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An architectural framework for distributed naval ship systems

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ABSTRACT

This paper introduces a framework for analyzing distributed ship systems. The increase in interconnected and interdependent systems aboard modern naval vessels has significantly increased their complexity, making them more vulnerable to cascading failures and emergent behavior that arise only once the system is complete and in operation. There is a need for a systematic approach to describe and analyze distributed systems at the conceptual stage for naval vessels. Understanding the relationships between various aspects of these distributed systems is crucial for uninterrupted naval operations and vessel survivability. The framework introduced in this paper decomposes information about an individual system into three views: the physical, logical, and operational architectural representations. These representations describe the spatial and functional relationships of the system, together with their temporal behavior characteristics. This paper defines how these primary architectural representations are used to describe a system, the interrelations between the architectural blocks, and how those blocks fit together. A list of defined terms is presented, and a preliminary set of requirements for specific design tools to model these architectures is discussed. A practical application is introduced to illustrate how the framework can be used to describe the delivery of power to a high energy weapon.

1. Introduction

The increasing importance and complexity of interdependent distributed systems, people, and components incorporated into naval ships makes it necessary to describe them as architectures of complex systems. In this paper, the authors present and demonstrate a framework to describe the architectures of distributed naval ship systems that enables engineers to better address system design in early stage naval ship design. The framework is intended to provide a conceptual method of capturing the key attributes of a distributed ship system. Thus, the objective is to describe such a system, ensuring all important aspects are covered, as opposed to presenting a design process for the system.

A distributed ship system representation needs to be multifaceted. It is the interrelationships between the different representations, or architectures, that allows a full understanding of the system. The presented framework is applicable to one given system, and is designed to cover the aspects that are important when analyzing and describing that system. Three primary facets of a system are considered, the physical, logical and operational architectures. The architecture of a system is defined as the manner in which its components are organized and integrated. The physical architecture represents the spatial and physical characteristics of the system and of its environment. The logical architecture describes functional characteristics of the system, and the linkages between each component of the system. The operational architecture describes temporal behavior of a system, including human-system interactions to some extent. The architectural framework presented in this article thus provides a basis for describing and understanding the impact of the architectural properties of systems aboard a vessel on the vessel's performance. The effort to develop this framework was motivated by a need to better understand the impact of distributed systems on ship design, especially with regard to survivability.

The past half century has brought with it a radical change in the

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design and control of high-risk systems. Technological change has brought with it highly complex, automated, capable, but opaque systems (Reason, 1990). This growth in system complexity and interdependence has made systems significantly more difficult to understand and design, in part due to increased potential for emergent properties that only arise once the system is complete and in operation. This increased the opportunity for latent errors (i.e. design errors which can remain dormant for a long time before the right combination of factors align to make the error emerge) and potentially catastrophic consequences on the ship's operability (Slabodkin, 1998; UK House of Commons Defence Committee, 2016). The opacity of the systems' interrelations has led to an increased opportunity for cascading failures, compromising the survivability of the vessel. As noted above, the framework aims to better understand the multidimensional relations between distributed systems, which can decrease the design's opacity.

With the increasing number, complication, and resulting complexity of systems aboard vessels, the authors argue this framework will bring a major step forward in early stage naval ship design and analysis, addressing a significant gap in our ability to investigate the complex nature of future naval distributed system design at this crucial decision point. Section 2 outlines the problem and justifies the need for an architectural framework in the design of distributed systems aboard naval vessels, while Section 3 presents the framework itself, with its three primary architectures and their interrelations. Section 4 discusses requirements for analysis tools and recommendations for the architectural framework implementation. In Section 5, an example application is given involving the powering of a vessel's high energy weapon. The Appendix defines the key nomenclature used in this framework.

2. Background: the need for an architectural framework

In the past several decades, technological developments have brought major changes to the way ships are designed and operated. Automation has pushed the boundaries of performance and increased the use of complex distributed systems aboard vessels. Although costly to introduce, automation has had an attractive payback to the maritime industry. The increase in complex systems and automatic monitoring systems has led to increased operational efficiency, increased crew morale and safety, and reduced maintenance cost (Ehlers et al., 2014). The advantages of all-electric powering over mechanically powered ships are also well documented, and have led many organizations to move towards all-electric ships. Some major advantages of all-electric powering were identified by Doerry (2014), including: increased power flexibility (the ability to shift power between ship systems as needed), increased power efficiency, and increased arrangements flexibility since prime movers are no longer restricted to the central position of the aft bottom decks.

The introduction of complex distributed systems and electric propulsion technologies aboard naval vessels has nevertheless significantly increased their complexity (Rigterink, 2014) and has left a gap in ship design methods and tools. The increasingly complex organizational and physical architectures of naval systems, with high interdependence between distribution systems, humans, and onboard components, are changing the design drivers and the focus of the naval architect. System integration is now as important as the traditional naval architecture disciplines since the arrangement of systems and usage of system interdependencies play a significant role in vessel cost (Dobson, 2014; Miroyannis, 2006), capability, and survivability (Doerry, 2007, 2006; Trapp, 2015). Thus, understanding the structure of the dependencies between various aspects of a distributed system and how they are best accommodated in the ship's physical architecture in the early stages of design is critical to the maturation of state-of-the-art vessel design (Brown and Waltham-Sajdak, 2015; Chalfant, 2015; Ouroua et al., 2007).

The changing design considerations of naval vessels that arise from the increased use of distributed systems have left designers with an inadequate set of tools for concept exploration (Doerry and Fireman, 2006; Kassel et al., 2010). Analyzing the implications of early stage design decisions on the physical attributes of the vessel only covers a limited aspect of early stage design – how components and discrete subsystems within compartments are geometrically related, and how the resulting configuration affects the functionality and performance of the vessel. With simpler, less demanding vessels, designers were able to use their implicit knowledge to determine performance and interaction issues that could occur between systems in a given general arrangement. However, with the increased impact of distributed systems and smaller margins driven by the desire to further optimize designs, new methods are needed to help designers integrate vessel solutions. These need to reflect the interdependent functionality of components within a vessel, how the functionalities provided by the whole vessel and the component sub-systems will be achieved, and geometric relationships caused by an arrangement. To the authors' knowledge, no cohesive framework exists for evaluating how the coupling of these interrelated design aspects culminates in determining the overall system performance.

Common methodologies for concept design of interacting ship architectures range from low fidelity parameterization based modeling to high fidelity simulation of systems (Andrews, 2012; Brown and Waltham-Sajdak, 2015; Chalfant, 2015; Chandrasegaran et al., 2013). Parametric methods perform well for evolutionary designs; however, their basis in previous data makes them ill-suited for the design of revolutionary vessels (Chalfant, 2015). Low fidelity simulation is also used for concept exploration in distributed system design. Trapp (2015) uses optimization on a multi-commodity flow network to explore a large state space and find a "minimum" cost of a vessel's integrated engineering plant with a given survivability constraint. His algorithm seeks the minimum cost survivability and avoids predicating a single solution. Cramer et al. (2009) use a genetic algorithm to solve minimax problems and applies it to the design of an integrated engineering plant with respect to survivability.

After the set of possible solutions is narrowed using low fidelity simulation, high-fidelity analysis of specific systems can be targeted. For instance, high-fidelity analyses have been performed to analyze the tradeoff between AC and DC electrical distribution systems (Chalfant et al., 2010), understand the impact of electrical weapons on power supply stability (Whitelegg et al., 2015), but also to understand the relationship between propulsion and maneuvering systems (Altosole et al., 2010). However, high-fidelity models often require a significant jump in design detail and can take up valuable time to model in early stage design, especially at a point in time where the chosen design solution has yet to emerge. The time issue can be addressed using tools that can easily produce and analyze distributed systems based on templates and product catalogues. The Electric Ship Research and Development Consortium (ESRDC) has developed the Smart Ship Systems Design (S3D) tool to perform high fidelity design and analysis of distributed naval systems (Chalfant, 2015). Fiedel et al. (2011) developed a cooling system design tool to analyze thermal loading and design appropriate cooling systems. This is a task which will become harder and more critical as the number of electrical systems aboard ships increases. The jump in design detail required for high fidelity models and templates still remains an issue, as they both strongly rely on previous solutions and assumptions, and on modeling detail which is based on decisions that can predicate the design, influencing it at a point in time where the chosen design solution has yet to emerge. This makes them ill-suited for concept design or for the creation of revolutionary designs like naval all-electric ships and radical ship configurations (Greig et al., 2009), where one should not fix large portions of the design while still conducting requirements elucidation (Andrews, 2013, 2011).

Addressing the architecture of naval distributed systems in novel vessel design is becoming a major component of concept exploration and is beset by technology uncertainty and concurrent mission development. Developing vessel concepts from legacy designs, tools, and fixed solution options significantly limits the designer's ability to take advantage of emergent opportunities and properly cope with evolving design requirements in early-stage design, when decision freedom is highest