MARITIME AUTONOMOUS SYSTEM DESIGN METHODS AND TECHNOLOGY FORECASTING

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ABSTRACT

As naval architects consider the construction of long-term autonomous maritime systems, the naval design process will be modified. The incorporation of reliability analysis in conceptual design is needed to enable systems incapable of in-theater maintenance. The use of reliability analysis is demonstrated with notional architecture, redundancy, and component requirement trades.

KEY WORDS
Autonomous systems; Conceptual Design; Reliability; Redundancy

INTRODUCTION

Long-term autonomous maritime systems are of considerable interest to many organizations. The increasing need for extensive distribution of naval capabilities with tactical agility has conceived the idea of long-term autonomous or unmanned systems which can perform with increased range and endurance in critical operations and uninhabitable environments for extended periods of time (Department of the Navy). Long term navigational capabilities of autonomous vehicles are affected by the prevailing uncertainties in the marine environment, with primary sources of uncertainties including motion uncertainty stemming from noise affecting system dynamics, sensing uncertainty arising from noisy sensor measurements, and environmental uncertainty resulting from uncertain obstacle locations. The surface vessel needs to avoid collision and maintain the defined course under the motion, sensing, and environmental uncertainties (RedwanNewaz et al.). Dull or dangerous missions such as denied area intelligence, surveillance, and reconnaissance (ISR) are the primary potential candidates for autonomous missions. ISR missions are conducted to improve security, safety, and operational capabilities in uncontested waters with uncertain physical layouts and traffic densities. Unmanned surface vessels can get closer to potential targets and yield greater volumes of environmental data while staying longer in dynamic environments, allowing for intelligence to be gathered without compromising human lives and mission.

A prime example of modern unmanned surface vehicles, the Sea Hunter, was developed in partnership between the Defense Advanced Research Projects Agency (DARPA) and the Office of Naval Research (ONR). Following a design process focused on the retrofitting of existing crewed ships, the Sea Hunter still features a prominently visible bridge. In design operation, the operator control station within the bridge is unused, except as a safety and backup feature should the autonomous systems fail. Onboard computers are the real drivers and controllers of the ship, with humans observing remotely and taking charge when needed only. This allows the vessel to navigate and perform patrols absolutely independently. With the addition of more advanced autonomy, the Sea Hunter could further be assigned more intricate tasks including offensive capabilities. In its current form, the Sea Hunter has a projected endurance of 60 to 90 days with a range of around 10,000 nm. Moreover, it has demonstrated groundbreaking capability for autonomous navigation during a 10-day mission between San Diego and Pearl Harbor using a sparse remote supervisory control model. The Sea Hunter was tasked with, and successfully performed the voyage with no human intervention for navigational purposes. However, while it was able to achieve this goal without an issue, obeying all seafaring regulations along the way, the Sea Hunter still needed to be boarded three times. Human operators performed repairs twice on the onboard generator and once on the engine with mechanical issues. The complete success of the Sea Hunter's autonomous navigation compared to the repeated mechanical issues demonstrates the failure of the traditional ship design process to capture the necessary reliability standards for fully autonomous systems. Hence, making reliability as the primary issue encountered in the Sea Hunter as a deployable asset (Eckstein, 2019).

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The elimination of human constraints in the design of unmanned surface vessels (USVs) offers unique opportunities to maximize performance and expand the potential mission set. However, achieving adequate endurance for a vessel incapable of in-theater maintenance poses a significant challenge (DARPA). Due to the crew availability for the repairing and maintenance process, reliability is not recognized as one of the decisive parameters in traditional ship designing process. Failure to consider reliability in the design methodology for autonomous systems such as the Sea Hunter, fundamentally limit the design of unmanned platforms and necessitate an expansion of the naval ship design process to include methodologies for satisfying long-term autonomous requirements through reliability. Design life of the system and reliability are the two attributes greatly impact the performance of the system over its lifecycle (Colombi 2017). Thus, inclusion of reliability as a conceptual design discipline would enable exploration of key design tradeoffs unique to USVs. In this paper, reliability analysis is introduced and demonstrated to perform notional tradeoffs. This process begins with developing a set of mission requirements to produce a target endurance for the system. Next, reliability is quantified as a probability of survival at the end of the mission duration. Increased reliability reduces loss rates while increasing the development and acquisition costs. Reliability data can be acquired during system development and testing or via historical data; using this data the reliability of new systems can be estimated using several design techniques such as fault tree analysis (FTA). In this paper, reliability analysis consists of modeling components with a two parameter Weibull distribution based on historical data and building up component reliability to system reliability using Fault Tree Analysis.

AUTONOMOUS NAVAL DESIGN

When investigating a ground-up design process for autonomous vessels, the largest change is the removal of the crew which flows down to affect many of the requirements and design disciplines. These disciplinary adjustments can be best defined through analyzing the traditional naval design process. Wolfe (2000) presents a sizing and synthesis process for naval vessels, shown in Figure 1. The manning section would be removed completely. The weight, area, and volume determination must be adjusted for the absence of quarters, galley, and storage for rations. The volume allotment for passageways can also be reduced while still allowing for maintenance. This can be further reduced by the inclusion of access panels or removable compartments depending on the size of the vessel and maintenance plan. The stability requirements used in seakeeping and maneuverability analysis would loosen or change with motion requirements since most of these requirements are set to minimize the disruption of crew operations. The cost estimations would also change significantly without the cost of crew support and wages. The accumulation of these changes could result in a lighter, more maneuverable ship, similar to the effects seen in unmanned aircraft. However, the removal of the crew leads to a maintenance detriment through the removal of near-constant maintenance operations.

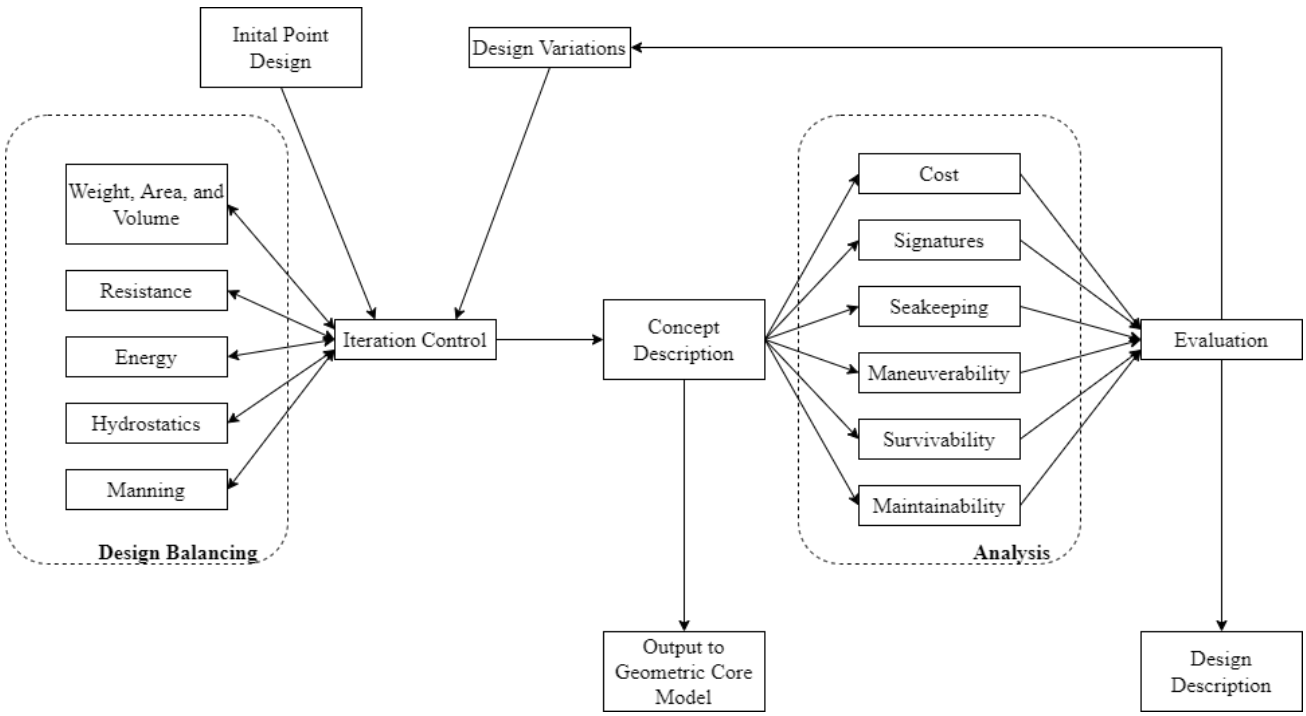

Figure 1: Traditional Naval Sizing Process (Wolfe, 2000)

Naval vessels have been built to maximize availability, or the percentage of time during a mission that the vessel is fully operational. This means that a frequent failure which is quickly, easily, and cheaply fixed would not be seen as a critical issue. Yet, when crew are removed, this repair cannot occur, leading to a paradigm shift from availability to reliability, or the chance that a component will fail. As mentioned, this issue was directly seen in the Anti-Submarine Warfare (ASW) Continuous Trail Unmanned Vessel (ACTUV) test voyage between San Diego and Pearl Harbor (Eckstein, 2019). The

vehicle was designed through a retrofitting technique where a previous design was adjusted and infused with technologies enabling autonomy. Since autonomous vessels would require long periods between routine maintenance and pose a significant capture risk from a critical failure during operations, a greater emphasis on reliability at the early stages of design is deemed necessary.

RELIABIABILITY INFUSED DESIGN PROCESS

After evaluating the potential changes to a naval design for an autonomous vessel, the reliability of the system was found to be the most significant gap in performance. Reliability is also the only disciplinary addition to the process. The other adjustments would rely on changes to correlation coefficients and other underlying assumptions of the core disciplines like volume or mass estimation. An iterative process is proposed in Figure 2 with the additions to the process shown in gray.

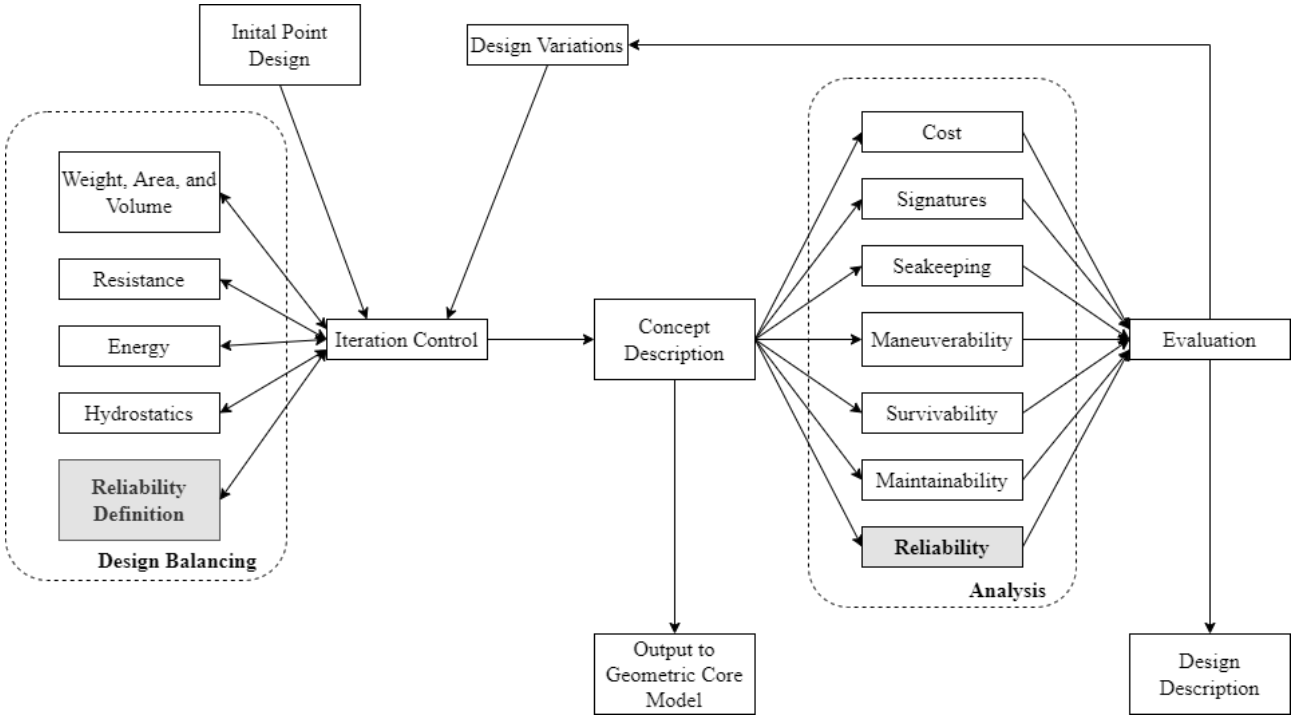

Figure 2: Proposed Design Process

The design balancing section is utilized to size the vessel's key parameters. The core naval processes were based on the process presented in Wolfe (2000). The addition to this process is the reliability definition block. This requires a method for defining component or subsystem reliabilities. This process is conducted until the calculated values match the initial design requirements. Once a configuration has been defined which meets the basic requirements, this configuration is evaluated based on mission performance.

In the proposed process, the vehicle must be analyzed over several operational domains. This requires a full definition of the target mission. Reliability is added as a proposed domain in this section. This area will be related to maintainability; however, it will focus on the length of time the vessel can go without maintenance. The maintainability analysis here will focus on ensuring space tolerances and access to key components for repair. The proposed mission analysis method requires the derivation of a reliability requirement from the mission duration and a methodology for system reliability evaluation. A fault tree analysis is presented for the latter. If the design is found to not meet the reliability requirement, the system configuration must be adjusted by changing the architecture to increase redundancy or by adjusting the component reliability levels. The final output of the process is a conceptual design represented by key parameters and an architecture of key components and subsystems. With the new analysis methods proposed in principle, a definition of the technical approach must be developed.

System Architecture Definition

Within the design balancing portion, an architecture definition activity is proposed. This allows the designer to determine how key components will be linked and if there are any redundancies within the system. The result would be a block diagram, potentially with associated load percentages if there is load sharing within the system. This process does not have to be conducted for every subsystem of the craft. Only the mission-critical subsystems need to be evaluated, and of those, only those which are deemed limiters are necessary. Additionally, there will be varying levels of detail in this section as a design matures.

At the conceptual level, which is the focus of this paper, the reliability definition should be used to establish general ranges of capability. At the preliminary design level, the authors see the details of the analysis increasing with a market study approach, where specific high-level values are requested from equipment manufacturers. Finally, at the contract design phase, reliability data for each component of the system would be defined and analyzed with consultation with the supplier. For conceptual design, an analogue can be drawn between this process and propulsion system design. While engine power outputs and fuel efficiencies are detailed parameters that require high levels of detail, a general range from the known performance of different classes of systems is selected at the conceptual level along with architecture decisions like the number of engines. A similar process for reliability is suggested since these limiting systems like propulsion will become the key drivers behind volume and mass with the removal of crew. Therefore, if a reliability decision in the late stages of design necessitates a change of architecture, a significant redesign could be required even including the geometry of the vessel. Therefore, the inclusion of a process with feedback from a system requirement tied to the mission requirements is necessary.

If the mission analysis results in insufficient reliability, this section of the design is where the most changes will be made. At first, different classes of components should be infused; however, if that is insufficient, the architecture will need to be adjusted as reliability is infused. The final potential change is a complete change of paradigm. For example, if no closing design can be found with a direct drive diesel engine, combined mechanical propulsion systems could be explored. Ultimately, this process is largely at the discretion of the designer if the result can be translated into a fault tree. If the designer does not have detail at the component level, working at the subsystem level is acceptable if reliability or failure information is well-defined for the subsystem of interest. It is suggested that key components such as generators or engines be modeled at the component level.

Reliability Definition Each component or subsystem will need a detailed reliability definition. This can be time variant or invariant. Time variant definitions are more accurate but require a more sophisticated distribution function. Weibull distributions are frequently used for this purpose. For the combination of reliability data, each component must be defined in the same space. Therefore, if the component reliability is defined by mean time to failure or a similar metric, then a conversion will need to be utilized.

Reliability Analysis

The suggestion of infusion of reliability analysis into architecture selection mandates a discussion of reliability analysis methods. While maritime systems have not traditionally conducted architecture or concept trades to meet reliability requirements, other design disciplines have been forced to address the issue. Reliability analysis methods can be categorized into two areas. Qualitative methods rely on subject matter experts to produce ranked lists of the most reliable architectures. As each additional concept requires a full subject matter expert evaluation, qualitative methods suffer scalability problems for performing architecture trades and will thus not be discussed in detail. The second type of reliability analyses are quantitative methods. Quantitative methods produce estimates of the system reliability based on component failure rates and/or historical data. Prior to a discussion of the various quantitative methods, it is important to discuss how reliability can be quantified. This paper will consider modeling reliability as a 2-parameter Weibull distribution. The 2-parameter Weibull distribution, shown below in Equation 1 is a common method for quantifying reliability in engineering systems (Pham 2006).

$$f(t;\beta,\eta) = \left(\frac{\beta}{\eta}\right)\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad [1]$$

The distribution, defined by two parameters: β (the shape parameter) and η (the scale parameter), allows calculation of a time varying failure density. The scale parameter tends to define the length of time it will take a component to become unreliable. The shape parameter defines how the failure rate, or the amount of failure per unit time, evolves over time. The failure rate function is shown below in Equation 2. For $\beta < 1$, the distribution represents infant mortality, or component wear-in, where the failure rate decreases over time. For $\beta > 1$, the distribution represents component wear-out, where the failure rate increases over time. For $\beta = 1$, the distribution represents a constant failure rate.

$$h(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \quad [2]$$

Integrating the failure density function to produce a cumulative distribution function, or CDF, allows calculation of the probability of the system failing by time t. This failure function is shown below in Equation 3. The survival function, or the probability that a component has not failed by time 't', can be simply determined as one minus the CDF and will be critical for evaluating the reliability of a system. The survival function is shown below in Equation 4.

$$F(t;\beta,\eta) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad [3]$$

$$R(t;\beta,\eta) = 1 - F(t;\beta,\eta) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad [4]$$

The expectation of the 2-parameter Weibull distribution is also commonly used when defining the reliability of systems (Pham 2006). The expectation of the distribution defines the component mean time between failure, or MTBF, and is shown below in Equation 5. The MTBF defines the average time it will take for a component to fail and can thus be determined from experimental data as simply the number of failures divided by uptime of the component. For cases

when the shape parameter is equal to zero, an evaluation of the gamma function produces one, meaning the MTBF is equal to the scale parameter for a 2-parameter Weibull distribution with a constant failure rate.

$$\text{MTBF} = \eta\Gamma\left(\frac{1}{\beta}+1\right) \quad [5]$$

Discussion of reliability analysis will now shift to methods for estimating system level reliability from component level Weibull distributions. There is a myriad of techniques available for quantitative reliability analysis including but not limited to reliability block diagrams, Markov processes, and stochastic Petri Nets (Ram 2019). This paper will demonstrate utilizing Fault Tree Analysis to perform the quantitative reliability analysis, a decision which will be discussed in detail below.

Fault Tree Analysis (FTA)

Fault Tree Analysis is one of the most popular reliability analysis techniques. Originally developed in 1962 for analysis of the Minuteman I Intercontinental Ballistic Missile Launch Control System, FTA models the top-level probability of a system as a function of the components (Ram 2019). FTA represents one of the many reliability techniques the space industry, which has a historic focus in reliability analysis, has used in the design process. The process begins by identifying a top-level characteristic of interest, in this case reliability, and the set of components which contribute to the top-level characteristic. The associated fault tree is a logical block diagram which is constructed to build up the reliability model from the component level. At the 'bottom' of the fault tree, component reliabilities act as inputs. Each subsequent level of the fault tree combines the lower-level reliabilities using Boolean algebra. Two notional logic gates are shown below; the AND gate requires all of the lower-level components to be functional, while the OR gate only requires one of the lower-level components to be functional.

$$\text{OR}(R(t)) = 1 - \prod_{i=0}^{n}(1 - R_i(t)) \quad [6]$$

$$\text{AND}(R(t)) = \prod_{i=0}^{n} R_i(t) \quad [7]$$

Leveraging the AND and OR gates, it becomes relatively simple to construct a fault tree. A notional fault tree containing six components is included in Figure 3 below. All components, items for which a 2-parameter Weibull distribution must be defined, are highlighted in gray. The fault tree defines subsystem one as requiring both components A and B to be functional, while subsystem two only requires one of components C, D, and E to be functional. The notional fault tree also shows that the system as a whole requires subsystems 1 and 2 as well as component F to be functional.

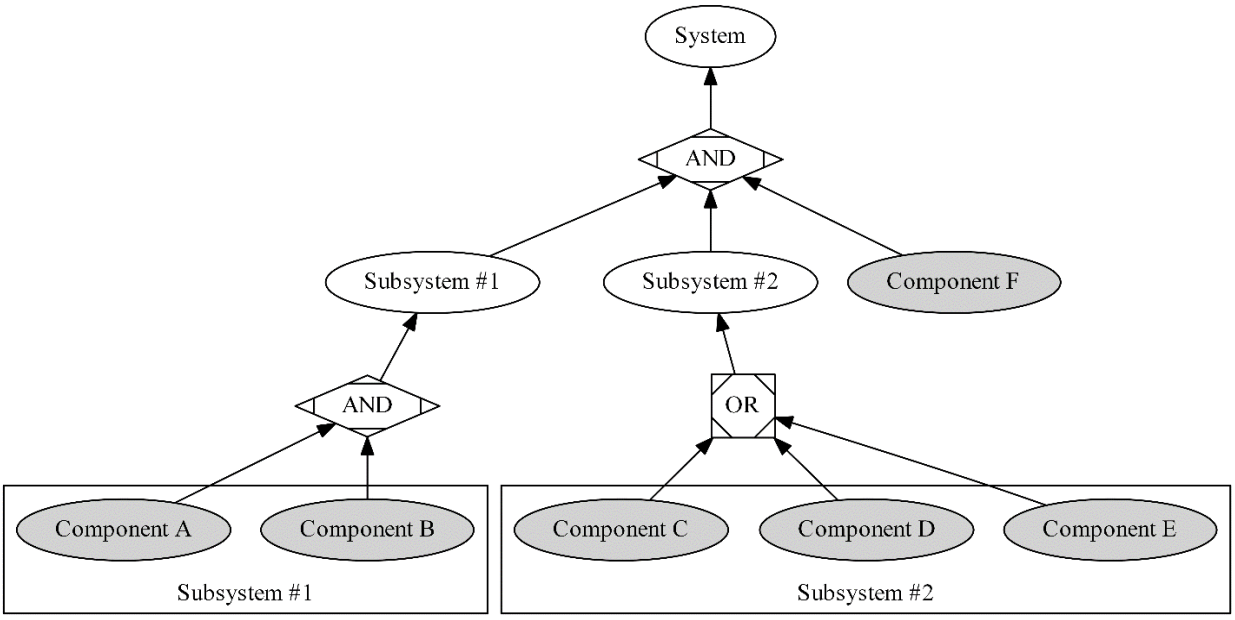

Figure 3: Notional Fault Tree Diagram

The total reliability of the system described in the notional fault tree diagram can be described by Equation 8. Note that a lettered subscript indicates the component a given reliability applies to, e.g., R_C describes the reliability of component C. As long as each component reliability can be calculated at a given point in time, the total system reliability can be determined at that point in time.

$$R(t) = (R_A R_B)\left(1 - (1 - R_C)(1 - R_D)(1 - R_E)\right)(R_F) \quad [8]$$

A number of assumptions are made when constructing the fault tree. The first is that component failures are independent. This assumption is tenuous and limits the applicability of fault trees to disciplines such as survivability or vulnerability where failures may originate from common causes. However, while survivability and vulnerability are similar disciplines

to reliability, the goal of this paper is to highlight changes in the design process to enable the design of autonomous vessels. In this case, FTA is appropriate due to the lack of concrete system definition in the conceptual design phase. In later design phases, when more information is available, more advanced reliability analysis techniques may be required to handle the dependence of component failure rates on the state of the other components. A suggested technique for modeling this is the Markov process, as is discussed in Ram 2019. The second assumption is that failures are binary, meaning that the system is either fully operable or completely inoperable. This assumption is also tenuous, as not all component failures result in complete mission failure. Instead, component failures are more likely to degrade the performance of the system, rather than rendering it inoperable. Once again, however, architecture trades occur during the conceptual design phase, when modeling degraded component and system performance is likely not feasible. Instead, it is recommended that the impact of system performance degradation is considered once an architecture has been selected and more information is available. Again, a Markov process is well suited for analyzing the system across multiple states.

Fault trees are not a novel method for analyzing the reliability of engineered systems; neither are they novel to maritime system analysis. The simplicity and flexibility of fault trees has made them one of the most used methods for reliability analysis; these characteristics are also what make fault trees well suited to performing architecture trades. Indeed, Krevor (2007) demonstrated the use of automatically generated fault trees to assist in architecture selection of space launch vehicles by linking cost and reliability. Similarly, this paper will discuss leveraging fault trees to assist in architecture selection of maritime systems. This paper will also demonstrate the use of fault tree analysis in assessing the need for redundancy as well as constructing component reliability requirements.

Reliability Requirement Derivation

To perform an evaluation of architecture, a requirement must be defined. This system analysis calls for two metrics of comparison: reliability at the end of a mission and the overall reliability requirement. The former is simpler to determine, but only applicable if time-variant reliability metrics have been defined for the system. The designer must set the acceptable risk of asset loss if the vessel had to extend its operations for a certain number of hours past the mission. This could be built off the availability requirements which are currently set for crewed vessels. In contrast, the overall reliability requirement should be set as a function of the mission time, but if the mean time between failures is designed to equal the mission time there is only a 37% chance that the asset would complete the mission. Therefore, a safety factor must be applied. When this safety factor (S.F.) is infused into the standard reliability equation (Eq.8), the mission time is reduced out leaving only the safety factor (Menčik, 2016). Further analysis of the failure conditions with time variance will allow for the intelligent selection of the safety factor value.

$$R = e^{-\frac{mission\ time}{S.F. \cdot MTBF}} = e^{-\frac{mission\ time}{S.F. \cdot mission\ time}} = e^{-\frac{1}{S.F.}} \quad [9]$$

DESIGN STUDY

Mission Definition

To capitalize on the advanced capability for autonomous navigation while testing improvement in reliability, an ISR mission was selected as a baseline for a vehicle designed with improved reliability considerations. In peacetime, the USV's primary mission would be pure ISR, detecting and identifying ship traffic and behavior within an assigned area, as well as collecting oceanographic data for additional monitoring of the operational environment. In wartime, such ISR missions would be continued with additional requirements for advanced situational awareness and decoy operations in support of human troops.

The USV would start from a forward operating base (FOB) and be assigned to a given area of responsibility (AOR) of a maximum 100x200 nm area. The USV should be able to autonomously deploy, perform its mission in the AOR, and reach a resupply point, ideally reaching a long-endurance goal of 180 days. An example mission profile can be seen in Figure 4 below.

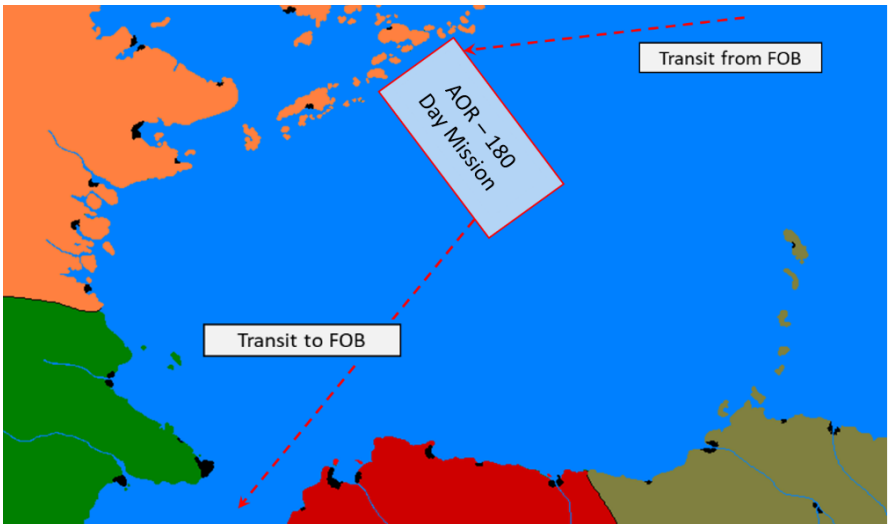

Figure 4: Notional transit operation OV-1

Throughout the mission, the USV needs to maintain communication with command to transmit data, request orders, and receive new tasks. In addition to the 180-day endurance requirement, the USV must also have a top speed of 12-15 knots. However, the USV is only expected to maintain this top speed 10% of its operational time. An average speed of 6-10 knots should be expected the majority (60%) of the time with the remaining 30% taken by an average speed of 0-5 knots. The USV needs to traverse the AOR under these requirements while identifying and reacting to environmental obstacles, as depicted in Figure 5 below.

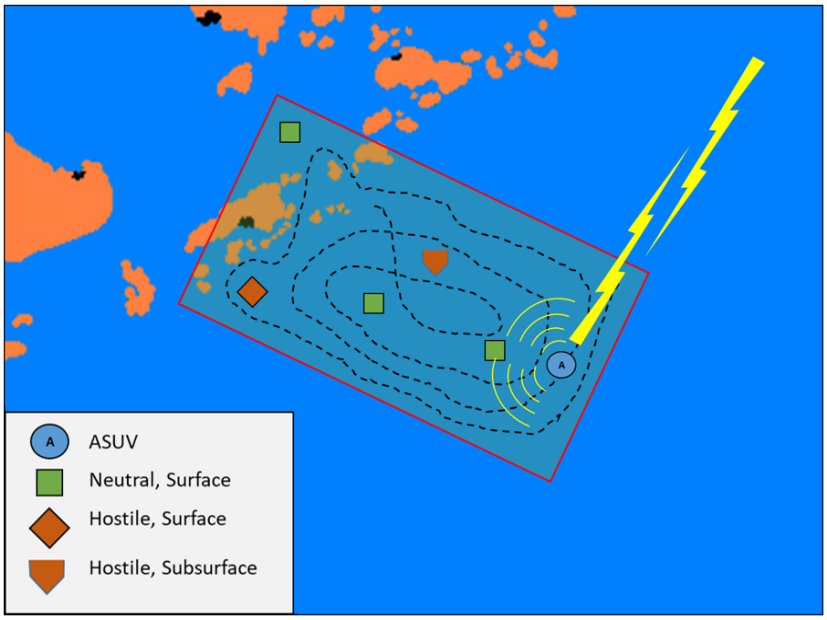

Figure 5: Notional AOR mission OV-1

Propulsion System Architecture

In order to conduct a thorough reliability analysis of an entire system it is important to start with the components and subsystems that have the largest impact on the overall reliability. According to a study conducted by Delft University, the five systems responsible for most fatal technical failures are the main engine, steering gear, fuel system, electrical system, and cooling water system with the main engine and propulsion systems being the root cause of the majority of those overall system failures as shown in the Figure 6. This is further supported by the discussion of Sea Hunter previously in the introduction. The limiting factor that caused the mission to fail was the fact that the engine and generators required mechanical intervention on three separate occasions.

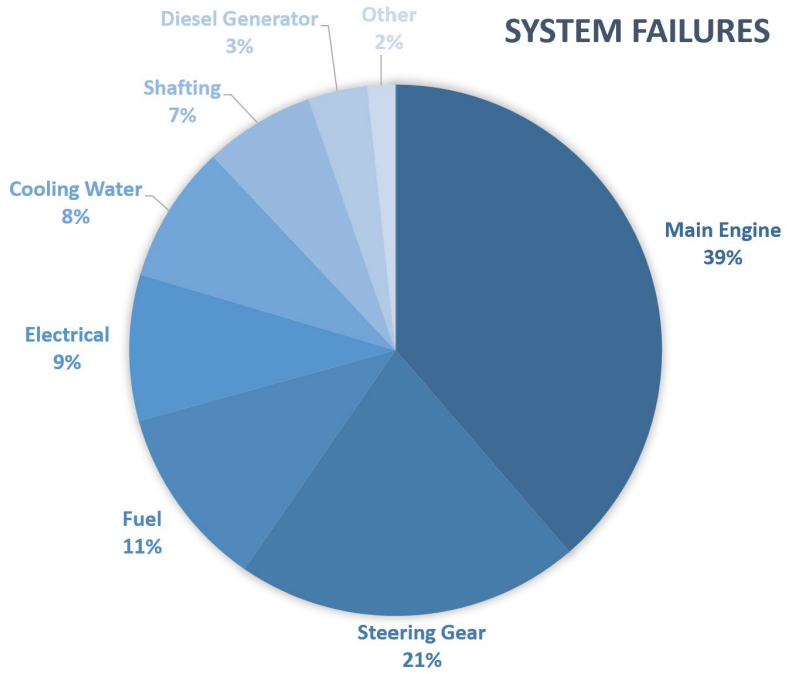

Figure 6: Ship subsystem failure rates (Delft University)

The propulsion system can be broken down into two different transmission types: mechanical drive and electrical drive. The mechanical drive consists of two engines (main and secondary) and a propeller/shafting system. The electrical drive consists of power conversion modules, main inverters, and main wire sizes in addition to the engines and propeller/shafting system. The propulsion can be directly tied to the zonal electrical distribution systems through an integrated power system (IPS). The power conversion modules shown in the Figure 7 act as the bridge to the ship service power in with the IPS.

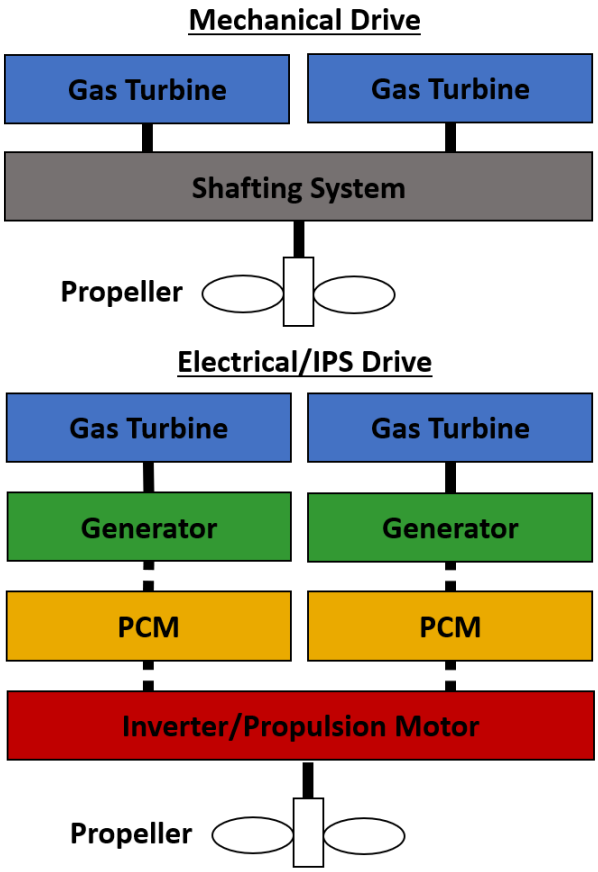

Figure 7: Mechanical and Electrical Drive Types

The ship service power can come from the power conversion modules with an integrated power system (electrical drive), or it can come from stand-alone generators (which is necessary with a mechanical drive). This is the general breakdown of the propulsion system architecture and the structure for component and subsystem reliability analysis with regard to this architecture.

In order to conduct analysis for the propulsion systems, a subset of propulsion architectures was chosen. This subset consists of a gas and diesel direct drive system, combined diesel and diesel (CODAD) system, combined gas or gas (COGOG) system, combined gas and gas (COGAG) system, combined diesel or gas (CODOG) system, combined diesel and gas (CODAG) system combined diesel electric and gas (CODLAG) system, and an integrated power system (IPS). The gas and diesel direct drive falls under the mechanical drive category and consists of a propeller, shaft, and engine. The CODAD system uses two diesel engines coupled with one propeller shaft which can offer weight and size advantages compared to a single engine. The COGOG system alternates between two gas turbine engines (one for lower speeds and one for higher speeds but they cannot be run at the same time. On the other hand, the COGAG system combines two gas turbine engines to increase fuel efficiency at cruise speeds. The CODOG system is similar to the COGOG system. However, instead of a second gas turbine for lower cruise speeds it uses a diesel engine instead. It still operates on the same principle of alternating between the two engines based on the given scenario. The CODAG system consists of two diesel engines that are used primarily for cruising and an extra gas turbine engine that can be switched on and combined with the diesel engines to achieve a much higher maximum speed. It is particularly common with modern frigates and corvettes. The CODLAG system is very similar to the CODAG system, but it also includes electric motors that are attached to the diesel engines and help contribute to the ship service power. This is a type of integrated power system. All of these propulsion systems are commonly used today and were included in the reliability analysis conducted below (Molland, 2011).

Fault Tree Generation for Propulsion Architectures

Following generation of propulsion architectures, fault trees were constructed to represent each architecture. A fault tree for a CODLAG system is shown below as an example. The fault tree demonstrates that the CODLAG system only fails when both the electrical drive and mechanical drive systems fail. The electrical drive system contains a voting gate to represent power generation where two of four diesel generators must be operating in order for the generator system to be active. The additional diesel generators and ability of this system to operate using electrical or mechanical drive demonstrates the redundancy described in the conceptual reliability section of this paper.

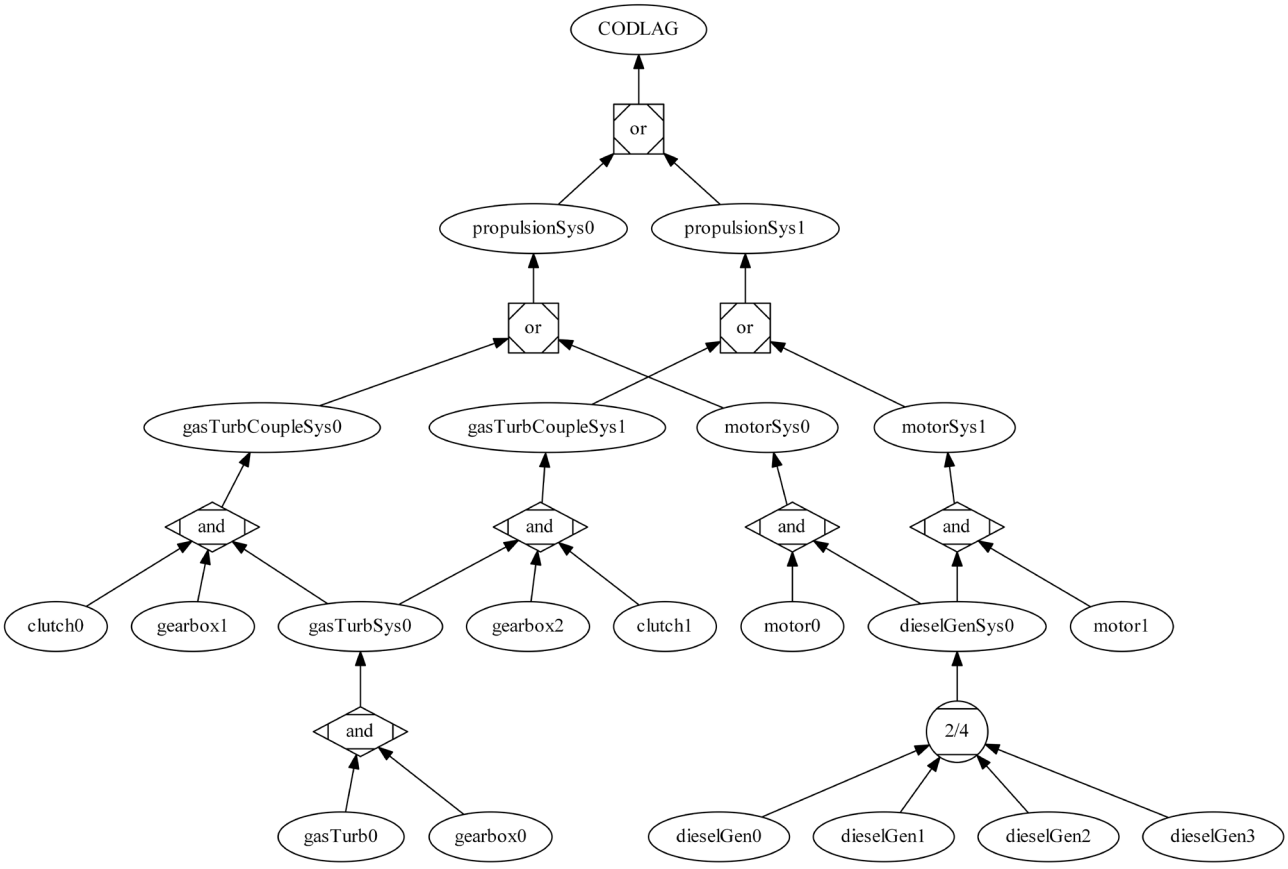

Figure 8: CODLAG Fault Tree Diagram

Each of the architectures discussed in the propulsion system architectures section, gas and diesel direct drive, CODAD, COGOG, COGAG, CODOG, CODAG, CODLAG, and IPS, are all analyzed.

Results

Architecture Trades

The reliability of each of the propulsion architectures is plotted as a function of time and shown below. The mission duration of 180 days with a 50% uptime of the propulsion system yields a 90 day, or 2160 hour, uptime which is shown as a dotted black line in the figure below. The most reliable systems at the mission duration are the IPS and CODLAG architectures. The high reliability of the IPS and CODLAG architectures is driven by the high amount of redundancy built into electric drive. The next group of propulsion architectures, COGAG, COGOG, direct drive gas turbine, CODAG, and CODOG, have system level reliability driven primarily by the reliability of the gas turbine. Here it is important to note the reliability of the CODAG and CODOG architectures are nearly identical and thus the curves lay almost exactly on top of each other. Finally, the direct drive diesel engine and CODAD system are limited by the low reliability of the diesel engine.

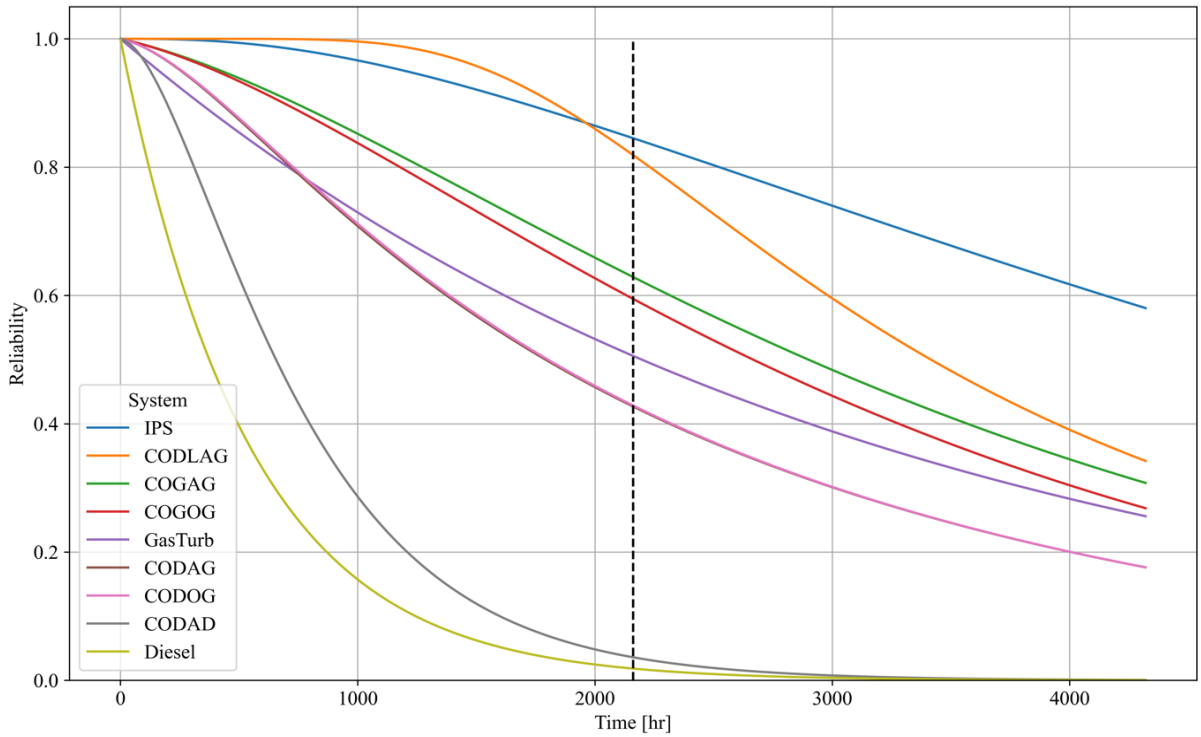

Figure 9: Propulsion Architecture Reliabilities

The MTBF of each propulsion architecture was also determined. As the architecture represents a combination of multiple Weibull distributions, there is not a closed form definition for the MTBF. Instead, the expectation of an architecture's reliability is found by numerically integrating the reliability from time zero to time infinity. This is accomplished by leveraging SciPy's implementation of QUADPACK library for numerical integration of infinite intervals. The estimated MTBF for each propulsion architecture is shown in Table 1, along with the reliability at 2160 hours.

Table 1: Propulsion Architecture MTBF and Reliability

Architecture	MTBF [hr]	Reliability at 2160 hr
IPS	6118	0.845
CODLAG	4130	0.819
COGAG	3588	0.629
COGOG	3307	0.595
Gas Turbine Direct Drive	3169	0.506
CODAG	2559	0.427
CODOG	2566	0.429
CODAD	803	0.036
Diesel Direct Drive	540	0.018

The table above quantifies the estimated MTBF and mission reliability of each architecture. Some interesting lessons can be drawn from the data above. First, it confirms the groupings observed in the propulsion architecture reliability. These groupings were: hybrid or fully electric architectures were most reliable, fully mechanical architectures with at least one gas turbine were less reliable, and fully mechanical architectures with only diesel engines were the least reliable. Second, the data shows that increasing the redundancy of a system does not always have a positive impact on the reliability of a propulsion architecture. Consider the case where a naval architect has determined one gas turbine is required for the vessel being designed and is now considering adding a redundant engine to enhance reliability. Introducing a second gas turbine to the propulsion architecture, thus producing a COGAG or COGOG system, would improve reliability, although perhaps not as significantly as one might expect. However, introducing a diesel engine as a redundant engine, thus producing a CODAG or CODOG system, reduces architecture reliability in the long term. As can be seen in Figure 9**,** the reliability of CODAG or CODOG architectures are greater than the reliability of a single gas turbine for about the first 800 hours of the mission. However, as the mission duration extends into thousands of hours, the single gas turbine becomes more reliable than CODAG or CODOG architectures. This phenomenon can be explained by the low MTBF of the diesel engine; as the mission duration increases the reliability gain afforded by the diesel engine diminishes while the reliability cost imposed by more the complex mechanical systems required for CODAG or CODOG architectures increases. As a result, in some situations adding an additional engine for redundancy reduces the total system reliability.

Assessing Redundancy

Reliability in conceptual design not only takes the form of which architecture should be selected, but how much redundancy is needed for a given propulsion architecture. In this section, redundancy in the form of additional diesel generators is considered for a CODLAG architecture. It is assumed that a minimum of two diesel generators must be operating for the electrical propulsion system to be operating correctly. The electric drive subsystem of the CODLAG system was selected as a unique opportunity for redundancy, as introduction of redundant prime movers is associated with significantly less additional complexity when compared to mechanical drives. As additional diesel generators are not associated with requirements for additional shafting, gearboxes, and clutches, it is expected that there is no reduction in reliability associated with the addition of redundant components.

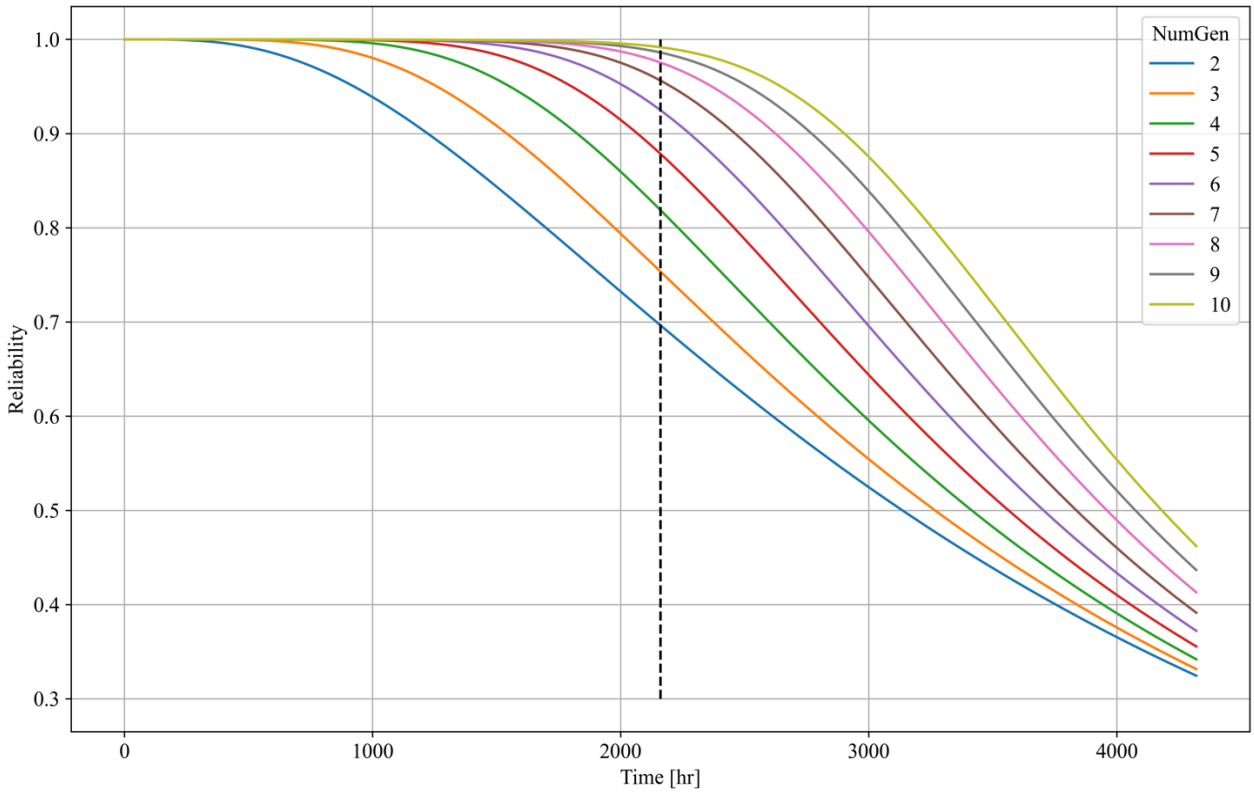

Figure 10: CODLAG with Redundancy Reliabilities

As is shown above in, increasing the number of diesel generators improves the reliability of the CODLAG system. The dashed line represents the target mission endurance. From the information shown in Figure 10 as well as Table 2, it can be determined that to reach any reasonable mission reliability, a significant number of redundant diesel generators are required. For example, achieving a 95% mission reliability requires seven generators, five of which are redundant, and achieving a 99% mission reliability requires ten generators, eight of which are redundant. This of course poses a

significant problem, as the inclusion of eight redundant generators clearly results in a significant increase in cost. Similarly, the number of generators required would likely require a significant increase in the size of the designed vessel. This not only poses a problem for ensuring that the design is able to close, but also could produce systems which are too large for the targeted vessel class. The infeasibility of addressing the reliability gap purely through redundancy motivates the need for more reliable components.

Table 2: CODLAG with Redundancy MTBF and Reliability

Number of Generators	MTBF [hr]	Reliability at 2160 hr
2	3840	0.697
3	3986	0.754
4	4130	0.819
5	4265	0.879
6	4389	0.925
7	4502	0.956
8	4606	0.975
9	4703	0.986
10	4793	0.992

Technology Impact Forecasting for Component Reliabilities

The discussion of redundancy made it is evident that improvements in component reliabilities are necessary to achieve the desired mission reliability. Of course, redundancy will still play a key role; however, the possibility exists that the reliability gap cannot be addressed solely with redundancy. Thus, improvements in today's existing technologies are required for future components to help meet the system reliability gap. This naturally raises the question of how much of a component reliability improvement is required to achieve a satisfactory system reliability.

Technology impact forecasting is used to determine the required reliabilities of both the diesel generator and the gas turbine in a CODLAG propulsion system. This CODLAG system modeled contains one gas turbine and four diesel generators, with two diesel generators required to be operational for the electric propulsion system to be operating. These specifications make the fault tree identical to the one shown in Figure 8. The scale parameter of each Weibull distribution varies across a range of values; for every combination of modified Weibull distributions, the mission reliability is evaluated at an uptime of 2160 hours. A contour plot representing mission reliability for varying component shape distributions is produced and shown below in Figure 11**.** Included in the figure is a point representing the reliability of today's system. The contour plot allows visualization of how improved component reliability changes the reliability of the entire propulsion system. It is immediately clear in this case that improvement in diesel generator reliability has a greater impact on total system reliability than improvement in gas turbine reliability. Depending on the desired system reliability, the contour plot can be used to determine the locus of component scale parameters required to meet the system level reliability. Examples are drawn below on Figure 11 to represent 90%, 95%, and 99% reliability targets for the propulsion system. The technology impact forecasting analysis demonstrated in this section shows the ability to perform conceptual requirements setting for component reliabilities. This provides the ability to either select existing components from various manufacturers or motivates investment in technologies to improve component reliabilities to a satisfactory level.

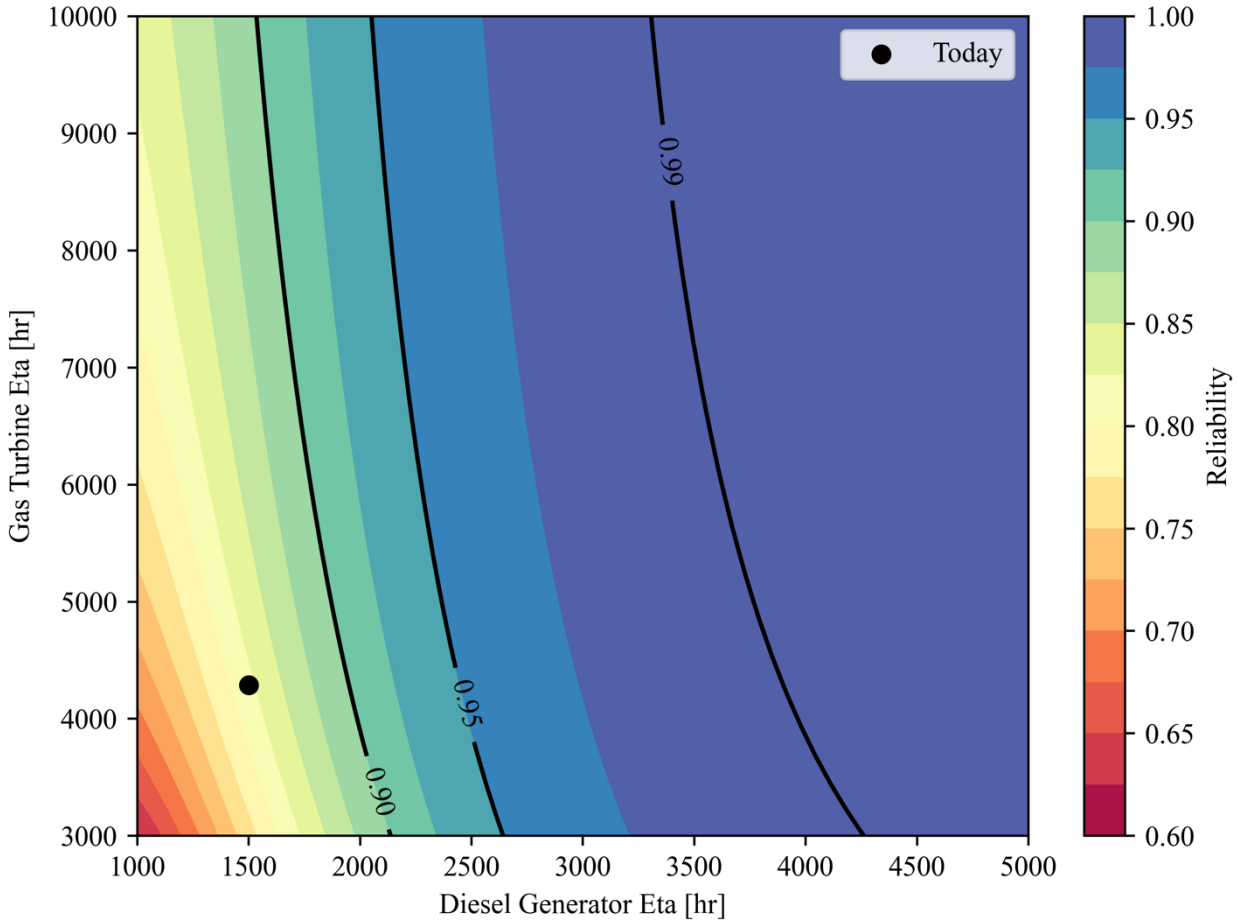

Figure 11: Technology Impact Forecasting CODLAG Reliabilities

CONCLUSIONS

Design of autonomous maritime systems represents a new frontier for naval architects. While almost every aspect of naval design will be influenced by the transition to no-manning systems, this paper has mainly focused on introducing reliability as a conceptual design discipline. Reliability was assessed as a key obstacle in deploying autonomous naval assets and was well demonstrated by the baseline vehicle called Sea Hunter. Reliability becomes a key conceptual discipline for long-term autonomy as the transition to uncrewed vessels removes the ability to perform in theater maintenance. As a result, reliability was introduced as a conceptual design discipline. The modified design process diagram demonstrates the notional inclusion of reliability as a parameter in conceptual design iterations. While there are many methods for assessing the reliability of engineered systems, this paper demonstrates reliability estimation via fault tree analysis. Fault tree analysis was selected as the preferred technique due to its simplicity and need for relatively little information. While these characteristics limit the fidelity of fault tree analysis, due to the limited amount of system information available in conceptual design these characteristics also make the method appropriate for performing conceptual design trades. This paper identifies leveraging reliability analysis in three ways for conceptual design. First, reliability analysis can be used to contrast distinct architectures. This paper demonstrated a notional case of contrasting propulsion systems. Second, reliability analysis can be used to assess redundancy. Redundancy assessment was demonstrated by trading the number of diesel generators with the reliability of a CODLAG propulsion system. Finally, component reliability requirements can be derived from system level reliability goal. These requirements can be used to either select components in detailed design or can be used as motivation to fund technology initiatives required to improve component reliabilities.

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