular decomposition is desired to:

- reduce the apparent complexity;
- build complex systems in a structured, incremental manner;
- allow incremental replacement of obsolete technology;
- reduce dependencies;
- provide graceful degradation.

Highly integrated supervisory control functions are expected to operate and cooperate via a generic ubiquitous computing infrastructure. These supervisory control functions could be implemented as intelligent software agents, which execute on any available computer. Component level intelligence is expected to be collocated with mission critical equipment.
Implementing supervisory control within the vehicle’s information infrastructure provides a feature rich environment fully integrated with tactical decision-making, maintenance, and administration. These supervisory functions are highly available due to their ability to execute on any available generic computers. Due to complexity of the ship wide networked computer system and software-based application programs, this infrastructure may be vulnerable to hostile disruptions and common mode failures. Automated, graceful degradation, of safety, and mission critical backup control functions is required. System integrity and fault-tolerance is dependent on both the level of redundancy and the redundancy management strategy. Analytic redundancy may provide a fundamentally new paradigm for redundancy management.

5.1. ONR control challenge reference problem

The ONR control challenge reference problem is presented to motivate and focus interdisciplinary research efforts. The reference problem and associated research objectives are intended as research guidance and should not be considered definitive or exhaustive. This research thrust emphasizes continuity of vital power, fluid, and communication services in lieu of traditional reliability and availability metrics. Future electric warships must provide mobility, power, and cooling management to sophisticated combat systems. These mission critical services must be continuously available under highly lethal combat conditions. In the heat of battle, a ship that goes dark cannot fight, putting the overall mission in jeopardy, and potentially dooming the ship to complete destruction. Machinery controls for existing U.S. Naval Engineering and Damage Control provide centralized, remote control with manual backup systems. Intelligence resides in the human operators, not the control system. As ships become more complex, are manned more austerely, and are expected to continue to fight despite battle damage, existing control strategies will no longer be adequate.

Modern military and civilian systems share a fundamental challenge: to ensure continuity of service for distributed mission and life critical services despite both natural and hostile disruptions. In this challenge problem, the system includes a spatially distributed, non-linear, variable structure physical plant and the associated hybrid sensing, communication, control, and actuation facilities. Damage is assumed to be clustered spatially and temporally resulting in concurrent disruption of both the physical plant and the control system. In both the civilian and the military sectors, the complexity and interdependence of emerging infrastructure technologies requires new strategies, methods, and tools. The primary objective is the derivation of innovative control strategies and algorithms that maximize continuity of service despite faults and failures.

A future surface combatant with a solid-state, integrated electric power system will supply approximately 100 MW of

![Fig. 15. Naval combat survivability testbed.](image_url)
power to propulsion, ship’s service, and weapon systems. This power generation, distribution, and consumer network is also dependent upon the delivery of seawater, freshwater, and chill water for cooling management. The ONR reference system is based on representative, non-proprietary, reduced scale, integrated power system testbeds established at Purdue University under a related Naval Combat Survivability initiative. The Purdue testbeds provide a prototypical AC propulsion drive with a provision for a future pulse weapons system load. Ship service power supplies convert AC propulsion power to DC for zonal electrical distribution. The DC zonal electrical distribution prototypical testbed was constructed at the University of Missouri-Rolla but has recently been moved to Purdue and is now collocated with the AC testbed. This consolidated configuration is shown in Fig. 15.

The ONR control challenge reference system is based on Naval Combat Survivability testbed experimentally validated models and simulations. More specially, the reference system consists of the three-zone DC distribution testbed coupled to two instantiations of the AC testbed. This consolidated configuration is shown in Fig. 15.

The ONR control challenge reference system is presented in Fig. 16.

Over the past decade, considerable effort has been made to define and refine power system architectures that are both affordable and survivable. The ONR reference system contains the minimum elements to represent an advanced integrated power system.

System characteristics include:

1. two finite inertia AC sources and buses;
2. AC bus dynamics, stability, and regulation;
3. redundant DC power supplies and zonal distribution buses;
4. DC bus dynamics, stability, and regulation;
5. three zonal distribution zones feed by redundant DC power buses;
6. a variety of dynamic and non-linear loads.

An actual ship would have a more complex configuration with additional generator capacity. The control challenge is to provide power continuity and regulation despite large variations in power demand, component failures, internal errors, and hostile system disruptions. Solid-state conversion modules introduce the potential to actively control the coupling between various system components and prevent the propagation of faults. The control challenge problem is a representative, finite inertia, tightly coupled, and isolated shipboard power system.

Specific research objectives include:
(1) control system integrity and fault tolerance despite component failures, internal errors, and hostile disruptions involving cascading failures;
(2) robust, real-time situational awareness with graceful degradation;
(3) continuity of power and thermal management for critical loads;
(4) self-organizing and self-healing operation which minimizes requirements for human intervention, calibration, maintenance, and repair;
(5) modular functional decomposition which leverages existing and emerging technology and standards to obtain implementation simplicity, affordability, and life cycle supportability;
(6) innovative architectures and control strategies which minimize subsystem interdependence;
(7) improved quality of service despite reductions in operating margins.

6. Recent research progress

This section presents two recent and relevant Energy Systems Analysis Consortium (ESAC) accomplishments funded under the ONR Electric Ship Research and Development Consortium program. Section 5 identified the need for dependable automation strategies including extensions to stabilizing non-linear control theory. The following summarizes the recent experimental validation of a generalized immittance-based stability analysis performed using the Naval Combat Survivability Testbed.

6.1. Generalized immittance analysis

The basic ideas of generalized immittance analysis are set forth by Sudhoff et al. (1998, 2000a,b, 2002a,b, 2003). These papers build on simple source-load systems with extensions and a MATLAB-based DC stability toolbox for large-scale systems. Single- and two-port converters are classified and defined. Once all converters are classified, a series of mapping functions is used to reduce any given system to the single source-load equivalent presented in Fig. 17.

The next step is to select frequency domain stability criteria to determine if the generalized source impedance and load admittance combination is Nyquist stable. Figs. 18 and 19 present experimental validation (Sudhoff et al., 2003) of the DC stability toolbox using the University of Missouri at Rolla Naval Combat Survivability testbed. In this example, the Ship Service Converter Module (SSCM) capacitance is modified to create stable and unstable operating conditions. As shown in Figs. 18 and 19, the stability toolbox predictions match the experimental observations.

6.2. Fault-tolerant delta-hysteresis motor drive

Section 5 also identified the need for systems which exhibit graceful degradation to damage. A novel example of ongoing research is the Digital Delta-Hysteresis Regulation (DDHR) scheme, which allows motor drive systems to maintain relatively accurate control of phase currents in the event of the loss of all phase current sensors. Within this scheme, line currents are reconstructed using knowledge of the DC-link current and switching states. The generation of switching signals is based upon traditional Delta-Hysteresis Regulation (DHR). However, modifications are made to DHR to ensure the DC-link current always contains sufficient information to reconstruct phase currents. The structure of the DDHR controller is presented in Fig. 20. Fig. 21 depicts the experimental setup, where the DDHR controller has been implemented in a DSP prototype system. Fig. 22 provides experimental results obtained from a vector-controlled induction machine. In particular, note the relatively small difference between the performance of the pre- and post-fault system. One advantage of this scheme is that it is independent of the load connected to the inverter. In addition, it can be readily incorporated into existing drive applications with relatively minor effort and cost.
7. Ongoing initiatives

Many of the system design and system survivability needs described in this article are being addressed in various forums and market segments. In particular, the aerospace community has developed sophisticated system design and fly-by-wire fault-tolerant control methodologies. One ongoing ONR initiative to leverage the aerospace community’s system of systems design processes is the Integrated Reconfigurable Intelligent System (IRIS) program. This project teams the Georgia Institute of Technology Aerospace Systems Design Laboratory (ASDL) with U.S. Navy domain experts at the U.S. Naval Academy, Purdue University and MIT. The introduction of aerospace technologies to shipboard applications is highly cost sensitive. An interesting example of cost-effective, dual use technology is the fault-tolerant time-triggered protocol, TTP, which is targeted to automotive steer-by-wire applications and has also been adopted by Honeywell for avionics. Although this article focuses on conventional control technologies, a number of interesting innovations are currently being explored. One active example is the application of distributed agent technology.
Uncited references


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References


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