DEVELOPMENT AND EVALUATION OF A LOW-COST PC BASED RECONFIGURABLE FLIGHT SIMULATOR WITH IMMERSIVE DISPLAY FOR AB-INITIO FLYING TRAINING AND ENGINEERING RESEARCH

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ABSTRACT

Flight simulation is an essential tool for pilot training and aerospace engineering research. While commercially available flight simulators offer high fidelity, they are often prohibitively expensive, whereas many PC-based simulators suffer from limited realism. Consequently, there is a need for a low-cost flight simulation system that provides an immersive training experience. The aim of this study is to design and develop a low-cost flight simulator featuring a high-fidelity immersive display with a 220-degree field of view, aimed at enhancing realism and replicating onboard flight conditions. The simulator design was divided into 4 subsystems integrating motion cueing effects, surround sound, controller and display/instrumentation to deliver a cockpit-like experience. System evaluation was conducted using a Cessna 172 aircraft model, with an instructor's monitoring display connected to the simulation computer to observe user flight operations. The simulator demonstrated effective motion cueing through seat vibration synchronized with engine revolutions. Evaluation results indicate that the system effectively supports pilot skill development, achieving a highest mean score of 4.76 among the assessed criteria. The proposed simulator offers a cost-effective solution suitable for trained pilots, ab-initio trainees, and engineering students engaged in aircraft design and flight training. Future work will focus on enhancing system realism through the incorporation of rudder pedals and the use of more durable materials in place of plywood for the immersive display structure.

Keywords: Controller, Embedded Systems, Flight Simulator, Immersive Display, Motion Cueing

1 INTRODUCTION

Flight simulators have long been an integral component of pilot training, providing a controlled environment in which trainees and professional pilots can acquire and refine flying skills. However, the cost of high-fidelity flight simulators is substantial. As a result, Personal Computer (PC)-based flight simulation systems have emerged as a cost-effective alternative, significantly reducing the financial burden associated with simulator-based training. Despite their affordability, many existing PC-based systems exhibit low fidelity, largely due to the limitations imposed by conventional computer display configurations used to represent the virtual flight environment. In contrast, real-world, on-the-job flight training carries considerable risks, including pilot anxiety, operational errors, potential damage to aircraft components, and the possibility of injury [1, 2], which underscores the necessity of initial training using flight simulators. Furthermore, real-world training requires extensive logistical support for site setup and continuous coordination, making it both costly and inefficient to implement [1]. The total number of training hours required is typically higher when flight simulator training devices (FSTDs) are not used; however, this requirement is significantly reduced with the integration of FSTDs. In addition, ground-based simulator training offers substantial advantages in terms of safety, operational efficiency, and environmental protection, as it is not constrained by adverse meteorological or environmental conditions and allows for long-duration, continuous training sessions—limitations commonly associated with onboard aircraft training. Through the use of FSTDs, trainees and pilots are afforded sufficient time to practise diverse flight scenarios and gradually overcome flight anxiety before transitioning to real aircraft operations [2, 3]. This project was therefore designed to enhance the safety of pilot trainees while supporting mission-oriented training that improves operational versatility. The simulator provides motion cueing effects corresponding to flight conditions, enabling pilots to manoeuvre the aircraft through a dedicated control interface under varying weather conditions, during both daytime and nighttime operations. The system is integrated with MATLAB to support control system development and engineering analysis. Furthermore, a wide field-of-view of approximately 220° was incorporated to improve simulator fidelity and situational awareness. Flight simulators are primarily developed to improve safety and productivity by enabling trainees to better understand aircraft attitude and behaviour through selectable first-person and third-person perspectives [4]. In emergency or hazardous flight scenarios, simulators allow trainees to practise critical procedures in a controlled environment, while instructors can pause training missions, analyse errors in real time, provide corrective feedback, and repeat specific flight sequences as needed to reinforce learning outcomes [2, 5] emphasis the role virtual reality plays in flight simulation design as it provide the users opportunity to gain expertise operating an aircraft without the real world consequences of making a fatal mistakes.

2 LITERATURE REVIEW

Eeffective flight simulator architectures rely on the seamless integration of pilot input devices, real-time flight dynamics modelling, visualization, audio, and motion cueing subsystems. Modular system architectures are commonly adopted to enable real-time data exchange between simulation engines and output devices, thereby enhancing realism and training effectiveness. The incorporation of immersive visual displays, synchronized audio feedback, and motion cueing mechanisms has been shown to significantly improve pilot situational awareness and skill acquisition [6]. Additionally, instructor monitoring interfaces are often integrated to support training assessment. Overall, well-designed flight simulator architectures balance realism, scalability, and cost, making them suitable for pilot training and aerospace engineering education [6]. [7] research contributes to the understanding of flight simulation systems by emphasizing the integration of accurate flight dynamics, real-time computation, and human–machine interaction. The study highlights how simulator fidelity is influenced by mathematical aircraft models, control system responsiveness, and synchronized visual and motion cueing. The results presented indicates that well-structured simulator architectures can effectively replicate real flight behavior and support pilot training and engineering evaluation. The work underscores the importance of system modularity and validation against real flight data to ensure realism and training effectiveness. In [2], the justification for using training devices in aviation training was well established. They stressed that such devices enhance safety by enabling flight crews to practise standard and emergency procedures in a controlled environment without exposure to real-world risks, while also significantly reducing the cost of flight training. In addition, training devices allow instructors to intervene immediately when errors occur by pausing the training session, providing real-time feedback, and repeating specific flight sequences as needed. This iterative training approach supports effective learning, error correction, and skill development. A real-time flight simulator for pilot training based on a mechatronics and cyber-physical systems approach was developed [8]. Their work implemented a virtual flight system responsible for control communication and aircraft animation using mathematical flight models integrated within a Unity 3D engine across a network of computers. To achieve realistic motion representation, an inertial motion platform was designed and developed to reproduce specific aircraft motions based on data generated by the virtual environment. The system also embedded real-time aircraft animation driven by mathematical models to simulate realistic flight conditions. They reported an evaluation result of the simulator with an overall performance accuracy of 94.70%. Validation was conducted using 15 professional military pilots previously trained on the Microsoft Flight Simulator, with results indicating comparable responses between the two systems. The simulator employed a Stewart platform for motion cueing, joystick-based controls, and LabVIEW for system modelling. The study demonstrated that the simulator effectively enhances military pilot training and aircraft control skills. [1] investigated the application of virtual reality technologies in education and workforce training, with particular emphasis on aviation training. The study highlighted the limitations of real-world training, including high costs, risk of material damage, potential injuries, and extensive logistical requirements such as training site preparation and coordination of personnel. These challenges are particularly evident in high-risk training domains such as aviation, medical, and emergency response training. To address these limitations, Carruth proposed a low-cost flight simulation solution capable of training pilots in handling various flight scenarios. The simulator utilized computer-aided design (CAD) models to replicate real-world environments, which were subsequently imported into a virtual environment for immersive training purposes. [9] proposed a reconfigurable flight simulator framework aimed at supporting novel and unconventional flight vehicle concepts. Their study emphasized that pilot training using real aircraft is both costly and inherently risky, making simulator-based training a safer and more economical alternative. The paper presented the design architecture of the simulator and demonstrated its applicability for human-in-the-loop flight simulation studies. At the initial stage of the project, several fundamental design requirements were established to ensure flexibility, adaptability, and realism within the simulator framework. The study highlighted the potential of reconfigurable simulators for research, training, and evaluation of emerging aircraft concepts. [10] conducted a comprehensive study on flight simulation training devices (FSTD), focusing on their applications, classifications, and role in pilot training. The authors noted that pilot training without simulators requires significantly more flight hours, resulting in increased training costs due to aircraft operation and maintenance. Real aircraft training also demands coordination with multiple services such as air traffic control and maintenance teams, in addition to suitable weather and visibility conditions. These constraints are mitigated through the use of FSTDs. The paper further emphasized that flight simulation is a multidisciplinary field involving aerodynamics, control systems, human factors, computer graphics, and real-time computing. The authors provided a broad overview of research efforts within the FSTD domain, highlighting the importance of integrating contributions from multiple disciplines to address the complexity of flight simulation systems. Furthermore, [11] conducted a survey of flight simulator evaluation methodologies and identified commonly used performance metrics. These include hit rate and task completion time, system latency, participant feedback questionnaires, achievement scores of control and experimental groups, task performance measures under varying immersion levels, biometric and physiological measurements, NASA Task Load Index (NASA-TLX), video recordings, head-tracking data, and observational feedback. These evaluation approaches provide a comprehensive framework for assessing the effectiveness, usability, and realism of flight simulation systems. [7] developed a flight simulator for autonomous vehicle. The simulator follows a modular design with an emphasis on extensibility. The core components include environment model, vehicle model, physics engine, sensor models, rendering interface, public API layer and an interface layer for vehicle firmware. Underlying technologies of flight simulation include mathematical modelling, real-time computing, motion actuation systems, visual image generation, and projection systems for visual cueing. Accurate aircraft mathematical models and characteristic flight behavior data are typically obtained through theoretical analysis, wind tunnel testing, and flight experiments. These models enable realistic representation of aircraft responses to pilot inputs and external disturbances. [12] compared consumer-grade virtual reality (VR) equipment with a full-scale physical flight simulator (PFS) of a Boeing 737-800NG to determine if VR can supplement or replace a PFS for cockpit familiarization through a survey questionnaire. They reported no significant differences in successful instrument reading tasks, error rates and task completion between PFS and virtual reality flight simulator (VRFS) during cockpit familiarization training (CFT). In addition to visual and motion realism, audio feedback plays a critical role in enhancing simulator fidelity. The cockpit environment is characterized by diverse sound sources, which can be broadly classified into two categories: cockpit noise and instrument alerts. Cockpit noise includes sounds related to airspeed, engine revolutions per minute, wind, subsystems, and ground rumble, while instrument alerts encompass warning signals, navigation identifiers, and radio communications. The integration of realistic audio cues significantly contributes to pilot immersion and situational awareness. X-Plane is a widely used flight simulation engine developed by Laminar Research since 1995. It is available on macOS, Windows, and Linux platforms, with FAA-certified versions provided for professional training applications. X-Plane 11 is recognized as one of the most comprehensive and powerful desktop flight simulators, offering a highly realistic flight model suitable for both training and research purposes.

3 METHODOLOGY

The flight simulator design consists of 4 subsystems which are: The Display and Instrumentation. The Controller. The Vibration Cueing System and; The Audio System. The integration of the whole system is depicted in Figure 1; this shows the overview of the PC- Based flight simulator depicting the four subsystems and their connection.

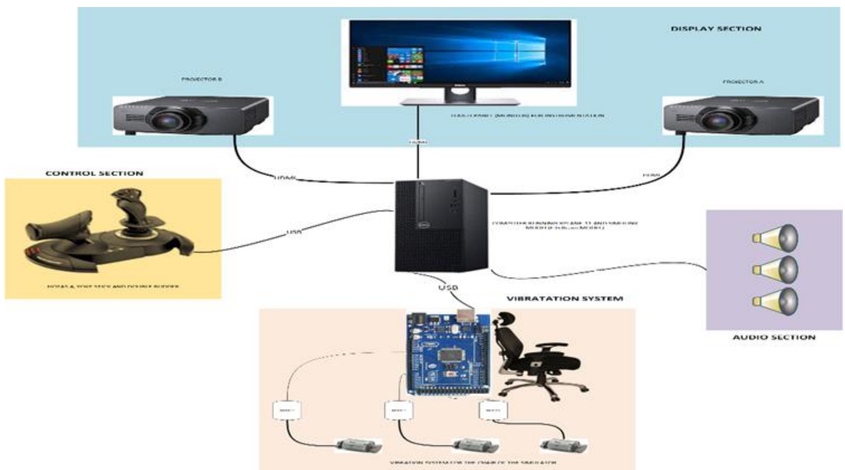

Figure 1. Schematic of the implementation of the PC-Based Simulator

3.1 The Display and Instrumentation

Visual information is relayed to the user via the display of the flight simulator. In this work the scenery was displayed using 2 projectors to cover the wrap-around immersive 220-degree field of view (FOV). Various perspectives of the 3-D design of the wrap around screen for the immersive display was designed. For the instrumentation, a 55-inch touch screen display was used for the instrumentation. The multiple projectors are connected to the main computer running Xplane via Space desk application. All the monitors have individual channel in order to adequately wrap around the display. Instrumentation and scenery display are assigned to individual monitors in the Xplane software home use standard. In the display and instrumentation schematics (Figure 2), the arrangement of the display 4 and 3 are the projectors for displaying scenery, while 1 and 2 display the instrumentation.

Figure 2. Display and instrumentation

The display screen displays the scenery of the in-flight as it could be seen when flying an aircraft. The display screen was sourced out for from locally made materials. A plywood was calved in the shape of a semi-circle to achieve a 220-degree immersion field of view (FOV). Two projectors were used in setting up a wraparound screen to minimize cost. Fly-Elise immersive display pro, the fly-Elise calibration pro and wide view are the software that made the wrap around possible. The fly-Elise calibration pro runs on the client machine(s). This gives the user the ability to select the mode of operations of each projector.

3.2 The Controller

The system focuses on the physical input device that actuates all the control surfaces of the aircraft model of the simulator system. The flight simulator joystick is used as the controller in this project (USB connectivity standard with 8-Way functionality). The simulator control system was achieved using a dual-rudder joystick. This was used to control the thrust, yaw, roll and pitch of the aircraft in the flight simulator. The yoke controls the roll and the pitch of the airplane while the rudder controls the yaw. The joystick is connected to the simulator through MATLAB/ Simulink (Figure 3). The X Plane and Matlab integration is made up of the HOTAS 4, dual yoke system and the aircraft model. It is embedded with the Research civil aviation model (RCAM) designed and modified in MATLAB Simulink. The model was tested in Flight Gear and Xplane.

3.2.1 Communication Interface Between X-plane and MATLAB/Simulink

The AH-25 model used was developed using plane maker. Plane maker is a program under X-plane with tools that allow users to design any aircraft. Plane maker provides an interface for design of vehicle based on physical specifications of the airplane like weight, wing span, control deflections, engine power, air-foils and so on. X-plane has a feature that allows it to communicate with the external environment through user datagram protocol (UDP). Simulink has built in blocks for exchanging information using UDP. Figure 3 shows Flight Simulator Implementation using Matlab/Simulink Model of Aircraft.

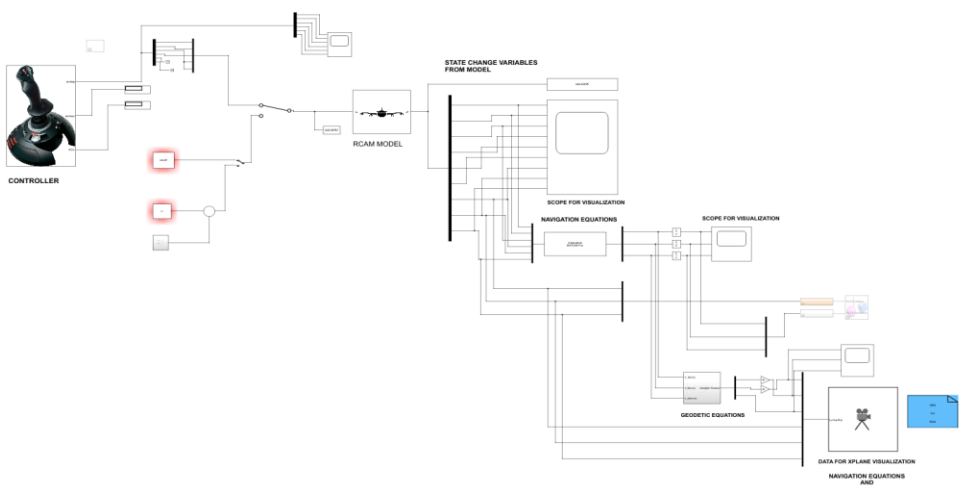

Figure 3. Flight Simulator Implementation using Matlab/Simulink Model of Aircraft

3.2.2 X-plane settings

This research established software-in-the-loop (SIL) simulation and hence the communication is established between X-plane and MATLAB/Simulink on one computer using the I.P address "127.0.0.1". Four access points (two for X-plane and the other two for MATLAB/Simulink) was used.

3.2.3 Setting up UDP in X-plane

Communication on X-pane follows a standard format known as User Datagram Protocol (UDP). UDP are sent in form of string of bytes called datagrams consisting of 41 bytes per sentence.

3.3 The Vibration Cueing System

Accelerations, which exert forces on the user's body, are called motion cues. They give the user a feeling of being in a real aircraft. The algorithms, which are responsible for generating these cues, are named motion cueing algorithms. A motion simulator or motion platform is a mechanism that creates the feeling of being in a real motion environment. In a simulator, the movement is synchronized with a visual display of the outside world. Motion platforms can provide movement in the six degrees of freedom (DOF) that can be experienced by an object that is free to move, such as an aircraft: These are the three rotational degrees of freedom (roll, pitch, yaw) and three translational or linear degrees of freedom (surge, heave, sway). Motion simulators can be classified according to whether the occupant is controlling the vehicle (such as in a Flight Simulator for training pilots), or whether the occupant is a passive rider, such as in a simulator ride or motion theatre. The aircraft seat containing some actuators that mimic motion cueing has been implemented. This system tries to emulate the vibration a pilot feels due the rotation of the engine of the aircraft and 6-DOF of the aircraft as depicted in Figure 4. This increases the realism of the simulator. Vibration motors attached to the seats are connected to the PWM pins of an Arduino-Mega via some switching devices. The interfacing and vibration cueing system schematics shows the connectivity to the flight simulator. The circuit diagram depicting the connections of the motors to the Arduino controller is shown Figure 5.

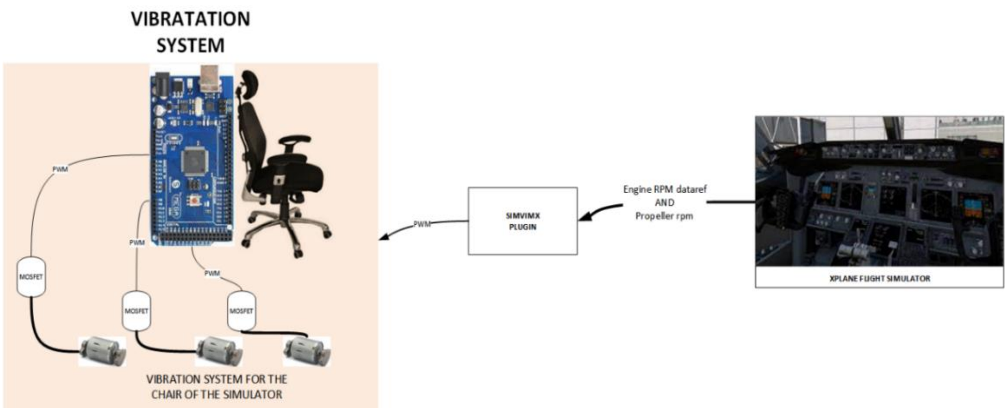

Figure 4. Interfacing Motion and Vibration Cueing System to the Simulator

The flight simulator seat operates with modern electric actuators and has drastically reduced noise and its more responsive, which helps with pilot's immersion. The simulator seat can work on a single-phase supply. The seats receive aircraft motion parameters from Xplane simulation software which are mapped to actuator demands. The connection to the seat was done via a USB cable. Figure 5 shows the Circuit Diagram of Motion and Vibration Cueing System.

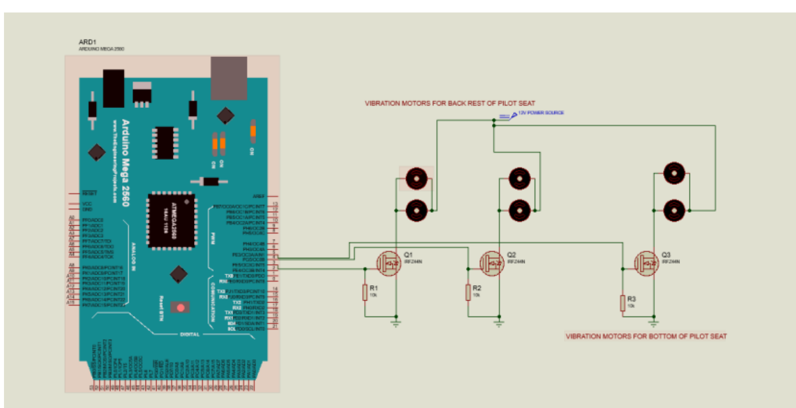

Figure 5. Circuit Diagram of Motion and Vibration Cueing System

3.4 The Audio System

An immersive audio system communicates the acoustics necessary for the flight simulator. The audio system for this project is a 5.1 channel surround audio system consisting of satellite speakers (Figure 6). The audio surround sound was synchronized straight from the flight simulator into the surround system to give that in-flight feel. This gives the instructor the ability to communicate with the user of the flight simulator directly.

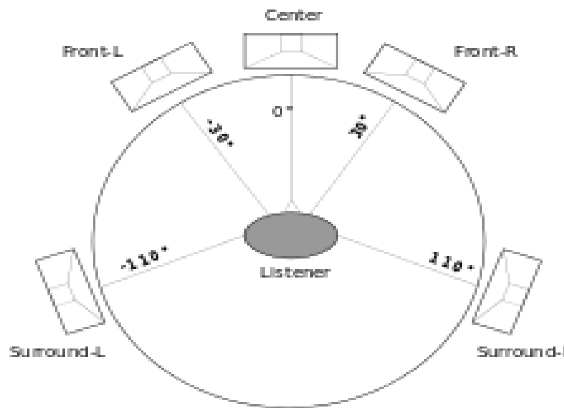

Figure 6. Surround Sound System

3.5 Software design

Setting up the projectors to give a wraparound display entails selecting the screen type and the dimensions are inserted in the left-hand dialog Figure 7. The projectors are inserted and the setup was tested to get a look and feel of the design. The design was adjusted until the optimal position is determined (Figure 8). The measurements were transferred to the real world. This gives a more effective means of designing immersive displays for the flight simulator. The software used is fly-Elise calibration Pro v7.1.

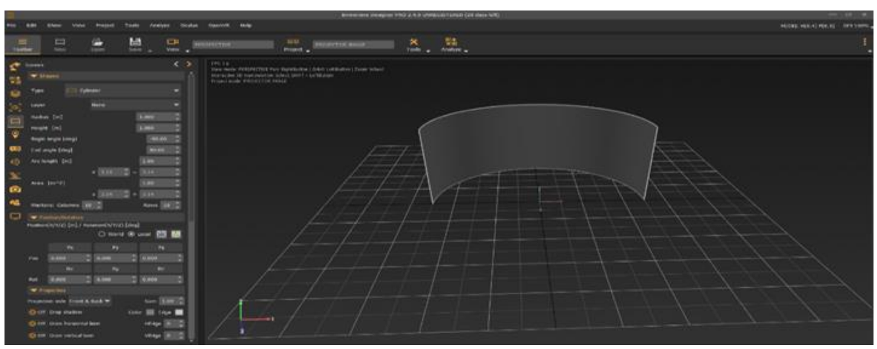

Figure 7. Wrap around setup on fly-Elise calibration Pro

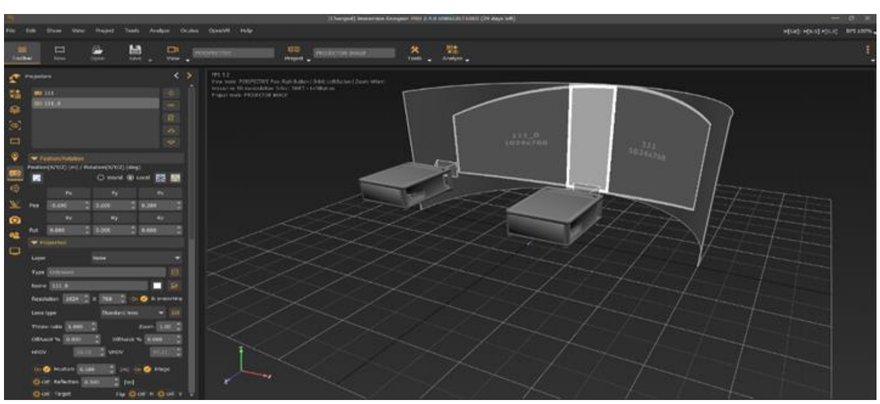

Figure 8. Projectors placement and calibration on fly Elise calibration Pro

A virtual reality headsets software for mobile devices (iVRy) that serves the purpose of using mobile devices as a stream virtual reality (StreamVR) headset for personal computer was used. This transforms mobile device into a PC VR headset which was connected through Wifi to run VR compatible personal computer software.

3.5.1 SimVim Configurator Plugins

Programming of the Arduino mega board was achieved by the SimVim plugin. The pin was assigned from the SimVim web from which a data file was generated, this data file was pasted in the SimVim folder which will allow data to be read. This programming serves to control all the cabin effect that is needed in the flight simulator. The SimVim Interface is depicted in Figure 9 while Figure 10 shows the SimVim cockpit configurator for setting the parameters for the Cessna 172 aircraft.

Figure 9. SimVim configurator plugin interface

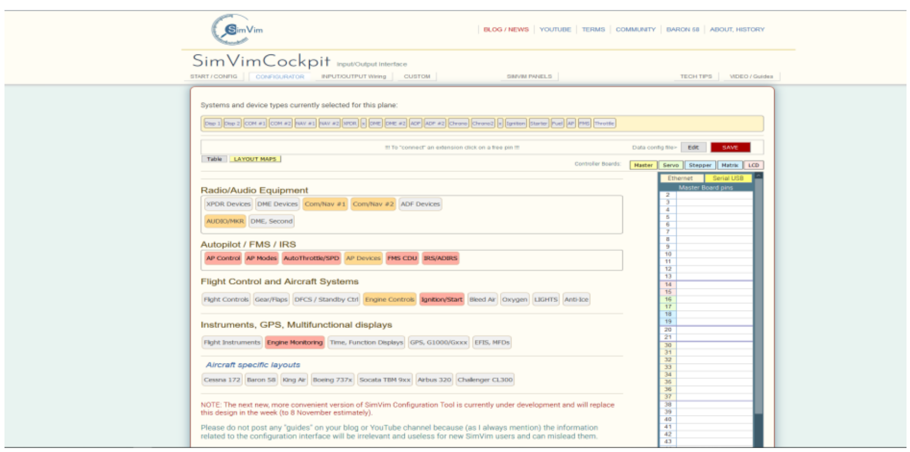

Figure 10. SimVim configurator plugin

4 RESULTS AND DISCUSSION

The system was evaluated using a Cessna 172 aircraft on the simulator. The instrumentation screen is shown in Figure 11. The instructor's monitor was connected to the computer. This display could be used to monitor the flight process of the user of the flight simulator. The seat vibrated along with the engine revolution and the motion cue was achieved. The immersive display only ran on a computer with NVIDIA GeForce graphic card. All other attempts to use other graphics cards failed. The sensors of the mobile phone running the iVRy client software were used to orient the user of the flight simulator in the Cessna 172 aircraft on Xplane.

Figure 11. Instrumentation screen of Cessna 172

A personal computer (PC) then combines virtual scenery generated by the flight simulator software with camera video allowing certain arears of the virtual cockpit to show VR scenery, and other arears to show the pilots and controls. The interrelationships among the simulator set up is depicted in Figure 12.

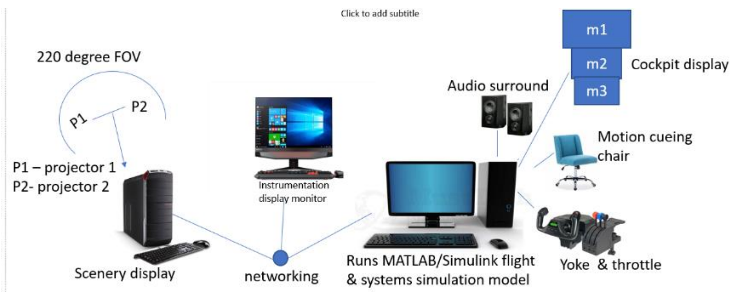

Figure 12. Inter-relation between the simulator system

Figure 12 presents the overall system architecture of the developed flight simulator, illustrating the integration of user inputs, simulation processing, and multimodal feedback subsystems. The architecture adopts a modular design approach, enabling seamless interaction between hardware components and software modules while supporting real-time flight simulation. At the input layer, pilot control interfaces such as the joystick, throttle, and keyboard provide real-time control commands to the simulation computer; this is similar to the method employed by Yu et al. [3]. These inputs are processed by the flight simulation engine, which computes aircraft dynamics based on predefined aerodynamic and control models. The use of a centralized simulation engine ensures synchronized processing of flight physics, environmental effects, and system states. The processing layer represents the core of the system, where the flight dynamics model, environmental modelling, and scenario management are executed in real time. The architecture supports continuous data exchange between the simulation engine and the visualization, motion, and audio subsystems. This real-time feedback loop is critical in achieving realistic pilot perception and training effectiveness. At the output layer, the computed simulation data is rendered through an immersive visual display system, audio subsystem, and motion cueing mechanism. The visual subsystem provides a wide field-of-view display to enhance situational awareness, while the audio system generates cockpit and environmental sounds synchronized with aircraft states. Additionally, the motion cueing system translates aircraft dynamics into physical cues, such as seat vibration and motion effects, thereby improving pilot immersion and realism. An instructor monitoring interface is also integrated into the architecture, enabling real-time observation and assessment of pilot performance. This component enhances the system's suitability for training and evaluation purposes by allowing instructors to supervise flight sessions and analyze pilot responses. Overall, the architecture demonstrates effective integration of simulation software, human–machine interfaces, and physical feedback systems. The modular and scalable design allows for future expansion, such as the incorporation of additional control devices, enhanced motion platforms, or more advanced aircraft models. The results indicate that the proposed architecture successfully supports real-time flight simulation with a balance between cost, realism, and system complexity, making it suitable for pilot training, engineering education, and aerospace research applications. The actual display setup of the flight simulator is depicted in Figure 13a, while the flight simulator in operation is shown in Figure 13b.


Figure 13a. The actual display setup


Figure13b. Setup in operation

4.1 Evaluation

A five-point Likert-scale questionnaire was used to evaluate usability, realism, training effectiveness and overall satisfaction of the developed flight simulator. Responses were rated from strongly disagree to strongly agree. A total of 25 respondents which comprises of Pilot and students evaluated the flight simulator and their responses is presented in Table 1. The evaluation results indicated high user acceptance and strong performance of the designed flight simulation system across all assessed dimensions. Mean scores for all questionnaire items are above 3.6, with most exceeding 4.0, demonstrating positive user perception of usability, realism, training effectiveness and overall satisfaction.

Table 1. Flight Simulator Evaluation results

Statement	Mean	Standard Deviation	Interpretation
The simulator interface is easy to understand	4.52	0.509902	Strongly agree
System controls are intuitive and responsive	4.56	0.506623	Strongly agree
I can complete flight tasks without difficulty	4.16	0.687992	Agree
Aircraft pitch, roll, and yaw responses feel realistic.	4.16	0.374166	Agree
Takeoff and landing behavior resemble real aircraft behavior	4.36	0.489898	Agree
The simulator accurately represents stall and recovery behavior.	3.6	0.5	Agree
The cockpit layout is visually realistic.	4.24	0.43589	Agree
Environmental visuals (terrain, weather) are realistic.	4.44	0.506623	Strongly agree
Engine and ambient sounds enhance realism.	4.52	0.509902	Strongly agree
The simulator improves understanding of flight operations.	4.08	0.276887	Agree
The simulator is useful for procedural training.	4.32	0.476095	Agree
The simulator supports skill development.	4.76	0.43589	Strongly agree
Overall, I am satisfied with the flight simulator.	4.4	0.5	Strongly agree
I would recommend this simulator for training purposes.	4.52	0.509902	Strongly agree

5 CONCLUSIONS

Our proposed simulator was designed with a high-fidelity display at a 220-degree field of view, which will enhance a real life feel of training on-board. The simulator was designed to minimize cost which can be used by both trained pilots and ab-initio trainees alongside engineering students for aircraft designs. The simulator was equipped with a motion cueing effects and also a surround sound which makes it feel like the cockpit experience. The flight simulator will increase safety and productivity while the trainees understand the flight attitude of the vehicle. In cases of dangerous emergency situation, it would assist flight crews to practise procedures and also allow instructors to react to errors that may have occurred while using the simulator This project was designed to ensure the safety of pilot trainees and also to assist them with several mission that will aid their versatility on-board. The simulator will give a motion cueing effect to the pilot as the situation warrants while the pilot can manoeuvre the aircraft via the control interface. A wider field of view of about 220-degree was incorporated to increase the fidelity of the simulator. Future research will incorporate electronic screen and advanced features so as to ease moveability of the simulator from places to places.

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