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Modeling and simulation for damage analysis of intelligent, self-reconfigurable ship fluid systems in early design phase

Kyungjin Moon *, Dimitri N. Mavris

Aerospace Systems Design Laboratory, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0150, United States

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ABSTRACT

This paper pursues a modeling and simulation (M&S) solution for performing a rigorous damage analysis in the conceptual or preliminary design of an intelligent, self-reconfigurable ship fluid system. As enablers to the solution, two essential elements were identified in the formulation. The first one is the graph-based topological modeling method which will be employed for rapid model reconstruction and damage modeling, and the second one is the recurrent neural network-based, component-level surrogate modeling method which will be used to improve the affordability and efficiency of the M&S computations. The integration of these two methods can deliver computationally efficient, flexible, and automation-friendly M&S which will create an environment for a more rigorous damage analysis. Finally, a demonstration of the damage analysis as it is applied to a notional ship fluid system is provided, with a description of the benefits of this approach.

1. Introduction

1.1. Background

One of the goals of the Navy's DD(X) program for the next-generation destroyer is to reduce manning levels to less than half of DDG-51 destroyers, while increasing ship survivability significantly [29]. In order to meet this challenging requirement, the Office of Naval Research (ONR) had conceptualized highly intelligent and distributed autonomy and automation of ship operations and damage controls by system reconfiguration via smart actuators to recover from damage and malfunctions [8]. Successful research progress includes the demonstration of agent-based control implemented into a chilled-water system testbed called Chilled Water Reduced Scale Advanced Demonstrator (CW-RSAD) built by Naval Surface Warfare Center, Carderock Division (NSWC-CD) [13,23].

As a next step, ONR is moving further into developing a multi-domain, multi-physics modeling and simulation (M&S) environment, which will not be crucial only for designing control systems, but also for designing any engineering system in a ship. This M&S environment should be based on a system-of-systems perspective rather than an unrealistic single-system response. In the modeling environment, all the simulation results of the models created by domain-specific M&S applications are stored and exchanged in a SQL server synchronously in order to simulate the interactions and interdependencies between the systems.

Such a multi-disciplinary M&S environment based on the integration of domain specific M&S tools is inevitable for simulation-based analyses in early design phases where very limited human, financial, and temporal resources are assigned, but it is easily challenged by two common problems of local domain tools. The problems are: first, the models created with

* Corresponding author.
E-mail address: kyungjin.moon@asdl.gatech.edu (K. Moon).

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domain-specific modeling tools are often incapable of, or poor at, performing damage simulation unless the modeling tools provide the libraries for modeling damages; second, the dependence on them for running simulation slows down the overall simulation speed and creates a large computational burden when it comes to simulation-based design approach.

The Navy's M&S environment is a good platform for exemplifying these two problems. This ship model includes electric power model, communication models, and fluid models. Among them, the fluid models were created with a 1-D pipeline fluid simulation tool called *Flowmaster*®, which contains no library for damage or rupture analyses. As a rudimentary approach to modeling damage analysis, a branched-off valve with one of its ends open to ambient pressure has been placed (see Fig. 17) [4] at a predefined location of interest in the model. Along with its problem of incorrect modeling, the approach is unable to support a rigorous and extensive damage analysis that is key to the design for resiliency and survivability, since it is virtually impossible to automate the damage analysis for a large set of damage scenarios.

The Flowmaster models are also slower than the rest of the models – so slow that their simulation speed dominates the speed of the integrated simulation. The reason for their computational cost was not only in the simulation cost of this tool, but also the computational overhead or inefficiency from its external interfacing to the integrating framework. This high computational cost can prohibit many design-oriented analyses that require a large number of simulation cases.

1.2. Research goal and scope

This research aims at developing an M&S method that is more suitable for performing damage or failure analyses in a design process, especially in an early design phase. The scope of M&S is limited to individual domain models, particularly types based on physical flow-based networks, such as fluid or electric power networks. Thus, developing a method of integrating domain models or signal-based network modeling is out of the research scope. Considering the research goal, the successful development of the M&S method must address the following challenges:

(a) Damage scenarios must be taken as the input to a domain M&S environment.
(b) In order to handle a large number of simulation cases, a model must be computationally affordable.
(c) Because of limited human and temporal resources, modeling should avoid intensive involvement of deep expert knowledge of domain disciplines and coding skills.

The development of such an M&S method will lead to the formulation of an M&S environment as the end-result. Although a military ship was chosen as the application platform, the method is generic and can be applied to any engineering platform that shares similar design paradigm – fail-proof design, design for reduced manning, maintenance, and operational cost by high level of autonomy or automation of the system. Again, the formulation was done for a fluid system which may be frequently found in many complex engineering products, but this research is expected to apply with minor modifications to electric power systems, another very popular type of subsystems found in complex engineering systems, due to their strong analogy to fluid systems.

1.3. Overview of M&S approach

The solution approach is the combination of two key ideas – topological modeling based on the digraph representation and component behavior modeling with a neural net-based surrogate modeling technique. Borrowed from the basic notion of graph theory [6,3], a fluid network was represented by a composite object made of edge and node objects and the incidence matrix which contained information about the connectivity between nodes and edges. This composite object is called the topological model of a fluid network by the author. In this modeling architecture, changes in the connection topology can be made simply by modifying the model's incidence matrix. Recalling the numerical versatility of matrices, the graph-based topological modeling can be a great enabler for automated manipulation of the system topology for damage modeling.

As the name implies, a topological model describes only the connection topological structure of a fluid system without reference to the behavior inside. For behavioral modeling, a component model function was linked to each edge object. A group of the model functions forms a component model library. The strategy of managing the topological model and the component models separately was especially beneficial when it came to generating models of different design alternatives, since one can create a network model with different choices or configuration of its components without modifying its topological structure, and vice versa.

The M&S approach included the additional, somewhat unusual setting in which the models in the component model library were created by a surrogate modeling technique. This required a presumed condition that there was already some form of component models from which surrogate models can be built.

Then, is a surrogate modeling approach really appropriate? This can be answered by explaining why the other possible approaches are not feasible solutions. One straightforward approach is creating all component models with an available domain M&S tool. If the computational cost of the domain M&S tool is low, this will be a reasonable choice, but often, it is not. Another approach may be hard-coding all the component models from scratch, and if the behavior of each component can be modeled by simple physics equations, this approach would be a solution that is both feasible and computationally affordable. However, the problem is that components of a fluid system are not easy to model. Even a single valve on a pipeline exhibits highly nonlinear dynamics whose relation with different valve opening ratio, flow speed, and geometric properties