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Modeling the Specification

ABSTRACT

A shipbuilding specification is an engineered product typically not tested until placed in service (i.e. placed under contract with a shipyard). Defects in the shipbuilding specification, as identified by the shipyard or by the Government in review of the shipyard's detail design, result in the delivered ship not meeting expectations, or in costly changes to the contracts and possible schedule delays. Shipbuilding specifications do not represent a particular ship design, but rather define a design space in which the shipyard must develop a detail design. The design space is intended to enable the shipyard to optimize the detail design for minimum cost. While any detail design that adheres to the shipbuilding specification should result in a ship that meets the Navy's expectations, the current specification development process does not ensure this happens.

While dynamic simulations and analyses are conducted as part of preliminary and contract design, they are typically done on "representative" systems and are generally not sufficient to ensure an arbitrary ship design that meets the shipbuilding specification will behave as intended. This paper addresses characteristics of the ship simulations necessary to minimize "defective specifications" in a shipbuilding specification and thereby reduce ship acquisition costs.

INTRODUCTION

For U.S. Navy ship acquisitions, the shipbuilding specification is part of the biddable technical package that conveys the required properties of a ship being acquired. It is part of the contract between the Navy and the shipbuilder and thus is a legal contractual document. As described in the Ship Design Manager (SDM) and Systems Integration Manager (SIM) Manual (NAVSEA 2012) the SDM is responsible for the development of the shipbuilding specification and other elements of a technical data package during Contract Design.

The shipbuilding specification is a translation of the engineering results and decisions from Preliminary Design into an organized text-based document. This document is subdivided into a number of sections, typically based on the Ship Work Breakdown Structure (SWBS). (See Moore et al. (1996) for a description of SWBS.) Each section is developed somewhat independently by teams of engineers and coordinated with Technical Warrant Holders (TWHs) and the developers of related specifications. Requirements management software tools such as DOORS or Cameo Systems Modeler may be employed to manage the specification development effort and to provide traceability to higher level requirements such as those in the Capability Development Document (CDD) (Joint Staff 2018).

Reading sessions are the principal means for ensuring the shipbuilding specification reflects a design that meets CDD requirements, is free of major technical inconsistencies, and that system interfaces are properly defined. For a new ship design, there are normally two sets of reading sessions. The first reading sessions take place just prior to placing the shipbuilding specifications under configuration management. The second, and final set of reading sessions can take up to six weeks long and take place just prior to certification by the appropriate TWHs (NAVSEA 2012).

Reading sessions are not effective in removing all defective specifications. A large portion of the change order budget in a ship acquisition, particularly for lead ship designs, is typically allocated to correcting defective specifications after the award of the contract and during the detail design and construction of the ship. This can amount to tens of millions of dollars in the procurement of a ship.

This paper proposes to use modeling and simulation specifically to identify specification defects that can lead to costly contract changes and schedule delays.

These specification defects can occur because shipbuilding specifications do not represent a particular ship design, but rather define a design space from which the shipyard must develop a detail design. The design space is intended to provide degrees of freedom that enable the shipyard to optimize the detail design for the shipyard production processes and lower material costs, thereby reducing overall cost. The Government's intention is that any detail design that adheres to the shipbuilding specification should result in a ship that meets the Navy's expectations. However, analysis is not currently performed to ensure this outcome is guaranteed.

Many times, a representative ship in the form of an indicative design is modeled during Pre-Preliminary Design and Preliminary Design to verify that a feasible design meeting the CDD requirements is possible and to form the basis of cost and schedule estimates. (NAVSEA 2012). Ship design engineers use modeling and simulation to analyze this indicative design as part of the verification process. The indicative design also becomes the basis for the development of shipbuilding specification sections. It is during this translation of what is learned from the indicative design into the words comprising the specification sections that the potential arises for the creation of defective specifications. Design teams have not traditionally used modeling and simulation to verify a specification.

CONTRACT ELEMENTS

A legal contract must have the following elements: (Leonard 2019, DAU 2017)

- Offer: The offer must clearly state what each party is providing to the other so that both parties have a common understanding. One of the parties voluntarily makes the offer to the other.
- Acceptance: The party receiving the offer must voluntarily accept the offer.
- Consideration: Each party must receive something of value from the other party. Typically, one party receives money and the other a product or service.
- Capacity / Competency: The parties must legally have the ability to enter into a contract.
- Lawful Purpose / Legal Intent: The parties must intend for the agreement to be legally binding and the offer must adhere to all applicable laws.

The shipbuilding specification is part of the offer. It must be in a form that is unambiguous so that both the Government and the shipbuilder have a common understanding of the characteristics of the ship that will be provided by the shipbuilder in exchange for the contract payments. It is for this reason that shipbuilding specifications have historically been in the form of text-based documents augmented with sketches and drawings.

MODEL OF A SPECIFICATION

In a traditional dynamic model of a component, the model attempts to include all of the relevant physics including parameter values of an existing physical component, or of a physical component that is realizable. A sensitivity analysis that varies parameter values may be performed, but the variation is rarely traced to specification requirements.

In a model of a specification for a component, the model need not strictly adhere to physics-based models. Instead the model treats the component as a black-box or a collection of black-boxes that demonstrate the dynamics and range of variability allowed by the specification. For example, Mil-G-21296 is a specification for diesel generator sets. It in turn provides requirements for governing system performance. One of those requirements is the maximum permissible recovery time in seconds following underspeed and overspeed (2 seconds). The model of the specification would establish a range of 0 to 2 seconds for this parameter.

The model of the specification may start within a SysML based tool such as Cameo Systems Modeler or other requirements management tool to decompose the specification into individual requirements, then allocate those requirements to specific elements of the specification model.

The implementation of the specification model itself may be in a traditional dynamic modeling language such as MATLAB-Simulink

The integration of component models must reflect the variability of system configurations allowed by the shipbuilding specification.

Model validation is somewhat different than for traditional modeling efforts. Instead of validating that a model properly predicts the behavior of a specific design, model validation in this context means that the model accurately covers the range of performance allowed by the specification.

TESTING A SPECIFICATION

Performing a modeling and simulation test of a specification (or a portion of the specification) requires the following:

a. A set of use-cases, perhaps auto-generated, that should be challenging, but consistent with the shipbuilding specifications.
b. The ability to populate parameter values within the component models and system models within the range allowed by the component specifications and shipbuilding specifications.
c. The ability to run a simulation that implements the use-case with the populated parameter values
d. The ability to evaluate the simulation results to determine if the results are acceptable or not.
e. A search algorithm to identify which combinations of parameter values result in unacceptable behavior.

Use Cases

Use cases define external inputs and initial conditions for running a simulation. See Stevens et al. (2015) for an example of mission-oriented uses cases for the ship's electrical power system. Since only a finite number of use cases can be simulated, a necessary assumption is that if the results of the simulation are acceptable for the given use cases, then the design will have acceptable results for an arbitrary use case. Effort should be made to increase the likelihood that this assumption is correct.

For example, if the shipbuilding specification is modified in response to the performance under one use case, then once acceptable performance has been shown for that use case, the use case should be retired and replaced with one or more similar use cases. This is intended to avoid having the shipbuilding specification optimized for one particular use case and to promote having the ship building specification robust to all likely use cases the ship will experience in service.

Ideally, an automated use case generator would create new set of use cases after each modification to the shipbuilding specification, and that sufficient use cases are employed to ensure robustness.

The Unified Naval Task List (UNTL) (OPNAVINST 3500.38B) provides a comprehensive list of tasks a naval ship may be assigned to perform. Consideration should be given to mapping use cases to the specific tasks in the UNTL that the ship being designed would be expected to do. The UNTL includes many mundane tasks a ship is expected to do, but not significant enough to directly mention in a higher-level requirements document such as the CDD.

Populate parameter values

The modeling environment must be capable of easily changing parameter values to reflect the degrees of freedom allowed by the specifications. The ability to easily change these parameter values is essential to implementing a search algorithm.

An example is illustrative. Consider MIL-DTL-3142E, DETAIL SPECIFICATION GENERATOR, ALTERNATING CURRENT, 60-HERTZ (NAVAL SHIPBOARD USE), section 3.4.26, which states, "The transient reactance shall not exceed 20 percent. The range of subtransient reactance shall be between 13 and 16 percent." Fitzgerald et al (1983) provide relationships for calculating transient reactance based upon machine design parameters.

$$x'_d = \frac{3}{2}\omega_{60Hz}\frac{I_{GenStatorBASE}}{V_{GenStatorBASE}} \cdot L'_d \leq 0.2$$

$$L'_d = L_d - \frac{3}{2}\frac{L_{af}^2}{L_{ff}}$$

$$L_d = \sum_{n=1,5,7,\ldots}^{\infty} \frac{3}{2}\frac{4\mu_0}{\pi n^2}\frac{1}{p^2}\frac{rl}{g}N_s^2\left(\sin\frac{n\alpha_s}{2}\left(\frac{\sin\frac{nm_s\gamma_s}{2}}{m_s\sin\frac{n\gamma_s}{2}}\right)\right)^2$$

$$L_{af} = \sum_{n=1,5,7,\ldots}^{\infty} \frac{3}{2}\frac{4\mu_0}{\pi n^2}\frac{1}{p^2}\frac{rl}{g}N_s\left(\sin\frac{n\alpha_s}{2}\left(\frac{\sin\frac{nm_s\gamma_s}{2}}{m_s\sin\frac{n\gamma_s}{2}}\right)\right)N_f\left(\sin\frac{n\alpha_f}{2}\left(\frac{\sin\frac{nm_f\gamma_f}{2}}{m_f\sin\frac{n\gamma_f}{2}}\right)\right)$$

$$L_{ff} = \sum_{n=1,5,7,\ldots}^{\infty} \frac{3}{2}\frac{4\mu_0}{\pi n^2}\frac{1}{p^2}\frac{rl}{g}N_f^2\left(\sin\frac{n\alpha_f}{2}\left(\frac{\sin\frac{nm_f\gamma_f}{2}}{m_f\sin\frac{n\gamma_f}{2}}\right)\right)^2$$

Subtransient reactance is a function of these inductances as well as the effective inductance of the damper windings (bars).

$$L_{kd} = \sum_{n=1,5,7,\ldots}^{\infty} \frac{3}{2}\frac{4\mu_0}{\pi n^2}\frac{1}{p^2}\frac{rl}{g}N_k^2\left(\sin\frac{n\alpha_k}{2}\left(\frac{\sin\frac{nm_k\gamma_k}{2}}{m_k\sin\frac{n\gamma_k}{2}}\right)\right)^2$$

The $\frac{1}{p^2}$ terms are determined by the electrical frequency, a function of the power system, here 60Hz, and the selected prime mover's speed. The $\frac{rl}{g}$ terms represent the size / rating of the machine, typically chosen by the customer. The $N_s\left(\sin\frac{n\alpha_s}{2}\left(\frac{\sin\frac{nm_s\gamma_s}{2}}{m_s\sin\frac{n\gamma_s}{2}}\right)\right)$ terms represent how the machine is to be wound, something entirely within the control of the equipment manufacturer and representing their degrees of freedom in achieving a specification-compliant transient and subtransient reactance. Winding a machine is a labor intensive, process driven manufacturing activity that is a major cost element of the delivered generator. Equipment manufacturers will have preferred approaches.

Run simulations

The modeling environment must be capable of running simulations either one at a time controlled by the user, or many synchronously or serially controlled by a search algorithm. These simulations test the simulation under the conditions of the use cases. Parameter values should be preserved as well as simulation results of interest. The user should be able to recreate a simulation based on the parameters to explore simulation results not initially preserved.

Evaluate acceptability

The modeling environment must be capable of determining if the simulation results reflect acceptable performance or not based on input from the user. Ideally the modeling environment should create a metric for the degree of acceptability to aid in implementing the search algorithm.

Search Algorithm

Normally, a search algorithm is employed to find the "best" solution based on a utility function. For this effort, the goal is very different: find regions of the design space where configurations are not acceptable. It is not clear what search algorithm is the best to use for this objective. A uniformly random search of the design space (such as in a Monte Carlo simulation) is likely not optimal, but could be adequate.

FIXING PROBLEMS IN SPECIFICATIONS

If the simulations indicate potentially undesirable configurations could be produced in accordance with the specification, the specification can be modified by adding a constraint that eliminates the problematic portion of the design space. The addition of this constraint should be tied to results of the simulation to ensure the reason for adding the constraint is well understood.

Once amended, the specification should be retested to ensure the addition of the constraint accomplished its objective and that feasible regions of the design space remain.

IMPLEMENTATION

Creating a dynamic model of a shipbuilding specification is a huge effort. It is not likely a program would be successful in creating such an all -encompassing model in one step. An incremental approach across multiple ship designs is more likely to succeed. A possible implementation path could be:

a. Model the shipbuilding specification in a few disciplines where dynamic models already exist. Use the experience gained in this effort to refine the process. The models may be federated.
b. Extend the modeling effort to additional disciplines where the risk of a defective specification has been evaluated higher than other disciplines.
c. Integrate the federated models.
d. Add additional disciplines until the entire shipbuilding specification is modeled.

The models created under this effort can also be used in source selection evaluations to determine if vendor proposals meet the stated requirements. This may require the RFP to specify model parameters that must be included in the proposal.

During the detail design and construction of the ship, the models can also be used to evaluate Engineering Change Proposals (ECPs) so that changes are not implemented that result in the ship not having desirable performance.

During sea trials, measured data can be used to validate model parameters. Once validated, the models can be incorporated into a Digital Twin framework to assist in the operation, maintenance, and modernization of the ship through its service life.

THE MODEL AS A SPECIFICATION

Ericsen (2006) proposed using the models as a specification, thereby eliminating the need to create the traditional text-based documents. He identified two types of models: requirement models and product models. Ericsen does not however, clearly articulate how the models are actually employed in the negotiation and administration of a contract. It appears that the requirements models are intended to be incorporated by the Government into the request for proposal (RFP) to specify required performance. As part of their response to the RFP, the offerors would provide a physics-based product model to describe their specific solution. The contractual requirements would be the combination of the two models.

Conceptually, this approach appears very attractive. However, a number of details still need to addressed:

a. Who pays for the development of the physics-based models? For a complex system, the development of the physics-based models could be substantial. In particular, is a company expected to pay for the development of the physics-based model if it does not win the contract? The Government could award multiple contracts to develop the physics-based models, then perform a source selection on the completed models.
b. How does the Government ensure the requirements model is self-consistent, realizable within available funding, and complete (i.e. any solution to the requirements model would be acceptable to the Government)? How would the requirements model differ from performance specifications that are currently produced? This requirements model would require testing as detailed in the other sections of this paper.
c. How are tolerances and degrees of freedom represented in the physics-based models? How is performance evaluated to ensure acceptable performance considering the tolerances and degrees of freedom? The degrees of freedom are the range of changes the offeror is allowed to make while still remaining in compliance with the contract.
d. If post contract award, analysis or testing reveals that the physics-based product model is not in conformance with the requirements model, who is responsible for funding changes to the physics-based product model (and potentially the final product) to achieve conformance?
e. How will the Government evaluate the physics-based models as part of source selection? Will the physics-based models be required to be in a specific format to be compatible with Government evaluation tools? Who is responsible for establishing and maintaining these data formats? How will translation errors from the modeling environment used by a contractor and the modeling environment used by the Government evaluation tools be addressed contractually? How will the Government evaluation tools be developed and who would be responsible for maintaining them?
f. How will the physics-based models be used to develop cost estimates to facilitate contract negotiations? This may be less of an issue if firm-fixed-price contracts are employed. The reduced technical risk associated with a physics-based model may warrant the use of firm-fixed-price contracts. Firm-fixed-price contracts may include award-fee incentives, performance or delivery incentives, and economic price

adjustments which can be employed to manage acquisition risks and opportunities.

g. How can the contracting officers be assured that nothing is hidden in the computer models? Since a legal contract depends on both parties knowing unambiguously what is required of the end product, data that is hidden, either intentionally or unintentionally, could result in both parties not having a common understanding of contract scope.
h. How should cost analysts use the requirement model and the product model to support negotiations for the contract "consideration?"
i. How are contract changes reflected in the product model?

These are not trivial issues. If solutions are found however, great savings are likely in both cost to the Government and in schedule. The work associated with translating models into text-based specifications by the Government and then back into engineering models by industry can be avoided. Furthermore, the reduction of defective specifications should minimize design and production delays and rework. Modeling the specification as described in this paper addresses one of the many issues.

RELATIONSHIP TO SET-BASED DESIGN

Set-Based Design (SBD) is increasingly being used as a design method for naval ship design. (Singer, Doerry and Buckley 2009) As described in Singer et al. (2017):

> "Set-based design (SBD) is a method for performing design discovery by way of elimination. SBD is characterized by:
> 1. communicating broad sets of design values,
> 2. developing sets of design solutions,
> 3. evaluating sets of design solutions by multiple domains of expertise,
> 4. delaying design decisions to eliminate regions of the design space until adequate information is known, and
> 5. documenting the rationale for eliminating a region of the design space.
>
> SBD concentrates on eliminating infeasible and highly dominated regions of the design space."

Modeling the specification is very synergistic with design processes that implement SBD. The initial variability allowed in model parameters is initially set to incorporate configurations that do not result in satisfactory designs. The simulation of the design space provides "adequate information" to eliminate the infeasible regions without being too conservative. By defining the design space in terms of variability allowed by the specification, the translation of the final design space into the specification becomes almost trivial, and since the design space has been validated through simulation, it should be self-consistent and free of most defects.

RECOMMENDATIONS

Based on the concepts presented in this paper, the following steps are recommended:

a. Establish an organization to create and maintain a modeling environment and models as described in this paper. Ensure this organization is adequately and stably funded.
b. Have this organization create and implement an incremental plan for developing and employing the models and modeling environment in all future naval ship preliminary and contract designs.
c. Use the model and modeling environment during source selection to ensure proposals are responsive to the RFP.
d. Use the model and modeling environment during detail design and

construction to ensure ECPs only have intended results.

e. Structure sea trials and special trials to validate the models.
f. Transition the models to a digital twin to support in-service operations, maintenance, and modernization.
g. Expand the organization's mission to implementing "Model as the Specification"

CONCLUSION

A shipbuilding specification is an engineered product typically not tested until placed in service. This paper proposes using modeling and simulation to validate that an arbitrary configuration meeting the shipbuilding specification will indeed work and have performance the Navy desires.

These same models and associated modeling and simulation environment can be used to assist in source selection, and contract administration. Once the ship is built, the models can become part of a digital twin implementation.

An organization should be created and funded to implement this concept. Eventually the concept can be extended to employing the Model as the Specification.

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