Proceedings of the 2008 Winter Simulation Conference
S. J. Mason, R. R. Hill, L. Mönch, O. Rose, T. Jefferson, J. W. Fowler eds.

MODELING AND SIMULATION OF INTEGRATED INTELLIGENT SYSTEMS

Yongchang Li
Michael Balchanos
Bassem Nairouz
Neil Weston
Dimitri Mavris

School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332, USA

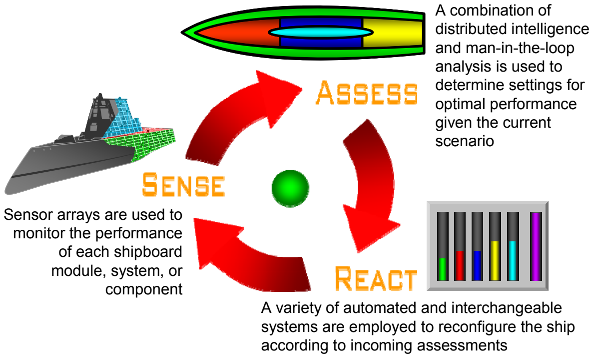
ABSTRACT

Complex systems consist of a large number of entities with their independent local rules and goals, along with their interactions. The effect of these properties tends to produce complex behaviors that are required to be understood in order to analyze and design the systems. However, these behaviors are difficult to be predicted *a priori*, and can only be studied through simulation. The study presented in this paper proposes a process for developing an integrated dynamic modeling and simulation environment designed for understanding the behavior of the next generation naval ship which is envisioned to be self-sensing, self-assessing and self-reacting. Various models, including power model, fluid model and control model, are developed to investigate the functionalities of the naval ship systems. An object oriented approach is employed to validate the architectural design of the integrated simulation environment and a surrogate modeling technique is utilized to accelerate the simulation speed.

1 INTRODUCTION

In the design and operation of the next generation naval ship, the rapidly changing fiscal and threat environment lead to an increased demand on affordability, ship survivability and mission effectiveness (US House of Congress 2005; Louden 2000).The Office of Naval Research (ONR) proposed an Integrated Engineering Plant (IEP) concept to meet such requirements (Dunnington, Garter and Stevens, 2003). IEP is a unified system that removes traditional system-level barriers between the various ship plants, such as propulsion, weapon, electrical and cooling systems. Thus, the ship plants can share the resources and information management systems which leverage the resources and deliver the information to the plants from a system point of view (Walks and Mearman 2005).

The successful design of an IEP for the Navy encapsulates all of the characteristics and issues that must be addressed when designing complex hierarchical systems and, as such, presents an ideal problem for basic research into methods development. The Integrated Reconfigurable Intelligent Systems (IRIS) is an initiative proposed by the Aerospace Systems Design Laboratory (ASDL) at the Georgia Institute of Technology as a solution to the IEP problem to satisfy the requirements of the next generation naval ship (ASDL 2004). The IRIS integrates many intelligent systems onboard to collect the information about the environment and ship state, assess the situation and then take a best course of action to reconfigure the ship into the state most suitable to handle the situation at hand (Hughes et. al. 2006). Therefore, the IRIS designed ship is envisioned to be self-sensing, self-assessing and self-reacting, as shown in Figure 1.



A combination of distributed intelligence and man-in-the-loop analysis is used to determine settings for optimal performance given the current scenario

Sensor arrays are used to monitor the performance of each shipboard module, system, or component

A variety of automated and interchangeable systems are employed to reconfigure the ship according to incoming assessments

Figure 1: IRIS Concept

978-1-4244-2708-6/08/$25.00 ©2008 IEEE

Using traditional systems engineering practices for the early design process followed by an integrated design environment, IRIS seeks to shift ship design to a distributed intelligent control architecture through increased automation. Since the design and analysis of the IRIS designed systems require understanding the behaviors of the systems, a simulation environment is needed due to the fact that the complex behaviors of the systems are difficult to predict *a priori* and can only be studied through simulation. IRIS are envisioned as more affordable, efficient and survivable platforms, thus this leads to extensive integration requirements of heterogeneous subsystems. In order to find the optimum or robust solution of a ship design for optimal mission effectiveness, the integrated subsystems need to be well studied and understood. Therefore, an environment is needed, for the purpose of integrating multiple physics-based models to accurately simulate the dynamic behavior that the systems exhibit. In addition, to meet the mission effectiveness and ship survivability objectives, a distributed intelligent control architecture should be developed for the implementation of the autonomous decision making process. This process will be strongly aided by the creation of a modeling and simulation environment to represent the total operations of typical naval ship architecture. It is also recognized that a human-in-loop study should be performed to investigate how the system prioritizes its tasks, how it interacts with the human operators and how any unsupervised operation can be avoided.

2 MOTIVATION

The challenge of designing next-generation ship systems that meet operational goals for system mission effectiveness, environmental compatibility, and reduced cost has grown to the point that traditional design methodologies are becoming ineffective. This situation is definitely supported by process related obstacles, such as highly demanding analysis requirements, large number of objectives and constraints, and different sources of uncertainty .

In addition, there is no standard and systematic method for integrating, validating, verifying subsystem models of complex systems. Naval systems are complex and composed of disparate systems (heterogeneous), with several interactions and interdependencies (integrated) and nonlinear (disproportionate cause-to-effects) and the behavior of the overall system (the macro-behavior) cannot be inferred from the analysis of the individual portions composing the larger system. Such complex systems need to be adaptable and reconfigurable, hence they are more “dynamic” in nature, and therefore, understanding these dynamic behaviors is critical. This revolutionary change in naval architecture and ship engineering requires a total ship systems engineering design approach for formulating and implementing the design methods and tools to develop ship system models and architectures and for assisting at the same time in acquiring an extensive, autonomous decision making environment.

However, previous research work in complex systems design and operation focused on methods which were only capable of dealing with systems that had a fixed topology. In order to satisfy the Navy’s requirement, new design methods and strategies must be developed to capture the behavior that these systems will exhibit in a dynamic environment.

All these characteristics lead to study the time-dependent and emergent behaviors of the integrated system. Eventually, this will assist in formulating a suitable and efficient integration strategy that will allow for a smooth and seamless integration scheme of the different subsystem models.

3 PROBLEM DEFINITION

A naval platform is composed of numerous subsystems that vary in complexity and discipline. This is further emphasized in an all electric ship where different subsystems closely interact and thus complicating the modeling procedure. Mechanical systems, electric systems, hydraulic systems, amongst many more comprise the electric ship, leading to a heterogeneous complex system. The Modeling and Simulation Environment (M&SE) has to allow for the inclusion of these diverse systems in a unified environment.

Subsystem models might be based on simple equations representing different components, or they might be more accurate physics-based models of higher fidelity. In either case, components of subsystems interact in a way that drastically increases the complexity of the entire system. Predicting the behavior of the system might be impossible in general, without running simulations. In addition, subsystem models are developed by disciplinarians who use a variety of software tools, thus, including all these models in a single M&SE is not always straightforward. Furthermore, the time dependency in each model further complicates the modeling and simulation problem.

As previously mentioned, subsystem models are built in different platforms, ranging from computer languages such as C++ or Java to sophisticated specialized software tools. The software platform should not drive the M&SE's architecture. The M&SE should have proper drivers or "wrappers" that provide proper interface with different software platforms used. An example of this would be using "com" components to provide well-defined interfaces that enable interprocess communication between the software and allow reuse of objects with no knowledge of their internal implementation. Consequently, disciplinarians working on their subsystem models can choose whatever tools they are more comfortable with. This puts a restriction on the allowable software platforms though. Only software tools with appropriate interfacing options to other external programs can be used.

The internal features of the subsystem models should have minimal, if any, effect on the M&SE architecture. Internal features include simulation specific properties such as the time step, the integration scheme, and the model specific features like the model's complexity or fidelity. Changing the subsystem model or even switching it with a completely different one should not mean that the whole M&SE architecture must be updated to accommodate for this change. In other words, the subsystem models should be transparent to the M&SE. The underlying assumptions of the rest of the M&SE components are not changed by switching the models, hence the difference in impact of the two models on the M&SE can be pinned down.

An important aspect that should not be changed in the M&SE's architecture is the interface between the subsystem models included in the environment. This interface is predefined, and should be standardized and given to disciplinarians responsible for modeling the different subsystems. Choice of the optimum interface is an iterative process that depends on the communication between the disciplinarian subsystem modelers and the M&SE system integrators.

A M&SE has to have means by which control can be applied to the various subsystems. This control can be internal in the subsystem or externally applied to it. The used models need to have enough inputs or parameters that can be used by external controllers or by the M&SE. In addition, the M&SE should allow for the use of different control architectures, such as distributed control, hierarchical control or centralized control.

As a result, a M&SE should be developed to possess several advanced features that allow it to take into consideration the heterogeneous nature of the system, and address the complexity and time dependency characteristics. The M&SE should be transparent to the used software platforms and the subsystem models and adheres to a specific predefined interface. The subsystem models exchange updated information as the simulation is running, allowing for capturing the interdependencies between subsystems. The complexity of the whole system is dependant on the modeling fidelity of the included subsystems, and could be modified by changing these components.

4 INTEGRATED M&SE DEVELOPMENT

4.1 Functional Decomposition

As illustrated in Figure 1, an IRIS designed ship possess three core functionalities: sense, assess and react. This complex system consists of various heterogeneous systems that work together to provide the required sub-functions to achieve the overall operational goal. In order to gain insight into the identity of the constituent systems, the hierarchical functional architecture of the IRIS ship should be explored. This is a task of incomprehensible magnitude without a structured methodology.

In this study, an object oriented approach is adopted to describe the system architecture details and component interaction in context of the IRIS functionalities. Firstly, an initial functional view of system is conducted to break down different ship functionalities. These functionalities then are organized and refined to obtain a functional decomposition of the system, as depicted in Figure 2. It can be seen that an IRIS ship not only have the "move" and "transport" functions that all other ships have, but it also has a key functionality of an iterative "sense-assess-react" procedure which make it capable of meeting the requirements placed by the naval next generation ship operations. After the core functions are identified, the systems that carry out these functions are identified through an object-oriented approach. With the use of the Unified Modeling Language (UML), various use cases are developed to capture those functions, and then the class diagrams can be created to describe the structure of the ship and the relationships among the systems. The development of a UML model of an IRIS ship is in sync with the inherent nature of the ship as a system of systems. This nature facilitates the adoption of the object oriented design and analysis to the system. This object-oriented approach helps to identify the models needed to be developed in order to understand the behaviors of the IRIS ship through the simulation, thus, a integrated simulation environment can be created by treating the system as a composition of interacting objectives. As a result, the object-oriented design and analysis can help to explore potential designs, and validate the

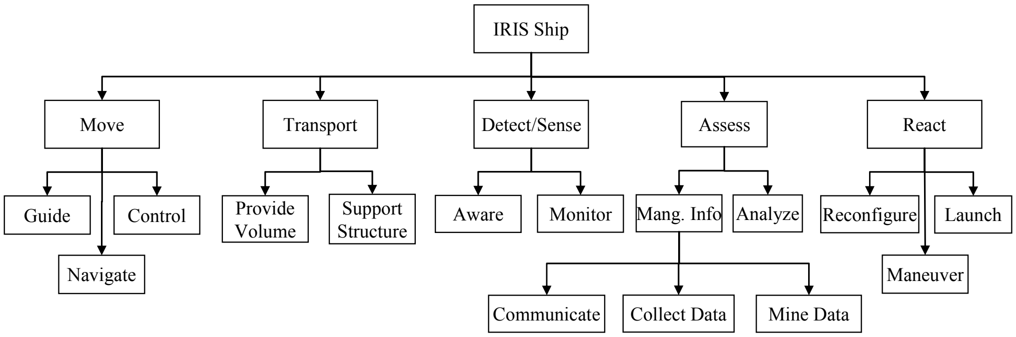


Figure 2: Functional Decomposition for IRIS System

architectural design of the integrated simulation environment.

4.2 Model Identification

Based on the above functional decomposition, a simplified system model needed to be developed to simulate the functionalities and demonstrate the capabilities of the IRIS designed ship. First, the models representing the major subsystems of the ship need to be identified. It can be seen that two types of subsystem models are needed. The first are models that implement the physics of the system such as electric power networks, fluid networks or communication networks. In general, these models have no built in intelligence and in some case a minimum level of automatic control is required to ensure the stability. Some are void from any controls and only present the pure physical dynamics of the system. The second type of subsystems are the controllers that enable the system to make autonomous decisions on reconfiguring the system into the mode best deal with the situation at hand. The separation between the control and physics allows for more design flexibility. In this study, the simulation environment will be mainly used to investigate the behavior of the system and demonstrate the reconfigurability of the system. Thus, the physics based models are identified as fluid mode and electrical model which will provide recourses (power and cooling fluid) needed by other subsystems.

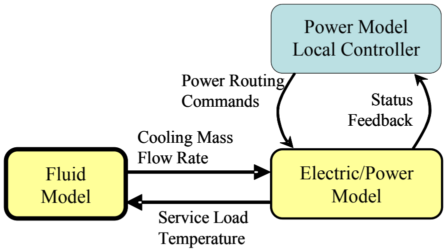


Figure 3: Physics Based Models

It is to be noted here that the two physics based models; the power and cooling models, are completely separated. They are heterogeneous as they are based on two very different disciplines. If one of the two models is used as a stand alone, it assumes all the inputs from the other model to be constant, hence drastically undermodeling the complexity of the whole system. The strength of the M&SE is evident because it models the complexity of the whole system by allowing for interaction between the subsystems.

The power model and the cooling model cannot achieve an acceptable performance without the use of appropriate controllers, thus a control mechanism is needed. A three level control architecture are proposed, each with a different function, as shown in Figure 4. These three levels implement a form of semi-centralized control.

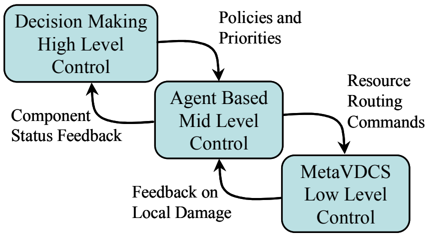


Figure 4: Three Levels of Control

The first and top most level is the decision making level as shown in Figure 4. Autonomous decision can be made at this level from a system point of view on resource allocation in order to reconfigure the ship to the best mode. The second level of control (Agent-Based Control) is responsible for doing the actual reconfiguration and execute the command received from the top level controller. The third and lowest level of control (Meta-VDCS) performs some pre-defined control. It utilizes simple logic to accomplish this task.

It is found that it is necessary to implement the human-in-the-loop control to allow the user to override some control commands in order to prevent the system from becoming instable. Thus, a Human Machine Interface (HMI) model is needed in this M&SE. It serves two main functions. First, it is used to show the results form M&SE visually. The second function of the HMI is to allow the user to interact with the simulation to explore its functionalities.

It is also noted that a scenario model is needed to generate inputs for the M&SE. Basically, it is a short representative database of component initial priorities or importance to the whole system. Based on the state of the ship, the scenario model chooses a set of priorities that are fed through to the physics based models and initialize the controllers. In addition, the scenario model can be used to simulate damage in any component included in the physics based models based on a preloaded matrix.

4.3 Modeling and Simulation

4.3.1 Model Development

After the models are identified, they are developed by domain experts using different platforms. In this section, the models that will be integrated in the M&S environment are presented.

4.3.1.1 Electric Power Model

The most critical subsystem to be represented by a high fidelity physics-based model in the IEP M&S environment is an electric power system that simulates the power generation and its distribution to the service loads. Two variations of a simplified electric power system model, a low fidelity power flow allocation tool and a physics-based higher fidelity small scale power model have been created. Simulink® has been identified as the most suitable software enabler for the implementation of the modeling tools. The main idea is that it should be possible for the two models to be used interchangeably. However, the ultimate goal is to merge the two power models into one, which will inherit the fidelity and functionality of the two earlier models.

4.3.1.1.1 Low Fidelity Power Model

The objective for the low fidelity power model was to create an architecture, similar to the one that is implemented in the ZELDA (Zonal Electrical Distribution Analysis) power flow allocation tool. However this power distribution and allocation tool does not model load interdependency, or the physics of the electrical system components.

The power distribution model has two zones, where each zone has 5 loads connected in parallel. Similar to ZELDA, the model has a port bus and starboard bus. The bus is composed of node modules which link to zones, and connector modules which connect nodes to each other. This model is considered scalable, i.e. adding new zones or expanding the model in general, is very straightforward process. Concerning the power allocation module, it receives power requests and priorities from loads, processes this data, and assigns power to each load, then sends this power assignment matrix on each bus. Power is divided between the two buses depending on the total power request on each bus. An overview of the power flow allocation tool is illustrated by Figure 5.

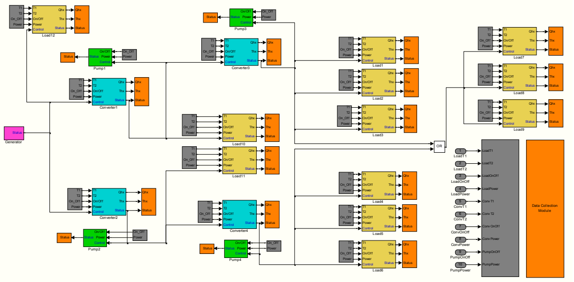


Figure 5: Low Fidelity Power Model

4.3.1.1.2 High Fidelity Physics-based Power Model

Based on a typical (DDG-51) power generation and distribution system, a simplified architecture has been developed and implemented within Simulink® (Kundur, 1994). The computational implementation of the aforementioned architecture is shown in Figure 6.

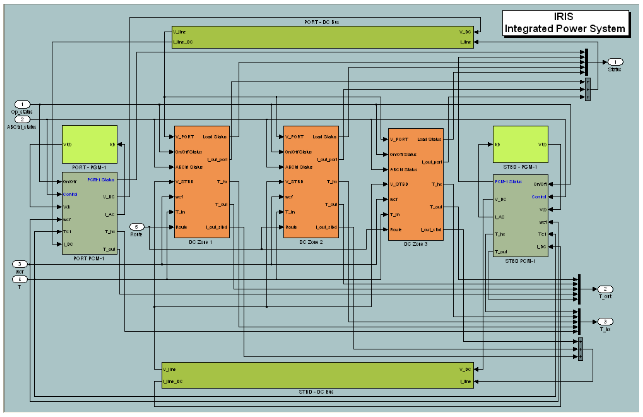


Figure 6: Simplified Physics-based Power Model

4.3.1.2 Cooling System Model

For simulating a cooling system for the IRIS designed ship, the Chilled Water Reduced Scale Advanced Demonstrator (CW-RSAD) model that has been obtained from NSWC Philadelphia is utilized. An overview of the complete CW-RSAD model is shown in Figure 7.

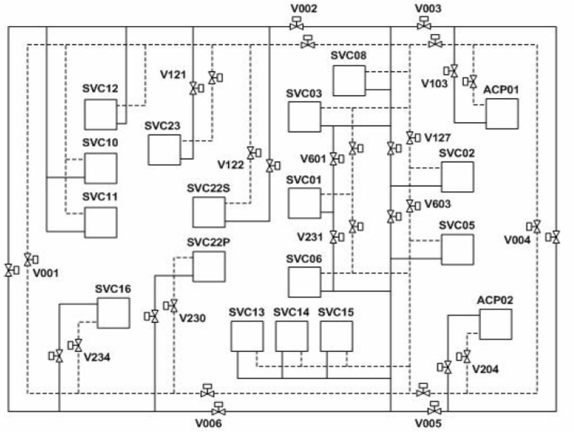


Figure 7: Chilled Water Reduced Scale Advanced Demonstrator (CW-RSAD) (Lively, Scheidt, and Drew, 2005)

A cooling system is included for the purpose of simulating the cooling operations on the service loads and on all the electrical components that demonstrate power losses. Such power losses are eventually converted into heat that needs to be extracted from the associated electrical components, in order to assure their proper operation.

For example, the mass flow rate of the coolant within the closed loop cooling system that is required to cool down a certain service load is predicted and regulated based on the heat that is being generated by this load and is responsible for the local temperature rise of the load component. This generated heat and should be eventually removed for this component not to exceed its operational temperature limits and operate under normal conditions.

Concluding, it is a network that contains 16 heat exchangers (or 16 placeholders for electrical system components that can be cooled down by its fluid network), two chillers and 72 valves. The current CW-RSAD model has the capability of simulating ruptures by "adding valves" at pipes that can possibly be damaged, based on a certain damage scenario.

4.3.1.3 Communications Model

A communications model for simulating the operation of wireless channels for signal transmission has been developed and will be included in the M&S IRIS environment. Successful simulation of wireless channels starts from the proper understanding of characteristics of communication channels. These characteristics include channel noise, signal fading, interference, multi-path noise, signal dispersion, lost data, etc. Amongst these factors, the effect of noise in the channel is the most common error source and therefore, this observation lead to the testing the channel performance with AWGN noise. Other characteristics can also be simulated, combined with channel noise or separately, but their effects to the data transmission appear the same as in noisy channels, that is, corruption in received data.

The objective of IRIS communication network research is to study the behavior of IRIS system under severely degraded communications environment. With IRIS system researches focused on developing the methodology of integrating heterogeneous systems, it is essential to study the system behavior under such conditions due to increased data transmissions between any subsystems on top, intermediate, and lower level. The simulation of such communication degradation, therefore, is to be applied on any levels of communication links, from top-level system integration to lower-level data transmissions, allowing various control subsystems in the IRIS to test their behavior or robustness under severely-degraded communication environment.

4.3.1.4 Controllers

An in-house implemented three level control architecture has been preliminarily developed, denoted as metaVDCS, ABCtrl and HLCtrl. Each one is a MATLAB® script that attempts to imitate the functions of Virtual Distributed Control System (VDCS), the OAK agents and the high-level controllers respectively.

4.3.1.4.1 Meta-VDCS

The metaVDCS script is attempting to capture the logic in the smart valve controllers. It accepts measurements of the pressure gradient through the valve and flow rate estimations for identifying pipe ruptures. If the change in flow rate exceeds a certain threshold, the controller assumes that there is a rupture and commands the valve to close. Furthermore, the valves can gradually open once the rupture has been discovered.

4.3.1.4.2 Agent-based Control System

At one level higher than the metaVDCS, there exists the Agent-Based Control System (ABCS) labeled ABCtrl. The ABCS uses more complex logic to regulate the flow through the different loads according to their priorities obtained from the High Level Controller (HLC). The ABCS also controls the pumps and chillers, and regulates their use as cooling is required by the service loads.

4.3.1.4.3 High Level Control

The High Level Control (HLC) at this stage serves as a simplified prioritization algorithm, assigning the priorities to each service load according to user inputs provided by the Human Machine Interface (HMI). Future work will involve incorporating a Markov Decision Making Process to account for the uncertainty in the state of the system.

4.3.1.4.4 Human-Machine Interface

The desire to optimize manning and the functions of the crew require that the ship be autonomously reconfigurable, but it is essential that operators have the ability to override the decision making systems. For this reason, a Human Machine Interface (HMI) has been developed that allows operators to supervise and interact with the system. The HMI model serves to send the data and receive commands from the interface. The HMI has been crucial in debugging the system and understanding the behaviors of the IEP and its controllers.

4.3.2 Integration and Simulation

With the developed models, a modeling and simulation environment need to be created to integrate the models in a single simulation environment to investigate the behavior of the IRIS concept. The integrated M&SE that has been developed is depicted in Figure 8 (Weston et. al. 2006). As it is shown, it incorporates two physics-based high fidelity models, along with a three level control system. A third model has been recently added for simulating the communications network that is responsible for the command signal propagation through the subsystems.

The model integration was done using Phoenix Integration's ModelCenter. The variables that are transmitted between the modules are also described. The environment transmits at each time step all of its information to a repository that stores all interdependent states and commands. From this central repository, the information is disseminated to the required analyses. This ensures that the model is synchronized and the time-domain data exchange is done sequentially. The embedded scheduler function in

ModelCenter allowed the modules or contributing analysis (CA) to be executed in different orders and frequencies.

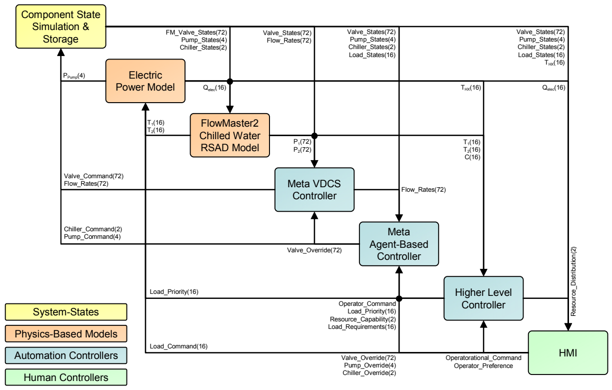


Figure 8: M&S Environment for IRIS Concept

4.3.2.1 Scheduler

Since all the models are time dependent, a Simulation Scheduler is needed to control the M&SE. The scheduler is responsible for passing necessary data between models, hence allowing for interdependency representation. For instance, the power model needs the amount of cooling flow to calculate a final temperature for each service load, and it gets this data from the fluid network model through the scheduler.

Another important task that the scheduler handles is the control over running the simulation. The models create data that change in time, based on inputs that also change in time. In general, these inputs are outputs of other models. The scheduler initiates the execution of all the models for a certain macro time step. All models run independently for this macro time step, utilizing their own solvers and own micro time step. Once each model reaches the macro time step, it stops and sends a signal to the scheduler, which in turn conducts the necessary exchange and update of data between models. The time advances with another macro time step and the cycle is repeated.

This proved to be a challenging job. The main requirement was that the scheduler should be screened from the models, allowing for the development and execution of models without taking into account the scheduler design. The solution was custom building the scheduler to the presented M&SE.

4.3.2.2 Data Transfer

The scheduler will direct the simulation in which data are transferred among models through the interface. In this context, the standards for data transferred between the different models in the M&SE is referred to as the interface. It is vital that the models be compatible and complementing in what inputs they require and data they calculate. In this section, a general description of the interface used between components is presented. A schematic diagram for data transfer in the M&SE is shown in Figure 9.

Before starting the simulation, the scheduler receives preloaded scenarios from the scenario model. Just before starting every time step, these priorities are recalculated based on current part of the scenarios and the feedback it gets from the controllers. It then signals the physics based models to start running. If at the end of every macro time step, the scheduler receives the temperature and status of all components from the physics based models.

The physics based models receive control inputs from the controller that include the desired statuses of their included components, e.g. the degree by which a valve is opened or the whether a particular load is to be turned on or off. This data is also transferred to the HMI.

Upon receiving the control inputs from the controllers, and the signal to start execution from the scheduler, the physics based models move to the new time step. They then feedback the final status of each component, some specific fluid network properties (such as mass flow rates) and the some electric power properties (such as the temperature of service loads to the controller. Most of this data is also routed to the HMI for visualization and through the scheduler for data logging. This is done every macro time step.

The HMI receives data from the controllers, the physics based models and the scheduler for visualization. All component states and important properties are accessible on the fly through the HMI.

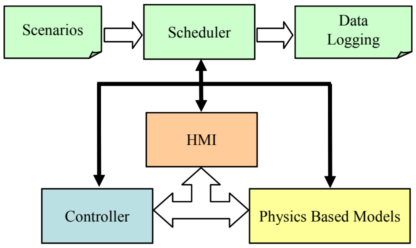


Figure 9: Data Transfer in the M&SE

4.3.2.3 Surrogate Modeling

After the integrated simulation is run, it is observed that the simulation time is dominated by only a few domain simulation models that are particularly slower than the rest, more specifically, the chilled-water cooling model in the integrated simulation is the slowest model and seriously degraded the simulation speed. In this study, a method is proposed to mitigate the simulation time by generating a neural network-based surrogate model of the chilled-water cooling system and use it to replace the original model.

A proof of concept has been constructed to develop the surrogate model for a test model. The test cooling system model is decomposed into multiple fractional subsystems. A surrogate model of each subsystem model was generated in the form of a recurrent neural network. The neural networks are then integrated to represent the entire model, and then the surrogate model is connected to ModelCenter to replace the original model. The comparison showed that the surrogate model ran 5-6 times faster than the original Flowmaster model under most running conditions.

4.3.2.4 Visualization

The study of the behavior of human-in-the-loop control is essential because the Navy's culture does not permit automation systems to work unsupervised, and therefore it is crucial to see how the dynamics of that interaction will play. The HMI is employed to visualize the simulation results and enable interactions between the simulation environment and the human participants. A schematic of the fluid network is shown from the HMI in Figure 10.

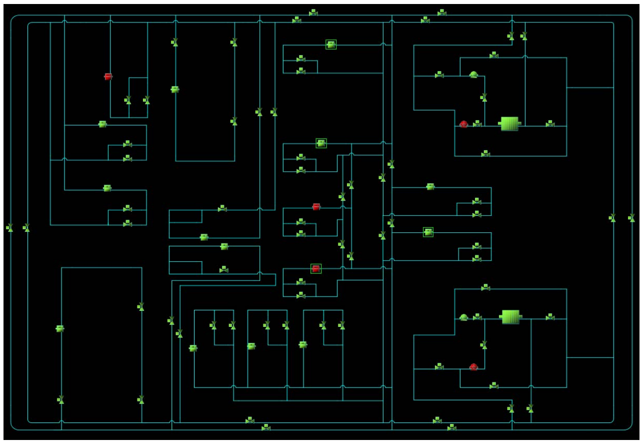


Figure 10: Human Machine Interface (HMI)

The component color indicates its status. As an example, if a breach in one of the pipes takes place, one can visually observe valves closing and isolating the breach. The visualization capabilities of the HMI allows for efficient communication of potentially large amounts of information. In addition, HMI has the capability to interact with the time domain simulation running in ModelCenter.

4.3.2.5 Scenario Study

In some situations, events, such as damage occur, mission changes or environment varies, may happen in the system operation process. These events often significantly affect the ship state, thus the control strategy needs to be modified to adapt this effect of the events. Two of the most common events that can occur in a scenario, representative of a naval mission are the rupture of valves of the cooling system or overheating of a service load in the electrical system.

Simulation results show that in the scenario that a service load is overheating, the system is able to make autonomous decision using the top level controller to reallocate the cooling resource. A high priority will be assigned to the service load, and then the midlevel and lowest level controller will find an optimum route to distribute the chilled water to that service load to cool its temperature down to the normal level. Simulation also demonstrates that when a rapture of valve happens, the system is able to reconfigure the fluid system to find a new route to distribute the required cooling recourse to the service loads by opening and closing the corresponding valves.

Concerning the other scenario type, a discrete event simulation approach will be required for simulating the abrupt heat excess that is being generated around a service load and is responsible for the immediate rise in the load temperature. Such events can be very possible during a naval mission and simulating this behavior can provide more insight as to how the controllers should respond with regulating the mass flow rates of the coolant fluid for rapidly extracting the excess amount of heat and bringing the temperature down to normal operating conditions.

5 CONCLUSION

This paper presented a process for developing the integrated M&S environment of IRIS system which is envisioned to be able to meet Navy's requirements with self-sensing, self-assessing and self-reacting functions. An object-oriented approach was employed to facilitate the model development through conducting functional decomposition. The models simulating various heterogeneous systems were developed, and a hierarchical, intelligent control architecture was constructed to investigate the reconfigurability of the IRIS ship. A HMI interface was designed to monitor the behavior of the simulated systems and realize the human-in-the-loop control strategy. These models were integrated in a single simulation environment to investigate the dynamic characteristics of the systems through a integration scheme using bond graph technique. To speed up the simulation, surrogate modeling was performed on the models consuming excessive computational power.

Several scenarios were studied to demonstrate the capabilities of the integrated simulation environment. The results showed that the developed M&S environment is able to reveal the behaviors of the ship system. It is also discovered that the IRIS designed ship is able to make autonomous decision and reconfigure itself into the mode best deal with the situation at hand.

In order to further explore the IRIS ship operations, more dynamic systems need to be investigated, modeled and integrated in the simulation environment. This requires further studies to be done on the scalability of the simulation environment. This will be one of future work for this research effort.

REFERENCES

Aerospace Systems Design Laboratory. 2004. Integrated Reconfigurable Intelligent Systems. Georgia Institute of Technology.

Dunnington, L., G. Garter and H. Stevens. 2003. *Integrated Engineering Plant for Future Naval Combatants - Technology Assessment and Demonstration Roadmap*. Systems Engineering Group, Engineering Technology Center, Marine Technology Division, Anteon Corporation.

Hughes, R., S. Balestrini, K. Kelly, N.R. Weston, and D.N. Mavris. 2006. Modeling of an Integrated Reconfigurable Intelligent System (IRIS) for Ship Design. Ships & Ship Systems (S3) Technology Symposium Change, Challenges & Constants.

Kundur, P. 1994. *Power System Stability and Control*. McGraw-Hill, Inc., NY.

Lively, K.A., D.H. Scheidt, and K.F. Drew. 2005. Mission Based Engineering Plant Control. Reconfiguration and Survivability Symposium.

Louden, J. 2000. Total Ownership Cost. *NAVSEA Naval Sea Systems Command*.

US House of Congress. 2005. Congressional Budget Data. *US House of Representatives Department of Defense Appropriation Bills*.

Walks, J. P. and J. F. Mearman. 2005. Integrated Engineering Plant. *2005 Distributed Intelligence for Automated Survivability (DIAS) Program Review*. Northrop Grumman Corporation.

Weston, N.R., M.G. Balchanos, M.R. Koepp, and D.N. Mavris. 2006. Strategies for Integrating Models of Interdependent Subsystems of Complex System-of-Systems Products. *IEEE Proceeding of the Thirty-Eighth Southeastern Symposium on Systems Theory*, pp. 310-314.

AUTHOR BIOGRAPHIES

YONGCHANG LI is a Research Engineer II in the Aerospace Systems Design Laboratory (ASDL) of the school of Aerospace Engineering at the Georgia Institute of Technology. He received both his Master and Ph.D. degree from Georgia Institute of Technology. Dr. Li's areas of specialization include design methodology development and multi-attribute probability decision making with applications in complex systems design and operation. Dr. Li, in collaboration with others, is currently working on the development of a modeling and simulation environment for Integrated Reconfigurable Intelligent Systems (IRIS), in order to improve the system's survivability and mission effectiveness through the use of autonomous decision making techniques.

MICHAEL G. BALCHANOS is a Graduate Researcher at ASDL of the School of Aerospace Engineering at the Georgia Institute of Technology. He obtained his Diploma in Physics from the Aristotle University of Thessaloniki, Greece and his M.S. in Aerospace Engineering degree from Georgia Tech. His current research efforts focus on the development of a robust methodology for the design of complex naval systems under mission effectiveness requirements, utilizing physics-based M&S environments. He has also been involved on understanding and developing electrical models for simulating naval ship operations and contributing in the integration of time-domain simulations in a comprehensive integrated framework

BASSEM NAIROUZ is a Graduate Researcher in ASDL, Georgia Tech. He received his BS and MS degrees from the Aerospace Department, Cairo University. He holds a post-graduate diploma in information technology from the Information Technology Institute, Cairo. He received a MS degree in systems engineering from the ASDL and is currently enrolled in the PhD. Mr. Nairouz has participated in research pertaining to satellite dynamics, controls, systems of systems, modeling and simulation. Currently, his research interests include modeling and simulation, systems integration and co-simulation, parallel time-dependant models' simulation, control system architectures and survivability modeling.

NEIL R. WESTON is a Research Engineer II with the ASDL at the school of Aerospace Engineering of the Georgia Institute of Technology. Dr. Weston has 15 years experience in the different phases of design, analysis, and testing of various complex systems. His main areas of interest include developing and implementing new methods for systems design and optimization, developing physics-based simulation models, and all areas of theoretical, applied and computational mechanics.

DIMITRI N. MAVRIS is the Boeing Professor of Advanced Aerospace Systems Analysis at the Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, and the director of its ASDL. Since his initial appointment as academic faculty in 1996, Dr. Mavris has consistently acted to expand his academic and teaching abilities and responsibilities. His primary areas of research interest include: advanced design methods, aircraft conceptual and preliminary design, and air-breathing propulsion design.