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Development of a Novel Codesign Method for Use in Early-Stage High-Performance Craft Design

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ABSTRACT

The performance requirements of modern vessels have increased significantly over time, introducing unique challenges in design and analysis. Driven by competition, such as in the case of racing craft, new high-performance vessels require design spaces that push the envelope of hydrodynamic technology. This optimization knowledge resides in the experience of racing experts and hasn't yet been translated into a naval architecture taxonomy. This paper seeks to bridge the knowledge gap between experienced race manufacturers and naval architects, and in doing so, delineate a design methodology. Modeling risk as a function of vessel speed, as well as coupling the design of the control system in conjunction with its physical design embodiment, allows the overall system to reach a greater point of optimality than what can be accomplished by traditional iterative design processes alone. The approach will be demonstrated utilizing the design of a University of Michigan student-led undergraduate high-speed, electric boat competition team design. The team's goal is to develop a vessel that has a top speed of 135 mph. The paper will discuss how the team used marine design methodologies integrated with a novel codesign method to create the design that is currently under construction for professional racing use by the team.

KEY WORDS

Codesign; Design Theory; High-Performance Craft; Racing; Speedboat.

INTRODUCTION

Powerboating and marine racing, also known as offshore powerboat racing, trace their origins back to the early 20th century, born from the desire to push the limits of marine engineering and hull design. The major modern competitors in powerboating include both manufacturers and private teams that specialize in the design, construction, and operation of these high-performance vessels. Prominent brands in the field include Cigarette Racing, Mystic Powerboats, Skater, and MTI (Marine Technology Inc.), which have developed reputations for their racing prowess and technological innovations. In terms of racing teams, organizations MCON Racing (pictured in Figure 1) have been very successful in international competitions such as Class 1 World Powerboat Championship. The marine racing industry has also grown to accommodate a variety of classes and different types of powerboats, from outboard engines to multi-engine offshore powerboats capable of reaching speeds exceeding 200 mph.

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Figure 1: Class 1 Offshore Race Boat ”Monster Energy MCON”; Source: mconracing.com (2023)

The advent of electric power in the marine racing industry has marked a major evolution, echoing the shift toward sustainability seen in automotive racing with series like Formula E. This rise of electric racing boats is propelled by the increasing global emphasis on reducing carbon emissions and harnessing renewable energy sources. Initiatives like the UIM E1 World Electric Powerboat Series showcase the potential of battery-powered craft, which offer a powerful yet environmentally friendly alternative to traditional internal combustion engines. As battery technology has advanced, with improvements in energy density, efficiency, and charging speeds, electric racing boats have become more competitive, promising high speeds, lower noise levels, and zero emissions.

A new addition to this transition toward electric racing craft is University of Michigan Electric Boat (UMEB), a team of students attempting to break the electric water speed record. UMEB was founded in September 2019 by a small group of undergraduate Aerospace and Naval Engineers to further develop battery-electric vessel technology. As the team developed, it became apparent that the limited budget, resources, and experience in a student project meant that designing and operating like a professional powerboat manufacturer was not feasible. Instead, the characteristics of the team’s operation more closely matched those of the wicked problems associated with large vessel and platform design. Thus, UMEB was presented with the following problem: translating the knowledge, best practices, and design elements developed from decades of experience of team contacts in the marine racing industry into a novel marine design methodology.

This paper delineates the methodology employed by UMEB in crafting a competitively adept racing vessel through the lens of naval architecture principles.

CHANGING LENSES

The Tragedy of *Snowfinkle*

The realization that UMEB needed to integrate naval architecture principles and methodologies into the design of speedboats was not immediate, and only years of failure taught the team to change. These failures began in 2021 with the team’s first true attempt at a performance vessel: *Snowfinkle*.

Before the design process even began, there were reductions in the design space in that the vessel’s hull form was limited to the 17-foot sailing catamaran that was donated to the team in the previous year. This meant that a successful craft would have to match the characteristics of a sailboat, which was designed purely to act in a displacement capacity and not able to plane. Electric battery systems have an inherent drawback in their low power density, which is somewhat incompatible with the dynamics of a very lightweight sailing craft. Navigating this problem is where the team made its first critical mistake in failing to assess the root cause of these problems and instead attacking the surface-level design incompatibilities. The team looked to the marine industry to find solutions, and seeing as industry offerings for battery-electric craft almost exclusively utilized hydrofoils to meet their operational requirements, the team embraced hydrofoils as a potential saving grace to the emergent design challenges. What should have been a question of what would create the best craft that met the requirements quickly turned into a question of how to make hydrofoils work. Consequently, the team followed a point-based design approach, with the initial conditions being the hull form and the hydrofoils. Due to 'walls' being put up between the propulsion, battery, hydrofoils, and structures teams to divide the work, systems integration became a major obstacle. This manifested throughout *Snowfinkle*, emerging most obviously between the physical junction of the hydrofoils and the rest of the craft, as well as the propulsion system. The team also stumbled into an endless need for weight distribution adjustments due to the poor balance characteristics of *Snowfinkle* while foiling, leading to consistent changes in general arrangement. As the team continued following the spiral, progressively more changes needed to be made, often compromising the overall vessel mass and the functionality of the vessel's control system. These changes often occurred after major portions of *Snowfinkle* had already been built, which further complicated the problem. No matter the decisions made, the initial conditions of the design meant that we could not converge to a point of optimality, let alone acceptability.

Figure 2: *Snowfinkle*

The methodology used on *Snowfinkle* illustrated a failure to execute proper marine design on many levels. With a bit more design space exploration, it would have become evident that the low drag characteristics of the hull meant that the craft could have easily met its design requirements with an 80-horsepower propulsion unit and no further changes to the hydrodynamics of the hull, thus the resultant design space would have greatly differed. Even had UMEB used spiral-based design (which might have been a necessity given a new and inexperienced team with limited resources) to generate *Snowfinkle*, delaying critical decisions would have led to a greater understanding of the driving variables with which the team worked, which might have had the potential to generate better initial conditions and eventually an acceptable convergence.

In the end, *Snowfinkle* experienced a complete and total system breakdown after nearly every interface had been reworked, then reworked again to no avail. The team decided that the countless hours spent fixing the unsolvable issues was not worth their effort, and instead began focusing on eliminating the issues with *Snowfinkle* through a much more mature approach to boat design.

A Step in the Right Direction

As the *Snowfinkle* was sunset, a new chapter began for UMEB. The team had grown significantly over two years both in number and in expertise, especially regarding battery, control, and propulsion systems. A growing team presence at the University of Michigan and the local community had opened up many doors in terms of resources, additions of physical workspace, and bargaining power with the school administration. Most importantly, however, the team's leadership changed: this time with a much greater focus on designing for high-performance.

Considering the new leaders were many of the people who experienced firsthand the failures of *Snowfinkle*, there was an early push to truly understand the design errors at a fundamental level. The team first identified that a marine design approach was needed, something the aerospace students who previously ran the team did not completely recognize or understand, and therefore could not execute successfully. In other words, a much more methodical and strategic process would be needed to avoid making premature decisions that would force the team into undesirable designs. Additionally, the walls put up across subteams needed to be broken down and instead replaced with collaborative systems thinking, with a much greater emphasis on cross-functional work to ensure interfaces were accounted for.

While the new leaders understood the issues with the poor design strategy correlated with *Snowfinkle*, the team identified that there were still significant gaps in our understanding of successful marine design processes. To address these gaps, team leadership began meeting with professors in the University of Michigan Naval Architecture and Marine Engineering department, especially Professor David J. Singer.

Requirements Elucidation

The first step UMEB took in improving its design methodology was working to better understand the speedboat design space. Due to the limited budget, timeline, and experience present in the project, there was a major need to derisk this design space and guarantee that whatever design elements were chosen would not result in emergent design failures that would compromise the project, much like what happened with *Snowfinkle*. To address this knowledge gap, UMEB performed a functional decomposition based on the team's overarching goal to travel at 100 knots for 5 nautical miles (See Figure 3). The goal of this process was to develop a knowledge structure that could guide our end embodiment and the decisions we made along the way, following the taxonomy presented by Goodrum (2020).

To perform this functional decomposition, we employed a Andrews (2021)-style requirement elucidation process. Within this process, we started at the overarching goal of our design, and from there worked our way down through design variables with the help of taxonomies, not to reach a feasible design, but more to learn about the complex interactions within the design space and discover requirements as we went.

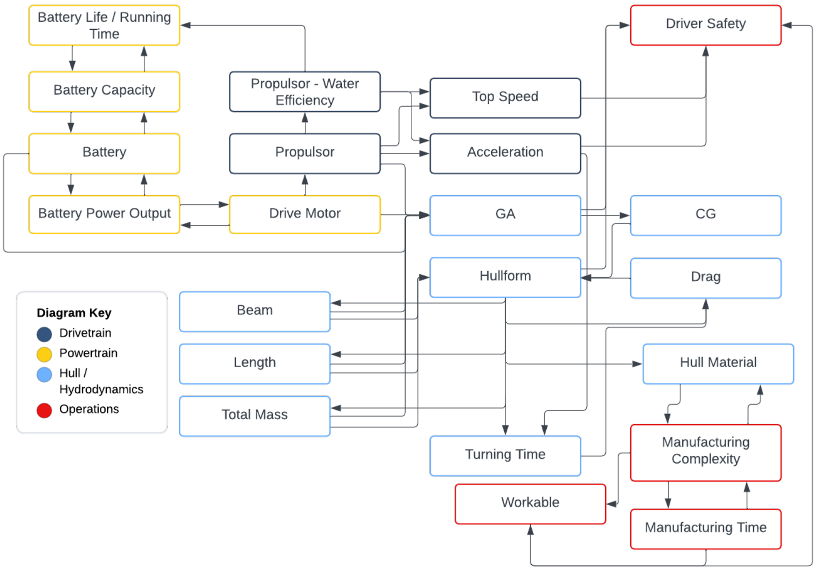

Figure 3: UMEB Functional Decomposition

One example of this was how we grew to understand lift within our design space. We knew from industry experts that lift was going to be a major part of being able to go fast efficiently, but breaking down the actual factors that drove that proved difficult. At this point, we were introduced to the sustension cube (See Figure 10) as explained by McKesson (2009), which provided us with a taxonomy to classify how different vessels produce lift. From here, we could analyze how other high-performance crafts fit onto the sustension cube. We found that the fastest craft we knew of had high passive aerodynamic and hydrodynamic lift characteristics, thus discovering the requirement that our vessel should structure its lift characteristics similarly. More specifically, we discovered the requirement that our vessel needed to have some sort of surface, be that wings, tunnels, or hull form, that would pressurize air beneath the craft and that the geometry touching the water needed to plane efficiently.

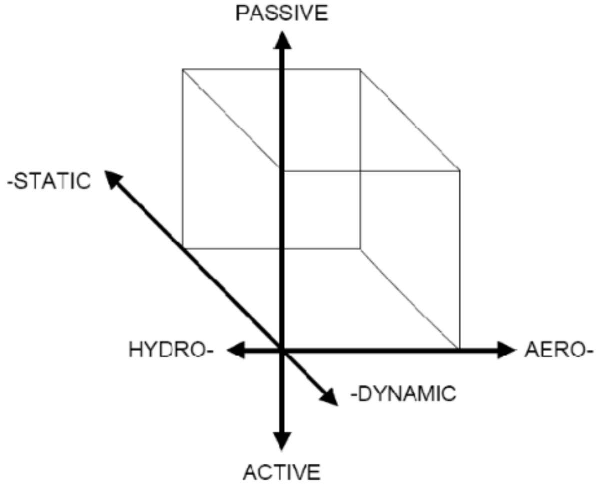

Figure 4: McKesson's Sustension Cube

IDENTIFYING DISCREPANCIES

As UMEB continued the process of functional decomposition, informing our new discoveries with the knowledge gained through previous design space explorations, team members would often talk to UMEB's industry partners, especially Skater and the American Powerboating Association (APBA), using their knowledge and experience as a feasibility check for the discovered requirements and design elements. The team discovered in this process that there were discrepancies in the way that the racing professionals analyzed the design space and how naval architects would do the same. To address our findings, the team contacted the best high-speed hydrodynamics experts they could find to further explore this. Specifically, UMEB explored the missing pieces of the problem through detailed analysis with Dr. Kevin Maki and Dr. Armin Troesch. In discussions with both, a similar conclusion could be drawn, best encapsulated in the following quote from Dr. Troesch: "Even the best naval architect can only design a 90% boat; it takes a different type of knowledge to get the last 10%". When the team brought up this issue with Peter Hledin, the owner of Skater and one of the most respected offshore catamaran designers in the world, he responded with the following (albeit heavily paraphrased due to the use of expletives): "[Naval Architects] know what the boat will do, but I also know what the driver will do and I know what the APBA will let me run". Quite simply, this explanation illustrated a framework for what design tools were missing.

Codesign

"I know what the driver will do"

With a little bit of abstraction, the role of the driver can be viewed as an active controller for the physical plant of the craft. When analyzing through this lens, there are many evident similarities to high-performance aircraft design, which uses a knowledge structure where design elements physical plant and design elements of its control system simultaneously inform each other. This aerospace concept is more colloquially referred to as codesign.

Codesign in Aerospace

Codesign has been a major tenet of aircraft design since the 1970s, specifically concerning projects within the US military black budget. Much of modern stealth fighter technology would not have proven viable had it not been for early-stage design exploration illustrating that an airframe with poor flight characteristics due to the requirement of a small radar cross-section could still be effective by combining pilot input with highly responsive flight computers according to Aronstein and Piccirillo (1997). The effectiveness of this design methodology is evident in its continued use in the defense industry despite nearly half a century of technological progress as evidenced by continued aerospace research on the topic from academic works such as Abedini et al. (2022). It should be noted that there exists very little academic research from a design theory perspective on this topic as the aerospace industry views codesign more as a strategy to address instabilities and less so as an overall methodology; the further complexity of the marine design space demands a more comprehensive approach.

Codesign in Marine Research

The use of codesign is not a foreign idea in the marine academic sphere; it should be noted that the most complete mathematical example comes from Castro-Feliciano (2016). This paper illustrates the potential benefits of coupling an active control system to the design of a planing craft, specifically concerning dimensional and numeric figures such as the longitudinal center of gravity. It can be argued that the math used by the authors is limited in scope to implementation in planing craft with very geometrically simple hull forms, as is standard. This becomes a problem within the research scope of this paper as many, if not all, of the racing vehicles that make use of advanced control surfaces, also make use of extremely complex hull forms with the addition of features like steps, multiple hard chines, and rear strakes according to Yun and Bliault (2012), not to mention multiple hulls. The highest-speed racing craft are further complicated with hull forms that in addition to planing also make use of the ground effect (often referred to in the industry as “packing air”) through the use of tunnels, Venturi tubes, and wing surfaces. The greatest benefit of Castro-Feliciano’s version of codesign concerning racing craft comes from his point that control systems can take advantage of traditionally undesirable dynamic nonlinearities and instead use them to increase vessel performance. Take porpoising, for instance. Without a control system, porpoising can lead to significant inefficiencies due to a change in lift characteristics and drag, which sharply limits the top speed of a vessel, or in more extreme cases, can lead to a crash. Despite the aggregate effect of porpoising being negative in terms of vessel performance, there is a point in the oscillation in which the craft is further out of the water and has lower overall drag than achievable without dynamic instability: this is where well-integrated control surfaces come in. If a control surface can provide lift during the periods when porpoising would force the craft downward, then the net effect of this controlled nonlinearity is less drag and therefore greater top speed. One problem with this approach is that it requires a working understanding of exactly what function a control surface will perform, which is sometimes not possible to derive in early-stage design. This approach can be reversed, however; by defining a control surface in terms of the function it must perform, which thus can generate design knowledge without reducing the design space.

Codesign in Marine Racing

Given that competition drives a need for designs to perform as optimally as possible, as many feasible designs as possible need to be considered when determining dominance. We can visually represent how codesign can be useful for expanding the set of feasible designs using Figure 5, which illustrates a hypothetical feasible set within an imaginary design space. Note that there exists a boundary where designs exit the realm of feasibility due to failure to meet a requirement.

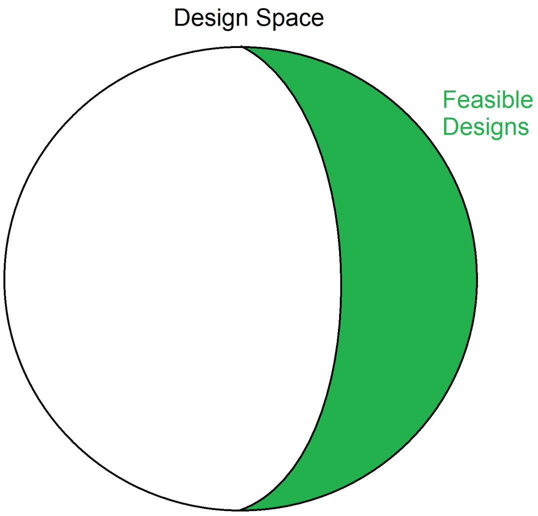

Figure 5: Hypothetical Design Space Example

This becomes problematic when we start comparing these designs, as there exist spaces in which the most dominant designs lie on the boundary due to a requirement acting as an active constraint. This can be visualized in Figure 6, where we can see the most optimal designs lying nearest to the boundary.

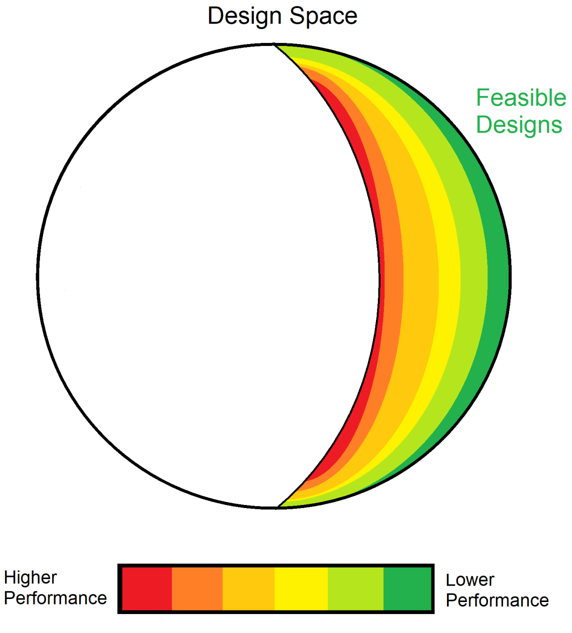

Figure 6: Design Space Dominance Example

With this in mind, there becomes a vested interest in expanding this boundary of feasibility to reach a higher performance but satisfactory design. This is where codesign can provide some advantages in the racing sphere. By taking advantage of designs that might not be conventionally feasible due to factors such as poor stability and then pairing them with a control system (be that a computer or a human driver) that can address this, a certain previously infeasible set of designs can once again enter the realm of feasibility. Following the other presented figures, Figure 7 illustrates the inclusion of more designs into the feasible set.

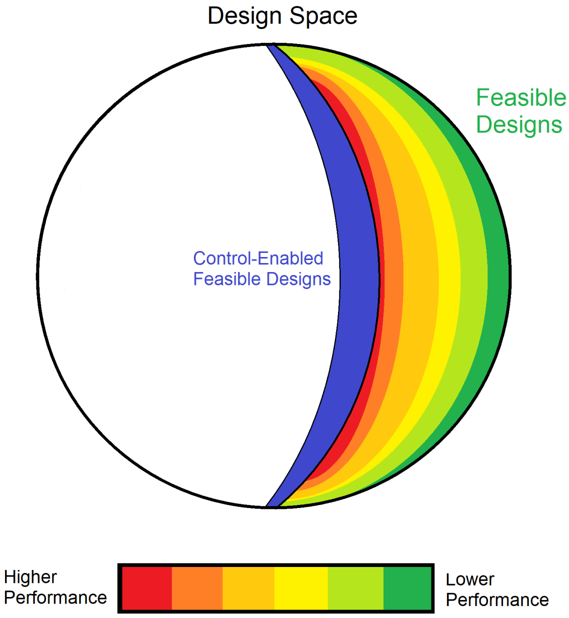

Figure 7: Feasibility Boundary Expansion Example

It should be noted that while controls can solve some level of instability, control authority is a design variable in itself and there are countless instances where the control requirements to reach stability are infeasible in themselves. To determine the feasibility of a control system, further modeling with the dynamics of the rest of the vessel is needed, thus requiring a mathematical model for codesign. This will be further explored in the implementation section of this paper.

The Risk Model

“I know what the APBA will let me run”

The second missing piece of the racing design problem comes from the inherent need for a craft to be competitive. In order to win, a racing craft must be pushed to its absolute performance limits. Simultaneously, an ideal racing craft should completely disintegrate as it crosses the finish line, which means that every component is being designed to be just robust enough to finish a race. This creates several problems, as pushing a craft to these performance limits with limited knowledge can be very irresponsible, given that the line between winning and dying can be very thin. This problem is well documented; according to Atwal (2024), seven of the thirteen people who have attempted to break the water speed record have died during their attempts.

Because of this, managing risk within the vessel’s engineering becomes the designer’s responsibility. Like any risk model, such as a HazID (see ABS (2020)), we can identify threats to the vessel with both their likelihood to occur and the associated consequences if they do. As a vessel has to exert greater performance, the consequences of failure as well as the likelihood of failure increase, thus coupling these two factors. Consequently, vessels operating with lower performance targets can exhibit fewer mitigation and prevention measures, often contextualized as safety features. For instance, the APBA (2022) states that cockpits on boats designed to travel faster than 150 miles per hour require a cockpit structural strength of

8,000 Newtons whereas cockpits designed for lower speed boats only require 2,000 Newtons. In conclusion, as a vessel's performance requirements increase, the degree of risk that can be taken significantly decreases.

One system that we have developed to understand and track this risk-based design space is a tool we call a Vessel Integrity - Vessel Speed (VI-VS) plot. Vessel speed, in this context, is a broad term that describes the inherent performance metric that a racing craft is trying to meet; for an endurance craft, this might be vessel velocity at range, for a circuit track craft, this might be velocity maintained through a turn, and for a drag boat, this might be acceleration over short distances. The other component of this relationship is vessel integrity; this is a measure of how likely the vessel is to experience an extreme event that would prevent it from continuing normal operation, "blowing over" or an engine failure for example. This plot helps a designer characterize both designs and requirements simultaneously. One critical piece of using a VI-VS plot to its full advantage is plotting a curve that represents the acceptable risk associated with a craft as it relates to increasing performance, or, in context, vessel speed. This is written as the minimum allowed the integrity of a design at a given "speed". As discussed previously, these minimum requirements almost always increase with speed, but the exact quantization and form of this relationship often come from competition rules, careful design consideration, and the quality of the relationship between the craft owners and their insurance companies. Once placed on the VI-VS plot, we refer to the relationship as the Acceptable Design Risk (ADR) curve. An example of a VI-VS curve with a sample ADR curve is shown in Figure 8. Further definition of how these plots are generated will be illustrated in UMEB's implementation of this concept.

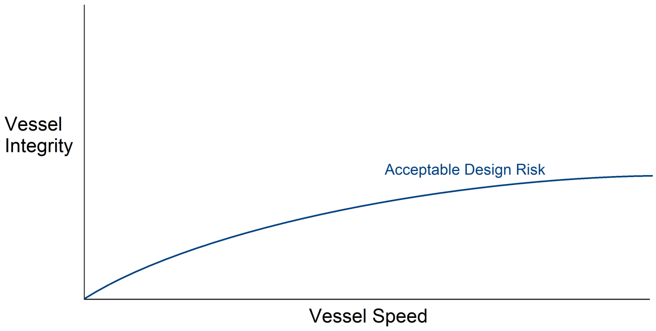

Figure 8: VI-VS Curve Plot (Acceptable Design Risk Only)

IMPLEMENTING NEW DESIGN TOOLS

With a greater understanding of what needed to be done to develop an optimal craft, UMEB moved forward in their design process, using a set-based design process based on Singer et al. (2010) including a novel codesign component to derisk the design and ensure the team would not experience another system-level failure. Improving on the walls of the past, UMEB used its subteams - powertrain (batteries), drivetrain (power transmission), and structures (safety and hydrodynamics) - as specialties to base our set conversion.

Expanding Feasible Design Sets through Codesign

UMEB used a very basic initial pass of designs using top-speed estimations based on Gerr (2001); afterward, the analysis became much more complex. While examining designs, UMEB focused extensively on seakeeping, as finding designs that wouldn't destabilize and flip over or crash proven to be the main limitation on feasibility. Because of this, the team first implemented codesign within a general stability equation. Given that the scope of the project is limited to racing craft that would only travel across extremely clean water (Sea State 1.5 or less), a linearized approach should suffice given that hydrodynamic disturbances due to waves will be minimal. With that information, Equation 1 defines a fairly accurate model of the dynamic relationships across the design space of vessels UMEB explored.

$$[m]\ddot{x} + [c]\dot{x} + [k]x = 0 \tag{1}$$

We will further expand this definition with Equation 2, Equation 3 and Equation 4. Note that this expansion includes all 6 degrees of freedom.

$$[m]\ddot{x} = \begin{bmatrix} m_{xx} & m_{xy} & m_{xz} & m_{xk} & m_{xm} & m_{xn} \\ m_{yx} & m_{yy} & m_{yz} & m_{yk} & m_{ym} & m_{yn} \\ m_{zx} & m_{zy} & m_{zz} & m_{zk} & m_{zm} & m_{zn} \\ m_{kx} & m_{ky} & m_{kz} & m_{kk} & m_{km} & m_{kn} \\ m_{mx} & m_{my} & m_{mz} & m_{mk} & m_{mm} & m_{mn} \\ m_{nx} & m_{ny} & m_{nz} & m_{nk} & m_{nm} & m_{nn} \end{bmatrix} \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \\ \ddot{\phi} \\ \ddot{\theta} \\ \ddot{\psi} \end{bmatrix} \tag{2}$$

$$[c]\dot{x} = \begin{bmatrix} c_{uu} & c_{uv} & c_{uw} & c_{up} & c_{uq} & c_{ur} \\ c_{vu} & c_{vv} & c_{vw} & c_{vp} & c_{vq} & c_{vr} \\ c_{wu} & c_{wv} & c_{ww} & c_{wp} & c_{wq} & c_{wr} \\ c_{pu} & c_{pv} & c_{pw} & c_{pp} & c_{pq} & c_{qw} \\ c_{qu} & c_{qv} & c_{qw} & c_{qp} & c_{qq} & c_{qr} \\ c_{ru} & c_{rv} & c_{rw} & c_{rp} & c_{rq} & c_{rr} \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \tag{3}$$

$$[k]x = \begin{bmatrix} k_{xx} & k_{xy} & k_{xz} & k_{x\phi} & k_{x\theta} & k_{x\psi} \\ k_{yx} & k_{yy} & k_{yz} & k_{y\phi} & k_{y\theta} & k_{y\psi} \\ k_{zx} & k_{zy} & k_{zz} & k_{z\phi} & k_{z\theta} & k_{z\psi} \\ k_{\phi x} & k_{\phi y} & k_{\phi z} & k_{\phi\phi} & k_{\phi\theta} & k_{\phi\psi} \\ k_{\theta x} & k_{\theta y} & k_{\theta z} & k_{\theta\phi} & k_{\theta\theta} & k_{\theta\psi} \\ k_{\psi x} & k_{\psi y} & k_{\psi z} & k_{\psi\phi} & k_{\psi\theta} & k_{\psi\psi} \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ \phi \\ \theta \\ \psi \end{bmatrix} \tag{4}$$

The terms inside of the matrices presented were gathered through computer simulation and estimation of existing hull forms; an example of one of the forms tested by this model can be shown in Figure 9.

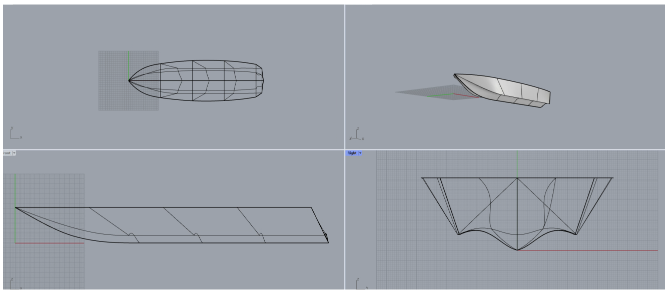

Figure 9: Example Hull Form

Given that the operational requirements given by the team were incredibly limited, the straight-line speed at the range of the vessel proved far more important than factors such as maneuvering and endurance. Because of this, the seakeeping equation can be reduced to only include trim, roll, and heave, shown in Equation 5. This reduction grants us sufficient knowledge to make design decisions while reducing the computational cost to simulate large numbers of design options; however, it should be noted that a more complex physics simulation is necessary when developing the final control system.

$$\begin{bmatrix} m_{zz} & m_{z\phi} & m_{z\theta} \\ m_{\phi z} & m_{\phi\phi} & m_{z\phi} \\ m_{\theta z} & m_{\theta\phi} & m_{\theta\theta} \end{bmatrix} \begin{bmatrix} \ddot{z} \\ \ddot{\phi} \\ \ddot{\theta} \end{bmatrix} + \begin{bmatrix} c_{zz} & c_{z\phi} & c_{z\theta} \\ c_{\phi z} & c_{\phi\phi} & c_{z\phi} \\ c_{\theta z} & c_{\theta\phi} & c_{\theta\theta} \end{bmatrix} \begin{bmatrix} \dot{z} \\ \dot{\phi} \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} k_{zz} & k_{z\phi} & k_{z\theta} \\ k_{\phi z} & k_{\phi\phi} & k_{z\phi} \\ k_{\theta z} & k_{\theta\phi} & k_{\theta\theta} \end{bmatrix} \begin{bmatrix} z \\ \phi \\ \theta \end{bmatrix} = 0 \tag{5}$$

The reality of the design space when discussing the craft of extreme speed regimes is that instability is near guaranteed at some point, thus there is a point at which the seakeeping dynamics of the craft do not converge to zero as they do in Equation 5. There are many reasons for this occurring, but often this has a lot to do with the hull form characteristics changing across different dynamic domains at different speeds. Mathematically, an error term appears in the equation to model how small disturbances while in a high planing state can propagate into instabilities or extreme events. This emergence of instability generates Equation 6.

$$\begin{bmatrix} m_{zz} & m_{z\phi} & m_{z\theta} \\ m_{\phi z} & m_{\phi\phi} & m_{z\phi} \\ m_{\theta z} & m_{\theta\phi} & m_{\theta\theta} \end{bmatrix} \begin{bmatrix} \ddot{z} \\ \ddot{\phi} \\ \ddot{\theta} \end{bmatrix} + \begin{bmatrix} c_{zz} & c_{z\phi} & c_{z\theta} \\ c_{\phi z} & c_{\phi\phi} & c_{z\phi} \\ c_{\theta z} & c_{\theta\phi} & c_{\theta\theta} \end{bmatrix} \begin{bmatrix} \dot{z} \\ \dot{\phi} \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} k_{zz} & k_{z\phi} & k_{z\theta} \\ k_{\phi z} & k_{\phi\phi} & k_{z\phi} \\ k_{\theta z} & k_{\theta\phi} & k_{\theta\theta} \end{bmatrix} \begin{bmatrix} z \\ \phi \\ \theta \end{bmatrix} = e(t) \tag{6}$$

Given the idea that a control surface can provide a certain degree of authority to force a system into stability, this error term can sometimes be a surmountable obstacle. To determine if the vessel can reach stability through controls, a term can be added to the seakeeping equation to represent the required effort of a control system to maintain stability through changing dynamic domains. This action is illustrated in Equation 7 and Equation 8.

$$\begin{bmatrix} m_{zz} & m_{z\phi} & m_{z\theta} \\ m_{\phi z} & m_{\phi\phi} & m_{z\phi} \\ m_{\theta z} & m_{\theta\phi} & m_{\theta\theta} \end{bmatrix} \begin{bmatrix} \ddot{z} \\ \ddot{\phi} \\ \ddot{\theta} \end{bmatrix} + \begin{bmatrix} c_{zz} & c_{z\phi} & c_{z\theta} \\ c_{\phi z} & c_{\phi\phi} & c_{z\phi} \\ c_{\theta z} & c_{\theta\phi} & c_{\theta\theta} \end{bmatrix} \begin{bmatrix} \dot{z} \\ \dot{\phi} \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} k_{zz} & k_{z\phi} & k_{z\theta} \\ k_{\phi z} & k_{\phi\phi} & k_{z\phi} \\ k_{\theta z} & k_{\theta\phi} & k_{\theta\theta} \end{bmatrix} \begin{bmatrix} z \\ \phi \\ \theta \end{bmatrix} = e(t) - C(t) = 0 \tag{7}$$

$$\begin{bmatrix} m_{zz} & m_{z\phi} & m_{z\theta} \\ m_{\phi z} & m_{\phi\phi} & m_{z\phi} \\ m_{\theta z} & m_{\theta\phi} & m_{\theta\theta} \end{bmatrix} \begin{bmatrix} \ddot{z} \\ \ddot{\phi} \\ \ddot{\theta} \end{bmatrix} + \begin{bmatrix} c_{zz} & c_{z\phi} & c_{z\theta} \\ c_{\phi z} & c_{\phi\phi} & c_{z\phi} \\ c_{\theta z} & c_{\theta\phi} & c_{\theta\theta} \end{bmatrix} \begin{bmatrix} \dot{z} \\ \dot{\phi} \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} k_{zz} & k_{z\phi} & k_{z\theta} \\ k_{\phi z} & k_{\phi\phi} & k_{z\phi} \\ k_{\theta z} & k_{\theta\phi} & k_{\theta\theta} \end{bmatrix} \begin{bmatrix} z \\ \phi \\ \theta \end{bmatrix} + C(t) = e'(t) = 0 \tag{8}$$

Distilling Control Requirements from C(t)

$C(t)$, as defined in the previous section, is at its core a measure of the error between desired and actual dynamic characteristics. To pull more specific information out of $C(t)$, it needs to be decomposed into error terms in each direction, which is shown in Equation 9. These functions can be fairly easily picked apart using a linear regression model using data points from the simulation.

$$C(t) = e_z(t) \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} + e_\phi(t) \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} + e_\theta(t) \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{9}$$

From this point, two key pieces of information are needed to determine the feasibility of the control system: the first of these is the required effort of the control system. This can be found by finding the maximum value of $|e_z(t)|$, $|e_\phi(t)|$, and $|e_\theta(t)|$ across the selected time domain. For instance, $max(|e_z(t)|)$ might return a value of 2000 Newtons, which tells us that our control system must be able to produce 2000 Newtons of lift when all surfaces are fully extended. This does not necessarily mean one control surface has to do this, but the aggregate effect of the control surfaces must produce that effect.

From here, the reactivity of that control system must be determined, or in other words, the speed at which the control system must fight a disturbance. the first step of determining this information is taking the derivative of the error functions, returning $e'_z(t)$, $|e'_\phi(t)|$, and $e'_\theta(t)$. From there, the maximum magnitude of the derivative of the error function should be found, $max(|e'_z(t)|)$ for instance. The last step is to determine the time domain in which controls must be able to engage. Generalized control reactivity values in the context of the reduction used by UMEB can be found in Equation 10, 11 and 12.

$$t_z = \frac{max(|e_z(t)|)}{max(|e'_z(t)|)} \tag{10}$$

$$t_\phi = \frac{max(|e_\phi(t)|)}{max(|e'_\phi(t)|)} \tag{11}$$

$$t_\theta = \frac{max(|e_\theta(t)|)}{max(|e'_\theta(t)|)} \tag{12}$$

This process during simulation should give enough information to determine the feasibility of a control-enabled design and avoid its loss to set reduction. Following this process, UMEB was left with a feasible set of designs that included the effect of control surfaces on vehicle dynamics.

Dominance through Risk Modeling

Once UMEB had a clearly defined range of design variables that was deemed to produce feasible results, the question of execution became increasingly more important. While the team had grown both in personnel and resources significantly, there were still limitations. The greatest block in the design process was that there were many components that the team knew were going to be impossible to manufacture in-house, which meant we had to purchase them; specifically, the hull and primary drive motor were both components that had to be purchased and not designed, thus creating anchors within the design space. There were a limited number of commercially available hull forms and drive motors that fell within the realm of feasibility, which discretized some of the design variables. Additionally, while all of these designs were feasible, UMEB wanted to pick the most competitive design possible in order to increase our chances of winning the electric boat arms race. Because of this, UMEB realized that comparison and dominance would have to be achieved through a method beyond set-based design. The team settled on the usage of Pugh's method of controlled convergence, shown in Figure **??**, to develop this knowledge, first laying out all of the commercially available hull forms and motor options that fell within the feasible set. To determine the dominance of designs, an evaluation criteria had to be used, which is where the VI-VS risk model became useful.

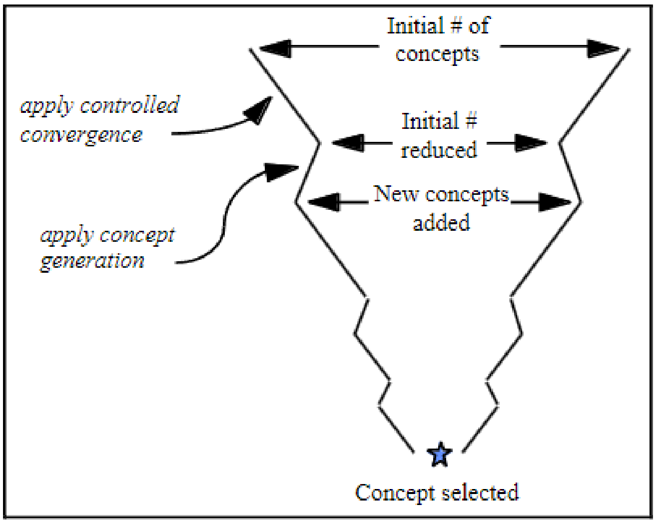

Figure 10: Visual for Method of Controlled Convergence from Bernstein (1998)

Quantifying VI-VS

As discussed earlier, Vessel Integrity and Vessel Speed both represent composite functions of many factors that contribute to safety and performance respectively. The team determined these functions in a manner very similar to AHP, where they subjectively categorized how important each element of each criterion was over another. Following this, they generated the comparison matrices found in Table 1 and Table 2.

Table 1: Preference Matrix for Vessel Integrity

	Trim Stability	Roll Stability	Driver Capsule Strength	Powertrain Stress (C-rate)
Trim Stability	1	7	4	3
Roll Stability	1/7	1	1/3	1/5
Driver Capsule Strength	1/4	3	1	3
Powertrain Stress (C-rate)	1/3	5	1/3	1

Table 2: Preference Matrix for Vessel Speed

	Top Speed	Turning Radius	Acceleration	Range
Top Speed	1	7	4	3
Turning Radius	1/7	1	1/5	1/6
Acceleration	1/4	5	1	1/3
Range	1/3	6	3	1

From here, the team took the eigenvectors of these matrices to determine a weight vector, with results shown in Equation 13 and Equation 14.

$$w_{VI} = \begin{bmatrix} 0.88 \\ 0.09 \\ 0.38 \\ 0.26 \end{bmatrix} \tag{13}$$

$$w_{VI} = \begin{bmatrix} 0.86 \\ 0.07 \\ 0.23 \\ 0.44 \end{bmatrix} \tag{14}$$

Similar to TOPSIS as defined by Sen and Yang (1998), the designers identified an upper and lower bound for each of these metrics; by normalizing these values throughout the process, a nondimensionalized measure is gained for both vessel speed and vessel integrity which can each be plotted as single variables.

Comparison with VI-VS

From this point, it became necessary to define an acceptable design risk curve that would act as the optimization goal. The team agreed that due to the policies of the University of Michigan, there was a baseline level of Vessel Integrity that was independent of Vessel Speed. There was also agreement that as Vessel Speed increased beyond around 0.500, there was no reason to increase the required Vessel Integrity much further as an extreme event at that level of performance would spell disaster regardless of the mitigation, prevention, and safety measures in place. For this reason, the team decided that the best way to model this behavior was through a square root relationship. Plotting this on the VI-VS curve generates Figure 11.

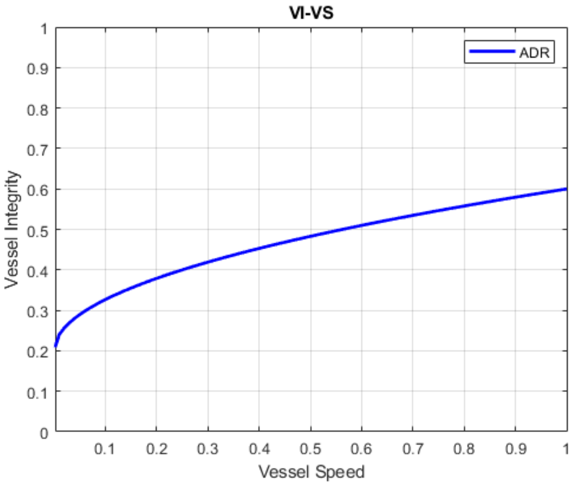

Figure 11: Decided ADR Curve

Once an ADR was established, the team moved onto using the VI-VS curve to analyze the dominance of individual designs by characterizing how Vessel Integrity changed across the domain of Vessel Speeds. Much of this was done subjectively or using simple curve fits from known points. Once a surrogate model had been established, dominance was determined based on the intersection between a design's VI-VS curve and the ADR curve. Take *Snowfinkle* for instance; due to the anhedral hydrofoils and poor weight distribution, *Snowfinkle*'s stability degraded quickly with increased performance, generating Figure 12.

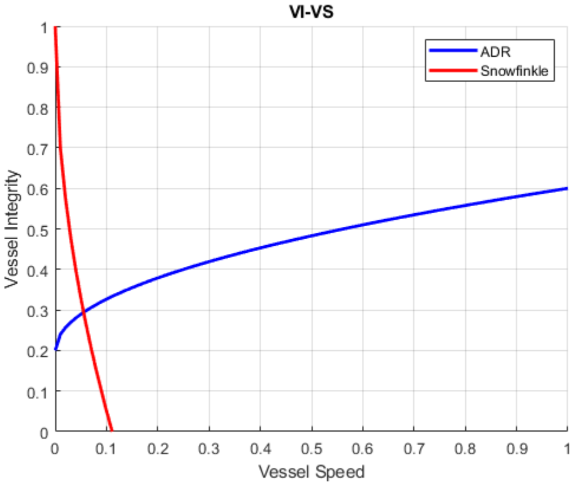

Figure 12: ***Snowfinkle*** **VI-VS Plot**

This can be extrapolated further by looking at the VI-VS curves for further designs in Figure 13. By analyzing the problem through this lens, one can determine that “Design Alternative 2” dominates the others, as it can extract the most performance without an unacceptable risk of an extreme event occurring.

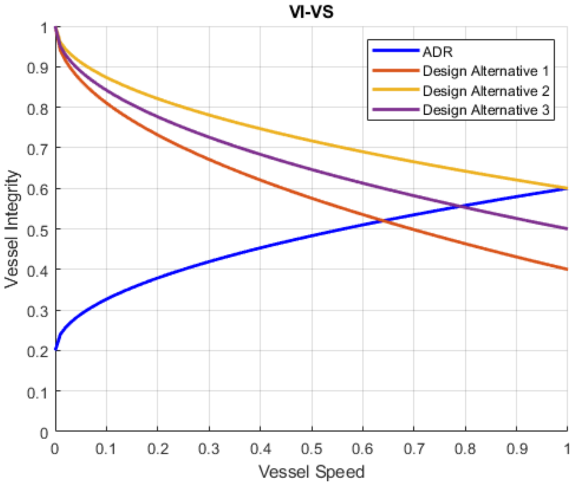

Figure 13: Sample VI-VS Plots

This kind of analysis drove the remainder of the early-stage design process for UMEB, and the team was left with a set of design elements that they were confident were strong enough to be competitive. Thus came the second, and much more entertaining, problem: how to take the chosen design from a spreadsheet to a working boat.

EXECUTION

First began the monumental task of figuring out how to pay for a 24-foot race boat. Due to the frontloading of the design work, UMEB had a very clear vision of what our end product was going to be; this was advantageous as it was much easier to illustrate this vision to potential sponsors comapred to past UMEB projects. Through building connections and sharing the plan, the team built more and more allies: powerboat builders, electric vehicle manufacturers, consulting firms, and software companies to name a few; UMEB's net worth passed a million US dollars within six months of starting fundraising.

With financial resources unlocked, the team experienced a shift in November 2023, as the time had arrived to start physically putting together the parts of the craft. This was kicked off by the arrival of the hull, which the team had to travel to pick up from a sponsor across the country. As the new craft was pulled into the team workspace, the team announced to the world the name of the project: *TiDE*. As the project progressed and grew in physical scale, more external eyes found the craft UMEB had created. Working with the resources and technical support of Skater Powerboats, the team was able to complete a structural canopy that met the required APBA rules. At the same time, UMEB worked with a Slovenian hypercar manufacturer to source a motor powerful enough to drive the craft.

Figure 14: *TiDE* in UMEB's Workshop

The team continued building and making component-level decisions, eventually leading to the creation of three patentable technologies, specifically concerning the extremely advanced battery system developed to address mass requirements. In less than a year, better leadership and design methodologies had turned around the trajectory of the team, pivoting from its greatest failure to its greatest success thus far. Most of these successes can be attributed to the extensive work done early on to characterize *TiDE*'s design space, unlock a broader range of feasible designs through advanced control theory, and use a careful process to lock in a final design. UMEB is a testament to the application of Naval Architecture and Marine Engineering to the racing world.

CONCLUSIONS

It is an understatement to say that there are a lot of gaps between how marine designers and high-performance racing teams create craft. Viewing racing through an academic lens has the potential to open a lot of doors in the realm of optimization, marine control theory, and uncrewed applications. Translating their methods into a space understood by naval architects, with concepts like risk management and codesign, we can better analyze extremely high-performance systems and learn from them. Additionally, developing a framework to marine design methods, like set-based design, opens the door for more optimal racing craft to emerge. An understanding of the bridge between these two worlds is important in furthering advanced marine technologies.

CONTRIBUTION STATEMENT

EJB: conceptualization, lead designer for UMEB, methodology; writing – original draft. **AMV:** conceptualization; methodology; writing – review and editing. **KM:** Conceptualization; **DJM:** conceptualization; supervision; writing – review and editing.

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