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Investigating physical solutions in the architectural design of distributed ship service systems

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A B S T R A C T

The design of distributed ship service systems, or distributed systems, integrates concepts of vessel layout, system functionality, and the distributed systems configuration. Understanding the design relationships between these concepts is a critical aspect of investigating and developing design requirements. Thus, in the design of complex naval vessels, the distributed systems configuration, called the physical solution, must be considered in early-stage design activities to ensure that emergent functional requirements are achievable and affordable. To address this, we propose a novel perspective for modeling and investigating physical solutions in the architectural design of distributed ship service systems. Our approach uses scalable network representations of vessel layout and functional relationships within systems to stochastically generate ensembles of distributed system solutions. Ensembles are then evaluated to determine system characteristics, bringing physical solution information into early-stage requirement elucidation. We demonstrate our approach using concept-level vessel knowledge to identify distributed system characteristics, and show the method's usefulness in understanding complex distributed systems design relationships.

1. Introduction

Advances in technology onboard naval vessels promise improved capability, mission effectiveness, survivability, and fleet support (Doerry, 2014; Piff, 2013). Realizing these benefits requires understanding how technologies and their supporting systems integrate into the overall vessel design (Kassel et al., 2010; Chalfant, 2015). Design decisions affecting physical system integration pose significant implications for vessel vulnerability (Doerry, 2006, 2007; Kassel et al., 2010; Trapp, 2015), producibility (Keane, 2011; Keane et al., 2015), cost (Dobson, 2014; Miroyannis, 2006), and other performance characteristics (Dellsy et al., 2015; Greig et al., 2009; Shields et al., 2015b, 2016). Providing insight into how early-stage layout and functional requirements affects these vessel characteristics can help inform related decision making processes (Brown and Waltham-Sajdak, 2015). However, this requires considering the physical configuration of distributed systems within the vessel during the formative stages of requirements elucidation (Andrews, 2016; Rigterink, 2014). In this paper, we demonstrate how network representations and stochastic solution configuration can deliver new insight into the early-stage design relationship between vessel layout, functional requirements, and distributed systems characteristics.

To facilitate our study, we describe the architectural design of naval distributed systems in terms of the structure and interactions of its *physical architecture*, *logical architecture*, and *operational architecture*.[1] Physical architecture defines the spatial information about the vessel, such as component locations, space definitions, and space adjacencies. Logical architecture defines the macroscopic functional relationships between components within the vessel (e.g. a generator supplies power to an electric motor). Operational architecture defines the purpose of the system in time - how parts of the vessel and its systems are used for a given scenario.

Here, we will focus on the interaction between the physical and logical architectures, which we call the *physical solution*. The interaction defines the physical description of components and distributed system routings between components. The physical solution is the physical definition of the distributed system, which implements the logical architecture within the physical architecture. While the physical solution does not consider the operational architecture, it still has a critical role in vessel performance (Rigterink et al., 2013). Thus, it is important to understand how decisions defining the physical and logical architectures will impact on the physical solution during early-stage design activities. However, eliciting this relationship in

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multirole naval vessels is a complex problem and must be addressed through the consideration of material solutions (Andrews, 2003).

In the case of vessel characteristics dependent on physical and logical architecture, design outcomes are manifested in the physical system solution. The proposed approach provides predictive methods to develop physical solution information earlier in the design process to enable trade-off analysis and requirements decision making based on distributed systems analysis.

2. Background

The design and integration of distributed systems in naval vessels is traditionally a split discipline. Naval concept development employs functional modeling to create preliminary representations of required system functions and vessel layout (Andrews, 2011; Brown and Waltham-Sajdak, 2015; Chalfant, 2015). Following functional modeling, the physical product is developed in increasing detail (Andrews, 2012a; Chandrasegaran et al., 2013). In naval design, once the physical distributed systems solution is available at a sufficient level of detail, testing and simulation are conducted to understand its overall performance characteristics (Cramer et al., 2011; Doerry, 2007; Fang et al., 2009). Here, the understanding of decisions regarding the physical and logical architectures lags the initial design. The detailed physical solution is predicated on concept design decisions about vessel mission, sizing and layout. Therefore, there is little opportunity to use feedback from distributed systems performance to refine decisions until after significant cost has been committed (Kassel et al., 2010; Mavris and DeLaurentis, 2000; Ullman, 1992). Addressing this requires designers to understand how the logical and physical architectures influence the physical solution earlier in the design process.

Currently ship designers have limited options for modeling and studying physical solution outcomes in early-stage design (Gillespie et al., 2010; Gillespie and Singer, 2012). Heavy coarse-graining can reduce the system implications to parameterization, exemplified by cost estimation (Ross, 2004; Watson and Gilfillan, 1977). Parameterization-based approaches are applicable for specific relationships in the design, but requires a representative database of similar vessels to be developed. Additionally, parameterization is limiting because it only predicts the outcome of a decision without revealing the underlying distributed systems configurations which drive the design relationship.

More recently, designers have addressed the physical solution with computer-aided design (CAD) models. This provides a detailed system model that can be analyzed to validate functions and predict attributes of the physical systems (Chalfant, 2015). Efforts in automated distributed systems design have been successful at introducing physical system solutions sooner in the ship design process (Chalfant et al., 2012, 2014; Dougal and Langland, 2016). Automated methods generate physical solution models through routing optimization (Fiedel et al., 2011), resource demand satisfaction (Trapp, 2015), and system templates (Chalfant et al., 2015; Chryssostomidis and Cooke, 2015) which are then integrated into a larger vessel model.

However, in the initial stages of concept design and requirements elucidation, automated design approaches may not be viable. From a methods perspective, CAD is used to visualize design concepts, providing new insight and enabling further solution definition and model development (Andrews and Pawling, 2003, 2006). This means that in early-stage design, the required product definition for CAD-based automation has not been well defined (Mistree et al., 1990). Despite the continuous improvement of CAD tools and applications, in concept design there is still limited information available.

Even in low-fidelity applications, generation methods need specification of system components and their usage profiles. Providing the necessary physical definition and system loads requires a significant amount of design knowledge about vessel geometry, mission, and operations. The amount of required knowledge is compounded by uncertainties caused by the concurrency of naval design and component development (Government Accountability Office, 2009; NAVSEA, 2012). The result is that meeting geometric modeling and design definition requirements can quickly become drivers or lead to decision making based on modeling goals or constraints (Andrews, 2012b; Pawling and Andrews, 2011; Pitts, 1970).

The potential impacts of automated approaches can be seen in the early-stage ship design automated arrangement program, Intelligent Ship Arrangements (ISA). ISA enables designers to automate the rapid generation of balanced space arrangements by considering large sets of constraints including separation and adjacency requirements, preferred locations, and space shape (Daniels et al., 2009; Parsons et al., 2008). ISA was quickly extended to explore passageway design based on lattice templates (Daniels et al., 2010, 2011). The approach produces high-quality arrangement designs, but requires significant design knowledge of space usage and relationships. This can overconstrain the solution space in early-stage design, creating dominant design outcomes and heavily biased solutions (Gillespie, 2012; Gillespie et al., 2013).

Automated distributed systems design methods also struggle to address the system design relationships from a process perspective. The goal of addressing distributed systems in early-stage ship design is to understand how the architectural design of distributed systems affects performance. Automated approaches bias this relationship by generating physical system solutions through optimizations and system templates. Similar to parameterization, this helps predict outcomes of the relationship, but does not help explain how or why the relationship causes the outcome.

Automated approaches can produce detailed solutions to well-defined design problems at specific modeling fidelity - often optimized to an objective function. The resulting physical system solutions and characteristics are then used as a basis for decision-making. However, early in the design process of complex multirole vessels, the problem is constantly developing (Andrews, 1981) and defining an appropriate objective function is problematic (Andrews, 2016). Further, the early-stage design activities have fidelity ranging from paper sketches to CAD representations of the physical product (Chandrasegaran et al., 2013). Thus, optimal solutions to fixed system objectives are poor grounds for understanding the possible design relationships. Instead, an early-stage approach to physical system solutions must be independent of an objective function.

Network-based methods and tools have previously proven effective for understanding interdependent relationships in naval design without relying on optimization or simulation. Network analysis studies the evolving interactions between parts of the design process and product (Parker, 2014). This allows designers to represent and analyze disparate information at multiple scales throughout the design process (Rigterink et al., 2013). For example, studying the interdependent coupling between arrangement constraints and physical architectures can identify optimization biases and predict vessel arrangements (Gillespie, 2012; Gillespie et al., 2013). Network analysis can also enable designers to identify design drivers built into the structure of naval architecture methods and tools (Parker, 2014; Parker and Singer, 2015; Shields et al., 2015a). Applied to studying physical system solutions, network-based methods provide insight into distributed systems functionality and design (Rigterink et al., 2013; Rigterink, 2014; Shields et al., 2015b, 2016).

In this paper, therefore, we focus on understanding the interdependent design relationship between logical architecture, physical architecture, and physical system solutions with a scalable and stochastic network method. This requires approaching physical system solutions in terms of its feasible configurations, not its optimal configurations. Network representations are used with stochastic system routing methods to generate feasible configurations of the physical system solution. Large sets of configurations are then evaluated to probabilistically explore the possible design relationships. The