A Real-Time Hardware-in-the Loop Simulation Environment for Shipboard Control and Navigation Systems

Troy Nguyen, Lamar Davidson
Lockheed Martin, ST&S
Orlando, Florida
Troy.V.Nguyen@lmco.com, Lamar.g.Davidson@lmco.com

Rod Holland
Holland Engineering Consultants
Fort Collins, CO
Holland@peakpeak.com

ABSTRACT

Advances in software simulation tools have significantly affected the way in which complex and highly dynamic systems are designed and analyzed. Software tools that accommodate real-time and hardware-in-the-loop simulation provide the capability for designers to examine system architecture and operational philosophy, in addition to the ability to analyze and predict system performance prior to actual hardware and software implementation. The discussion in this paper centers on a simulation environment that utilizes high-fidelity mathematical models and a human machine interface (HMI) for replicating shipboard systems with special emphasis on operational performance, situational awareness, and dynamic human-computer collaboration. The paper reviews the state of the practice in real-time, hardware-in-the-loop simulation and its application to shipboard control systems, and also addresses several technical issues including model fidelity, system interfaces, and HMI features. For design and analysis purposes, the level of fidelity in the system models is considered in order to assure the simulation is reasonably useful for examining system architecture, design features, and system operational performance. For systems having a large number of input/output signals where it is not practical to incorporate full hardware-in-the-loop simulation, different computer network interfaces are considered to facilitate implementation of large-scale dynamic simulations. The paper also discusses the importance of robust implementation of human-computer interfaces to provide realistic scenarios in which the system operators interact with the simulation models as though they are controlling and monitoring the real systems. A key consideration in HMI features is the ability to inject faults into the system models mimicking real-life, human-in-the-loop operations that can be used for operator training purposes. Core technologies facilitating the development of the simulation environment include component modeling methodologies, high-speed network communications, simulation hardware and software architecture, and graphical user interface tools for prototype development. Finally, an example is drawn from the area of ship propulsion and navigation systems, including an illustration of real-time control and monitoring of the ship platform

ABOUT THE AUTHORS

Troy Nguyen is the R&D principal investigator for Ship Automation Systems at Lockheed Martin in Orlando, Florida. For over 16 years, he has been working in control design and analysis for gas turbines, steam turbines, diesel engines, and auxiliary systems for power generation and ship propulsion application. He received a BSME and a MSME from the University of North Dakota and a Ph.D. in Systems Engineering from Colorado State University.

Lamar Davidson is a senior software engineer for Ship Automation Systems at Lockheed Martin in Orlando Florida. He has 18 years experience in Machinery Control Systems. For the past three years, he has been working in the Ship Automation Systems laboratory on IRAD projects for future ship control systems. He received his BSCS from the University of Southern Maine.

Rod Holland is a consultant in control systems and simulation. He has 20 years experience in control system design and analysis for gas turbines, steam turbines and diesel engines as applied to power generation, petrochemical and ship systems applications. He received his BSEE, MSEE and Ph.D. in Control Systems from Colorado State University.

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INTRODUCTION

The ability to quickly prototype a physical system during the design process reduces technical and schedule risks associated with many large-scale development projects. Cost and logistics issues have made prototyping via simulation the method of choice.

Typical shipboard system design involves multiple highly complex electrical/mechanical equipment with inherent interfaces to ship operators for control and monitoring purposes. The complexity in the design and sophistication of the development necessitates a way to test out design concepts ranging from equipment interaction, control system performance, and Human Machine Interfaces (HMI).

This paper presents an approach to modeling and simulating a ship navigation, propulsion, and electrical system in which design details and interfaces are included to produce a realistic assessment of the system in question. Modeling and simulation steps lead to an integrated simulation platform that is used for design validation of control and monitoring logic including the human machine interfaces.

TYPICAL SHIPBOARD CONTROL AND MONITORING ARCHITECTURE

Figure 1 depicts the basic elements in state-of-the art ship control system architecture:

Controlled element: Electro-mechanical devices that perform sensing or actuating, such as a valve, circuit breaker, or a diesel engine. These devices are generally referred to as the "Plant"

Data acquisition and control unit (DACU): Hardware devices that execute software control algorithms to monitor the plant status via sensors and effect control actions to accomplish a desired response.

Human Machine Interface (HMI): This is the application software that runs on one or more computers and provides the operator the ability to monitor and control the plant equipment via a graphical user interface. The HMI software interfaces with the lower level DACU, generally through a local area network (LAN). The HMI software allows the system to operate either in manual or automatic mode. Manual operations include an operator who monitors and adjusts the control and monitoring processes as necessary. Automatic operation is enabled from the HMI and implemented by software algorithms that perform the control and monitoring without human supervision.

These elements are combined with network communication interfaces and databases into an integrated system that is typical for advanced ship control and monitoring architecture.

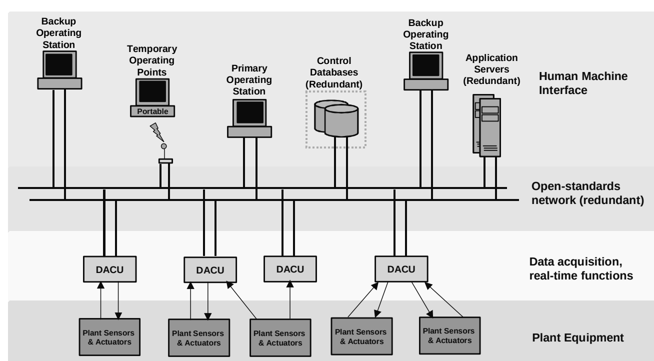

Figure 1. Shipboard Control and Monitoring Architecture

REPLICATING SHIPBOARD SYSTEMS

As shipboard systems become increasingly more complex and interlocked, there is a greater need for modeling and simulation of the design during the development process. In most cases, the modeling and simulation extend beyond the component design into operational philosophy as well as the various interfaces among the subsystems. Frequently, for large systems, the system analyst needs to consider the benefit/cost of utilizing complex models for accuracy versus simpler models that can be developed quickly. Simple models of the ship equipment are often sufficient for most simulation requirement. For instance, a lube oil pump may be simulated using a first order transfer function whose input is a step signal from the control system and whose output represents the pump outlet pressure. For some ship equipment such as a gas turbine engine, a higher fidelity model is necessary to accurately represent the inherent complex dynamics. A typical modeling approach is to implement first order models and then improve the simulation with higher fidelity models on a case-by-case basis, as time permits.

Mathematical Models

Most ship systems can be modeled by first or second order linear transfer functions. For critical complex sub-systems such as gas turbines, high-fidelity models are typically required to achieve reasonable accuracy. It is generally not practical to embed a detailed thermodynamic model of the gas turbine within a time domain system-modeling environment. Instead, it is customary to develop a representative model of the gas turbine, using simplified dynamics and non-linear look-up tables (LUTs) that characterize the gas turbine performance as a function of engine speed and fuel flow. Such models are specific to a particular gas turbine, and generally, the turbine manufacturer can provide design data that can be used to derive the LUTs that characterize the dynamic behavior of the machine. In the absence of a manufacturer LUT-based model, a choice between expediency and accuracy must be made.

Real Time Hardware –In-The-Loop (RTHIL) Simulation

Ship equipment and associated control systems have become increasingly complex such that it is difficult to analyze their design performance with conventional techniques. The complexity lies not only in the nonlinear behavior of some system elements, but also in the large number of operational scenarios, including unpredicted events, that require timely responses from both the ship operators and the control systems. Real time simulation with hardware in the loop enhances the capability of the designer to address the various issues of system performance and interfaces.

The ideal goal in RTHIL simulation is to have all hardware assembled in a test configuration and allow the simulation models to run in real time mimicking the system behavior in the real world as much as possible. The validation of performance is accomplished by running the simulation in various operational scenarios.

Model and Simulation Development Process

The basic steps in the modeling and simulation development process are:

1. Determine the model inventory - i.e. the systems and subsystems that it contains.

2. Determine the input/output (I/O) interface from each system or subsystem. Define the model input and output measurements needed to support the specific simulation.

3. Determine a suitable model for each ship component or subsystem that cannot be included for practical reasons. The description should be a realistic fit for the application purpose and support the required interface I/O. Model accuracy may be sufficiently supplied by a steady-state model or a simple linear transfer function. For detailed analysis and extremely accurate simulations, complex, non-linear, dynamic models are required.

4. Define the parameter list that regulates the behavior of inventory components. Exact parameter determination before model development is not required. It is useful to have an approximate idea of the parameters required, and their relative value range.

5. Work hierarchically to create large, complex system simulations. The global system should be broken down into smaller, more manageable subsystems. For each subsystem, follow the same development rules as the component inventory.

Software Simulation Tools

Software simulation tools are commonly used for modeling and simulating complex and highly dynamic systems. There are several factors that need to be considered when selecting a software simulation package for hardware in the loop simulation

- Real Time Capability
- Flexible Simulation Implementation
- Ease of Implementation

Real Time Capability: For demonstration and training purposes, a non-real time simulation of the physical systems may be acceptable. However, when building a simulation model for system performance analysis, the prudent choice to adhere to strict real time sampling. A simulation tool such as Matlab®, when properly implemented, is very capable of executing large-scale simulation in real time.

Flexible Simulation Implementation: Although standard programming languages may be used for simulation, a typical method of programming for simulation is through the use of graphical block programming. The advantages of graphical block programming are:

- Pictorial language, easily understood
- Programming in functions typically introduces less errors in the simulation
- Program print out also serves as documentation for the simulation or system (where as C code, for instance, may not be sufficient)

Usually the block programs are translated into C code by an interpreter program. The C code file is then compiled and loaded to the microprocessor performing the simulation. This is done automatically, and is transparent to the user who creates the block program.

Hardware In The Loop

The "hardware in the loop" portion of the RTHIL is a combination of interface hardware and Data Acquisition and Control Unit (DACU) hardware. This configuration allows the testing of the proposed DACU design by implementing the control level of the shipboard architecture.

The interface hardware consists of circuit cards connected to the simulation through software on one side, and the DACU on the other. The interface hardware provides the exact discrete and analog I/O signals that are monitored and controlled by the DACU. Interface hardware requirements include compatibility with the simulation and availability of design required I/O types. I/O types vary greatly depending on the equipment used on the ship. For example, systems with transducers generally include 4-20 mA circuits, where specialty circuit cards for generating millivolt signals and controlled frequency signals for magnetic pick-ups may be required.

The DACU hardware usually consists of programmable logic controllers (PLC) made by manufacturers such as Allen Bradley or Siemens. The DACU contain both the hardware for interfacing to the hardware circuit cards and the software algorithms for controlling the simulated systems. Including the DACU in the loop helps assure the final control system design meets specifications.

The simulation and RTHIL make up the lower two levels of the shipboard control and monitoring architecture shown in Figure 1. Human interaction at these levels is generally left to the simulation design engineer using development tools. The engineer can monitor the internal actions of the simulation and perform data mining functions which are typically not accessible to the operator. Operator interaction with the control system requires the implementation of a human machine interface in the architecture.

Human Machine Interface (HMI) Features

The following section presents the HMI for a shipboard control system that provides an interface to monitor and control the ship equipment. The design of a shipboard HMI incorporates common characteristics similar to other HMI applications. The interface provides status information and controls for performing actions. The HMI implements standardized user-friendly attributes such as consistency in location, size, color of screen graphic objects and text information.

HMI Ship Equipment Interface

Ship control requires an interface to ship equipment systems such as electric generation, propulsion, fuel fill and transfer, and damage control. The HMI allows an operator to view the status of these systems and to command changes.

The HMI generally resides on distributed networked workstations each capable of controlling all of the ship systems. The workstations are placed in locations such as the bridge, central control room, and machinery spaces. The workstations communicate over a common Ethernet network to the DACU. The DACU are wired directly to the system equipment providing commands to and status from the system equipment.

HMI Hierarchy of Information

One method of displaying information on the HMI is a hierarchy of screens populated with graphical layouts of the ship's systems. The hierarchy is composed of overview screens of each major system (electric plant, propulsion etc). Below each system overview screen are detail screens that provide monitoring and control of a subsystem, such as the lube oil system for the propulsion system. This hierarchy allows the operator to get a quick status of all systems from the overview screens, and if further detail is needed, the operator can "drill" down to a detail screen.

Control Location Flexibility

To allow control from any workstation, a transfer of control (TOC) scheme is required in the HMI. TOC facilitates the control of any ship system from any HMI workstation. However, only one workstation is in control of a system at one time, thus there is no conflict of commands. Control should be offered or requested from another workstation through a series of messages between the operators of the two workstations. An emergency option should be provided for taking control from one workstation to another without consent.

Alarms and Filtering

Alarms are generated in the HMI based on preset parameter set points, categorized by priority, and delivered in a number of formats including text, colored indicators, and audible alarms. A dedicated alarm window provides constant visual access to vital information. An alarm status indicator above the alarm window attracts the operator's attention even at a distance from the display, and conveys the severity of the alarm. Displaying only alarms relevant to the current display screen provides filtering to prevent operator distraction. Clicking on an alarm to bring up the alarm detail screen is a helpful feature. The operator can be directed to alarms on other systems by changing the color of screen navigation buttons.

Automation

The HMI provides the operator the information and ability needed to control and maintain ship operations. The HMI design challenge is to allow the operator to control all machinery systems without becoming task overloaded. Incorporating automation into HMI design is necessary for the operator to effectively carry out control of the ship. The operator selects the control mode, ranging from complete automation to manual control of each ship system (electric plant, propulsion etc.). For example, the electric generation auto mode allows the control system to start, stop, and adjust generator loads without operator attention. Providing this automation allows the operator to focus on non-automated tasks such as maintenance.

EXAMPLE SHIPBOARD CONTROL SYSTEM REAL-TIME, HARDWARE-IN –LOOP SIMULATION ENVIRONMENT

The ideas of the previous sections were implemented to prove ship control system design concepts and provide for demonstration and training. The implementation consists of an HMI, control interfaces and the ship simulation. The system was comprised of an electrical generation system, propulsion system, and hydrodynamics of a water jet propelled ship. The architecture of the environment is depicted in Figure 2.

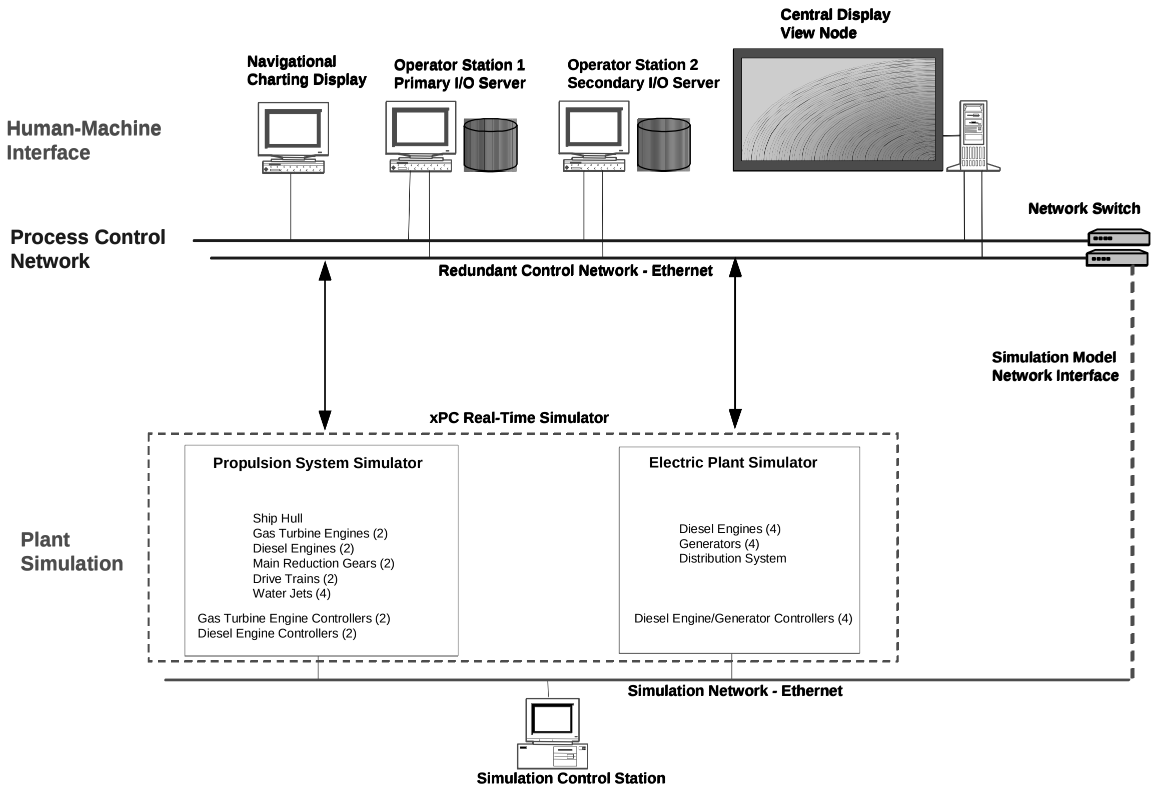

Figure 2. Shipboard Control Architecture

Page limitations necessitate focusing the following discussion on the architecture and the HMI of the propulsion system. The propulsion system consists of two gas turbines and two diesel engines operated in a CODAG (Combined Diesel and Gas Turbine) arrangement. Each turbine and diesel engine pair was coupled into a gearbox whose output was used to drive a pair of water jet propulsors. A hydrodynamic model and rudimentary positioning methods were employed to predict navigational movements of the ship from the propulsion model. In addition, controls were included for load scheduling between the paralleled gas turbine and diesel engine, heading control for the ship via stearable water jets.

The HMI implemented in the example contains screens with two basic components; 1) the border and 2) the tactical area. The dark blue border is included for consistency in look and feel. The border has an alarm window, control buttons for transfer of control (TOC) and buttons for display actions in the center. The TOC buttons allow transferring control of the displayed system from one workstation to another. The display buttons allow placing a signal trend window in the upper right or sending messages between workstations. The left portion of the border displays the date, time, name of workstation, operator logged onto the Workstation, and navigation buttons for displaying different tactical windows. The tactical window area has a gray background and contains monitoring and control graphics in a representative layout of the different the different ship systems. This interface allows for sending commands to and receiving data from the real-time ship simulation.

The HMI screen pictured in Figure 3 shows the propulsion tactical overview screen. Controls on the tactical window allow sending start, stop, and other engine commands to the simulation. The throttle sends speed demand to the simulation. The simulation responds by increasing scheduled power to the engines online.

Figure 3 . Propulsion Screen

The Conning screen in Figure 4 allows bridge level control of the ship simulation. Steering, heading, and throttle control inputs command the ship model's speed and course. The compass and heading readout are the result of the ship model simulations.

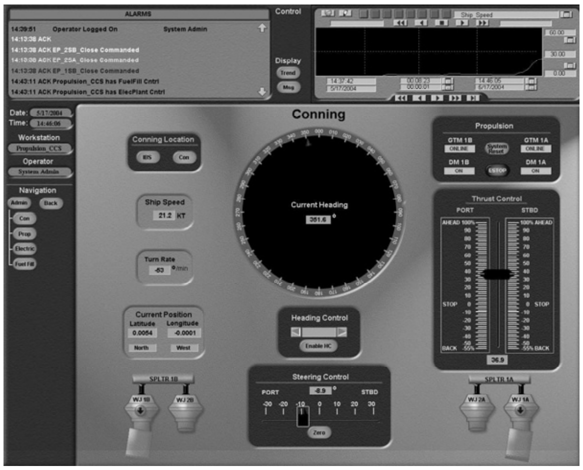

Figure 4 . Conning Screen

The navigational charting screen displayed in Figure 5 is an application containing charts for the northeast coast of the United States. The simulated ship's heading, position and speed are fed into the charting application via a GPS interface. This charting application provides a global positioning dimension to the simulation.

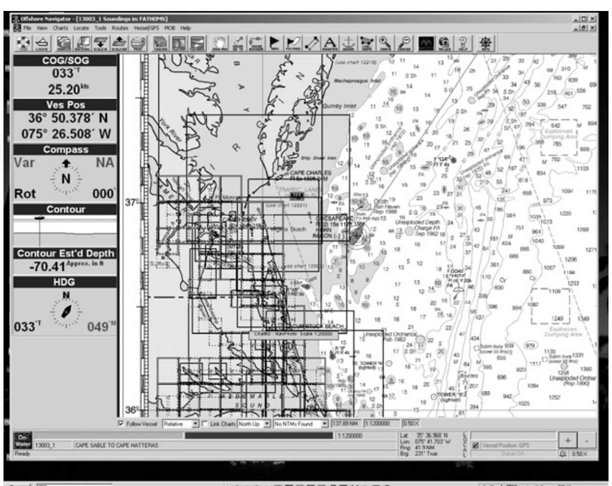

Figure 5 . Navigational Charting Screen

Through these HMI screens, testing and ship control demonstrations have been accomplished. Expansion plans include configuring hardware in the loop for the propulsion system. Currently, the propulsion system simulation is directly connected to the HMI via the Ethernet LAN.

Model Fidelity

Models were created from first principles; however, non-linearity were minimized, and included only where the "feel" of the simulation would have been affected. Some specifics of subsystems are:

- The gearbox models were linear but allowed for gain changes as the inertia changed when engines were clutched in and out.
- The water jet model was created from a lag and non-linear performance maps found on the Internet.
- Ship drag tables were created using commercially available software, and included as look-up tables for drag in the final implementation.
- Some compensation factors were included to make the ship "drive right" based on the assessment of experts who had experience with similar size vessels.

FUTURE ENHANCEMENTS

Future plans include incorporating hardware in the loop for the propulsion system. This hardware will be implemented as described in the first part of this paper with DACU and interface hardware to include true discrete and analog signals. Inclusion of this hardware will help extend the capabilities of the simulation environment for verifying DACU control algorithms. Plans also include implementing onboard training into the simulation environment.

On Board Training (OBT)

The shipboard system component replaced most often is the operator. Frequent rotations and multiple systems skill proficiencies make operator training a constantly on going process. This process requires 3 things; 1) available manpower, i.e. the operator and replacement operator 2) the training environment, and 3) time availability to place the operator and training tool together so that training may take place. On board training (OBT) addresses all 3 of these requirements.

Integration of On-Board Training

Typically on ship, operators with multiple skills are available, hence scheduling an operator for training and an alternate operator for duty is feasible. Embedding a training system in the hardware of the ship provides the training environment, and the since both the operator and hardware are on the ship, distance of separation is minimal. This negates the need for shipping personnel to a shore facility for training and allows ongoing training of personnel.

OBT provides opportunity for continuing operator training by integrating training into the HMI. This allows operators to train on equipment with interfaces identical to those used to perform his/her normal job function. An operator or group of operators can receive training on any of the systems controlled by the HMI. Training is performed on the actual HMI equipment in an off-line mode. Active on-board training does not impact normal HMI operations. The OBT function allows an instructor and trainee to work through a variety of plant operation scenarios, including both normal and casualty events. This is accomplished through embedding simulation of plant machinery in the training console to provide realistic response.

By taking one or more workstations off-line, access is gained to a duplicate set of HMI display screens that correspond to the tactical screens (including alarms and navigation between screens). The exception is that each screen clearly indicates training mode status. The screens are driven by a database of simulated HMI signals. Different sets of initial conditions can be provided for this database to simulate pier-side plant configuration, maneuvering, normal operation, normal operation, and General Quarters.

SUMMARY

Beyond simple system testing and verification, software simulation has advanced significantly over the last decade. Advancement in ship systems have promoted a high degree of interconnection as well as becoming microprocessor driven. By matching state of the art interconnected ship systems with full-scale computer driven simulations, complex scenarios may be tested and validated. Prior to these large-scale simulations, this level of testing was only available in the nearly finished product. The introduction of large-scale simulations has reduced the number of inevitable design changes. The value added has been in testing the control architecture, philosophy of system design and operator-in-the-loop for the overall system rather than validation testing of individual subsystems, many of which have hereditary designs.

We have briefly discussed the implementation of large-scale ship propulsion system simulation, and its benefits for demonstration, testing, and operator training. The simulation includes the equipment functionalities and the human machine interface necessary for replicating ship operational scenarios. Truly large-scale simulations tend to be built over a period of time and the value of the simulation is not recognized until the simulation has been created and demonstrated. In this case a gas-turbine driven, water jet propelled ship was modeled and simulated to demonstrate a conceptual ship design. The result is a simulation environment that can be utilized design concept testing as well as for training purposes.

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