Dimensional Optimization Process of a Boat for Riverine Combat Training Simulation

Proceso de optimización dimensional de una embarcación para simulación de entrenamiento de combate fluvial

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ABSTRACT

This work presents the basic design phase for the dimensional optimization of a training boat to be used in a riverine combat simulator prototype for operational training the of Colombian Navy. The prototype system will operate on a motion platform capable of realistically reproducing the dynamic and ergonomic conditions required for trainees to gain hands-on experience in riverboat operations. Through a geometric, structural, and kinematic qualitative analysis of three representative shallow-draft boat models, critical variables were identified, including load distribution, crew arrangement, and dynamic response. The resulting design reduces the scale and weight of the vessel for integration into commercially available three-degree-of-freedom platforms, prioritizing the pilot and bow gunner positions as key points of interaction. This optimization enhances mechanical control, system response agility, and energy efficiency, while simultaneously reducing manufacturing, transportation, and operational costs.

Keywords: design optimization, motion simulators, riverine training, scale reduction, system dynamics, virtual immersion.

RESUMEN

Este trabajo presenta la fase de diseño básico para la optimización dimensional de un bote de entrenamiento que se utilizará en el prototipo de simulador de combate fluvial para el entrenamiento operaciones de la Armada de Colombia. El sistema del prototipo funcionará con una plataforma móvil que tendrá que generar de manera realista las condiciones dinámicas y ergonómicas que permita a los aprendices acumular experiencia de operación de bote fluvial. Mediante un análisis cualitativo geométrico, estructural y cinemático de tres modelos representativos de botes de bajo calado, se identificaron variables críticas de carga, distribución de tripulación y respuesta dinámica. El diseño resultante reduce la escala y el peso de la embarcación para su integración en plataformas comerciales de tres grados de libertad, priorizando las posiciones de piloto y artillero de proa como puntos clave de interacción. Esta optimización permite mejorar el control mecánico, la agilidad en la respuesta del sistema y la eficiencia energética, al tiempo que disminuye los costos de fabricación, transporte y operación.

Palabras Clave: dinámica de sistemas, entrenamiento fluvial, inmersión virtual, optimización de diseño, reducción de escala, simuladores de movimiento.

1. INTRODUCTION

Operational training is essential for the performance of any armed force. As such, there are commercial technologies specialized in maritime operations, such as coast guard or port activities [1, 2]. However, in countries like Colombia, riverine environments are particularly significant, and training solely with these types of configurations reveals a disadvantage, as they do not align with the realities of rivers and other inland water bodies. These scenarios therefore require training specifically designed for them.

In this regard, the Colombian Navy (Armada de la República de Colombia - ARC) has various simulation equipments and infrastructures for training purposes, including: i) the laboratories of the Research, Development and Innovation Center for Maritime Activities (CIDIAM) in Cartagena, which allow for training in maneuvers and emergency handling in simulated maritime scenarios [3, 4]; ii) a Full Mission bridge simulator with a 360° immersive visual system for practicing maritime activities; and iii) a prototype flight simulator with low-cost pitch and roll movement, used to train spatial disorientation response at the Naval Aviation School located in Barranquilla, among others. When aiming for the closest approximation to the riverine combat experience, training in real environments and with actual units is preferred. However, this entails high operational costs, inherent risks for personnel and equipment, as well as logistical constraints due to the limited availability of vessels and maneuvering areas. These challenges led ARC to develop a custom in-house solution to train personnel in operating its riverine combat fleets.

In this context, this article describes the basic design process of a simulator prototype, considering the system's load optimization to strike a balance between the realism of real-boat training and the device’s laboratory-scale setup, ensuring its replicability within the Colombian Navy.

The article is organized as follows. Section 1 introduces the research context and outlines the motivation and objectives of the study. Section 2 reviews related works, establishing the theoretical and technological background and defining the current state of the art. Section 3 describes the methodological approach adopted for the dimensional optimization of the boat simulator, including the design assumptions and optimization criteria. Section 4 presents and discusses the main results, with particular emphasis on structural design adjustments, load distribution, and improvements in the simulator’s motion response. Section 5 provides a qualitative economic analysis of the optimized simulator, comparing its characteristics with those of full-scale simulators and real riverine vessels. Finally, Section 6 summarizes the main conclusions and outlines directions for future research.

2. CONTRIBUTIONS

The present study makes several significant contributions to the field of military training simulation, particularly in the context of riverine combat operations.

i. The study demonstrates that, for training in the operation of river vessels, the simulator can be reduced to the functions of a pilot and bow gunner. This saves on individual platform manufacturing costs and, consequently, facilitates the scalability of the solution for a large entity such as the Colombian Navy.
ii. Through the geometric and dynamic analysis of three representative models of shallow-draft vessels, the research identified weight distribution of the boat, crew arrangement, and the role approach to the operation, as critical variables. These variables determine which dynamic behaviors must be reproduced and which should be excluded for the boat's optimization so that it can be mechanically optimized on a two- or three-degree-of-freedom motion platform.
iii. The optimized simulator reduces manufacturing, installation, logistics, operating, and energy costs. This increases access to advanced training technology for institutions with limited budgets, while maintaining the realism of tactical training for the Colombian Navy. This, in turn, is key to increasing trainee training hours more economically and safely.

3. RELATED WORKS

The dimensional optimization of naval vessels has been the subject of intensive study over the last few decades, particularly in the context of military and training applications. Significant work in this field dates back to the studies by Peri and Campana [5], who developed multidisciplinary optimization methodologies for naval combat surface vessels, laying the foundations for the systematic analysis of structural and hydrodynamic variables.

In the specific field of naval training simulators, Yardley et al. [6] conducted a comprehensive study on the use of simulation for training in the United States Navy, identifying significant benefits in terms of cost reduction and improved training effectiveness. This work established the theoretical foundations for the development of simulation systems that faithfully replicate real operational conditions. Kong and Roh [7] propose a practical method for implementing a ship navigation simulator capable of producing realistic virtual data—useful for pilot training and testing detection, avoidance, and control algorithms when real-world trials are not feasible. This approach also enables large-scale, labeled dataset generation for machine-learning applications. The generation of virtual environments and synthetic data using virtual reality (VR) and simulated sensors (AIS, cameras, LIDAR, meteorological data) facilitates both crew training and validation of autonomous navigation systems.

In the context of riverine vessels specifically, Carreño Moreno et al. [8] conducted full-scale maneuvering tests of Colombian Navy riverine support patrol boats, providing valuable data on the dynamic characteristics of these vessels under real operational conditions. This work established crucial reference parameters for the development of simulators specific to riverine operations. Manoeuvrability is also studied by Chunai Wang et alters, in an article about numerical simulation to consider several water conditions to get more realistic attitude of the ship in simulated environment [9].

More recently, Tezzele et al. [10] have made progress in dimensional reduction techniques in heterogeneous parametric spaces with application to shape design problems in naval engineering. Their work has demonstrated the feasibility of applying advanced optimization methods to reduce dimensional complexity without significantly compromising operational characteristics.

4. METHODOLOGY

This work is based on a qualitative methodology focused on a case study of the boats currently used by the ARC for its riverine operations. The first step is a baseline characterization based on field study. Then a basic design stage of the simulator is made to distinguish between the primary parameters that must be maintained in the initial design and those that can be omitted prior to subsequent detailed optimization calculations. The final stage defines the option that accomplish the required necessity the best. This process is schematized in **Figure 1**.

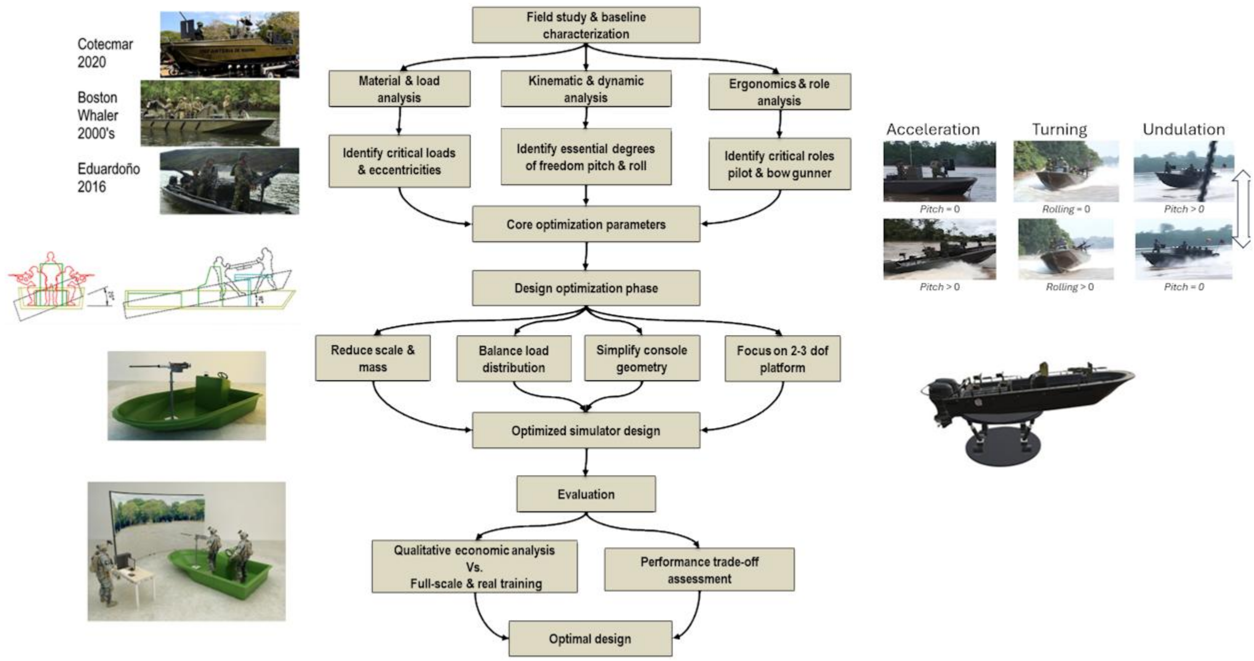

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Figure 1. Methodology scheme for riverine combat boats analysis and size optimization

Phase 1. Initial Analysis of case o boats, training and commercial motion platforms.

The engineering work begins with a comprehensive field survey and baseline characterization only of the main riverine boats currently used by Colombian army. The study focuses on three representative models: Boston Whaler in 2000's and 2010's versions [11], Eduardoño, 2016 version [12], COTECMAR (In spanish: Corporación de Ciencia y Tecnología para el Desarrollo de la Industria Naval, Marítima y Fluvial) low draft, 2020's version [13]. These units were analyzed to determine their dimensions, hull geometry, crew distribution and roles, and console design. The console was analyzed in whole and specific planes morphology, control layout, materials and design highlights.

Then the load distribution was studied based on materials, crew location on board, and needs of realism in action for training. Qualitative dynamic analysis was important based on kinetic modeling (as seen in **Table 2**) which shows the direct dependence that static and dynamic forces have on fundamental physic variables such as mass, position and velocity.

This was followed by a kinematic schematization for the behavior of the riverine boats motion simulator based on six fundamental degrees of freedom (see Figure 5) to determine the most relevant to obtain best tradeoff between simulation realism and load capacity of motion platform.

Phase 2. Basic boat simulator design and size optimization.

In this phase, the simulator design was optimized by translating the insights gained from the characterization of real boats into a reduced yet functionally representative model. The focus was placed on replicating the critical crew positions—specifically the pilot and the bow gunner—since these concentrate the highest operational and ergonomic demands. To achieve this, the boat's structure was strategically shortened and widened, preserving essential spatial relationships while improving stability and accessibility. This dimensional optimization not only ensured ergonomic functionality but also minimized the overall mechanical load on the motion platform, enabling smoother operation and reduced energy consumption.

By simplifying non-essential components and prioritizing the fidelity of movement and interaction at key stations, the design strikes a balance between technical feasibility, cost efficiency, and training effectiveness. This step laid the foundation for the integration of motion systems and control interfaces in later phases, ensuring the simulator could provide realistic and focused training scenarios without unnecessary structural complexity.

Phase 3. Qualitative valuation.

The final stage of the study consisted of a comparative qualitative analysis between three alternatives: the smaller optimized simulator, a simulator built at real boat scale, and the actual riverine training boat. The objective was to establish not only the technical and ergonomic differences among them, but also their relative value in terms of feasibility and efficiency for training applications.

To this end, a set of evaluation categories was defined, including quality of achieved performance, unitary manufacturing cost, impact on training space requirements, transport cost, and operational cost. For each category a 1 to 5 scale was made according to available (and/or reserved) information. This scale should be understood as: the more favorable criterion, the more points got in the scale. Thus, less transport cost, for example, is preferred to more cost, then lowest cost has higher points. Zero points are exceptionally used to express totally neglectable or outlier value. The scale is not necessarily linear.

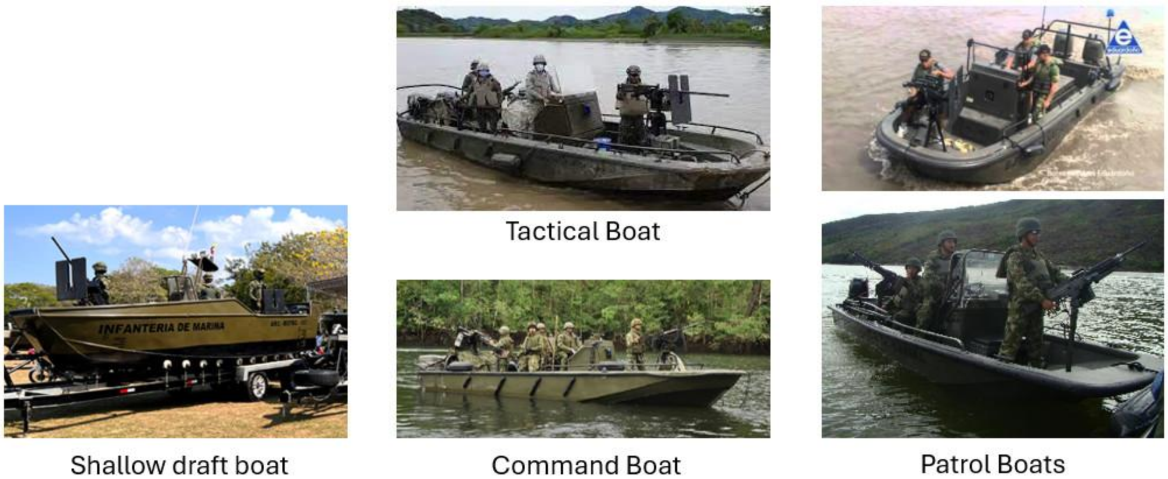
In this way, the valuation provided a structured framework for decision-making, guiding future choices between full-scale replication and optimized training-focused solutions.

5. RESULTS AND DISCUSSION

This section shows the principal outcomes derived from the analysis of riverine combat boats and the design of a training simulator. It highlights the vessels' geometry, structure, and ergonomics, and explains how crew distribution and load dynamics inform the modeling of pitch, roll, and heave. The section then shows how dimensional optimization enhances weight efficiency, motion fidelity, and crew interaction, concluding with the economic and operational benefits of the optimized design for cost-effective and realistic training.

Initial Analysis of Real Riverine Combat Boats

The first step is the analysis of the shallow-draft riverine fleet units used in the country. It was found that several similar models exist, but there was no geometric or ergonomic standardization until 2020 when a development project was launched in collaboration with COTECMAR for the on-demand production of shallow-draft boats [8, 11, 14]. Figure 2 shows the three main models of riverine units currently used in Colombia.



a) Shallow-draft riverine combat boat. Produced by COTECMAR since 2020. [12]

b) “Piraña”-type riverine combat boat. Adapted from the Boston Whaler model. Taken from Montenegro 2021 [10].

c) ECFL-type boat. Patrol boat 195. Manufactured by Eduardoño.
Taken from Eduardoño, Youtube 2016 [11].

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Figure 2. Riverine combat boats analyzed

The typical dimensions of the boats range from 3.5 m to 7 m in length, and from 1.6 m to 2 m in beam, while the depth is approximately between 1 m and 1.5 m, depending on draft limitations and the required buoyancy (see Figure 3-a). In the analyzed cases, typical crews range from 4 to 8 members. The roles are distributed as shown in Figure 3-b: bow gunner, pilot, commander, side gunners, and a commander or instructor in training scenarios. The Table 1 summarizes the results of the command console analysis, which aimed to identify opportunities for weight and space optimization in the training boat.

In the described cases, the following distribution of roles and weaponry is consistently observed: i) At the bow is the main machine gun, which carries the greatest offensive power and is therefore the heaviest, especially when accounting for ammunition. To facilitate its operation, it is mounted on an articulated support that relieves the gunner from bearing the weapon’s weight, allowing them to focus solely on aiming and firing based on professional judgment; ii) At the center of the boat is the console that holds various control and monitoring instruments. Apart from storage compartments for boat maintenance, this area does not bear significant loads; iii) At the stern are the infantry personnel who provide flanking fire coverage. The heaviest loads in this area come from the weight of the crew, their weapons, and ammunition. They are usually seated, with minimal movement, and symmetrically positioned along the longitudinal axis, so eccentricity is not a concern; iv) Fuel, ammunition, and other supplies are distributed as evenly as possible throughout the boat's volume, typically stored below deck.

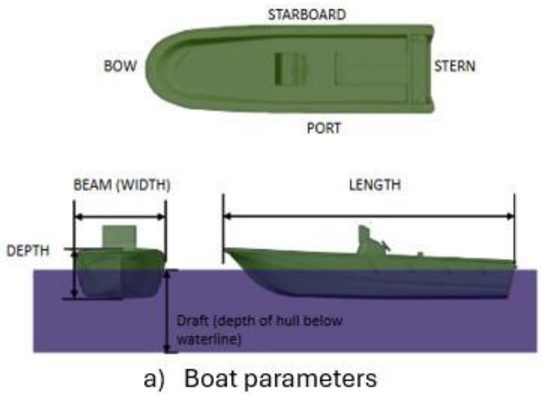

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Figure 3. Geometry and crew distribution of the combat boat.

Materials Analysis

The selection of materials for the construction of river combat vessels is a critical factor that determines not only the operational characteristics of the vessel, but also its viability for simulation applications. The materials used to build river combat boats are chosen to combine lightness, strength, and durability in hostile environments.

The hulls of shallow-draft vessels typically feature hulls made of epoxy polymer reinforced with fiberglass, stainless steel, and marine grade aluminum. According to Mouritz et al. [15], advanced composite materials offer significant advantages over traditional metallic materials in marine applications, including higher specific strength, better corrosion resistance, and superior damping properties.

Aluminum 5083, one of the most popular marine-grade aluminum alloys, is recognized for its high strength and superior corrosion resistance, making it a prime choice for boat hulls [16]. Glass fiber reinforced polymer (GFRP) composite materials have proven particularly effective for naval applications where weight reduction is critical. Galanis [17] documented that fiberglass composites can achieve weight reductions of 30-50% compared to equivalent aluminum structures, while carbon fiber composites can provide additional reductions of 30%. To maximize structural efficiency, sandwich structures are implemented using closed-cell PVC foam cores. Shkolnikov [18] has documented that these core materials provide exceptional stiffness while maintaining minimal weight. Stiffening supports are often integrated into the hull itself, and the cavities are filled with polyurethane foam to provide additional buoyancy and thermal and acoustic insulation.

Structural railings, raised platforms, metal supports, and protective structures for communication equipment also use this variety of materials, along with other polymers such as PVC, polypropylene, or polyethylene.

Table 1. Details of the consoles of the analyzed boats.

Criterion	**Boat models analyzed**			
	Boston Whaler analog dashboard, 2000. [11]	Boston Whaler digital dashboard, 2010. [11]	Eduardoño, 2016. [12]	COTECMAR low draft, 2020. [13]
Morphology	Trapezoidal	Trapezoidal	Flattened trapezoidal	Complex truncated-cone geometry
Dashboard inclination	40°-45°	60°- 80°	50°-60°	Stepped with recessed low wall
Control layout	Dashboard, steering wheel, and throttle on same plane	Dashboard separated above, lower steering wheel	Steering/throttle below; gauges above	Stepped layout similar to digital BW
Windshield	Aligned, sometimes absent	Inclined	With support structure forced by handrail	Inclined forward
Side planes	Handrails aligned with edges	Enclosed with structural handrail	Extended structure serving as handrail	Backward-inclined handrail on upper section
Console front	Straight to the floor	Ends at vertical third	Step-like protrusion for gunner	Backward-inclined handrail on upper section
Material	Fiberglass / closed-cell polyurethane foam	Fiberglass / closed-cell polyurethane foam	Fiberglass (modified V hull)	Aluminum (according to COTECMAR reference)
Main innovations	Integrated design, comfortable footing	Plane separation, optimized steering wheel position, slim appearance	Sectoral division of dashboard, step for gunner, support structure	Complex truncated-cone geometry, advanced stepped configuration

Source: the author's own creation

Load distribution analysis

The analysis of load distribution in river combat vessels during training operations has unique characteristics that differ significantly from conventional maritime vessels. The dynamic nature of military operations introduces complex variations in weight distribution that affect both the longitudinal and transverse stability of the vessel.

This analysis indicates that crew loads on the boat are not predominantly static but rather shift during operation. Typical load distribution includes: 1) Main weapon load: The bow-mounted machine gun typically weighs 150-200 kg including ammunition, concentrated in the forward 25% of the hull; 2) Crew load: 4-8 crew members with an average weight of 80 kg each, including 25-30 kg of personal equipment. 3) Fuel and supplies load: Distributed evenly in lower compartments, typically 200-400 kg depending on the required range.

The most significant movements are made by the bow gunner, who constantly rotates around the weapon's mount, introducing a persistent eccentricity in the weight distribution. In extreme—yet common—cases, the bow gunner exceeds their designated deck position by stepping onto the gunwale to achieve specific aiming angles. Additionally, the boat operates under dynamic conditions, with a center of rotation skewed toward the stern, which means that the bow gunner's movements contribute to eccentricity across much of the vessel's length [19]. The pilot also moves, though to a lesser extent, and their displacement is limited to their body's geometry, as their role requires constant contact with the steering and throttle controls. Moreover, training exercises may be conducted with a full crew or simulating casualties, which can further alter crew positions onboard (see Figure 4).

Source: the author's own creation

Figure 4. Schemes of displacements and crew viewpoints on a Combat Boat.

Boat movement analysis

Theoretically, a riverine combat boat exhibits all the degrees of freedom analogous to those of a seagoing vessel (see Figure 5). An observation of the system's kinematics shows that its motion can be reduced to three common movement patterns, as illustrated in Figure 7: i) Pitch: oscillation around the transverse axis, occurring during acceleration, braking, or when crossing over waves; ii) Roll: lateral tilt, associated with maneuvering and the natural sway of the hull around the longitudinal axis; iii) Heave: vertical translational motion, linked to vibrations, impacts, and local wave action [20].

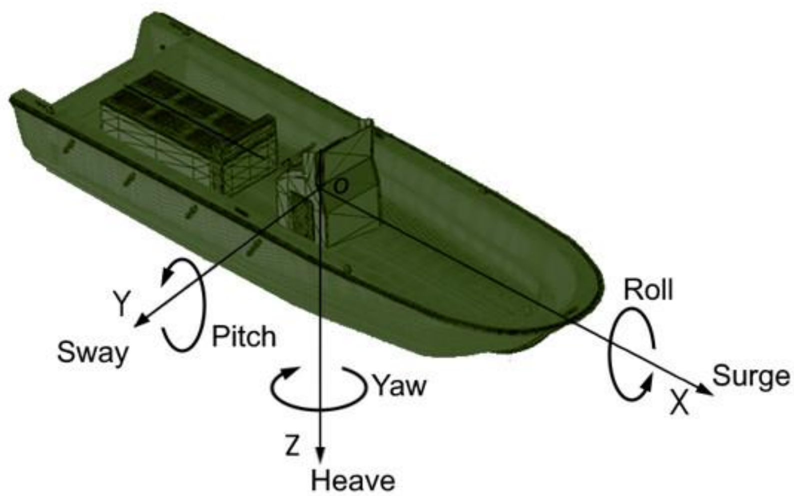

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Figure 5. Reference axes for the boat's motion analysis

Based on the above, two primary base movements can be identified: transverse rotation (pitch), which occurs when the boat accelerates or is subjected to wave undulation (see Figure 6); and longitudinal rotation (roll), which occurs when the boat tilts to port or starboard to reorient its heading. Heave is highly relevant in maritime navigation where translations, caused by tides or waves, can be several times the vessel's depth distance; however, in boats on a river, these displacements remain a small fraction of the depth (see Figure 3). Consequently, when it is necessary to simulate heave, it can be reasonably approximated through pitch disturbances.

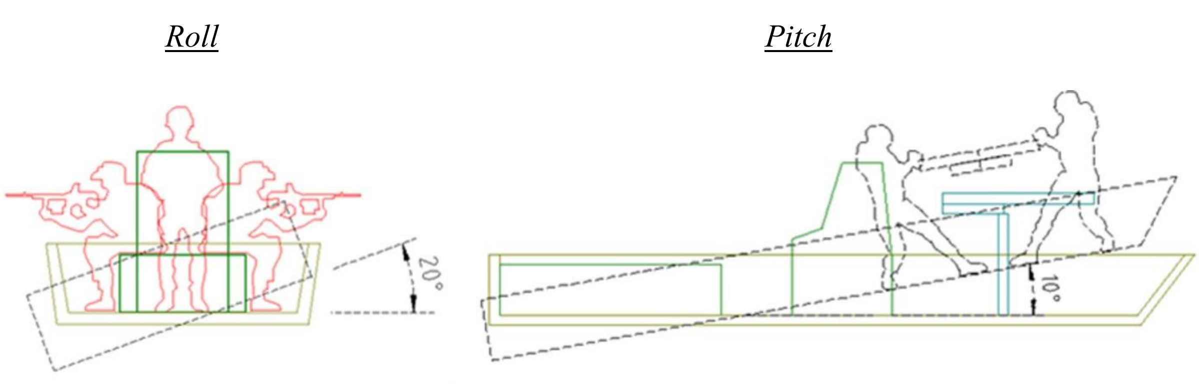

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Figure 6. Boat inclination angles based on the "Boston Whaler" model.

Source: the author's own creation

Figure 7. Observable turning movements of the boats under study

Realism and training need analysis

Before moving on to the design of the simulation system, it is important to highlight the roles that will most significantly experience the practical technology being developed.

The gunner needs to train shooting accuracy under dynamic conditions, perceiving in real time the mechanical disturbances and vibrations typical of an active riverine environment. Meanwhile, the pilot must train the maneuverability of the steering system and control of the throttle, with direct feedback based on the behavior of the simulated hull. Both roles rely on the simulator's ability to physically and immediately replicate the oscillations, inclinations, and forces that affect boat stability during actual operations.

This operational focus further justifies the dimensional optimization of the simulator: by centering the design only on the most critical points of interaction, it enhances motion transmission to relevant occupants, reduces total mass, avoids unnecessary eccentricities, and improves the system's responsiveness to commands and external disturbances. Thus, the simulator not only visually replicates a riverine combat scenario, but also allows for accurate training of reflexes, coordination, situational awareness, and decision-making in a sufficiently realistic environment prior to field training.

Boat movement simulation

The analysis of the boat's movement directly informs the simulator's design, as it directly impacts the fidelity of the training experience. The crew's relative field of view aboard the boat varies according to their specific roles. At all times the crew has the potential for 360º vision, although during operations each member must focus on their designated sector.

Considering that the simulator will be operated in a stationary setup, translational movements along the three axes are simulated through a computer-generated virtual environment, while the mechanical platform is responsible for rotational motions. This setup allows for the replication of the gunner’s experience, who commands the main firepower from the bow-mounted turret.

Located closer to the boat’s center, the pilot lacks direct frontal visibility during acceleration—when the bow lifts—and must rely on peripheral vision to port and starboard for guidance. The side gunners do not play a significant role in the decision-making process during training exercises (see Figure 8).

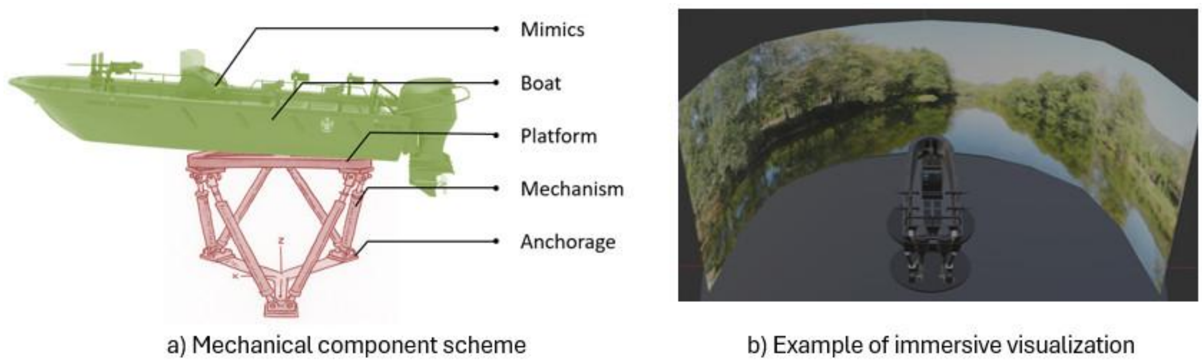

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Figure 8. Illustrative image of immersive simulation components.

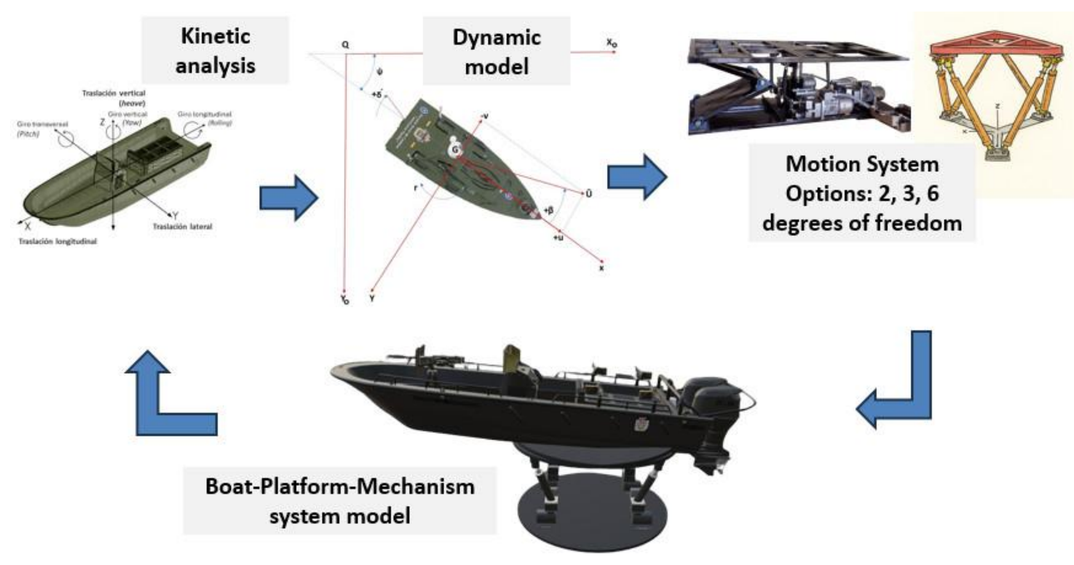

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Figure 9. Design and dynamic control diagram of the simulator's motion system.

Motion solution options are implemented using platforms driven by mechanisms with 2, 3, or 6 degrees of freedom (DOF), supported by a precision control system (see Figure 9). These systems have physical limitations regarding maximum accelerations (ranging from 4–6 m/s²) and angular motion amplitude (±15° to ±30° in pitch and roll), which must be respected to ensure simulator stability and actuator durability.

In this context, replicating a full-scale (1:1) riverine combat boat within a simulation system presents technical challenges. These challenges arise due to the structural characteristics of the vessels commonly used by ARC, which are typically designed to accommodate 6 or more crew members (see Figure 10). Thus, maintaining realism through full-size replication conflicts with laboratory scale limitations and the budget required to power a machine capable of supporting the weight, movements, and nonlinear dynamics involved.

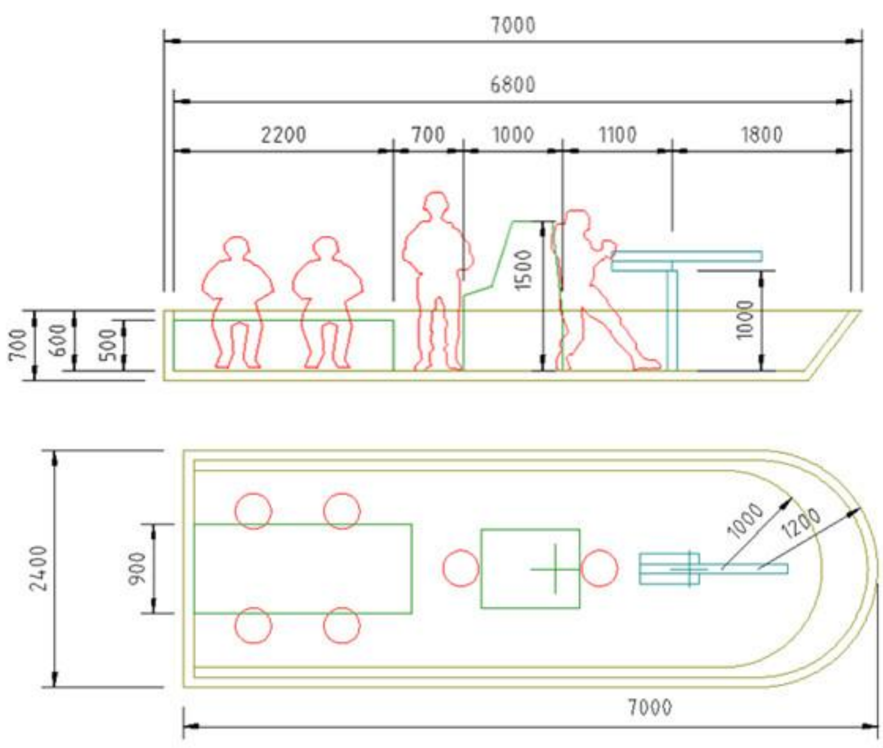

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Figure 10. Boat basic dimensions based on the “Boston Whaler” model (measurements in mm).

The simulator's mass directly impacts its ability to replicate these movements and maintain precise control (see Table 2). A strategic reduction in hull weight and size allows the actuators to accelerate more quickly and with lower energy consumption, reduces strain on the actuators, and increases the efficiency of motion transmission. Additionally, it improves the sensitivity and immediacy of the system's response to simulation software commands, thereby enhancing the credibility of the virtual environment.

Table 2. Kinetics equations of motion.

Velocity equation	$\boldsymbol{F} = \frac{\boldsymbol{d(s)}}{\boldsymbol{dt}}$
Force equation	$\boldsymbol{F} = \frac{d(m\boldsymbol{v})}{dt}$
Kinetic energy equation	$E_K = \frac{1}{2}mv^2$
Potential energy equation	$E_P = mgh$
Power equation	$P = \frac{d(E_K)}{dt}$

Source: the author's own creation

Finally, it is important to highlight that measurement systems, such as encoders or IMUs (Inertial Measurement Units), operate with greater precision in controlled mass environments. Excessive loads not only slow down the system but can also introduce positioning errors, resonances, or even failures due to saturation, compromising the user experience and the pedagogical value of the training.

Therefore, the boat's size is reduced to enable the use of a mechanical platform like those commercially available, while still having sufficient capacity to train at least two crew members: the pilot and the bow gunner, and optionally two side gunners. This is valid from a tactical training standpoint, as the users who require fully immersive experience are fundamentally the pilot and the bow gunner.

This design results in an average static weight of 800–900 kg, representing the weight of the boat, crew, and weapons. A dynamic component must also be considered, which can reach up to 50% of the total weight due to the active movements of users during training. Therefore, the platform's payload range should fall between 1 and 2 tons.

Figure 11 shows the optimized dimensions, highlighting the focus on two crew members: the pilot and the bow gunner. Optionally, two additional personnel may be accommodated at the rear, depending on the capabilities of the motion mechanism. The console is shortened by 70% along the longitudinal (lengthwise) axis and widened at the top. This configuration provides enough space to install the steering and throttle controls, while also allowing the lower section to be recessed, giving the pilot more room to position their feet and knees further forward—enhancing space efficiency and improving load optimization. The console and pilot's movement area are aligned with the center of the 3DOF platform to balance the load distribution. The bow section eliminates the space previously allocated for extreme maneuvering margins and ammunition storage, as these are not essential in virtual training. This change reduces the load eccentricities caused by the gunner's movements.

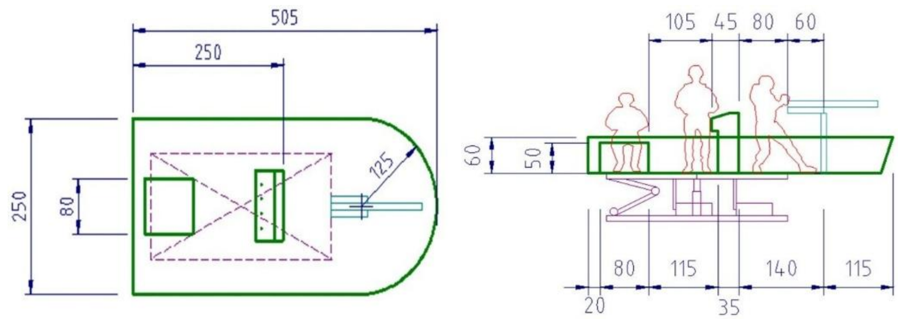

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Figure 11. Suggested boat basic dimensions optimized for 4 crew members on a 3-degree-of-freedom mechanism with a 1–2-ton capacity (Measurements in cm).

This dimensional optimization is complemented by increasing the density of the composite sheet material to allow for thinner walls, greater reinforcement, and reduced overall weight. Visual focus is directed toward the front bow section, eliminating the need for the gunner to fire rearward, which would otherwise introduce additional eccentric loading. Operational procedures will also be established to ensure the equipment is used within the allowable ranges of weight and dynamic stability.

Economic Analysis of Optimized Design

A final comparison is shown summarized in Table 3, where the optimized design shows advantages in costs because of trading in less necessary geometrics. These advantages are more important when compared to real boat in river training.

- Reducing the boat's dimensions to the optimal minimum enables precise mechanical control, provides trainees with essential prior experience, and thus allows for better utilization of field practice with real boats and weapons.
- Dimensional optimization leads to a reduction in the total manufacturing cost of the simulation system. This makes simulation technology more accessible to institutions with limited budgets, thereby optimizing investment in training.
- An optimized simulator requires less physical space in training facilities, which also reduces infrastructure costs and promotes group usage—something that is more difficult to achieve in real field scenarios.
- Transport costs—whether during initial installation or later for maintenance or relocation—are also reduced due to the smaller size of the boat.

- Finally, long-term operational costs are optimized, as the lower instantaneous power required to move lighter masses reduces the actuators’ energy consumption.

Table 3. Comparative valuation of optimized design vs real sized boat.

Criterion	Optimized boat on simulator (smaller)	Real sized boat on simulator (bigger)	Real boat on river
Total Weight	3«	5«	5«
Realism for all crew on board training	3«	4«	5«
Realism for bow gunner training	4«	4«	5«
Realism for pilot training	3«	4«	5«
360° visualization compatibility	5«	4«	5«
Mechanism complexity	4«	5«	3«
Mechanical controllability	5«	5«	5«
Dynamic forces controllability	5«	4«	3«
Complete crew capacity	3«	5«	5«
(Reduction of) Manufacturing cost of mechanical and control system	5«	3«	1«
(Reduction of) Maintenance cost of mechanical and control system	5«	3«	1«
(Reduction of) Space needed for simulator´s room.	5«	3«	0«
(Reduction of) Transport cost (as new or for moving)	5«	3«	2«
(Reduction of) Energy and power consumption	5«	4«	1«
(Reduction of) Users operational cost and logistics.	5«	5«	0«

The more favorable criterion, the more points got in the scale.
The scale is not necessarily linear.
Zero points indicate outlier minimum values.

Source: the author's own creation

6. CONCLUSIONS

The strategic decision to dimensionally optimize the riverine combat boat model for integration into a motion simulator—rather than replicating it at full scale—offers a fundamental advantage. This approach enables the efficient use of commercially available motion platforms by adapting to their load capacities and standard dimensions. It leads to a substantial optimization of the simulator’s dynamic response by reducing system inertia, resulting in a more accurate and agile recreation of the boat's dynamics, and also significant acquisition and operational costs reductions. The basic design shown in this work is the previous step to further detailed design.

This innovation is essential for developing advanced, accessible training tools for military forces engaged in riverine combat. It aligns fully with the Colombian Navy’s continuous improvement programs and strategic vision for personnel training.

Future research line

While the current design relies on a 3DOF platform to replicate pitch and roll with approximated heave, future efforts could explore the integration of full 6DOF systems to achieve greater realism, especially for extreme maneuvers or high-intensity riverine conditions. Another area for development is the incorporation of advanced sensory feedback, such as haptic systems or force-feedback weapon mounts, to further immerse gunners and pilots in combat scenarios. Additionally, this work did not implement real-time hydrodynamic modeling of shallow-draft boats under varying river conditions, which could enhance fidelity when coupled with environmental simulations of currents, obstacles, and weather effects. On the materials side, the simulator prototype could benefit from research into lighter composite structures that combine durability with reduced energy demand. Finally, a broader validation campaign involving active naval crews would provide empirical data to refine ergonomic layouts, training protocols, and performance metrics, ensuring the simulator evolves from a proof of concept into an operationally validated training asset.

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