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Development of an advanced flight training simulator for the c-130H aircraft: an approach to optimizing training capabilities for the Colombian Aerospace Force

Desarrollo de un simulador avanzado de entrenamiento de vuelo para la aeronave c-130H: un enfoque en la optimización de capacidades de entrenamiento para la Fuerza Aeroespacial Colombiana

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Abstract: The research project focuses on the design, development and implementation of an Advanced Training Device (AATD) for the C-130H Hercules aircraft, key for the Colombian Aerospace Force in tactical, humanitarian and rescue missions. This simulator seeks to reduce dependence on external equipment, optimize resources and costs, and improve local training through training adapted to national scenarios. The AATD integrates advanced technologies, such as XPlane 12, Air Manager, and Immersive Calibration, and is designed to replicate real-world flight conditions, develop critical skills, and ensure operational safety. Its methodology includes conceptual design, software and hardware development, testing and implementation, achieving intensive and effective training for pilots and technicians. In addition, it fosters technological innovation within the FAC, consolidating its preparation to face various operational situations with efficiency and competence.

Keywords: flight simulator, flight controls, flight conditions, control panel.

Resumen: El proyecto de investigación se centra en el diseño, desarrollo e implementación de un Dispositivo Avanzado de Entrenamiento (AATD) para la aeronave C-130H Hércules, clave para la Fuerza Aeroespacial Colombiana en misiones tácticas, humanitarias y de rescate. Este simulador busca reducir la dependencia de equipos externos, optimizar recursos y costos, y mejorar la capacitación local mediante entrenamientos adaptados a escenarios nacionales. El AATD integra tecnologías avanzadas, como XPlane 12, Air Manager e Immersive Calibration, y está diseñado para replicar condiciones reales de vuelo, desarrollar habilidades críticas y garantizar la seguridad operativa. Su metodología incluye diseño conceptual, desarrollo de software y hardware, pruebas e implementación, logrando un entrenamiento intensivo y eficaz para pilotos y técnicos. Además, fomenta la innovación tecnológica dentro de la FAC, consolidando su preparación para enfrentar diversas situaciones operativas con eficiencia y competencia.

Palabras clave: simulador de vuelo, controles de vuelo, condiciones de vuelo, panel de mandos.

1. INTRODUCTION

The C-130 Hercules aircraft is critical to the Colombian Air Force due to its versatility and operational capability. This aircraft is essential in tactical and transport missions, allowing for the rapid deployment of troops and equipment in various conditions, including unprepared runways. In addition, the C-130 Hercules is crucial in humanitarian aid operations, rescue and response to natural disasters, strengthening the Aerospace Force's ability to maintain safety and support the population in emergency situations [1].

That is why the implementation of an Advanced Training Device (AATD) is crucial for the Colombian Aerospace Force for several reasons:

- Reduced Reliance on External Simulators: Currently, the need to use external simulators involves high costs and complex logistics. An in-house AATD would allow training to be carried out more efficiently and economically, eliminating the need for travel and rental of external equipment.

- Increased Local Training Capacities: Having an AATD locally increases the frequency and quality of training. Pilots and maintenance personnel can carry out more regular and specific practices, adapted to the needs and operational scenarios of the Colombian Aerospace Force.

- Adaptation to National Scenarios: An AATD can be configured to simulate conditions and missions specific to the Colombian environment, improving the preparation of personnel for real situations that they could face in the country.

- Improved Safety and Operational Efficiency: Constant practice on an AATD allows pilots and technicians to hone their skills without the risks associated with real flights. This not only improves safety, but also optimizes operational efficiency by reducing wear and tear on real aircraft [2].

- Development of Technical and Technological Capabilities: The implementation and maintenance of an AATD fosters the development of technical and technological capabilities within the Aerospace Force, promoting innovation and specialized knowledge.

Flight simulators are essential tools in crew training, allowing training in a controlled and safe environment. Likewise, the existence and importance of the different types of simulators should be highlighted, each with specific characteristics and applications:

Full Flight Simulators (FFS): These simulators are the most advanced and realistic, accurately replicating the behavior of the aircraft in various flight conditions. They are used to train pilots in complex and emergency situations, improving decision-making and coordination in the cockpit [3].

Flight Training Devices (FTDs): Although these are less sophisticated than FFS, the devices provide a realistic flight experience without full motion [4]. They are ideal for training basic procedures and maneuvers, as well as for familiarization with aircraft systems.

Basic Aviation Training Devices (BATD) and Advanced Aviation Training Devices (AATD): These simulators are mainly used for initial pilot training. BATDs are simpler and are used for teaching the fundamentals of flight, while AATDs offer greater complexity and realism, allowing for more advanced practices.

Mission-Specific Simulators: Designed to train crews on particular missions, such as rescue, combat, or cargo transport operations [5]. These simulators allow pilots and support personnel to practice in specific scenarios and develop skills critical to their roles.

1.1. Background on Simulator Training in Military Aviation

Going back to the beginning, the use of simulators in military aviation began to gain relevance during World War II with the creation of the "Link Trainer", a device that simulated mechanical movements and allowed pilots to practice flight maneuvers in a safe environment. Since then, simulation technology has advanced significantly, incorporating electronic and digital systems that offer increasingly realistic training experiences.

In short, the use of simulators will continue the transformation in military training, allowing for more intensive and specialized training. In this process, it is important to clarify that simulators not only prepare pilots for routine flight situations, but also for complex and high-risk missions, thus improving the operational capability and safety of the armed forces.

In addition to that, in the process of adapting and implementing technology in military training protocols, the use of simulators in such training has been a fundamental practice for decades, maintaining an optimal, controlled and safe learning environment for the development of activities related to flight and air combat, exempting the risks associated with real operations. allowing ease of access and reduction of costs on operations.

1.2. Benefits of Using Simulators

Based on the background, the relevance of simulators in military formations in terms of clarifying their benefits.

Safety: Simulators eliminate the physical hazards associated with training on real aircraft.

Cost-Efficiency: Training in simulators reduces operating costs, such as fuel and aircraft wear and tear.

Flexibility: They allow the recreation of a wide variety of scenarios and flight conditions, including emergency and combat situations.

Repeatability: Pilots can repeat maneuvers and exercises as many times as necessary to hone their skills.

2. METHODOLOGY

In order to carry out the implementation plan of the AATD simulator in the Colombian Air Force, effectively, the requirements that are pertinent for its proper execution must be clarified, starting from the definition of the objectives and needs of the simulator. Within this process, the activities to be developed are based on gathering information from end users, analyzing the technical specifications of the aircraft, and establishing the parameters of performance and functionality of the simulator, resulting in a detailed document of requirements that will guide the entire development process.

Likewise, in the Design and Implementation of this, it is proposed to create the conceptual and technical design of the simulator. In its execution, conceptual models, flow diagrams and technical specifications are developed, implementing the design using specialized software and appropriate technologies. As a result, a working prototype of the simulator is obtained that meets the established requirements.

As a result of the above, tests and adjustments are carried out, where the operation of the simulator is verified and validated, to proceed with the performance of exhaustive tests where errors can be identified and corrected, adjust the simulator to ensure that it meets quality standards and user expectations, complying with a fully functional simulator optimized for operational use.

In short, the research advances to the Generation of Knowledge Deliverables whose purpose will be to document and transfer the knowledge acquired during development through user manuals, maintenance guides and technical reports, which will be functional to train personnel in the use and maintenance of the simulator, obtaining as a result the complete documentation and the personnel trained to operate and maintain the simulator efficiently.

3. THEORETICAL FRAMEWORK

The C-130H Hercules is a tactical transport aircraft that has played a crucial role in military aviation since its introduction in the 1950s. From its versatility and payload capacity, the C-130H is known for performing a wide range of missions as it can transport troops, equipment, supplies, and vehicles, making it a critical piece for military logistics operations. Its maximum payload capacity is approximately 38,556 kg, allowing it to carry large volumes of military and personnel material.

Among its strengths are its ability to operate in extreme conditions and on short and unprepared airstrips. This makes it ideal for missions in conflict zones and remote areas where airport infrastructures are limited. In addition to its military applications, the C-130H has been used in numerous humanitarian and rescue missions. Its ability to transport large quantities of supplies and its ability to land on makeshift airstrips make it ideal for relief operations in natural disasters.

That is why, over the years, the C-130H has undergone various updates and modernizations to maintain its relevance and operability. These improvements include the upgrade of its engines, avionics systems and surveillance capabilities, thus having a strategic and significant impact on the operational capability of the armed forces of many countries, as their ability to perform critical supply, medical evacuation and troop transport missions has redefined the logistical and tactical possibilities of the air forces.

4. SIMULATION SOFTWARE SYSTEM

4.1. XPlane12

It is the latest version of the flight simulator series for Windows, Mac, and Linux. Simulation software is the core of the AATD, responsible for accurately replicating the behavior of the aircraft, its systems and recreating the operational environment of the aircraft allowing graphics to be generated according to the simulator's requirement [6].

Key features include:

C-130 Aircraft Systems Simulation: The software simulates engines, control systems, navigation systems, flight instruments and automatic control systems (autopilot, autothrottle) [7].

Fig. 1 *Model of the aircraft.* ***Source****: Xplane website*

Flight Procedures: Allows for the practice of normal, abnormal, and emergency flight procedures, including engine and system failures [8].

Instructor Operation Interface (IOS): An instructor control station that allows monitoring and modifying flight conditions, entering faults, and evaluating pilot performance [9].

Fig. 2 *Airport scenarios.*
Source*: Own elaboration*

4.2. Airmanager

Instrument Panel Customization: A versatile and powerful tool used in flight simulators to create and customize 2D instrument panels. This app allows users to design their own panels or modify existing ones, providing a more realistic and immersive flight experience. Air Manager automatically connects to flight simulators such as X-Plane, FS2020, FSX, and Prepar3D [10], allowing control of instruments through the use of mice, touch screens and devices such as the Knobster1. In addition, its ability to integrate additional hardware, such as buttons, switches and rotary encoders, makes it easy to create a highly interactive training environment that is adaptable to the specific needs of pilots and technicians.

Fig. 3 *Instruments in Airmanager.*
Source*: Own elaboration*

4.3. Imaging

The projector is used LS832WU which uses the second generation phosphor/laser technology that provides 30,000 hours of life, higher brightness, better heat resistance and instant on/off in a more compact design, the main feature to be used is the ultra short throw of 0.25 offers 100" images at a distance of only 28 cm in high definition [11]. For the projection of the visual environment, three projectors were used on a circular screen.

4.4. Screen design

The design of the screen is of the circular type with a metal structure with a pressed curtain as seen in the following figure, which provides the pilot personnel with a 180° visual projection, being required to carry out the process of alignment with the cockpit to determine the appropriate position generating a real environment of the flight operation.

Fig. 4 *Screen designed.*
Source: *Own elaboration*

4.5. Immersive Software Calibration

Geometric Correction: An advanced tool used in flight simulators to ensure accurate and realistic visualization through geometric correction and edge blending in multi-projector setups [10]. This software allows for automatic alignment of the three projectors using cameras to scan and adjust the projection, ensuring that images are displayed distortion-free and with correct perspective. Immersive Calibration PRO's ability to handle complex configurations of curved screens and multiple views significantly improves immersion and training quality, providing pilots with a simulation experience closer to reality.

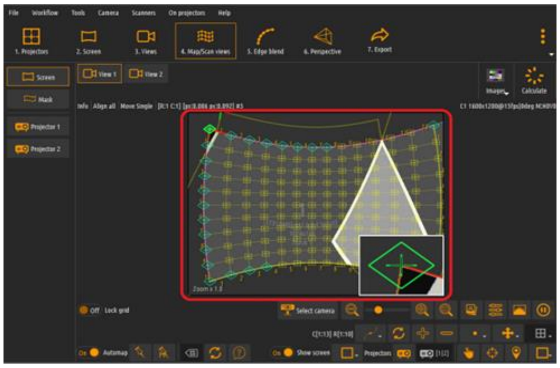

Fig. 5 *Immersive Calibration.*
Source*: Software website*

In this phase, the soft edge mixture is carried out, providing a mesh of control points. By adjusting the position of the control points, the projected screen can be mapped onto the curved surface.

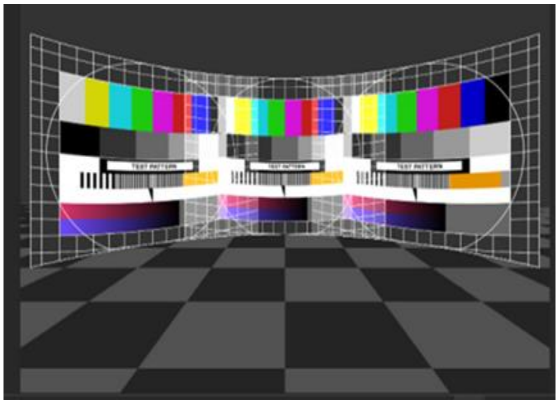

Fig. 6 *Corrected light projection.*
Source*: Software website*

4.6. Aircraft cabin design and manufacture

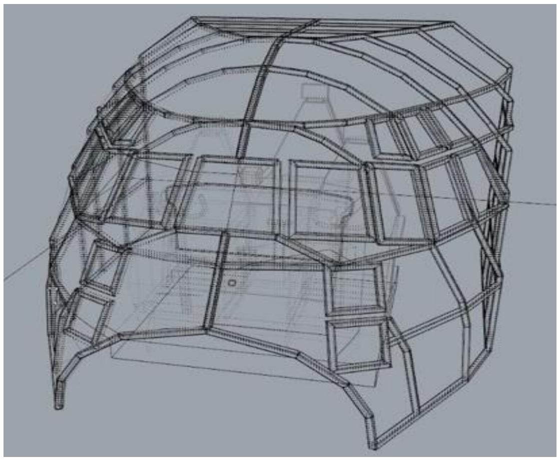

Fig. 7 *Design in Fusion 360*
Source: *Own elaboration*

The design of the aircraft cockpit is one of the most important challenges of the project since it must recreate in a real way the distribution of equipment, spaces of each of the crew members with the control panels where the interaction is carried out in the different phases of flight, to meet this objective the Autodesk fusion 360 software is used which is a CAD type platform, CAM, CAE for Design and Modeling [12].

For the design, the plans and manuals of the aircraft are used as a reference, the 3D scanning of the real cabin is carried out, determining the location of the windows to recreate the visual environment and arrangement of the control panels as accurately as possible.

Fig.8 *Royal Cab C-130*
Source: *Own elaboration*

Based on the dimensions and distribution of the panels, the 3D modeling of the cockpit prototype is carried out as seen in the following figure where the areas of the room where the simulator is located were established, the space required for the projectors, distribution of the pilots' chairs, flight engineer, control panels, control controls, navigation screens, instrument panel, in accordance with compliance with national and international aeronautical regulations and guidelines for the flight simulator, for certification and approval of the same [13].

Fig. 9 *Cab design and simulation*
Source: *Authors.*

Subsequently, the manufacturing process of the cabin is carried out by means of the steel laser cutting technique, it is an important subtractive manufacturing process in the machining industry that involves the precision cutting of steel using a high-power laser beam.

The laser beam hits the material, melting or vaporizing it, obtaining a clean and precise cut. Because laser cutting is precise and accurate, complex parts can be easily created [14].

Fig. 10 *Manufacture of C-130 cab*
Source: *Own elaboration*

The gasless MIG welding technique is used for the assembly of the parts, or flux-cored welder, is a welding machine that uses a fluid wire to weld instead of an external shielding gas. This is its most important and remarkable characteristic. Unlike traditional MIG welders that use an inert gas such as argon or carbon dioxide to protect the molten metal from atmospheric contamination, gasless MIG wire welders use a flux-cored or flux-cored welding wire [15].

***Fig. 11** C-130 cab assembly*
***Source:** Authors.*

***Fig. 12** Control panel manufacturing*
***Source:** Own elaboration*

4.7. Control panel and instrument design

An aircraft's instrument panel is a suite of instruments that provide information critical to flight control and navigation: the aircraft's performance, system operation, and the aircraft's location in space [16].

For the C-130 aircraft, there are two screens, one in front of the pilot and the other in front of the co-pilot, which are called Primary Flight Display or PFD, which provide vital information for the navigation of the aircraft. This panel displays essential flight instruments, including:

- Air velocity
- Altimeter
- Variometer
- Mach Speed
- Artificial horizon
- Turning Coordinator
- Steering indicator
- VOR and DME

Additionally, integrating the Navigation Display or ND system is another crucial display [17]. It offers a graphical representation of aspects such as:

- Aircraft Route
- Radio aids
- Weather radar
- Wind indicators
- Nearby air traffic

For the manufacture of the control panel and instruments, 2024 hard aluminum sheet in T3 heat treatment is used, making laser cuts and engraving of the faces in CNC.

4.8. AATD Simulator Software Architecture and Design

4.8.1. Flight Simulation Module

Essential to replicate real flight conditions in the simulator. This module implements the flight models and physics of the aircraft, ensuring that aerodynamic forces, propulsion and flight dynamics behave realistically. It includes the aerodynamic model, which simulates the forces and moments acting on the aircraft, the propulsion model, which represents the behavior of the engines, and the flight dynamics model, which calculates the response of the aircraft to control inputs and environmental conditions [18].

4.8.2. Control and Navigation Module

It seeks to develop the algorithms necessary for autonomous navigation and control of the aircraft. This module includes control algorithms that implement control laws to maintain the stability and performance of the aircraft, navigation systems that use sensor and GPS data to determine the position and trajectory of the aircraft, and route planning, which generates optimal routes for flight missions [19]. Its goal is to ensure that the aircraft can navigate and be controlled autonomously and accurately.

4.8.3. User Interaction Module

It provides the graphical interface and input/output devices necessary for user interaction with the simulator. This module includes the graphical user interface (GUI), which features displays and visual controls, input devices such as joysticks, pedals, and control panels, and output devices such as monitors, projectors, and audio systems that provide visual and auditory feedback [20]. Its objective is to facilitate an intuitive and effective interaction between the user and the simulator.

4.8.4. Scenario Management Module

He is responsible for the creation and management of training scenarios. This module includes a scenario editor, which allows you to design and configure different flight situations, a scenario database, which stores the predefined and customized scenarios, and a scenario simulation engine, which runs the scenarios during training sessions [21]. It aims to provide a variety of training situations that simulate real-world flight conditions.

4.8.5. Registration and Analysis Module

Dedicated to recording flight data and analyzing user performance. This module includes a data logging system, which captures and stores flight data in real-time, analysis tools, which allow evaluating performance and training results, and reporting, which creates detailed reports on user performance and flight metrics. It aims to evaluate user performance and provide feedback to improve flight skills.

5. CONCEPTUAL DESIGN

5.1. Main Instrument Panel

Made of metal and painted with textured paint, it includes all the elements such as the FCU, EFIS, stopwatches and other additional panels. The primary flight instruments (PFD, ND, EICAS) and reserve instruments are fully functional.

Fig. 13 *Main Instrument Panel*
Source*: Own elaboration*

5.2. Pedestal

Composed of individual connected modules, allowing easy and quick replacement of each element. It includes MCDU, RMP, AUDIO, and ATC modules, as well as flap controls, speed brakes, parking brake, and ECAM panel.

Fig. 14 *Power pedestal.*
Source*: Own elaboration*

5.3. Top Panel (Overhead)

Designed in a modular way for easy access and maintenance. It includes all operational elements, such as the fire extinguishing system, with backlit panels.

Fig. 15 *Top Panel (Overhead).*
Source*: Own elaboration*

The integration of specific operation scenarios and the planning of simulations are essential components to maximize the effectiveness of flight simulator training. This process can be broken down into several key stages:

Identification of Operational Scenarios: scenarios are selected based on the typical missions and operations of the aircraft and crew. This includes normal, abnormal, and emergency situations that pilots might face in real life.

Scenario Design: scenarios are designed in detail, specifying initial conditions, triggering events, and learning objectives. Templates and design tools are used to ensure that all necessary elements are included and correctly interrelated.

Implementation in the Simulator: the designed scenarios are programmed into the simulator software. This includes setting flight parameters, simulating system failures, and creating specific weather conditions.

Simulation Planning: a simulation plan is developed detailing the training schedule, the specific objectives of each session and the evaluation criteria. This plan ensures that all critical areas of operation are covered and that pilots receive comprehensive training.

Execution and Evaluation: during simulation sessions, instructors monitor pilot performance and provide real-time feedback. At the end, a briefing is held to discuss strengths and areas for improvement, based on the established learning objectives.

Adjustments and Improvements: based on the feedback and results of the simulations, adjustments are made to the scenarios and the simulation plan to continuously improve the quality of the training.

This structured approach allows flight simulator training to be highly effective, preparing crews to face a wide variety of operational situations with confidence and competence.

6. RESULTS AND DISCUSSION

The Advanced Flight Simulator (AATD) is designed to meet high standards of training and evaluation, providing a robust and versatile platform for crew training. Expected results include:

Ability to Perform More Than 70 Procedures: The simulator will enable the execution of a wide range of operating procedures, including takeoffs, landings, in-flight maneuvers, and emergency procedures. This capability covers both normal and abnormal situations, ensuring comprehensive and thorough training for pilots and maintenance personnel.

Validation in Simulated Conditions: The procedures will be validated in a simulated environment that replicates with high fidelity the real flight conditions. This includes simulating environmental factors such as weather, turbulence, and system failures, providing a realistic scenario for practice and skills assessment.

Improved Preparation and Proficiency: By allowing for repetitive practice and familiarization with a variety of operational situations, the simulator will contribute significantly to improving the preparation and competence of crews. Pilots will be able to develop and hone their skills in a safe and controlled environment, reducing the risk of errors in real operations.

Optimization of Resources and Costs: The implementation of the simulator will reduce the dependence on real aircraft for training, optimizing the use of resources and decreasing operating costs. This will allow for a greater frequency of training and better management of available resources.

Continuous Evaluation and Feedback: The simulator will provide tools for the continuous evaluation of pilot performance, allowing instructors to offer immediate and detailed feedback. This will facilitate a more dynamic and effective learning process, adapted to the individual needs of each crew member.

7. CONCLUSIONS

In conclusion, in terms of usefulness, flight simulators are essential tools for pilot training, improving their skills and allowing the practice of emergency procedures and situations in a controlled environment.

Likewise, the versatility of these is wide, since they can represent practically any real aircraft and its functions, being used both in aviation schools and in aeronautical study centers and leisure places.

As for its portable design, the project proposes a portable simulation panel design, facilitating its transfer to educational promotion events, taking into account that its technology is advanced and IOCards electronic cards and SIOC software, specific for aerial simulation, are used, which allows an efficient and adaptable implementation.

CONFLICT OF INTEREST

The authors confirm that this work has not been used or published elsewhere. The authors also confirm that there are no conflicts of interest.

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