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Development of Hull, Mechanical, and Electrical Autonomy to Enable Medium and Large Unmanned Surface Vessels

Abstract

As stated by the Chief of Naval Operations, Unmanned Surface Vessels (USVs) will comprise 25% of the surface fleet. For USVs to be considered a viable element of the fleet they must have reliable, sustainable, and maintainable Hull, Mechanical and Electrical (HM&E) systems and autonomous controls. Maturation of HM&E autonomy from foundational principles to predictive and intelligent capabilities that are linked via C2 to the operational battlegroup is the desired, if not required, end state for HM&E autonomy. Rolls-Royce is developing the Artificial Chief Engineer®[1] to achieve this desired end state.

Artificial Chief Engineer is an autonomous system being developed to replace the decision making traditionally performed by Marine Engineering Watch standers. The principal requirement for Artificial Chief Engineer is to manage and control HM&E systems and subsystems, which will be primarily accomplished by aligning a vessel's equipment to meet the mission needs. In the event one or more failures occur, Artificial Chief Engineer will realign equipment to account for failures and meet the needs of the mission as best as possible. In this paper, the motivation and features of Artificial Chief Engineer will first be discussed. Next, development objectives and the high level development approach will be presented. The paper will end with a brief discussion of results and conclusions based on the latest developments. In summary, a key subset of Artificial Chief Engineer functionality has been demonstrated using control hardware-in-the-loop proving the feasibility of the technology.

Introduction

The Navy is adopting autonomous vessels as part of their solution for the Fleet. Starting in earnest in the 2017-2018 timeframe with the introduction of Ghostfleet, through the identification of significant resources for autonomy and finally the Navy's Unmanned Campaign – there is no doubt that autonomous vessels are here to stay.

To date, principal efforts have focused on navigation and mission autonomy, the two cornerstones of autonomous capability. Despite the progress made in these areas, perhaps the most significant challenge remains in trying to achieve the endurance requirements of 60 or 90 days or even 12 months in the case of the No Manning Required (NOMARs) program. In order to achieve these requirements, it is essential that the propulsion system be highly reliable. Further allocation of the requirements to the mechanical and support systems will be needed to achieve the requirements. However, there are physical limits of the mechanical systems ability to meet the requirements. The addition of a fully autonomous Hull, Mechanical, and Electrical (HM&E) control system will be essential to enabling the physical systems ability to perform. A fully autonomous control system will be able to monitor system performance, learn the causal factors associated with a casualty, effect plant reconfiguration and report platform capabilities. Artificial Chief Engineer® (ArChEr) is the foundational technology that will provide this capability.

ArChEr is an autonomous system that is being developed by Rolls-Royce to replace the decision-making traditionally performed by Marine Engineering Watch standers. ArChEr is the primary intelligence associated with HM&E systems of a minimally manned and Unmanned Surface Vessel (USV). The principal requirement for ArChEr is to manage and control HM&E subsystems, which will be primarily accomplished by aligning a vessel's equipment to meet the mission needs. In the event one or more failures occur, ArChEr will realign equipment to account

[1] Artificial Chief Engineer is a registered trademark of Rolls-Royce plc

for failures and meet the needs of the mission as best as possible. The function of ArChEr represents a cardinal operational requirement for minimally manned surface vessels and USVs.

In 2019, Rolls-Royce Marine North America (RRMNA) and Rolls-Royce North American Technologies (LibertyWorks) initiated the development of ArChEr. This development work drew from years of development already underway at the Rolls-Royce UK-based defense group. This intra-company collaboration allowed the RRMNA and LibertyWorks team (Rolls-Royce North America (RRNA) or ArChEr development team) to quickly offer a mature autonomy concept to potential customers.

ArChEr Overview

An autonomous algorithm like ArChEr will necessarily incorporate a high level of complexity to achieve required functionality and manage the numerous subsystems comprising the HM&E system. Since this level of complexity is difficult to develop in a single design iteration, RRNA has planned to complete several design iterations en route to a fully functional ArChEr. In Design Iteration 1 (DI1), ArChEr was developed to manage and control three HM&E systems. These systems are the propulsion, electrical power generation, and fuel transfer systems.

Figure 1 shows a Systems Modeling Language (SysML) Block Definition Diagram of the Artificial Chief Engineer within its DI1 system context. The modules comprising the system context are the Mission Manager, Equipment Health Monitoring (EHM) System, HM&E Automation System, Propulsion System, Electrical System, and Fuel Transfer System. As seen in Figure 1, ArChEr interfaces with the Mission Manager, the HM&E Automation System, and the EHM System. Ultimately, ArChEr manages and controls the HM&E systems via the HM&E Automation System.

Conceptual designs of the HM&E systems (Propulsion, Electrical, and Fuel) were needed to enable development of the ArChEr algorithm. To meet this need, the ArChEr development team created conceptual designs for these systems. These designs are a part of the RRNA developed Banshee4 USV concept. This concept is comprised of four Main Propulsion Diesel Engines (MPDEs), three Diesel Generator sets (DGs), six fuel oil (FO) storage tanks, two FO day tanks, and FO pumps/valves/filters/piping, Figure 2. This concept was developed to represent HM&E systems that may be found on a typical medium to large USV. It was matured to sufficient fidelity to enable ArChEr DI1 development.

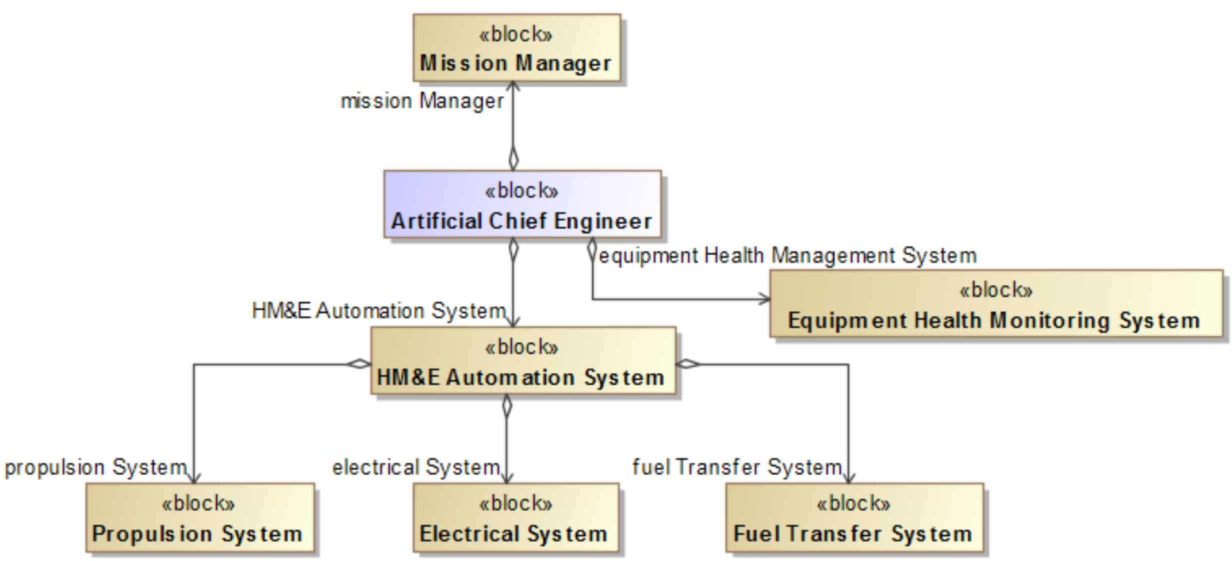

Figure 1. Artificial Chief Engineer System Context

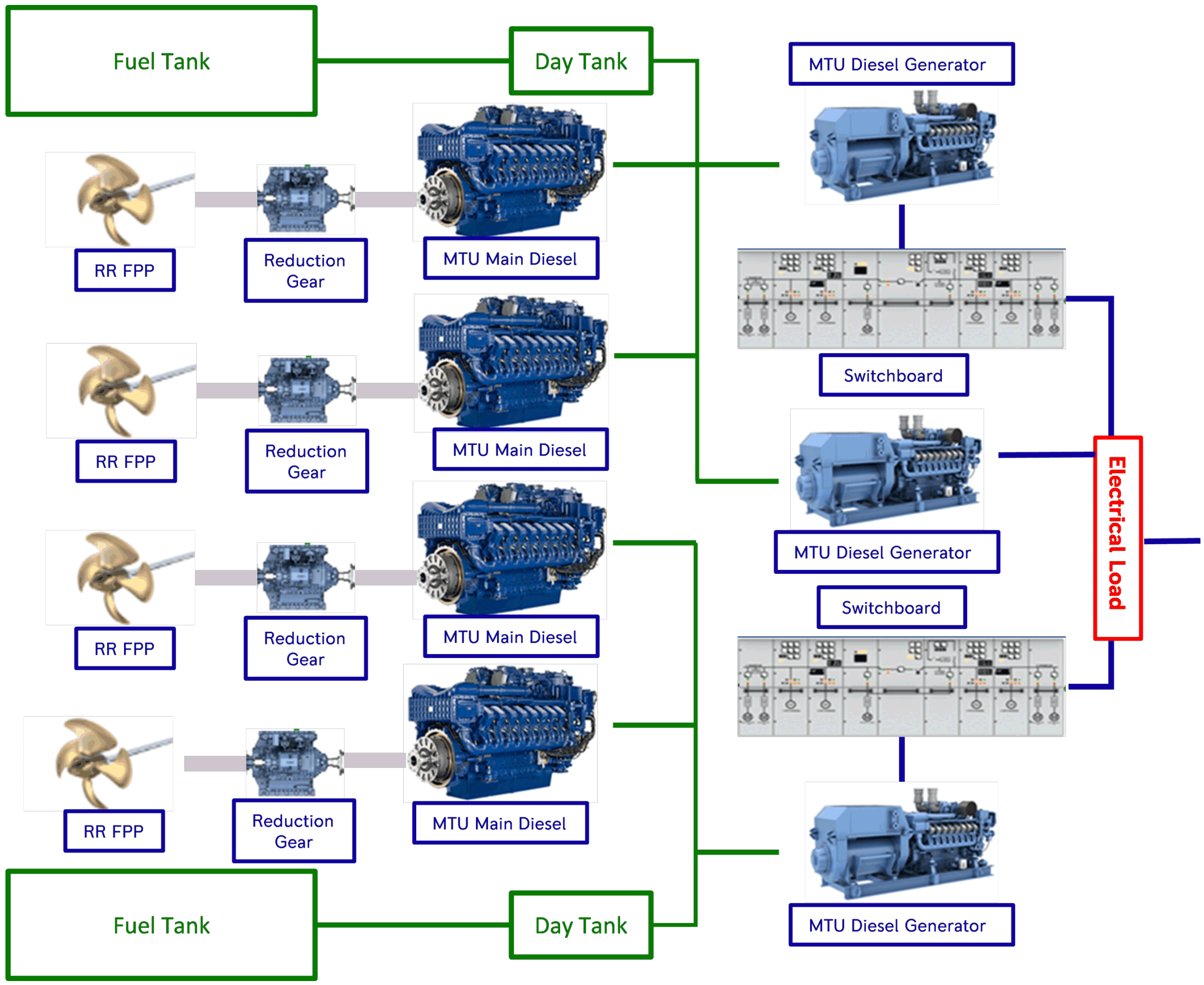

Figure 2. Conceptual USV Power and Propulsion System

ArChEr Development

For DI1, RRNA completed three development phases. The illustration in Figure 3 represents these three phases and the key characteristics of each. Phase 1 was concept development, Phase 2 was desktop modeling and simulation, and Phase 3 was a control hardware-in-the-loop (HIL) demonstration. The focus of Phase 1 was to use Model-Based Systems Engineering (MBSE) to capture, define, and analyze requirements as well as to define the rules-based functionality of the ArChEr algorithm. For the ArChEr project a SysML model was developed to facilitate the MBSE process.

The SysML model was used to drive the development of the ArChEr algorithm. This algorithm was developed as a MATLAB®/Simulink® model and was the focus of Phase 2 and Phase 3 development work, Figure 3. Phase 2 was a desktop simulation that culminated in Demonstration 0 and Phase 3 was a control Hardware-In-the-Loop (HIL) demonstration that culminated in Demonstration 1. The control hardware in the loop for Demonstration 1 was a ruggedized computer hosting the ArChEr algorithm. This computer is capable of being deployed on a vessel for future demonstrations. Both Demonstration 0 and 1 used Simulink models that were developed by the ArChEr development team to enable ArChEr algorithm development. The objectives for this development work were as follows:

1. Mature dual-use ArChEr technology
2. Prove RRNA capability via showing ArChEr functionality to perspective customers and industry partners

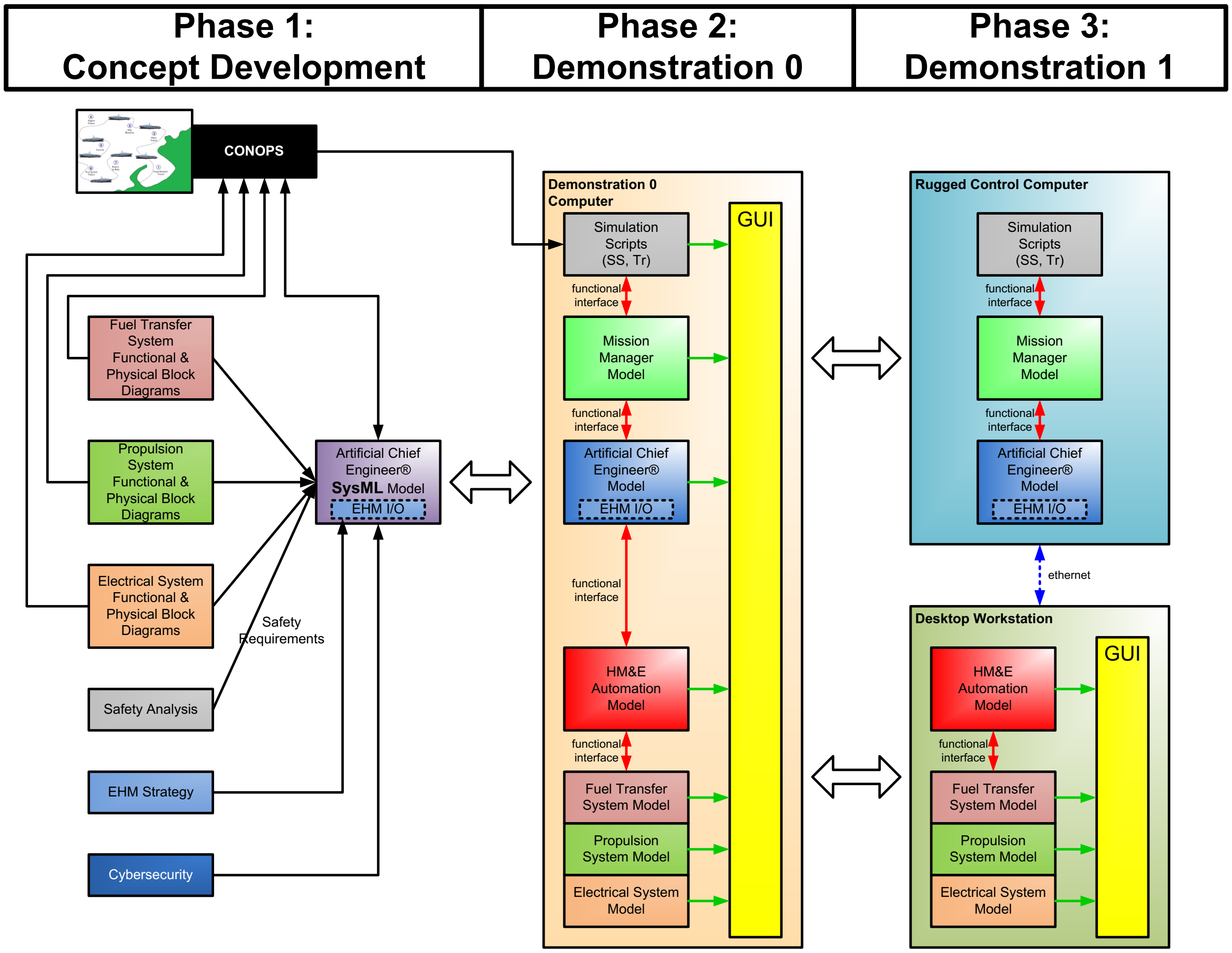

Figure 3. Artificial Chief Engineer Design Iteration 1 (DI1) Development Overview

3. Capture key intellectual property of dual-use ArChEr technology
4. Identify major roadblocks and risks for TRL 6 ArChEr and future ArChEr products

The purpose of this paper is to present the development of the ArChEr algorithm, models, Demonstration 0, and Demonstration 1 towards achieving the objectives listed above. The general arrangements of the models will be discussed, the basic functionality of the ArChEr algorithm will be presented, and simulation results will be shown to demonstrate proper functionality. This report is organized to flow according to Figure 3. Following the Introduction, Phase 2 (Demonstration 0) will be discussed then Phase 3 (Demonstration 1) will be discussed. Phase 1 (Concept Development) is not discussed in this paper.

Phase 2 Development

As described by Figure 3, Phase 2 was a desktop simulation comprised of Simulink models for the mission management module, HM&E automation module, propulsion system, electrical system, and fuel transfer system, as well as the ArChEr algorithm. These models were integrated to form a single model representation of ArChEr and its system context. Simulation scripts capturing the modes and behaviors of the concepts of operation (CONOPS) were created and used to define simulations. These simulations were used to tune ArChEr functionality and demonstrate its initial capabilities.

ArChEr Integrated Simulink Model Overview

The Simulink plant model developed during Phase 2 consists of models representing the mission manager, the ArChEr algorithm, HM&E automation, propulsion, electrical and fuel systems. Descriptions of the main signals in the integrated ArChEr model are listed in Table 1.

The propulsion model is a generic model which includes equations of motion, ship resistance and thrust calculations. It also includes a typical propulsion control system which was adapted to incorporate a ship speed controller. The electrical model uses Simscape models for bus ties and circuit breakers along with Simulink models for the generators and loads. The generators are

Table 1. Description of the Main Signals in the ArChEr Demo 1 Integrated Model

Description	From	To
Propulsion Engine Start /Stop Commands	ArChEr Software	Propulsion System
Generator On/Off Commands	ArChEr Software	Electric Power System
Fuel System Pump On/Off Commands	ArChEr Software	HM&E automation /Fuel System
Fuel System Valve Open/Close Commands	ArChEr Software	HM&E automation /Fuel System
Fuel System Tank Volumes	Fuel System	HM&E automation /ArChEr Software
Fuel System Tank High/Low Signals	Fuel System	HM&E automation /ArChEr Software
Fuel System Filter Plugged State		Fuel System
Ship Speed Command	Propulsion Inputs	Propulsion System
Engine Fault	Propulsion Inputs	Propulsion System
Generator Fault	Electric Power System/Commands	Electric Power System/Generators
Fuel System Pump/Valve Faults		Fuel System
Propulsion Engine Fuel Flow	Propulsion System	Fuel System
Genset Engine Fuel Flow	Electric Power System	Fuel System
Engine States (On/Off, Faulted)	Propulsion System	ArChEr Software
Generator States (On/Off, Faulted)	Electric Power System	ArChEr Software
Fuel System Pump/Valve States (On/Off, Faulted)	HM&E automation /Fuel System	ArChEr Software
Operating Profiles Available (Sprint Capable etc.)	ArChEr Software	Mission Manager
Operating Profile Change Request	ArChEr Software	Mission Manager
Vignette (Operating Profile) Selected	Mission Manager	ArChEr Software
Generator Health Scores		ArChEr Software
Generator Remaining Useful Life		ArChEr Software
Propulsion Engine Health Scores		ArChEr Software

functional equivalents, which are controlled using voltage-controlled voltage sources. The electrical model uses a DC system to represent the power drawn by the actual system which is AC. Most of the electric power system is not modelled beyond the main generators and three load banks. The fuel system model consists of simplified functional equivalents for valves and pumps. Net flowrate in and out of the fuel tanks is integrated to obtain a result for the volume of fuel in each tank. The fuel system pumps and valves, the propulsion engines and genset engines respond to on/off commands from the ArChEr algorithm. Simulated sensor information is sent back to the ArChEr algorithm. Sensors are modelled as perfect except for time delays. The HM&E automation system is modelled at a high level for the fuel system only. The HM&E automation model consists of pass-throughs and time delays.

The three main systems function independently except that the fuel system day tank outflows are based on the fuel flows calculated by the propulsion and genset engine models. Electrical load power is scheduled in the input script. Electric power usage of components in the fuel and propulsion systems, such as fuel transfer pumps or electronic engine control is not tracked or accounted for. Simulations are initialized and executed with a Matlab script. All significant events such as propulsion, electrical and fuel system faults, as well as the ship speed command are scheduled in the run script, which also sets the search paths and runs separate scripts to set up the propulsion, electrical, and ArChEr models.

Mission Manager Simulink Model Overview

The mission manager provides ArChEr the mission orders. It provides ArChEr insight to the mission plan in the form of an operational mode, a requested operational profile, a requested ship speed, and a heading. The mission manager can be a computer input plan or it can be a human input plan. It sends a requested operating mode and operating profile value to ArChEr in the form of integers. Table 2 identifies the operating mode with an operating mode value. Table 3 identifies the operating profile with an operating profile value.

Table 2. Operational Mode List

Mission Manager Operational Mode	Operational Mode Value
Basic Operations	0
Restricted	1
Survival	2

Table 3. Operating Profile List

Mission Manager Operating Profile	Operating Profile Value
Sprint	1
Stationing High	2
Stationing Medium	3
Stationing Low	4
Transit – Normal	5
Transit – Limited	6
Loiter – Low	7
Loiter – Drift	8

The mission manager is simulated by sending an initialized mission plan. In the event that ArChEr cannot meet the mission plan due to failure, ArChEr will provide operational availability to the mission manager. The mission manager responds by accepting ArChEr recommendations and passing forward the minimum operating profile value available, i.e. 1 being the lowest, and 8 being the highest.

ArChEr Simulink Model Overview

For the Propulsion and Electric systems, ArChEr places priority on meeting the request from the mission manager. Assessing the operational mode, operational profile, and engine health ranking score, ArChEr selects the best engines and generators available to meet the needs of the mission plan. In the event that the operational profile cannot be met by either the propulsion or electrical configuration, ArChEr will send a request for a new mission with what operational profiles are available within the operational mode. Table 4 describes the ArChEr operating profile capabilities. ArChEr decision capabilities are managed within the three operational modes. Each operational mode contains specific decision-making for each of the eight operating profiles shown in Table 4. These modes are Basic, Restricted, and Survival operational modes and will be discussed next.

Table 4. ArChEr Operating Profile Requirements

Operating Profile	Operating Profile Value	Required Number of MPDEs To Meet Operating Profile	Required Number of DGs To Meet Operating Profile
Sprint	1	4	1
Stationing High	2	4	2
Stationing Medium	3	3	2
Stationing Low	4	1	2
Transit – Normal	5	1	1
Transit – Limited	6	4 (*limited with 2 & 3, incapable 0 & 1*)	2
Loiter Low	7	1	1
Loiter Drift	8	0	1

ArChEr Basic Operational Mode

In the event that ArChEr is in basic operational mode, the priority is given to maintaining propulsion engines online and minimum necessary generators online with an available backup online. All four engines are expected to be online, conserving fuel by reducing drag. In the event that a propulsion engine is lost, ArChEr verifies it can still meet the minimum mission requirements with the available equipment that is online. Table 5 describes the ArChEr decision-making when it receives an operational profile request from the mission manager when Basic operational mode is active. In the event that equipment goes down, ArChEr follows the Operating Profile capability as described in Table 5. In the event that multiple generators are needed, ArChEr will turn on the minimum number of generators required and one backup. Generators are selected based upon the healthiest generator EHM score.

ArChEr Restricted Operational Mode

In the event that ArChEr is in restricted operational mode, the priority is given to the minimal operation of equipment required to meet the mission plan. Table 6 describes the ArChEr decision-making when it receives an operational profile request from the mission manager when Restricted operational mode is active.

In the event that multiple engines are required, preferred and partner engines are selected for ship stability purposes. In Demonstration 1, Engine 1 and Engine 4 are preferred partner engines. Engine 2 and Engine 3 are preferred partner engines. The engine with the best EHM health score is selected and its partner engine is selected. In the event that the preferred partner engine is not available, ArChEr will choose the other partnership. If an engine is not available from either partnership, then backup partner of each engine is selected.

In the event that multiple generators are needed, ArChEr will turn on the minimum of generators required, and does not keep on any more generators than the minimum required. Generators are selected based upon the healthiest generator EHM score. A backup generator is not online in restricted mode.

ArChEr Survival Operational Mode

In the event that ArChEr is in Survival operational mode, the priority is given to full capability of the vessel, regardless of mission manager requests. All propulsion engines and all generators are online and made available for the mission plan. Table 7 describes the ArChEr decision-making when it receives an operational profile request from the mission manager when Survival operational mode is active. In the event that equipment goes down, ArChEr follows the Operating Profile capability as described in Table 7.

Table 5. Basic Operational Mode

Operating Profile	Operating Mode	If Engines Available, Min Engines Online	If Generators Available, Min Gen Online (Backup Included)
Sprint	Basic	4 x MPDE on-line	Any 2 of 3 DG Min. required
Stationing High	Basic	4 x MPDE on-line	Any 3 of 3 DG Min. required
Stationing Medium	Basic	4 x MPDE on-line	Any 3 of 3 DG Min. required
Stationing Low	Basic	4 x MPDE on-line	Any 3 of 3 DG Min. required
Transit – Normal	Basic	4 x MPDE on-line	Any 2 of 3 DG Min. required
Transit – Limited	Basic	4 x MPDE on-line	Any 2 of 3 DG required
Loiter Low	Basic	1 x MPDE on-line	Any 2 of 3 DG required
Loiter Drift	Basic	0 x MPDE on-line	Any 2 of 3 DG required

Table 6. Restricted Operational Mode

Operating Profile	Operating Mode	If Engines Available, Min Engines Online	If Generators Available, Min Gen Online
Sprint and Stationing Medium	Restricted	3 x MPDE on-line	Any 2 of 3 DG required
Stationing Low	Restricted	2 x MPDE on-line	Any 2 of 3 DG required
Transit – Normal	Restricted	2 x MPDE on-line	Any 1 of 3 DG required
Transit – Limited	Restricted	4 x MPDE on-line	Any 2 of 3 DG required
Loiter Low	Restricted	1 x MPDE on-line	Any 1 of 3 DG required

Table 7. Survival Operational Mode

Operating Profile	Operating Mode	If Engines Available, Min Engines Online	If Generators Available, Min Gen Online
Sprint	Survival	4 x MPDE on-line	Any 1 of 3 DG Min. required
Stationing High	Survival	4 x MPDE on-line	Any 2 of 3 DG Min. required
Stationing Medium	Survival	3 x MPDE on-line	Any 2 of 3 DG Min. required
Stationing Low	Survival	1 x MPDE on-line	Any 2 of 3 DG Min. required
Transit – Normal	Survival	1 x MPDE on-line	Any 1 of 3 DG Min. required
Transit – Limited	Survival	4 x MPDE on-line	Any 2 of 3 DG required
Loiter Low	Survival	1 x MPDE on-line	Any 1 of 3 DG required
Loiter Drift	Survival	0 x MPDE on-line	Any 1 of 3 DG required

Rolls-Royce Demonstration 0 Graphical User Interface (GUI)

A Graphical User Interface (GUI) was developed and used to demonstrate the operation of ArChEr. This GUI is shown in Figure 4. Multiple sequential vignettes or CONOPS compounded with failure modes were simulated. The underlying behaviors resulting from the CONOPS and failure scenarios are outputs from the ArChEr integrated Simulink model discussed previously. A set of data was captured from simulations using this model and used to drive animated features of the GUI. The GUI vignettes described showcase the following 3 USV power and propulsion functions:

- Ship Propulsion
- Electrical Power Generation
- Fuel Delivery System

These vignettes and simulations were used to tune ArChEr functionality and demonstrate its initial capabilities prior to Hardware-In-the Loop (HIL) testing in Phase 3.

Phase 3 Development

When Phase 2 development was complete, the RRNA team focused on Phase 3 development. As described by Figure 3, Phase 3 culminated in Demonstration 1 which was a control Hardware-In-the-Loop (HIL) demonstration.

Hardware-in-the-Loop Setup

The setup for Demonstration 1 is implied within Figure 3 under "Phase 3: Demonstration 1". For this demonstration, the ArChEr algorithm model and mission manager model developed in Phase 2 were implemented on a rugged control computer with an i7 quad core CPU. This computer was set up with the Windows 10

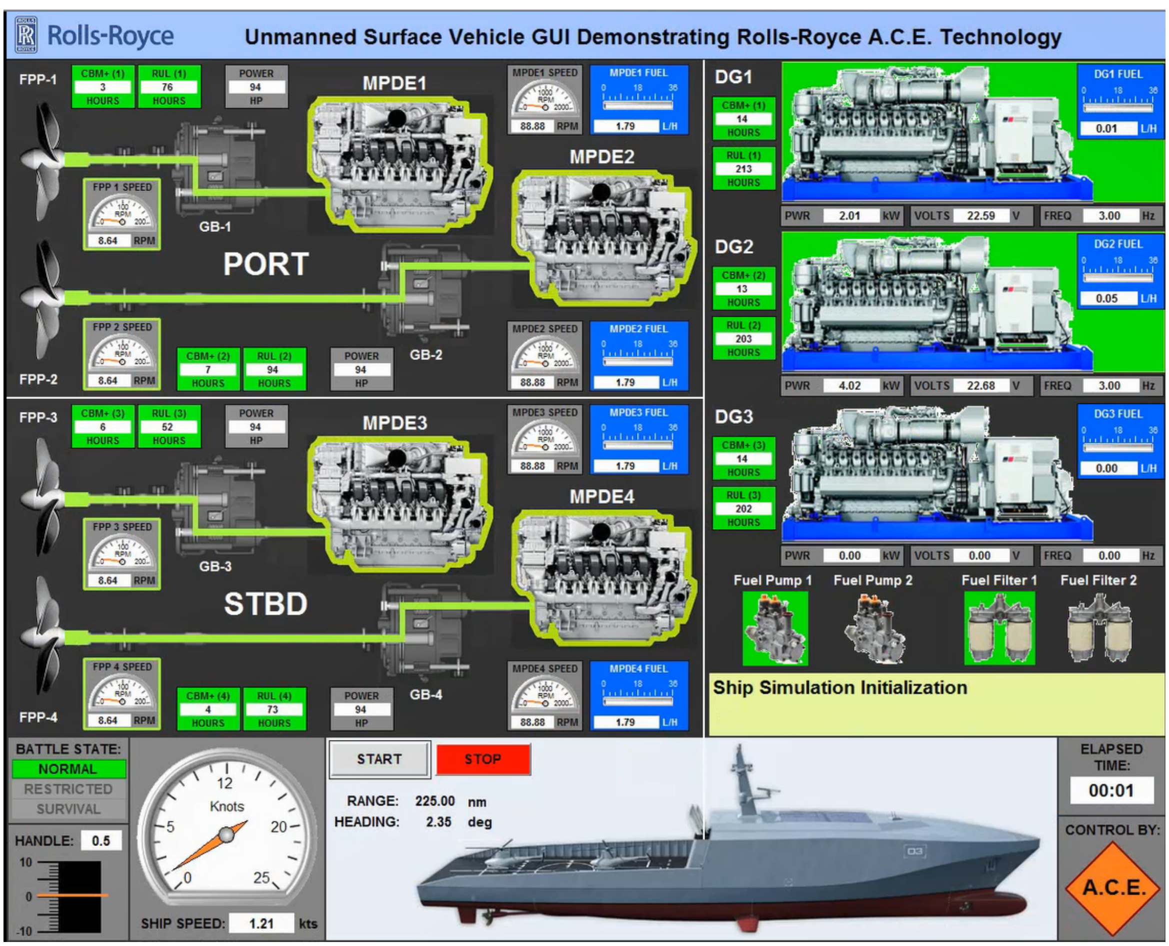

Figure 4. Rolls-Royce Demonstration 0 Graphical User Interface (GUI) with Operation Description

operating system and MATLAB®/Simulink® with Simulink Desktop Real-Time™. Both models were run as real-time applications on this computer via Simulink Desktop Real-Time. A workstation computer was also set up to run real-time Simulink models of the HM&E automation module, propulsion system, electrical system, and fuel transfer system. These models were also developed in Phase 2. Similar to the rugged computer, this workstation used an i7 quad core CPU and was set up with the Windows 10 operating system and MATLAB®/Simulink® with Simulink Desktop Real-Time™. All of the aforementioned models were run on this workstation as real-time applications via Simulink Desktop Real-Time.

The rugged computer and the workstation computer used Simulink Desktop Real-Time to communicate via UDP communication protocol over TCP/IP through a network switch.

Demonstration 1 Simulated Vignettes & Results

For Demonstration 1, ArChEr was tested against 8 vignettes designed to demonstrate ArChEr capability to make the appropriate configuration decisions given the environmental state. Each vignette was programmed in the models with changes occurring every 5 minutes. Results for each vignette are discussed below and summarized in Table 8.

Vignette 1 Test: Sprint and a Plugged Fuel Filter

The mission manager sends ArChEr a request to configure for a Basic operational mode and a Sprint operating profile. During this event, a fuel filter becomes plugged and flow is diverted to the second fuel filter.

Vignette 1 Result: Sprint and a Plugged Fuel Filter

The mission manager is initialized and sends ArChEr an operational mode value of 0 (Basic) and operating profile value of 1 (Sprint). ArChEr checks the day tanks and performs a day tank fill. The filter is plugged, so the differential pressure valve is opened and fuel flow to fill up the day tanks is diverted to the second fuel filter. ArChEr also configures for a sprint scenario, commanding all 4 engines on and Generators 1 and 3, as those 2 generators have the better EHM score.

Vignette 2 Test: Sprint and Engine 1 Degraded

The mission manager remains in the Basic operational mode and at the Sprint operating profile. Engine 1 becomes degraded and should be taken offline to avoid engine failure. With this, ArChEr should be unable to meet the mission plan. As a result, ArChEr should send a status update and respond to a new mission manager request based on the current status.

Table 8. Summary of Demonstration 1 Results

Vignette	1	2	3	4	5	6	7	8
Operational Mode	0	0	2	2	2	0	0	0
Operating Profile	1	3	3 to 1	1	3	3	5	5
Engine 1	Start	Stop	Stop to Start	Start	Stop	Stop	Stop	Stop
Engine 2	Start	Start	Start	Start	Start	Start	Start	Stop
Engine 3	Start	Start	Start	Start	Start	Start	Start	Stop
Engine 4	Start	Start	Start	Start	Start	Start	Start	Start
Generator 1	Start	Start	Stop	Stop	Stop	Stop	Stop	Stop
Generator 2	Stop	Stop	Start	Start	Start	Start	Stop	Stop
Generator 3	Start	Start	Start	Start	Start	Start	Start	Start

Vignette 2 Result: Sprint and Engine 1 Degraded

When Engine 1 is considered inoperable due to degradation, ArChEr keeps the available engines and generators running, sends a status update, and a request for mission update. ArChEr informs the mission manager that the minimum mission ArChEr can meet is the Stationing Medium operating profile (operating profile value 3). The mission manager responds by sending an operating profile value of 3 to ArChEr. ArChEr responds by accepting the mission manager request, configuring to command the degraded engine to stop, and configuring to turn on all three generators to meet the request for the Stationing Medium operating profile from the mission manager.

Vignette 3 Test: Survival Mode Initiated

The mission manager remains in Basic operational mode and at the Stationing Medium operating profile. The mission manager changes the operational mode to Survival and then changes the mission operating profile to Sprint. Once available, ArChEr should configure Engine 1 to come online and run at the Sprint operating profile.

Vignette 3 Result: Survival Mode Initiated

The mission manager changes the operational mode from Basic to Survival. The mission manager continues to give an operating profile value of 3, which is Stationing Medium. Once Engine 1 operation becomes valid, ArChEr sends the command to bring the engine online, and updates the mission manager that Engine 1 is available. The mission manager changes the operating profile to Sprint, and ArChEr maintains the engine configuration and provides the mission manager with system capability.

Vignette 4 Test: Generator 1 Failure

Generator 1 sustains damage and fails. The mission manager maintains the Survival operational mode and the Sprint operating profile. ArChEr should receive the generator failure, and keep all available engines and generators running. ArChEr should identify the mission can still be maintained, and bring down Generator 1, while maintaining the mission.

Vignette 4 Result: Generator 1 Failure

Generator 1 fails. The mission manager still sends the operational mode value of 2 (Survival) and the operating profile value of 1 (Sprint). ArChEr identifies the failure, and sends the stop command to Generator 1. ArChEr keeps the other generators and engines running, and updates the mission manager that the current configuration can still maintain the mission.

Vignette 5 Test: In Survival Mode, Engine 1 Failure and Operating Profile Reduced to High Stationing

The mission manager remains in the Survival operational mode and at the Sprint operating profile. Engine 1 fails. ArChEr is unable to meet the mission plan. ArChEr should send a status update and respond to a new mission manager request based on the current status and operational mode.

Vignette 5 Result: In Survival Mode, Engine 1 Failure and Operating Profile Reduced to High Stationing

When Engine 1 is considered inoperable due to degradation, ArChEr keeps the other available engines and generators running, sends a status update, and a request for mission update. ArChEr informs the mission manager that the minimum mission ArChEr can meet is the Stationing Medium operating profile (operating profile value 3) in the Survival operational mode. The mission manager responds by sending an operating profile value of 3 to ArChEr. ArChEr responds by accepting the mission manager request, configuring to command the failed engine to stop, and configuring to turn on all three generators to meet the request for the Stationing Medium operating profile from the mission manager.

Vignette 6 Test: Operating Mode returned to Basic Operations

The mission manager changes the operational mode to Basic but maintains the operating profile value of 3 (Stationing Medium). ArChEr should keep the available generators and engines running, and should not request any update because it is able to meet the mission.

Vignette 6 Result: Operating Mode returned to Basic Operations

The mission manager changes the operational mode from Survival to Basic. The mission manager continues to give an operating profile value of 3, which is Stationing Medium. ArChEr keeps the available engines and generators running, as the requested configuration is able to meet the mission.

Vignette 7 Test: Generator 1 and Generator 2 Failure

Generator 1 is already failed. Generator 2 fails. The mission manager maintains the Basic operational mode and the Stationing Medium operating profile. ArChEr is provided the status of 2nd generator failure, and should keep all available engines and generators running. ArChEr is unable to meet the mission plan. ArChEr should send a status update and respond to a new mission manager request based on the current status.

Vignette 7 Result: Generator 1 and Generator 2 Failure

When the 2nd generator fails, ArChEr keeps the available engines and generators running, sends a status update, and a request for mission update. ArChEr informs the mission manager that the minimum mission ArChEr can meet is the Transit – Normal operating profile (operating profile value 5). The mission manager responds by sending an operating profile value of 5 to ArChEr. ArChEr responds by accepting the mission manager request, configuring to command the failed generators to stop, and configuring to keep the remaining available engines and generators running to meet the request for the Transit – Normal operating profile from the mission manager.

Vignette 8 Test: Engines 2 and 3 Failure

Engine 1 is already failed. Engines 2 and 3 have failed. The mission manager maintains the Basic operational mode and the Transit – Normal operating profile. ArChEr is provided the status of 2nd and 3rd engine failure. It should keep all available engines and generators running. ArChEr is still able to meet the Transit – Normal operating profile in the Basic operational mode.

Vignette 8 Result: Engines 2 and 3 Failure

When the 2nd and 3rd engines fail, ArChEr keeps the available engines and generators running. ArChEr can meet the Transit – Normal operating profile (operating profile value 5). ArChEr responds by sending stop commands to the failed equipment, and configures the plant to keep the remaining available engines and generators running to meet the request for the Transit – Normal operating profile from the mission manager.

Summary and Conclusions

This report describes the ArChEr development team's work to complete Phase 2 and Phase 3 of ArChEr Design Iteration 1. The primary objectives for this work were to mature the dual-use ArChEr technology and prove RRNA capability. In Phase 2, the ArChEr development team created Matlab/Simulink models for the mission management module, HM&E automation module, propulsion system, electrical system, fuel transfer system, and the ArChEr algorithm. These models were integrated together on a single computer to create the ArChEr integrated Simulink model. 8 vignettes including component failures were created based on USV CONOPS. These vignettes were used to exercise the integrated Simulink model, tune the response of the ArChEr algorithm and demonstrate proper functionality. A GUI was created and run with the simulation data to demonstrate the functionality of the ArChEr algorithm. This constituted Demonstration 0 and signaled completion of Phase 2.

Upon completion of Phase 2, the team pivoted fully to Phase 3 where the focus was to complete a HIL demonstration. For this demonstration, the hardware in the loop was a ruggedized computer used to run real-time applications of the ArChEr algorithm model and mission manager model. In the future, this device may be used to host ArChEr software and interface with real ship's systems or high fidelity representations to show that the technology is TRL 6. For DI1 Phase 3, this computer was interfaced with a desktop workstation that was running Matlab/Simulink models of the HM&E automation module, propulsion system, electrical system, and fuel transfer system. All models used in Phase 3 were taken from Phase 2 development where they were debugged and tuned in preparation for Phase 3. The vignettes developed and used during Phase 2 were also used in Phase 3. This work all culminated in Demonstration 1 where the capabilities of the ArChEr algorithm were showcased in a HIL demonstration. It was concluded that the performance of the ArChEr algorithm running on the HIL setup aligned properly with required functionality. Completion of Demonstration 1 also showcased the ability of the RRNA team to mature and demonstrate USV autonomy algorithms. The processes, models, tools, and lessons learned during DI1 have placed RRNA in an ideal position for continued development of the ArChEr technology and for applying this technology to other USV platforms.

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