Strategies for integrating models of interdependent subsystems of complex system-of-systems products.

Neil R. Weston, *Member, IEEE*, Michael G. Balchanos, Michael R. Koepp and Dimitri N.Mavris

***Abstract*— The Office of Naval Research has established a need for improved design and analysis methods for the next generation of naval surface combatants. The Aerospace Systems Design Lab (ASDL) has initiated the Integrated Reconfigurable Intelligent Systems project to address design issues associated with the future systems. A goal of this program is to define preliminary approaches for developing an integrated modeling and simulation environment for complex systems. Since such systems are heterogeneous, dynamical and interdependent we suggest that a system-of-systems multidisciplinary approach is most appropriate for investigating and executing solutions. An integration methodology employing innovative techniques and a framework of tools that can be used to couple disparate models and simulations is presented. Methods for validating the final product to justify the selected approach and demonstrate a proof of concept for the integrated model are also discussed.**

***Index Terms*— Reconfigurable Systems, System-of-systems, Integrated Model, Interdependent Systems, Interrelationship Mapping, Conceptual Decomposition, Multidisciplinary Simulation.**

I. Introduction

SEVERAL programs supported by the Office of Naval Research (ONR), including the Integrated Engineering Plant (IEP) [1], [2], Damage Control—Automation for Reduced Manning (DC-ARM) [3], and Reduced Ship's-crew by Virtual Presence (RSVP) [4] have introduced a number of objectives for achieving the levels of autonomous survivability and reconfigurability required for the advanced war fighting capability of next generation naval surface combatants. Extensive research has been done on identifying methods for achieving the IEP objectives, as they have been defined by the ONR.

The Aerospace Systems Design Laboratory (ASDL) at the Georgia Institute of Technology has developed the Integrated Reconfigurable Intelligent Systems (IRIS) initiative as a systematic framework that attempts to provide a group of methods to resolve issues and difficulties that have arisen as a result of the Navy objectives and eventually become part of a solution for the concept. The need for an integrated modeling and simulation environment along with the preliminary approaches for its development, are the main topics that will be introduced in this paper.

II. Background

One of the first tasks planned under the IRIS initiative was to understand the basic requirements and recognize the difficult aspects of the problem. How to achieve key goals, such as increased survivability and autonomous decision making capability, along with significant manpower reduction for the ship's operation, are questions that the IRIS approach seeks to address. The process will involve the design of large dynamic networks, consisting of highly complex systems that may demonstrate high levels of interdependency among each other. Typical examples are power system components, or ship service loads that may be coupled with parts of the cooling system or the sensor grid.

The development of an integrated modeling and simulation environment involves different disciplines, linked together either physically or theoretically, along with their associated time dependencies to reflect the dynamic nature of a ship's operations. Due to the system's complexity, and since every component can be considered a system itself, it is advisable to take a system-of-systems approach. Finally, for a study of a system of this size, it would be impossible to proceed without the aid of a virtual prototyping tool, not only from the aspect of available financial resources and time, but also due to the difficulty of building a hardware prototype without prior knowledge of the system behavior.

The dynamic nature of this concept is another strong reason supporting the development of an integrated model. In the IRIS environment models need to capture the time dependencies associated with each subsystem. Synchronization of individual models with multiple time scales is the biggest challenge here, and methods are under development to ensure the harmonious interaction of the lower level models. This will add the capability of running event driven scenarios that can affect the operation of all systems, with the expectation that the system controls will also be able to drive and reconfigure the system in the course of the simulation.

This virtual prototyping tool will consist of models and software that will be used during the IRIS implementation studies before building an actual hardware prototype. This tool, an Integrated Modeling and Simulation Environment, is a virtual computational representation of an actual system. It consists of a set of subsystem models, properly combined and linked to each other, for the purpose of creating an environment to allow for the user/designer to simulate the operation of naval ship systems under given mission scenarios.

III. Interrelationship Mapping

Systems Engineering is one of today's most popular approaches to the understanding and analysis of complex systems comprised of a number of heterogeneous subsystems. For depicting this heterogeneity, it is vital to capture and map the physical and theoretical/functional interdependencies among these systems. This allows for an overall system representation that is characterized by high fidelity with the capability of returning accurate and rich results.

For a systematic method of capturing the system component interdependencies, a method called Interrelationship Mapping is proposed. In order to build an interrelationship map, the functional and physical system decompositions are the first performed in order to determine interdependencies between subsystems, equipment, and components at several levels of detail. This two-step process is also known as the "conceptual decomposition" of a complex system and will also be useful in the mapping of outputs of each subsystem component model to the inputs of associated dependent subsystems [5].

The first part of the conceptual decomposition, involves the breakdown of the complex system in the physical domain, decomposing it into its lower level components. Affinity diagrams and tree diagrams can be used for visualizing the results of this process. Fig. 1 shows a tree diagram representation of the physical decomposition of a notional system consisting of a computer coupled to a thermostat-controlled coolant pump; this system serves as a test platform for initial modeling and integration studies and will be referred to throughout this paper.

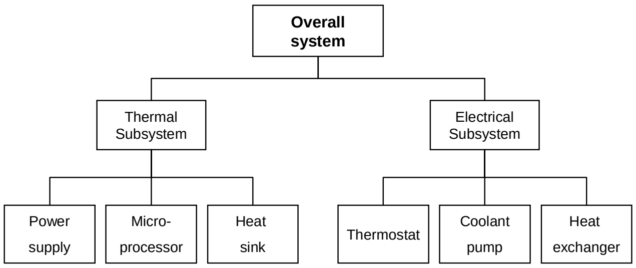

Fig. 1. Tree diagram for demonstrating the physical decomposition of a thermal/electrical system.

The second part is to identify what functions these components must perform to allow the total system to operate as expected. This is known as the functional decomposition, where every component is mapped to the set of actions that it is taking or, its physical behavior, during a period of system operation. Functional decomposition of a system can be documented through a table which includes a set of information for every subsystem/component into which the top level system is broken down. The physical inputs and outputs need to be identified (along with a corresponding metric if possible) as well as the function that is performed within the module. Other side effects can also take place while the function is performed and these are documented as secondary functions that have their own responses to the same inputs. A demonstration of the functional decomposition of an electrical/thermal system is shown in Table I.

TABLE I
Functional System Decomposition

System	Component	Input	Output	Function	Side Effects
Electrical	Power supply	Mechanical Power	Electrical Power	Deliver electrical power to load	Produce heat
	Microprocessor	Electric Power	Heat	Perform calculations	Produce Heat
	Heat sink	Heat/ Coolant flow	Heat	Extract heat from processor/ power supply	None
Thermal	Thermostat	Temperature	Control Signal	Control operation of coolant pump	None
	Pump	Electric Power	Coolant flow	Circulate coolant	None
	Heat exchanger	Heat	Heat	Exchange heat with environment	Increase temperature

In a highly dynamic system, the physical decomposition should not be different than the process applied in a static system. However, the functional decomposition will require additional mapping of the event sequence and the time intervals between actions, given the fact that the systems concerned are not only highly complex but also time-dependent. Events and functions performed may have a specific sequence and may have time intervals between actions. A flowchart similar to the one shown in Fig. 2 can be used for this purpose. Events or functions performed by a component are denoted with a circle and the arrows represent the activities that lead from one event to another.

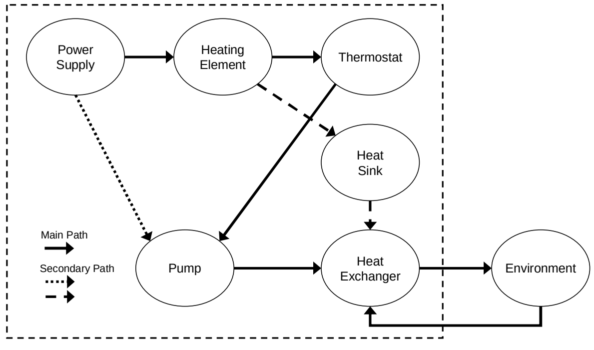

Fig. 2. Network diagram for mapping of the event time sequencing

Diagrams such as the previous one are not only useful for mapping event time sequences and activity durations, but also allow for activity optimization, where functions can be further simplified, redundancies and thus costs of performing functions can be reduced. In a modeling sense, additional modules not only mean higher complexity but also require extra simulation time to run a case.

The overall system function can be viewed as the result of having every physical component performing its individual function according to the hierarchy and time sequence of events that is defined by the physical decomposition. This is the actual outcome of the Interrelationship Mapping process and the result for the thermal/electrical system is shown in Fig. 3.

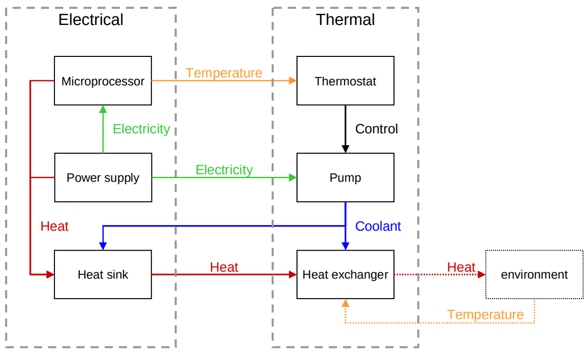

Fig. 3. Interrelationship mapping for the overall system

It should be noted that, the way that system components are physically and functionally interrelated is not necessarily unique. These relationships can be an object of improvement. In other words, in a component computational model domain this means that there may be more than one way for the component models to be integrated to a complete model of the overall system. This results in a tradeoff decision for the modeling effort. On one hand it is desired to have a simpler and leaner configuration with fewer interdependencies and less complex connectivities, for improved computational performance and reduced operating costs. However it may also be desirable to have a design with more interdependencies and functions that need to be captured in order to develop a more accurate integrated model that is closer to reality. In this case though, more interdependencies will increase redundancy for the connectivities and for the event time sequence complexity.

IV. Multidisciplinary Simulation

The introduction of an Interrelationship Mapping strategy now prompts definition of a method and tools by which this can be put into practice. Multidisciplinary Engineering has introduced novel concepts for preliminary analysis of integrated system-of-system design. Multidisciplinary analysis (MDA) [6], [7] allows an integrated product team to make contributions from various fields (e.g. structures, hydrodynamics, sea-keeping, signatures, operations, etc.) and deliver a more complex picture of how the interdependent systems function. Fig. 4(a) shows this organizational schema illustrated as a Design Structure Matrix, with notional processes A-D linked with a set of feed-forward and feed-back relationships. Typically, computation of results relies on numerical solution methods such fixed-point iteration [8]. These results, either single responses or functions thereof, can be used as a set of evaluation metrics.

Since analyses of complex dynamic systems such as naval surface warships will most likely include time-domain simulations, it is necessary to further extend the methods of multidisciplinary analysis. The concepts that underlie multidisciplinary optimization (MDO) [9], [10], [11] especially decomposition-based methods [12], can be applied to creating an organizational structure for joining together and running dynamic models of subsystems. Fig. 4(b) and 4(c) demonstrate the adaptation of existing multidisciplinary methods to the application of integrating heterogeneous time-domain analyses. Instead of an optimization algorithm as shown in Fig. 4(b), an external clock is used to synchronize the execution of the models, and a vector of initial conditions provides information for calculation of the first time step as in Fig 4(c). Metrics may also be distilled by calculating properties of simulation results, such as integrals, maximum or minimum values, time intervals. etc. Using an optimizer-like strategy has several benefits:

1) Control is maintained over the parameters that influence how the integrated simulation is scheduled and executed.
2) As in optimization-based decomposition, the MDA derived from interrelationship mapping can be parallelized.
3) Different versions individual analyses can be exchanged without having to reorganize the entire simulation framework.

Iteration through the desired time interval yields a time history of model outputs and/or composite responses obtained from functions of the individual output vectors. High level metrics can be found by integration, selection of maximum or minimum values, or some other numerical process.

Although current proof-of-concept models are simple enough that complex data handling is not required, the amount of data that will be involved in running simulations of complex, interdependent systems will be considerable. Especially when time-domain models are run, a system for organizing, transmitting, and storing data will be extremely useful. To this end, one option would be to set up a customizable, dynamically accessible database or file system that all relevant applications could communicate with and extract data from. This could be as simple as text or XML files, or a more complex Excel- or SQL-based database.

Regardless of the method employed for managing data, a backplane for linking all the models and their associated inputs and outputs is necessary. Since many analysis codes are full-featured standalone design tools, it is necessary to provide conduits for execution and data acquisition. Typically this is done using shell scripting that accesses a given analysis application via COM or OLE objects, or by a developer-provider application programming interface

(API). The data backplane, models, and other tools can also be implemented in a commercially available process integration platform.

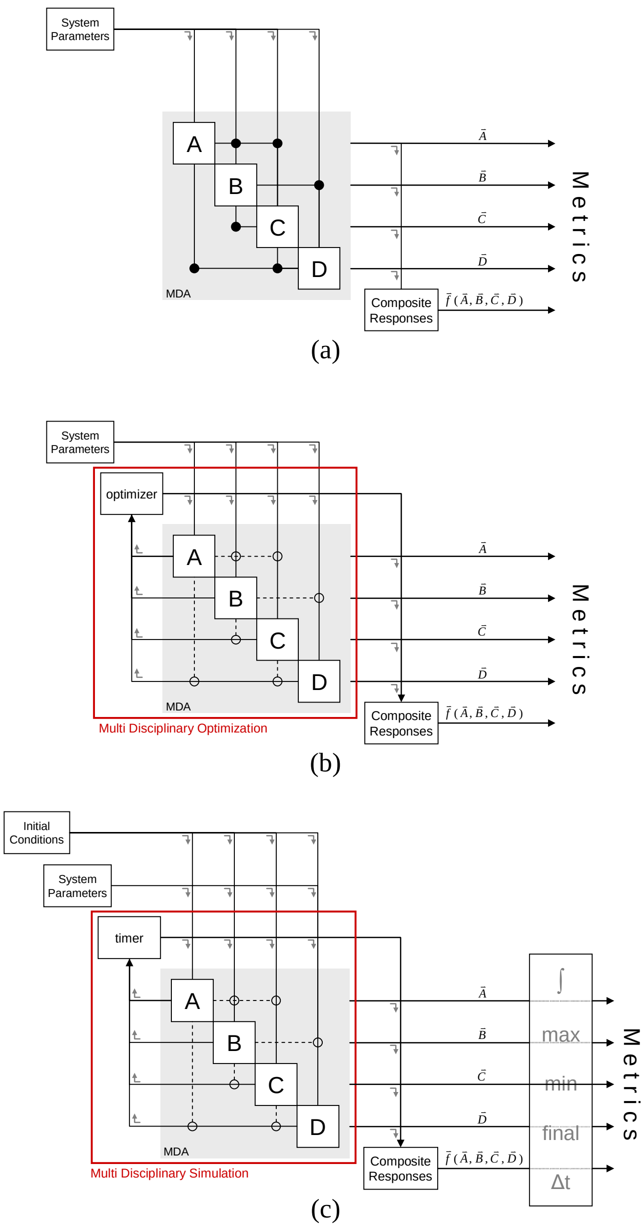

Fig. 4. Derivation of MDS schema from multidisciplinary methods

The last hurdle of this area involves coupling time-domain simulations and running them in parallel; for example, how can a model of an electrical system be coupled to a simulation of a fluid thermal management system? The main issues to be addressed include synchronized execution, and dynamic updating of parameter values. Work in this area is ongoing; to date the models used in this study have identical timescales.

V. Preliminary Results

A Simulink™ model of an electrical/thermal system was created that would exhibit time-dependent, nonlinear behavior to mimic what will be observed in an integrated naval system model. A process integration tool called ModelCenter™ published by Phoenix Integration [13] was selected to provide the backplane for integrating individual models, storing and exchanging data, and scheduling and driving execution of analysis codes.

To enable ModelCenter to handle dynamic models, a custom component called ‘Simulator’ able to drive the simulation using ModelCenter’s data and scheduling infrastructure was written. It is a Java class that is called by ModelCenter, and uses the Phoenix Integration Java API to interact with the simulation components specified by the user. The user interface is a drag-and-drop interface that specifies links between input and output parameters for each code.

Data validation and computational speed were the two most pressing performance aspects that had to be confirmed before using this tool for future studies of actual research codes. Validation of data was done by running the test simulation (the thermo-electric Simulink code) in a variety of configurations; the data matched very closely between all the methods implemented. As shown in Fig. 5, the differences between the original total system simulation and the ModelCenter-based multidisciplinary simulation are negligible.

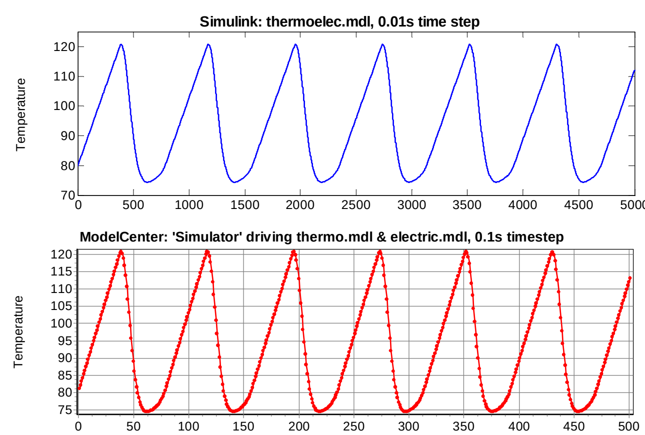

Fig. 5. Results from the MDS method show data validated against a total system simulation

Computational efficiency turned out to be within acceptable limits for the simple model studied so far. Using the complete thermoelectric model, execution time ranged from real-time (Δt = .01s) to 10x real-time (Δt = .1s). Running the simulation using the linked-code method driven by the Simulator component, required 30-45% more execution time.

VI. Conclusion

We have demonstrated a framework that meets initial requirements and expectations. The next phase of this part of the IRIS research initiative will be to link more complex codes, such as IEP electrical and thermo fluid simulations. It is unknown how well the linked-code Modelcenter simulation method will scale to larger models or to having more linked simulation codes. The experiments performed thus far have used only two models with a total of eight state variables; a fluid system model alone may have hundreds of state variables. It has been shown, however, that it will be possible to utilize a process-integration tool (e.g. ModelCenter) to link and automate the execution of simulations. Furthermore, if load distribution strategies (such as utilizing Centerlink, Phoenix Integration's job scheduling tool) can be used, or if analyses can be dedicated to certain workstations connected to the ModelCenter network, faster-than-real-time simulation of complex systems may be possible.

The modeling and simulation environment can be leveraged to do several types of studies:

Control as an independent variable – More precisely, system and resource management techniques and algorithms can be applied to the virtual system as an additional dynamically interactive component. A set of experiments can be run that focus on the parameters of the management solution, or compare different control/management architectures.

Design space exploration – through the use of designs of experiments, surrogate models, and statistical tools, designs can be evaluated or, using requirements/constraint-driven methods, can be narrowed down based on their predicted performance (i.e. inverse design).

Reliability analysis – A given system can be simulated under a variety of initial conditions, to gauge its response to changing environments and/or a spectrum of damage conditions.

Human-in-the-loop simulation – An interactive prototype "advisor" console could be used to test methods of presenting automated and assistive decision-making to the operator.

In addition, making such a methodology and framework available to domain experts, can facilitate trade studies of low-level parameters by looking at their influences on high-level responses.

References

[1] K. Lively, D. H. Scheidt, K. F. Drew, "Mission Based Engineering Plant," ASNE Reconfiguration and Survivability Symposium, Feb 16-18, 2005

[2] J.P. Walks, J.F. Mearman, "Integrated Engineering Plant," ASNE Reconfiguration and Survivability Symposium, Feb 16-18, 2005

[3] F.W. Williams, "DC-ARM Final Demonstration Report," Naval Research Laboratory, Code 6180, June 23, 2003

[4] G. Schwarz, "Systems Engineering Study for the Reduced Ships-crew by Virtual Presence(RSVP) Advanced Technology Demonstration (ATD)," May 14, 1999

[5] G.E. Dieter, *Engineering Design: A Materials and Processing Approach*, McGraw Hill, 2000.

[6] T.R. Browning, "Applying the Design Structure Matrix to System Decomposition and Integration Problems: A Review and New Directions," IEEE Transactions on Engineering Management, Vol. 48, No. 3, Aug. 2001. pp. 292-306.

[7] D.E. Acton, J.R. Olds, "Computational Frameworks for Collaborative Multidisciplinary Design of Complex Systems," AIAA 98-4942, 7th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, St. Louis, MO, September 2-4, 1998.

[8] S.C. Chapra and R.P. Canale, *Numerical Methods for Engineers*, McGraw-Hill, third edition, 1998.

[9] I. Kroo, "Multidisciplinary optimization applications in preliminary design - Status and directions," AIAA-1997-1408, AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit, 38th, and AIAA/ASME/AHS Adaptive Structures Forum, Kissimmee, FL, Apr. 7-10, 1997.

[10] K. F. Hulme, C. L. Bloebaum, "A comparison of solution strategies for simulation-based multidisciplinary design optimization," AIAA-1998-4977 AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, 7th, St. Louis, MO, Sept. 2-4, 1998.

[11] T. Cormier, A. Scott, L. Ledsinger, D. McCormick, D. Way, J. Olds, "Comparison of Collaborative Optimization to Conventional Design Techniques for a Conceptual RLV," AIAA 2000-4885, 8th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Long Beach, CA, September 6-8, 2000.

[12] L. Ledsinger, J.R. Olds, "Multidisciplinary Design Optimization Techniques for Branching Trajectories," AIAA 98-4713, 7th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, St. Louis, MO, September 2-4, 1998.

[13] H. Ng, S. Guleyupoglu, F. Segaria, B Malone, S. Woyak, G. Salow, "Collaborative Engineering Enterprise with Integrated Modeling Environment," Paper # 03E-SIW-034, Euro-Simulation Interoperability Workshop, Stockholm, Sweden, June 2003.