Research article

Advances of the Armada de la República de Colombia in the Design and Implementation of an Immersive Riverine Combat Boat Simulator Prototype

Avances de la Armada República de Colombia en el Diseño e Implementación de un Prototipo de Simulador Inmersivo de Bote de Combate Fluvial

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Abstract: La Armada República de Colombia (ARC) is globally recognized for its active role against illegal groups. Due to the need for adaptability in diverse geographical environments, the training of its personnel, and efficiency in resource utilization, the ARC is developing an advanced technological option to complement and enhance riverine combat training at the Marine Infantry training schools. This is achieved through the integration of a mechanical degrees-of-freedom system with immersive visualization generated by virtual scenario-generative software, and the reinforcement of river combat doctrine in the country's rivers. Emphasis is placed on the roles of the pilot and gunner, allowing instructors to monitor the development of skills and knowledge required on the battlefield while respecting human rights. Currently, the project is under development and progress has been made in the design of the mechanical platform, the instrumentation required for pilot training, and integration with a combat simulator. The interconnection network has been designed, and the visualization systems have the selected equipment ready for implementation. Tests of the mentioned components through a scale prototype show how effective these types of simulators are in qualitatively enhancing training in military schools.

Keywords: Immersion; River combat; Simulator; Technology; Training

Resumen: La Armada República de Colombia (ARC) es reconocida mundialmente por su papel activo contra grupos al margen de la ley. Por necesidades de adaptabilidad en entornos geográficos diversos, de capacitación de sus hombres, y por eficiencia en el uso de recursos, la ARC desarrolla una opción tecnológica avanzada para el complemento y la mejora del entrenamiento de combate fluvial en las escuelas de formación de infantería de marina mediante la integración de un sistema mecánico de grados de libertad con visualización inmersiva generada por software generativo de escenarios virtuales y el refuerzo de la doctrina de combate en los ríos del país. Se hace énfasis en los roles del piloto y artillero, permitiendo que al personal instructor el seguimiento del desarrollo de habilidades y conocimientos requeridos en el campo de batalla y en el respeto de los derechos humanos. Actualmente, el proyecto se encuentra en desarrollo y se han logrado avances en el diseño de la plataforma mecánica, la instrumentación requerida para el entrenamiento del piloto y la integración con un simulador de combate. La red de interconexión se encuentra diseñada y los sistemas de visualización ya cuentan con los equipos seleccionados para su implementación. Las pruebas de los componentes mencionados a través de un prototipo a escala, muestra lo efectivo que son este tipo de simuladores en el incremento cualitativo del entrenamiento en las escuelas militares.

Palabras clave: Combate fluvial; Entrenamiento; Inmersión; Simulador; Tecnología

1. Introduction

The public order situation experienced by the country over recent decades has positioned the Colombian National Navy (Armada Nacional de Colombia, ARC) as an international benchmark in riverine warfare [14], as well as in the training of Marine Corps personnel for the acquisition and development of the competencies required to integrate a riverine unit [17], ranging from boat handling to weapons synchronization [9]. The costs associated with this training such as equipment wear, personnel transportation [13], and preventive and corrective maintenance, are typically high. In addition, the limited availability of resources such as fuel and ammunition [6] restricts feedback opportunities and, consequently, hinders the assimilation of riverine doctrine and the correction of critical errors, such as proper boat positioning for firing or enabling the gunner to effectively engage targets [7]. Furthermore, the availability of these courses at the Riverine Combat School (ESCOFLU) is constrained by the four boats assigned for instruction in riverine combat, riverine pilot, and riverine gunner courses [11].

This context encourages the implementation of simulation technologies that facilitate student learning while reducing the costs and risks associated with full training aboard a riverine combat boat. Although ARC schools have virtual training rooms [8], these do not provide a fully immersive experience and, in most cases, are acquired from foreign manufacturers, which limits the customization, modification, and updating of training missions [1].

In this regard, previous reviews on virtual reality have highlighted its relevance in education, military training, and professional instruction, mainly because of its capacity to simulate complex scenarios and reproduce specific conditions required by instructors for repeated and controlled practice [18].

This project aims to design a prototype of an immersive riverine combat boat simulator, to be developed domestically by Navy personnel and collaborators within naval facilities. This approach ensures the development of a simulator model tailored to the needs of riverine combat doctrine, the competencies established in academic curricula, the evaluation rubrics defined by instructors, and the learning styles of students.

The structure of this article is organized as follows: Section 2 presents the main contributions of this work. Section 3 describes the methodology used for the design of the mechanical platform, virtual environment, visualization system, and scale prototype. Section 4 presents the results of the design process and the scale prototype implementation. Finally, Section 5 summarizes the conclusions and outlines perspectives for continuing the development of the full-scale immersive simulator.

2. Contributions

This work presents the following contributions:

- i The design of an immersive riverine combat boat simulator prototype, integrating a mechanical motion platform with a virtual simulation environment to support pilot and gunner training.
- ii The development of a Stewart-type mechanical platform concept with two to three degrees of freedom, capable of reproducing realistic motion dynamics and supporting representative operational loads.

iii The definition of a semi-immersive visualization and simulation architecture, aligned with riverine combat doctrine, enabling the generation of performance metrics for training and evaluation.

iv The implementation and validation of a scale prototype, demonstrating the feasibility of system integration, motion control, and interaction between the mechanical platform and the virtual combat simulator.

3. Methodology

The prototype design consists of the following essential components: a mechanical platform that emulates the movements of the BOSTON WHALER Piraña-type boat used by the Navy in riverine combat, enabling training in the pilot role; a virtual environment that simulates the natural combat scenario, including details characteristic of Colombian geography, providing an immersive experience together with a visualization system; and a gunnery training system that interacts with the virtual simulation and generates evaluation metrics for the riverine gunner role.

3.1. Mechanical Motion Platform

Given the dynamics of the boat, motion simulation can be approximated based on two of the six axes shown in Figure 1. These basic movements are: rotation about the y axis or transverse axis (pitch), which occurs when the vessel is accelerating or when it is subjected to the undulation of the water surface; and rotation about the x axis or longitudinal axis (roll), which occurs when the boat heels to reorient to port or starboard [21]. Strictly speaking, motion can occur along all axes; however, these two are the most significant in this case, since in a river the dynamic effect of tides and large waves on the boat is much smaller than at sea. Additionally, this reduced effect can be sufficiently simulated through the relative motion of the visual projection of the environment. Nevertheless, in the pursuit of increased realism, a third basic order of motion may be added: translation along the z or vertical axis (heave) [15]. The result of the above analysis indicates that the mechanical platform should provide two to three degrees of freedom to produce an immersive experience.

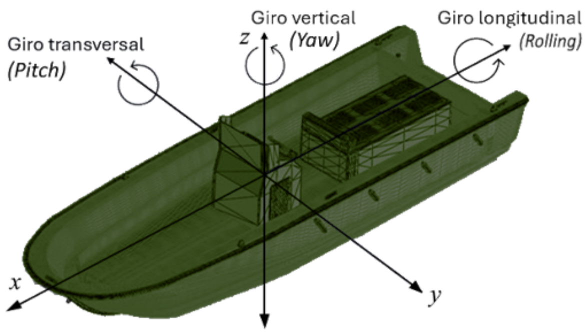


Figure 1. Reference axes for the analysis of boat motion.
Source: The authors.

3.2. Weight Analysis of the Mechanical Platform

In the weight analysis of the elements that make up the simulator prototype, conducted to determine the capacity and type of actuators to be implemented, it was established that the mechanical platform would support a crew weight between 800 kg and 1,000 kg, depending on the number of people on board, their body weight, and protective equipment. The weight of weapons and ammunition ranges from 100 kg to 300 kg [10], depending on the type of weapon and the roles of each crew member within the boat's tactical configuration [10;12]. The estimated weight of the boat model itself is between 100 and 150 kg. Altogether, the static load would be approximately 900–1,100 kg. Additionally, the dynamic load must be considered; taking into account the type of motion, the expected acceleration should not exceed 5 m/s^2. This corresponds to approximately 50% additional load [2]. Consequently, the initial analysis of mobile platform options focuses on a payload range of 1 to 2 tons. Lower payload capacities are also possible; however, they would limit the amount of equipment on board and the range of exercises that could be conducted in the simulator prototype, as weight would need to be reduced to match the load capacity.

3.3. Virtual Simulator

A comparison was conducted among available software solutions for the generation of virtual combat environments [4]. Although these platforms offer different options in mission creation and levels of realism, all require a computer capable of rendering and processing large-scale graphical data, as well as sufficient connectivity to interact with users through peripherals assigned to each role. Therefore, a design criterion is that the system must be equipped with a state-of-the-art processor and graphics card, as well as a display with a refresh rate above 144 Hz, high resolution to achieve the required level of detail and clarity such as Full HD (1920×1080) and 4K Ultra HD (3840×2160) and a screen size greater than 32 inches.

The simulation software must generate the operational environment of the boat along the river and surrounding areas, interacting with the mechanical platform [19] and the gunner's role, while accounting for the pilot's possible maneuvers. It must generate target contacts and evaluation metrics to assess firing effectiveness. Gunner training requires a sensor system capable of tracking weapon position and shots fired, following the gunner's actions in real time in response to training exercises and enabling optimal performance evaluation [3].

3.4. Visualization System

The implementation of an immersive simulator prototype in military training aims to generate a sense of immersion [20] among the crew, reflecting their roles and spatial distribution from their respective viewpoints, as shown in Figure 2. In this project, particular emphasis is placed on the pilot's role in executing boat maneuvering operations and on the gunner's role in the detection and engagement of contacts. A semi-immersive category was selected, employing special display devices such as wall-sized screens [16].

Figure 2. Crew positions on the riverine combat boat [5].
Source: The authors.

4. Results

The project is currently in the execution phase; therefore, the final immersive riverine combat boat simulator prototype has not yet been completed. However, a set of designs, a scale prototype, and selected equipment can already be identified, which are expected to lead to a successful final product.

4.1. Mechanical Platform Blueprints

Based on the load and motion analyses conducted, it was determined that the mechanical platform would correspond to a three-degrees-of-freedom Stewart-type platform, capable of supporting a load between 1,000 kg and 2,000 kg. The platform would use three three-phase motors rated between 3 HP and 4 HP, each equipped with a brake and encoder, and controlled by variable frequency drives. Figure 3 shows the platform schematic, the distribution of the motors, and the mechanical joints that enable the movements required to provide an immersive experience for users in their different roles.

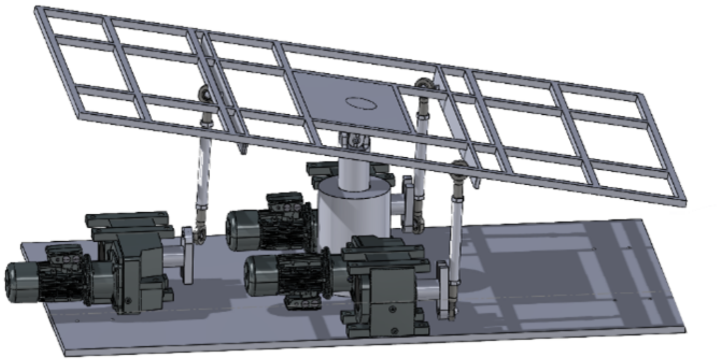


Figure 3. Mechanical platform diagram.
Source: The authors.

4.2. Virtual Simulation Network Design

According to the hardware requirements defined by the selected virtual environment generation software, as well as the roles established by the nature of military doctrine training and naval schools, the network design shown in Figure 4 was determined. This design includes a server connected through a router to the systems assigned to the pilot and riverine gunner roles, as well as the projectors selected for visualization via Wi-Fi.

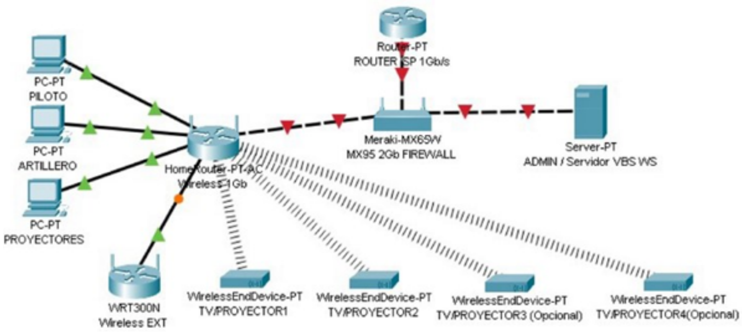


Figure 4. Virtual simulation network diagram.
Source: The authors.

The equipment required for the server was selected with the following technical specifications: Intel Core i9-12900K processor, 64 GB DDR4 RAM, NVIDIA GeForce GTX 1080 GPU, and a 5 TB SSD. The client systems have similar specifications, except for graphics processing capacity, as they are equipped with an NVIDIA RTX 3080 GPU, since these systems handle video processing and include local storage of 1 TB SSD, as they only require storage of local information.

4.3. Visualization Design and Equipment

Plans were developed to define the location of the projection surface relative to the positions and viewpoints of the pilot and gunner, based on proper visualization requirements. Figure 5 shows the dimensions of two alternative screen configuration options. The semicircular or C-type configuration involves visualization from a single viewpoint, with a radial horizon. The split or U-type configuration is based on two or more viewpoints; in this case, the lateral viewpoints have their own visual fields that extend the forward (bow) view. The final determination of the visualization type is still under study.

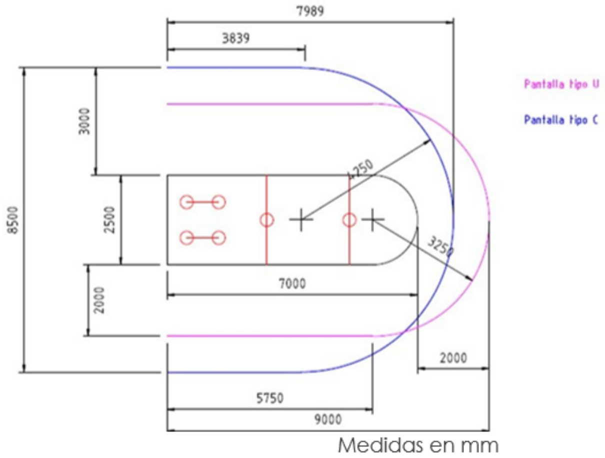
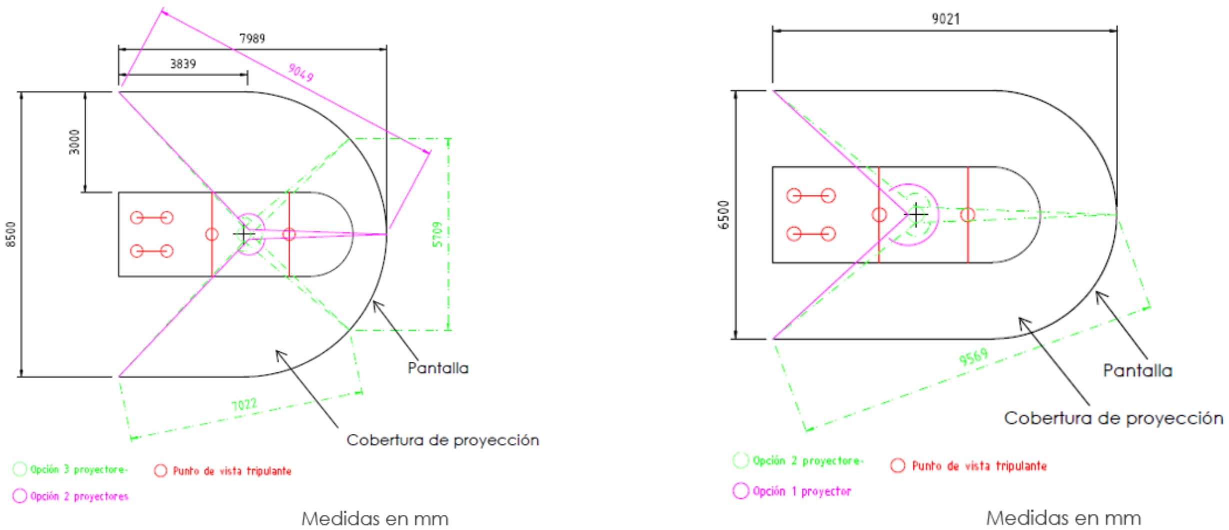


Figure 5. Visualization system layout.
Source: The authors.

The type of screen determines the available projection equipment options and their quantity. Figure 6a shows the projection layout for a C-type screen, which may use two or three projectors, whereas Figure 6b represents the projection options for a U-type screen, with configurations using one or two projectors.



(a) Projection options for C-type screen. **(b)** Projection options for U-type screens.
Figure 6. Projection configurations: a. Projection options for C-type screen. b. Projection options for U-type screens.
Source: The authors.

4.4. Scale Prototype

The evolution of the project involves integrating the mechanical platform with a virtual simulation scenario through peripherals and electronic instrumentation elements in order to provide an immersive experience for the user. This level of complexity made it necessary to build a scale platform to facilitate the design of electronic instrumentation, as well as the development and evaluation of control algorithms for the platform and the configurations required for communication with the virtual simulator.

Figure 7 presents the functional diagram of the control system implemented in the scale prototype. Three main blocks can be distinguished: remote control, control and power, and the motion unit.

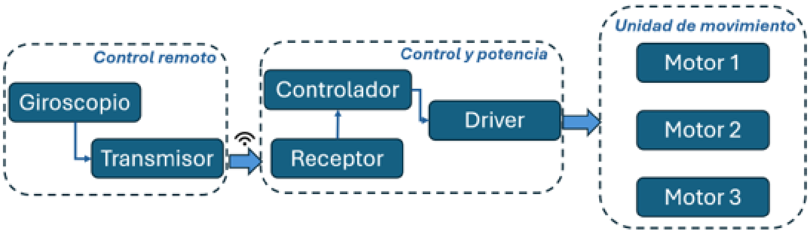


Figure 7. Motor control circuit.
Source: The authors.

The remote control block integrates a gyroscope coupled to a transmitter module, which wirelessly sends orientation and acceleration information to the receiving system. This scheme allows the movements detected by the controller to be replicated on the scale platform, facilitating the validation of stability algorithms and dynamic response. In the control and power block, the receiver delivers the data to the controller, which is responsible for interpreting the signals and generating command instructions to the driver. The driver, in turn, supplies the power required to actuate the motors. The motion unit is composed of three electric motors that represent the main actuators of the system, reproducing the degrees of freedom required to simulate the movements of the combat boat.

Figure 8 shows the scale prototype of the mechanical platform, featuring three servomotors and mechanical connectors similar to those that would be used in the final prototype.

Figure 8. Functional scale prototype.
Source: The authors.

For platform control, a circuit based on the micro:bit V1.5 development board was designed to control the motors, as shown in Figure 7, and to transmit orientation data from another board using an RF communication protocol.

The system was integrated with a computer to link the movements of the platform with those of the combat simulator, demonstrating successful results of the integrated system, as shown in Figure 8.

5. Conclusions

This paper presents the design and preliminary implementation of an immersive riverine combat boat simulator prototype aimed at improving training processes within the Colombian Navy. The proposed system integrates a mechanical motion platform, a virtual simulation environment, and a semi-immersive visualization system, offering a cost-effective and flexible alternative to traditional training methods.

The motion and load analyses support the selection of a Stewart-type platform with two to three degrees of freedom, capable of realistically reproducing the most relevant riverine dynamics. Additionally, the development of a scale prototype validated the control architecture and system integration, demonstrating the technical feasibility of the proposed solution and its potential for future full-scale implementation and doctrinal alignment.

Author Contributions: Luis Escorcia: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Aldo Lovo:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition.
All authors have read and agreed to the published version of the manuscript. Please refer to the CRediT taxonomy for the definitions of the terms. Authorship should be limited to those who have made substantial contributions to the reported work.

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Institutional Review Board Statement: Not applicable, since the present study does not involvehuman personnel or animals"

Informed Consent Statement: This study is limited to the use of technological resources, so nohuman personnel or animals are involved.

Conflicts of Interest: Under the authorship of this research, it is declared that there is no conflict of interest with the present research.

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