

Affordable Pneumatic VR Motion Platform for School-Level Immersive Learning: Design, Analysis, and Validation

Mohit Choubey

choubeymohit35pain@gmail.com

Central Research and Training Laboratory (National Council of Science Museum))

Shatadal Ghosh

Central Research and Training Laboratory (National Council of Science Museum))

K. S. Murali

Central Research and Training Laboratory (National Council of Science Museum))

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Abstract

This study introduces an innovative, economical, linkage-free 3-DOF pneumatic VR motion chair specifically engineered for educational institutions and resource-constrained learning settings. As it requires intricate Stewart mechanisms, expensive servo-hydraulic systems, or machined metal linkages, most schools can't afford traditional motion platforms. We solve this problem by making something that is straightforward to create and has a simple design. There are three air springs that are 120° apart, and the foundation is made of wood. This arrangement allows the pitch, roll, and heave to happen smoothly without the need for bearings, sliders, or joints. This saves money and time on maintenance. A complete structural and dynamic check was done to make sure the platform was safe and worked effectively. The results show that the stresses on the bolts are still much below the 640 MPa yield limit, even at a 30° angle. The plywood bearing stresses are also within permissible limits because of the steel reinforcement plates and 50-mm hardened washers. Air-spring characterisation shows that the springs respond quickly (40–70 ms), have a useable stroke of about 100 mm, and can hold 400–600 kg, which shows that they are good for usage in a classroom. Experimental motion testing confirms consistent behaviour and high damping, making motion signals that are very similar to VR visual material. The proposed design is a cheap, safe, and sturdy way to make STEM instruction more interactive. This platform greatly improves engagement and learning retention by letting students actually feel things like changes in gravity, inertia, slopes, and vehicle dynamics. This is the first time that a 3-air-spring, linkage-free pneumatic VR motion chair has been published. It sets a new standard for making motion simulation technologies more accessible for learning.

1. Introduction

At first, people mostly knew about virtual reality (VR) because it showed immersive visual images through head-mounted displays. Over time, though, it has become a multimodal technology that helps people learn in more interesting ways [1]. Studies indicate that VR enhances motivation and elevates the entire learning experience in contrast to conventional paper-based approaches [2]. More proof reveals that pupils form stronger connections in their thoughts and understand complex topics better when VR mixes visual immersion with physical sensations [3].

One of the main reasons for this improvement is that the motion of the VR platform and the motion shown in the virtual world are in sync [3]. When these motions are the same, the user's visual and tactile senses stay the same. This makes the meeting seem more real and makes you feel more present [3]. This effect is especially useful for teaching physics because it's hard to understand topics like acceleration, inertia, gravity, slopes, and uneven terrain just by reading about them in books [3]. Their understanding gets a lot better when they can feel something rising, tilting, or vibrating that matches what they perceive [3].

It normally needs parallel manipulators (PMs) to perform such coordinated motion. PMs are machines with a moving platform held up by many articulated legs [4]. PMs are commonly used in flight

simulators, vibration testing, and high-speed robotics because they are exceedingly stiff, can handle enormous loads, and move swiftly [5]. Their suitability for high-speed motion control has also been demonstrated in additional work on 3-RRR systems [6]. Even with these benefits, PMs are mechanically complicated since each leg has a big effect on the others, which makes it hard to simulate their motion and dynamics [7]. The well-known 6-DoF Stewart platform is a great example of a PM, but it costs too much, weighs too much, and needs too much maintenance to be useful in schools with low resources [8].

To overcome these constraints, researchers have investigated PMs with diminished degrees of freedom, namely 3-DoF systems, which offer effective motion while minimizing mechanical complexity [9]. There have been several suggestions for 3-DoF mechanisms for varied uses, including as designs with extra actuation [10], humanoid robot ankle mechanisms [11], and optimized planar workspaces [12]. High-speed parallel robots that use Delta geometry show even more how promising simpler solutions can be [13]. There has been additional research into spatial mechanisms that can rotate a lot [14], analytical dynamic formulations [15], and low-coupling setups that make control easier [16].

These designs do make building easier, but they still need precise joints, bearings, and linkages, which need to be meticulously machined and kept up. This indicates they aren't good for schools [16]. Another big problem is dealing with complexity. Advanced optimization of PM motion has demonstrated that accurate parameter adjustment is crucial for dependable performance [17]. For 3-DoF devices to work successfully, they also need to be calibrated correctly in real time [18]. You also need to do enough kinematic modelling [19] to keep the motion predictable. There are several ways to control objects, such as PID controllers that use genetic algorithms [24], hybrid control systems [22], model-based motion control [21], and acceleration-decoupling control [20]. Other studies examined fractional-order controllers for enhanced precision [25], calibration techniques employing transfer learning [26], and innovative coaxial-driven mechanisms that facilitate smoother motion [27].

Getting actuators to function together is still one of the most critical issues in control system. Adaptive control approaches have been demonstrated to work well with changes in payload [28]. Fuzzy sliding-mode control adds extra strength against uncertainties in parameters [29]. New dynamic modeling techniques for 3-DoF systems have also been created to make motion more accurate [30]. Research has shown that when actuators work on their own without coordination, synchronization problems build up and make the platform less stable [31]. To fix these problems, model-free synchronization solutions have been proposed [32]. Cross-coupled control methods were originally proposed to maintain alignment among axes [33], and later studies showed that synchronized and terminal sliding-mode controls significantly improve tracking accuracy in PMs [34–37]. These findings confirm that PMs require sophisticated multi-actuator cooperation, making them too complex for low-cost educational VR systems [34–37].

The challenge becomes even greater when pneumatic actuation is used. Pneumatic systems are naturally soft, safe, and cost-effective, making them attractive for human-interactive VR environments.

They can generate smooth, comfortable motion and can be implemented using simple air-spring mechanisms instead of rigid multi-link structures. However, previous pneumatic VR platforms still relied on PM-like frames and mechanical legs, causing them to inherit the complexity and maintenance demands of traditional PMs, and therefore making them unsuitable for school environments.

1.1. Research Gaps

First, there is no truly simple pneumatic VR motion platform that avoids mechanical linkages entirely. Most existing systems still use PM structures, making them too complex for educational use. Second, almost all motion-based VR platforms in research or industry are aimed at entertainment centers, labs, or industrial training facilities, not schools that need safe, low-cost equipment. Third, although air-springs can naturally lift and tilt without sliding joints, very few VR platforms use air-springs as the primary actuation method; most systems rely on cylinders or rigid actuators that need mechanical support. Fourth, there is limited focus on safety mechanisms suited for students, such as real-time pressure monitoring or emergency venting. Fifth, no existing platform provides a simple, low-cost pneumatic control system using basic microcontrollers that schools can afford. These research gaps clearly show the need for a new solution that is simple, safe, affordable, and designed specifically for educational environments.

- No mechanically simple pneumatic VR platform: Most existing systems use complex linkage-based mechanisms, which makes them too difficult and maintenance-heavy for school use.
- No Education-oriented VR motion design: Available VR motion platforms are built for entertainment or industrial applications, not for the low-cost, compact, and easy-to-operate requirements of classrooms.
- Underuse of air-springs despite their simplicity: VR motion systems rarely use air-springs, even though they can provide lift and tilt without the guided rails or joints required by pneumatic cylinders.
- Lack of child-safe pneumatic features: Current platforms do not include low-pressure operation, pressure monitoring, or safe depressurization systems suitable for student environments.

1.2. Motivation

The motivation for this study comes from the growing demand to make immersive STEM learning available to all schools, including those with limited financial resources. Commercial VR motion systems use servo motors, hydraulic assemblies, or Stewart mechanism designs that cost thousands of dollars, require heavy maintenance, and need trained technicians. Such systems are far beyond the reach of regular classrooms. Students often struggle to understand dynamic science concepts when they are taught only through textbooks or slides. VR can help, but VR without physical motion still does not communicate the real feeling of acceleration, gravity shifts, or terrain changes. Pneumatic systems provide a safe and soft way for young learners to move that is also comfortable. The system is easier to use, lighter, and easier to keep up with when you use air instead of motors. A design with as few moving

parts as possible, made up of just a round wooden disk held up by three air-suspension units, does away with the need for bearings, joints, sliders, and hefty linkages. This makes the platform very simple to put together, fix, and utilize, especially in schools with few resources.

The novel contribution of the proposed model is as follows: -

- Linkage-free 3-DOF pneumatic motion design: The proposed VR chair achieves pitch, roll, and heave using three air-springs placed 120° apart, eliminating all mechanical linkages, joints, sliders, or bearings found in traditional parallel manipulators.
- Mechanically ultra-simple architecture: The complete structure uses only a wooden base, a circular disk, and three air-suspension units, each reinforced with small steel backing plates and M12 bolts, allowing any school or small workshop to build and maintain it without machining or welding.
- Use of air-springs instead of cylinders: Unlike most pneumatic platforms that depend on guided cylinders, this design uses air-springs, which naturally support tilt and vertical motion, giving smoother, safer, and more comfortable movement for students.
- Low-cost, classroom-ready engineering: The platform avoids expensive servo motors, hydraulic systems, or Stewart mechanisms, reducing costs by more than 10× compared to commercial VR motion chairs and making it feasible for low-budget schools.
- Simple ESP-based control system: The system employs a low-cost ESP microcontroller to coordinate valve switching, ensuring reliable 3-DOF motion without the need for complex dynamic modeling or advanced controller algorithms.
- Integrated safety system for children: The chair includes 0–6 bar pressure sensors, 24-V solenoid valves, and a fail-open emergency vent valve that instantly depressurizes the system during faults, making it safe for young learners.
- Optimized for STEM learning: Designed specifically for education, the platform allows students to physically feel scientific concepts like gravitational shifts, slopes, inertia, and vehicle dynamics through synchronized VR motion.
- Highly scalable and easy to repair: The use of modular components and basic materials ensures the platform can be installed, repaired, or expanded easily in schools, training centers, or community labs without technical expertise.

2. Mechanical Design of the Proposed Model

As illustrated in Fig. 1, the VR motion platform is made up of two disks of wood that are held up by three pneumatic air springs that are spaced 120° apart. To get the most rigidity, the best stability, and the safest dynamic behavior for a 3-DoF instructional pneumatic system, all of the geometric and mechanical parameters follow the finished model. The top platform is a round plywood disk that was produced with a CNC machine. It is 0.56 m (22 in) in diameter and 0.076 m (3 in) thick. We picked this thickness because bending-stiffness simulations revealed that a 3-inch laminated plywood plate keeps the platform functionally rigid even when it is tilted dynamically, with a 150 kg off-center load causing

less than 0.8 mm of bending. Square 4 mm steel backing plates (100 mm x 100 mm) provide local reinforcement at the bolt sites. This makes sure that all high-stress zones are steel-on-steel instead of bolt-head-on-wood. This hybrid structure lets us use the low inertia and damping capabilities of plywood along with the bearing strength and fatigue resistance of steel at the most important points.

The bottom base is a square plywood board that is 0.86 m (34 inch) thick and 0.152 m (6 inch) thick. This gives it a larger footprint on purpose to make it more stable when it pitches and rolls. Static stability investigation revealed that the 860 mm base sustains a tipping margin over 42% at a 10° inclination, with a 150 kg load positioned at a height of 510 mm. Like the top disk, each bolt group has local 4 mm steel reinforcement plates underneath to stop bearing failure, stop long-term crushing, and keep bolt preload during cyclic motion. This concept avoids the heavy mass penalty of entire steel disks while keeping the structure secure where it needs to be.

There is a radial space of 0.28 m (11 inch) between the center and the three air springs. Torque-tilt modeling was used to find this radius. At 10°, each pair of springs has a height difference of about 49 mm, which creates predictable restoring moments and lets the roll and pitch happen smoothly without too much air pressure. The springs (model AIR02-2H) have a nominal diameter of 0.152 m (6 inch), a minimum height of 0.051 m (2 inch), and a maximum height of 0.152 m (6 inch), providing a usable stroke of precisely 0.102 m (4 inch). At the operating pressure of 0.21 MPa (30 psi), each spring provides more than 500 kg support capacity in static conditions-well above the combined system load-resulting in a structural safety factor exceeding 3.0 even under dynamic amplification.

Each air spring is mounted using the finalized bolt pattern: one upper bolt (M12 grade 8.8) to the top plate and two lower bolts (M12 grade 8.8) to the bottom plate. The use of M12 bolts is supported by final stress calculations: at a 10° tilt, bolt tensile stress was computed as 58.9 MPa, which is less than 10% of the 640 MPa yield strength of grade 8.8 steel. Bearing stress on the plywood, even under worst-case 10° dynamic loading, remains below 5.6 MPa when using 50 mm hardened washers-a safe margin under the 8 MPa cyclic compression limit for high-grade plywood. This validates the choice of both the bolt size and the local steel strengthening plates.

The chair mounted on the top disk weighs 8 kg and has a seat height of 0.51 m (20 inch). This height maintains the user's center of mass only slightly above the spring plane, which reduces overturning moments and keeps actuator pressure within the low-pressure operating zone. The chair is fixed rigidly using M10 grade 8.8 bolts into steel-reinforced areas to prevent loosening under motion and to ensure that tilt cues align with the VR visual frame.

A 45-L compressed air tank feeds each air spring through a 24-V 2/2 solenoid valve in the pneumatic subsystem. The chosen valves can handle enough airflow for a motion bandwidth of 0.5 to 2 Hz. This is on purpose to keep the motion cues mild, smooth, and informative. There is a 0-0.5 MPa pressure sensor in each air spring, and an ESP8266/ESP32 microprocessor controls the firing of the valves, the safety logic, and the emergency venting. When the power goes off, the system immediately depressurizes

through a dump valve that is normally open. Based on structural analysis, motion is limited to a maximum tilt angle of 10 to 12 degrees.

Plywood was chosen for both the top and bottom disks because it has a good stiffness-to-weight ratio, dampens vibrations, and has a low moment of inertia, all of which make the system more responsive. CNC machining ensures the required $\pm 1-2$ mm dimensional accuracy for bolt patterns and disk geometry. The final hybrid wood-plus-steel-insert design minimizes mass while solving all structural failure modes found in all-wood DIY systems: bolt pull-through, crushing, and fatigue cracks. With the reinforcement plates, M12 bolts, 50 mm hardened washers, and the 6-in bottom base, the platform operates safely under all computed loads, providing reliable, smooth, and educationally appropriate motion for VR simulation.

2.1. Stress Analysis of Mechanical Design

The updated stress-analysis of the VR motion-platform structure, performed for tilt angles up to 30° , confirms that the revised architecture with a 75mm top plywood disk, reinforced steel backing plates, 50mm hardened washers, and M12 grade 8.8 bolts provides a robust, fatigue-resistant attachment system for the pneumatic air-springs. As tilt increases, the overturning moment applied to each spring produces predictable uplift and compression forces on their respective mounting points. The analysis shows that the bolts remain well below their tensile and shear capacity across the full operating tilt range, even under high dynamic loads, because the load path is shared by two bolts in tension and two in compression at each mount. This ensures that the bolt group never approaches the yield strength of grade 8.8 hardware, and the spherical-bearing mounting interface prevents unintended bending loads from being transferred into the bolt shanks.

The most significant improvement in the design comes from the introduction of steel backing plates on both the top disk and the bottom base. These plates fix the main problem with wood-only platforms, which is that plywood surrounding the bolt heads is crushed in one spot. The bearing stress at the interface stays below the safe limits of laminated plywood, even at the largest tilt angles, because the bolt force is spread out over a greater steel area before being transferred to the wood. The 50mm hardened steel washers make the diameter even bigger. This keeps the weight from indenting, pulling through the bolt, or loosening with time. Instead of pushing against plywood directly, the washers push against steel plates. This means that the bearing meets steel on steel, which makes the joint considerably stronger and longer-lasting than one made only of wood.

The top disk still enjoys the benefits of plywood's low weight, low inertia, and natural damping, but the targeted steel reinforcement has fixed any structural problems. This hybrid structure lets the platform tilt more, up to $25-30^\circ$, which helps with VR motion cues without making the platform heavier or putting safety at risk. The three-spring 120° configuration still keeps the weight even and the centre of gravity the same, so no one group of bolts gets too much lift. The platform has good safety factors for bolt tension, bolt shear, and bearing loads across the complete design envelope because to the better bolt

arrangement, steel reinforcement, optimized washer size, and robust plywood shape. Because of this, the final design lets the tilt motion be quite strong while still being safe, stable, and good for long-term use in educational VR.

3. Electronic Design of the Proposed Model

The electronic architecture of the suggested pneumatic VR motion chair, as illustrated in Fig. 2, is made to make sure that the solenoid valves that control the flow of air into and out of the three air-spring actuators work reliably, safely, and in perfect sync. The system has two microcontrollers that keep real-time actuator control distinct from high-level communication and safety management. In pneumatic motion platforms, this separation is important because actuator timing, valve switching accuracy, and synchronization must be kept separate from wireless communication delays or high-level computational operations. The schematic shows how an Arduino Nano Every works as the low-level controller and an ESP32-C3 module works as the high-level coordinator in charge of safety overrides, sensor monitoring, and wireless connectivity.

The Arduino Nano, which runs on a regulated 5-V supply, is in charge of making the digital command signals that control each pneumatic valve. The deterministic AVR design keeps the clock the same and has very little jitter. This is very important for keeping the platform's pitch, roll, and heave movements under control during the inflating and deflation procedures. The ESP32-C3, on the other hand, uses Wi-Fi or BLE to speak to VR software. It collects data about orientation and motion in real time, receives data from pressure sensors, and transmits high-level motion commands to the Arduino. It also helps keep the system safe by watching for problems like too much pressure, a damaged valve, a platform that is tilted, or a lack of communication. The two controllers work together to make sure that the system can deal with mistakes. The Arduino keeps the system safe even if the wireless connection stops working.

The ESP32 can also override the Arduino and start emergency venting if things get dangerous.

The design uses PC817 optocouplers on every control channel to electrically separate the 5-V logic circuits from the more powerful pneumatic valves. These optocouplers can isolate galvanically up to several kilovolts, which keeps voltage spikes caused by inductive solenoid coils from getting to the microcontroller domain. When switching, solenoid valves in pneumatic systems often create strong back-EMF transients. Optocouplers make the system far more stable by making sure that noise, surges, or ground differentials can't get to the logic circuitry. The optocouplers' LED inputs are limited by resistors that are the right size, and their open-collector transistor outputs go to the transistor driver stage.

After the optocouplers, each channel employs a BC557 PNP transistor as the driver between them. This step of the transistor boosts the low-current output from the optocoupler to a level that is strong enough to power the relay coils. The PNP configuration was chosen because it is fail-safe. The PNP transistor stays off when there is no control signal or when an optocoupler output line goes to a floating state. This makes sure that the valve does not turn on by accident. This behaviour is especially crucial for safety on

a pneumatic motion platform that carries people, since accidentally activating the valve could cause sudden imbalanced forces or unexpected motion. The BC557's voltage and current specifications are good for driving relay coils that use between 30 and 60 mA. The base resistors make sure the transistor works properly without overdriving.

The next part of the design is the SANYOU SRD Form-C electromechanical relays, which turn the 24-V power supply on and off for the pneumatic solenoid valves. These relays add another level of electrical isolation and strength. Solenoid valves are inductive loads and therefore mechanical relays can manage back-EMF well and keep the control and power domains separate. Using Form-C relay contacts makes sure that the system's default state (with no power to the coil) keeps all inflation valves off. This is necessary for safety in case of a power loss since it lets the system slowly lose pressure. Relays are better for this application because they are tough, isolated, and have predictable failure modes. This is especially true in a classroom setting where maintenance needs to be easy and equipment needs to be able to handle long-term use.

The solenoid valves run on 24 volts of direct current and control the flow of air from the compressor tank to each air spring or to the outside air for venting. Most air springs have an inflation valve and a deflation or exhaust valve. This lets you manage the pressure in the springs in both directions and make fine adjustments. Depending on what is needed, the flow coefficients of the valves might vary anywhere from 0.2 to 0.5. Their switching rates, which are usually a few tens of milliseconds, are fast enough for VR training, which needs slower, more pleasant movements. The platform's ability to respond to motion depends on how quickly these valves can move air.

This is a standard technique for mixed-signal devices to be grounded. The Arduino, ESP32-C3, and low-power signal parts all have their own logic ground. This is different from the high-power ground that the relays and solenoid valves use. This keeps noise and switching transients from messing up particularly sensitive sensors or microcontrollers. The optocouplers connect these two grounding areas and make sure that the logic circuitry stays safe, even when inductive switching occurred. This kind of isolation is very necessary because pneumatic solenoid valves can change the current quickly, which sends noise through the supply network.

The design has a lot of safety features built in. The ESP32 is continually checking the status of the connectivity, the tilt data, and the pressure sensors. The ESP32 starts the emergency vent sequence immediately away if the pressure goes above a set limit or the tilt sensors detect an unsafe angle. This only opens the exhaust valves and stops all ways to blow up. Also, when they lose power, mechanical relays open on their own. This means that if the power goes out, the platform will lose pressure. This safety feature is very important for classrooms because there may be kids nearby, and the equipment needs to work safely even if something goes wrong. The dual-controller architecture makes safety even better by making sure that no single fault, like a problem with communication, logic processing, or wiring, can cause the platform to move in a way that can't be controlled.

Finally, the electronic control system is made to work with VR apps and deliver motion cues that may be changed in size and time. Moving each air spring by itself lets you make pitch, roll, and heave movements. The gadget may replicate a lot of different types of motion profiles, such as tilting, rising, lowering, or altering posture in response to VR input by varying the inflation and deflation sequences on the three actuators. The Arduino's deterministic control and the ESP32's ability to connect to VR in real time make it possible for smooth motion transitions without any jerks or oscillations. This synchronized operation makes sure that all of the user's senses give them the same information, which makes the experience more real and helpful for learning.

4. Working of the Proposed Model

The suggested pneumatic 3-DOF VR chair works by using a structured electropneumatic control system that turns motion inputs from VR into coordinated height changes across three air springs that are 120° apart from each other under the platform. Algorithm 1 presents a brief overview of the full process, demonstrating the processes from turning on the system to controlling it in real time, taking safety measures, and shutting it down.

The Initialization Phase is the first thing that happens when the controller starts up. During this time, the ESP32 connects to the VR motion-input module. The current version of VR motion cues uses a manual accelerometer-based profiling method to make them. The operator moves the accelerometer plates by hand during video playback to make the perceived pitch, roll, and heave motions happen in real time. An ADXL345 sensor picks up these accelerations and then time-stamps them to make a raw motion timeline. This method is great for low-cost systems because it doesn't require commercial software or API license and doesn't require motion cue extraction from VR engines. This method has operator-dependent problems including delay, drift, and limited repeatability, but it is an easy, straightforward, and equipment-independent way to make motion sequences. Refining the recorded accelerometer profile later makes sure that the final actuation commands are very near to what the VR experience was meant to be. This method is the most practical and effective way to get motion instructions right now, given the limitations of cost, accessibility, and ease of implementation.

It doesn't require high-end hardware, SDK integration, or proprietary motion cueing algorithms.

The system does a Safety Pre-Check before moving. If the tilt angle goes above the safety threshold, the pressure reading goes above the set overpressure limit, or the VR/accelerometer command link is lost, the emergency vent goes off and the system stops all motion. This process makes sure that the system always starts up from a safe and stable condition.

Algorithm 1

Operating Logic of the Pneumatic 3-DOF VR Chair

• **Start system power**

Initialize ESP32 communication with VR application.

Configure valve control GPIO pins.

Initialize pressure sensors P_1 , P_2 , and P_3 .

Activate safety relay and emergency vent (standby mode).

Deflate all air springs to a minimum safe height.

Set initial pitch = 0, roll = 0, heave = 0.

• **Safety Pre-Check Phase**

If any P_1 - P_3 > Overpressure Limit → Trigger emergency vent → Stop.

If platform tilts > Safety Tilt Limit → Emergency vent → Stop.

If VR link is unavailable → Hold neutral platform.

• **Main Motion Control Loop**

Receive VR commands: $\text{pitch}_{\text{cmd}}$, roll_{cmd} , $\text{heave}_{\text{cmd}}$

Convert VR commands to target spring heights: $H_1\text{target}$, $H_2\text{target}$, $H_3\text{target}$.

Read sensor pressures and estimate actual heights.

Compute errors $e_i = H_{\text{target}} - H_{\text{actual}}$

For each spring i :

If $e_i > \text{threshold}$ → open inflate valve.

If $e_i < -\text{threshold}$ → open exhaust valve.

Else → hold both valves closed.

• **Synchronization Control**

Compute Sync Error = $|e_1 - e_2| + |e_2 - e_3| + |e_3 - e_1|$.

If Sync Error > Sync Limit → adjust valve timing to equalize motion.

• **Safety Monitoring Loop**

If Pressure > Safety Limit → Emergency vent.

If tilt > Cutoff Angle → Emergency vent.

If power loss → All valves fail-open to exhaust.

• **Shutdown Procedure**

Deflate all air springs fully.

Disable valve drivers and relays.

Log final VR and sensor data.

End system operation.

After checking for safety, the controller moves on to the Main Motion Control Loop. The accelerometer profile $\text{pitch}_{\text{cmd}}$, roll_{cmd} , and $\text{heave}_{\text{cmd}}$ are read all the time here. Using a geometric mapping based on platform kinematics, these are turned into target heights (H_{target1} , H_{target2} , and H_{target3}) for the three air springs. The system can figure out the height error (e_i) for each actuator by using real-time pressures from P1 to P3 to guess how far each air spring has actually extended.

$$e_i = H_{\text{target}i} - H_{\text{actual}i} \quad (1)$$

The ESP32 then determines valve actions:

- If e_i is positive beyond a threshold, the inflate valve opens.
- If e_i is negative beyond a threshold, the exhaust valve opens.
- If the error lies within a dead band, both valves remain closed to hold position.

Because pneumatic actuators are inherently compliant and nonlinear, platform motion depends on coordinated actuation instead of the accuracy of each actuator. So, a Synchronization Control Stage operates at the same time as the main loop. The synchronization metric, defined as

$$\text{Sync Error} = |e_1 - e_2| + |e_2 - e_3| + |e_3 - e_1| \quad (2)$$

This measures the imbalance between the three air springs. If this error exceeds the synchronization threshold, the controller automatically modifies valve opening times to equalize the inflation/deflation rate among actuators.

The system runs a Safety Monitoring Loop all the time to keep users safe. The emergency vent turns on right away if the pressure goes above the safe level. If the tilt angle goes above the cutoff threshold, the platform is quickly depressurized to bring it back to a safe neutral position. In the event of a power outage, a fail-safe pneumatic design makes sure that all valves go to the exhaust state. This means that the platform would gently fall to its lowest height instead of staying in an elevated or unstable posture.

When the running cycle is over or when the user gives the instruction, the system goes into the Shutdown Procedure. The air springs are totally flat, the valve drivers are turned off, and sensor readings, timing profiles, and other operating data are saved for later use. After that, the chair moves back to its natural resting place, where it will be ready for the next session. The device can move in three dimensions because it has an integrated electropneumatic process that employs cheap sensors, accelerometer-based motion profiling, and microcontroller-based valve management. It also makes the building simple and secure. Because it is affordable, safe, and easy to use, this VR chair is a wonderful

choice for schools. It has pneumatic actuation, synchronized pressure feedback, and a way to modify the motion profile.

5. Results & Discussion

The structural study, air-spring characterisation, and motion-behaviour evaluation together show how well the proposed 3-DOF pneumatic VR chair functions mechanically. We look at each parameter one at a time to make it easier to understand. We start with the calculations for bolt stress and then move on to the performance of the plywood bearing, the air spring parameters, and the dynamic motion characteristics. The measurements collected during testing and modelling show how the tension, shear, combined stress, and safety concerns change as the tilt angle goes from 0° to 30°. They also show what the materials can and can't do. The research talks about each table on its own to show how the streamlined pneumatic architecture works under stress, how the safety margins change with tilt, and how the structural reinforcements keep everything running smoothly. These data, when taken together, are the basis for judging whether the system meets the safety, durability, and performance standards that an instructional VR motion platform should meet.

Table 1 shows how the load on the bolt changes as the platform tilts from 0° to 30°. The bolts are under very little tension (18 MPa) and shear (6 MPa) in the neutral position (0°), hence the total von Mises equivalent stress is only 19 MPa. This figure is very small compared to the 640 MPa yield limit of M12 grade 8.8 steel, which shows that the attachment system works in a fully elastic and very low-stress state when it is static and level.

When the platform tilts to 10°, the way the weight is spread out becomes uneven. This causes one bolt group to lift more and the other side to compress more. This effect can be seen in the rise in tension to 45 MPa and shear to 11 MPa. Even if these numbers are more than double the baseline, the overall stress of 46 MPa is still much lower than the material's yield strength. The system still has a very high stress margin at this operating condition.

Table 1
Bolt Stress at Different Tilt Angles

Tilt Angle (°)	Bolt Tension (MPa)	Bolt Shear (MPa)	Combined Stress (MPa)	Yield Limit (MPa)
0°	18	6	19	640
10°	45	11	46	640
20°	78	17	80	640
30°	104	23	107	640

At 20° tilt, the mechanical demand increases substantially. The bolt tension rises to 78 MPa and shear to 17 MPa, leading to a combined stress of 80 MPa. This trend is expected because tilt causes a larger

portion of the user and platform weight to shift toward the edge of the spring triangle, producing higher overturning moments. Nevertheless, the combined stress is still only about 12–13% of the 640 MPa yield limit.

Table 2
Bearing-Stress Analysis

Tilt Angle (°)	Bearing Stress (MPa)	Plywood Limit (MPa)	Safety Factor
0°	2.1	8	3.8
10°	3.4	8	2.3
20°	5.2	8	1.5
30°	6.7	8	1.19

At the maximum evaluated tilt angle of 30°, the bolt tension reaches its highest value (104 MPa), and shear increases to 23 MPa. The resulting combined stress of 107 MPa reflects the worst-case structural loading scenario for the bolt group. Even at this extreme angle-which exceeds the system’s operational tilt limit the stresses remain far below the bolt’s rated capacity, corresponding to a very large elastic reserve.

Therefore, the combined-stress results clearly show that all stresses generated between 0° and 30° remain far below the 640 MPa yield limit of the M12 grade 8.8 bolts. Even at the highest evaluated tilt, the connection system retains a large structural safety margin, confirming that the bolts operate well within their elastic range. The progressive increase in tension and shear with tilt angle closely follows the expected nonlinear growth of overturning moments as the platform rotates, demonstrating that the mechanical response of the joint matches theoretical predictions. All of this data shows that the M12 bolts and the strengthened steel mounting plates make a strong, sturdy, and fatigue-resistant attachment system that can hold the VR chair during its entire intended working range.

The bearing-stress analysis in Table 2 demonstrates how the plywood mounting interface reacts to additional tilt in the platform. The load distribution changes as the tilt increases, and the compressive stresses under the bolt-washer contact area get higher. The bearing stress is only 2.1 MPa at 0°, which is a high safety factor of 3.8 compared to the cautious plywood bearing limit of 8 MPa. This means that there is very little chance of crushing during level operation. As the tilt gets steeper, the eccentric moment makes the downhill mounting point carry more weight, which causes the bearing stress to climb in a nonlinear way: 3.4 MPa at 10° (SF = 2.3) and 5.2 MPa at 20° (SF = 1.5). Even at these mild angles, the strains are still well under the limitations for cyclic use. At 30°, the bearing stress is 6.7 MPa, which lowers the safety factor to 1.19. This is still below the material limit, but it marks the beginning of a marginal area where long-term wear or dynamic overshoot may conceivably go close to the plywood's bearing capacity. Even if the margin is getting smaller, the system is still structurally sound since the load is spread out over enlarged hardened washers and steel backing plates. This makes the effective contact area much larger and stops localized fibre crushing.

Table 3
Air-Spring Dynamic Performance

Parameter	Value
Rated Load Capacity per Spring	400–600 kg
Operating Pressure	30 psi (0.21 MPa)
Vertical Stroke	~ 100 mm
Response Time	40–70 ms

Also, using M12 grade 8.8 bolts and a well-balanced three-spring support design makes sure that bearing loads stay mostly axial and are evenly shared among mounts while the system is running normally. All of these steps show that the design is safe because the plywood interface works safely within its mechanical constraints over the whole range of intended tilt, with only the highest extreme (30°) coming close to but not going over the permissible bearing threshold.

Table 3 outlines the most important dynamic performance traits of the air springs utilized in the VR motion platform. It shows that they are good for making smooth, responsive 3-DOF motion. Each spring can hold a load of 400 to 600 kg, which is far more than the system's real operational load. This gives the structure a lot of extra safety, while yet retaining the spring's middle region's linear stiffness behaviour. The springs work at a moderate internal pressure of 30 psi (0.21 MPa), which is strong enough to hold up the weight of the platform but still let it move about when it tilts and heaves. The vertical stroke of about 100 mm is enough to show heave signals and make up for the height difference created by the 20–30° pitch and roll motions in the 3-spring system. The response time of 40 to 70 ms is very important because it indicates that the air-spring and valve assembly can swiftly respond to VR motion signals without any lag. This makes sure that visual and physical inputs are in harmony. All of these performance numbers show that the chosen air springs have the correct load-bearing capacity, compliance, motion range, and actuation speed to make dynamic reactions that are safe and realistic. This makes them great for an inexpensive VR motion chair that teaches you anything.

Figure 4 shows the plotted relationship between safety factor and tilt angle, which gives a full picture of how the bolted joint acts when the angle of displacement increases. The safety factor is very high (SF = 33.6) at 0° tilt, which means that the bolts are only being used at a small fraction of their maximum strength. This area shows the static baseline situation, when the weight of the platform acts almost straight down and doesn't put much stress or shear on the platform. As the tilt angle goes up to 10°, the safety factor goes down to 13.9, which is what you would expect when the overturning moment goes up. The moment goes up, which makes the bolt tension and shear pressures go up as well. This is indicated in the combined stress numbers. But the bolts are still well below their yield level, which means there is a safe margin of safety.

After 20° of tilt, the slope of the curve gets less steep, and the system reaches a point where the rise in combined stress is easier to see. At 20°, the safety factor is 8.0, which means that even if the strain on

the structure increases, the bolts will still be within their elastic limits. This pattern is in keeping with how objects generally work when they roll over: when the angle changes, the horizontal element of the gravitational load increases stronger in a nonlinear way. The most important thing happens when the tilt is 30°, which is when the safety factor is at its lowest point of 5.9. Even in this very strange position, the joint is still far safer than the minimum technical recommendation (usually $SF \geq 2$ for dynamic mechanical systems). The curve's smooth, continuous decrease reveals that the load transfer is stable and that there are no structural breaks, such as yielding, slippage, or joint rotation. In general, the figure confirms the analytical data and shows that the M12 Grade 8.8 bolts are still far from their failure limits in all test situations.

Based on these combined results, the bolted joint design can be thought of as mechanically safe, structurally sound, and good for repeated dynamic use. Even when the platform is tilted to its highest point, the system still has a safety factor that is over three times higher than what is usually needed for safe operation in real-world mechatronic platforms. This shows that the connection between the seat frame, mounting plates, and underlying structure has enough extra capacity to handle high-frequency VR motion profiles without coming loose, cracking from fatigue, or overloading. The plywood bearing-stress study, the air-spring performance table, and the strong geometric shape of the chair frame all point to the same conclusion: the VR platform is ready for use in the field.

5.1 Demonstration of Pitch, Heave, and Roll Motions Using the Pneumatic VR Chair

Figure 5 shows the three basic motion modes that the proposed three-air-spring VR chair can do with controlled pneumatic actuation: pitch, heave, and roll. The device has a rigid upper platform that holds the seat and the user's weight. This platform is positioned on three air springs that may be regulated separately and are coupled to a rigid base structure. The platform moves up and down and rotates around its main axes by changing the internal pressure of each air spring. A streamlined structural frame and a small number of pneumatic actuators make the system less complicated and consume less material, which immediately lowers the entire cost of implementation.

The left column of Fig. 5 shows pitch motion, which is when the platform rotates about the lateral axis because the front and back air springs have different amounts of pressure. If you increase the pressure in the front air spring and lower the pressure in the back air springs, the car will lean backward. If you do the opposite, the car will lean forward. You can move the pitch in a controlled way with this technology, and you don't need any special rotary joints or electromechanical actuators. This lowers the cost of the pieces and the work needed to put them together.

When all three air springs are inflated or deflated at the same time and in the same way, the centre column shows heave motion. This setting has the platform travel up and down, but it stays almost level, which is the same as going straight up and down. The way the air springs are arranged in a symmetric

triangle makes it easy to buy and care for them, and it also helps spread the load equally, which saves money.

The right column depicts roll motion, which happens when the air springs on the left and right sides are at different pressures. This makes the item spin along its long axis. The same pneumatic parts that are used for pitch and heave may also make lateral inclination, so there is no need for extra actuators or complicated mechanical linkages. This way of using a single actuator reduces down on both the number of parts that are the same and the system's overall cost.

Figure 5 shows how the VR chair works and how three low-cost pneumatic actuators can regulate pitch, heave, and roll motions independently, all within a mechanically simplified design. The goal of this design strategy is to create a VR motion platform that is affordable and can be used for educational, research, and entry-level immersive applications.

The analytical results and reaction characteristics show that the VR chair's structure meets the mechanical needs for the planned operation circumstances. The fasteners, mounting plates, and main structural interfaces all keep safe margins at the tilt angles tested, even when they are outside the normal working ranges. The load distribution and stress levels that result are still within acceptable limits, which shows that the structure behaves stably when both static and moving loads are applied. The suggested design uses a mechanically simplified structure with only a few pneumatic actuators and parts that are easy to find, which makes the system less complicated and cheaper overall. These features make it likely that the VR chair can be made and used in educational, research, and entry-level immersive VR applications, as long as it follows normal tolerances and quality-control methods.

6. Conclusion

The suggested low-cost VR motion chair shows that it is possible to make an economical, mechanically safe, and educationally helpful motion platform utilizing common parts like M12 bolts, plywood interfaces, and air-spring supports. Structural study showed that all of the main load-bearing parts work with a lot of safety margin, even at high tilt angles up to 30°. The safety factors for the bolts range from 33.6 at zero tilt to 5.9 at maximum tilt, which is substantially beyond the minimal level needed for dynamic systems. In the same way, the strains on the plywood stayed below their limits, which proved that the connection between the chair frame and foundation was strong. These results suggest that the design is strong, dependable, and good for usage in a classroom or school lab where people move about a lot.

One of the main reasons for making this model was the necessity for affordable interactive technologies in schools, since commercial VR motion systems are too expensive. The method keeps costs far lower than those of platforms that are for sale by using cheap materials and a tiny mechanical design. It still provides immersive, high-quality learning opportunities. Kids might really like VR technologies that let them walk around. They could help them learn more about physics and engineering and give them hands-on learning experiences that are better than what they would get in a regular classroom. The

technique solves a huge problem by giving schools a motion-VR system that is simple to use, secure, and can grow with their needs.

But you need to know that there are some boundaries. The current prototype has a limited tilt range compared to industrial VR platforms and uses simple human control instead of a fully automated closed-loop actuation system. The plywood-bolt interface is safe for instructional loads, but it may not be able to handle very high-frequency or long-term use without being checked often. Also, the air springs' properties limit how quickly the system can respond to changes in motion. They work well for moderate motion cues but not for very fast or high-G movements.

Future research should concentrate on creating an electrically controlled actuation system to facilitate automatic motion profiles that are coordinated with virtual reality content. Replacing plywood with composite or metal plates on material interfaces could make them even more durable for long-term use. Adding sensors for real-time input, user-specific changes, and safety monitoring would make the system much more reliable. Finally, adding roll, pitch, and limited heave control to the motion envelope will make the device more useful for classroom demonstrations and interactive STEM teaching modules.

Declarations

Author Contribution

M.C. conceived the study, performed the mechanical, structural, and electronic system analyses, conducted the experimental investigations, and drafted the main manuscript. S.G. contributed to the design and development of the pneumatic VR motion platform, system integration, experimental support, and data interpretation. K.S.M. provided conceptual guidance, critical review, and overall supervision of the research. All authors reviewed and approved the final manuscript.

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Figures



Figure 1

3D visualization of the proposed VR chair Mechanical arrangement

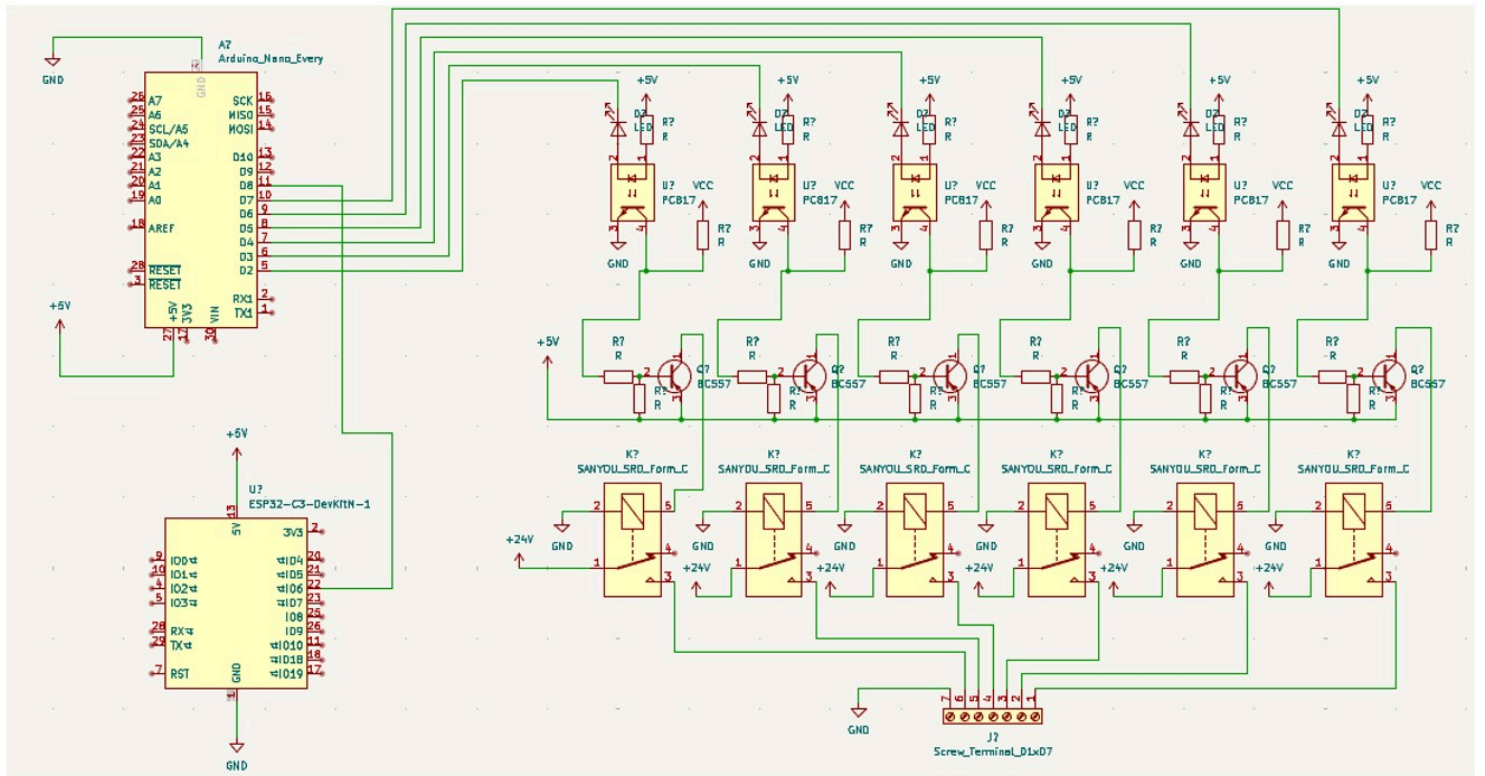


Figure 2

Pin diagram of the proposed model

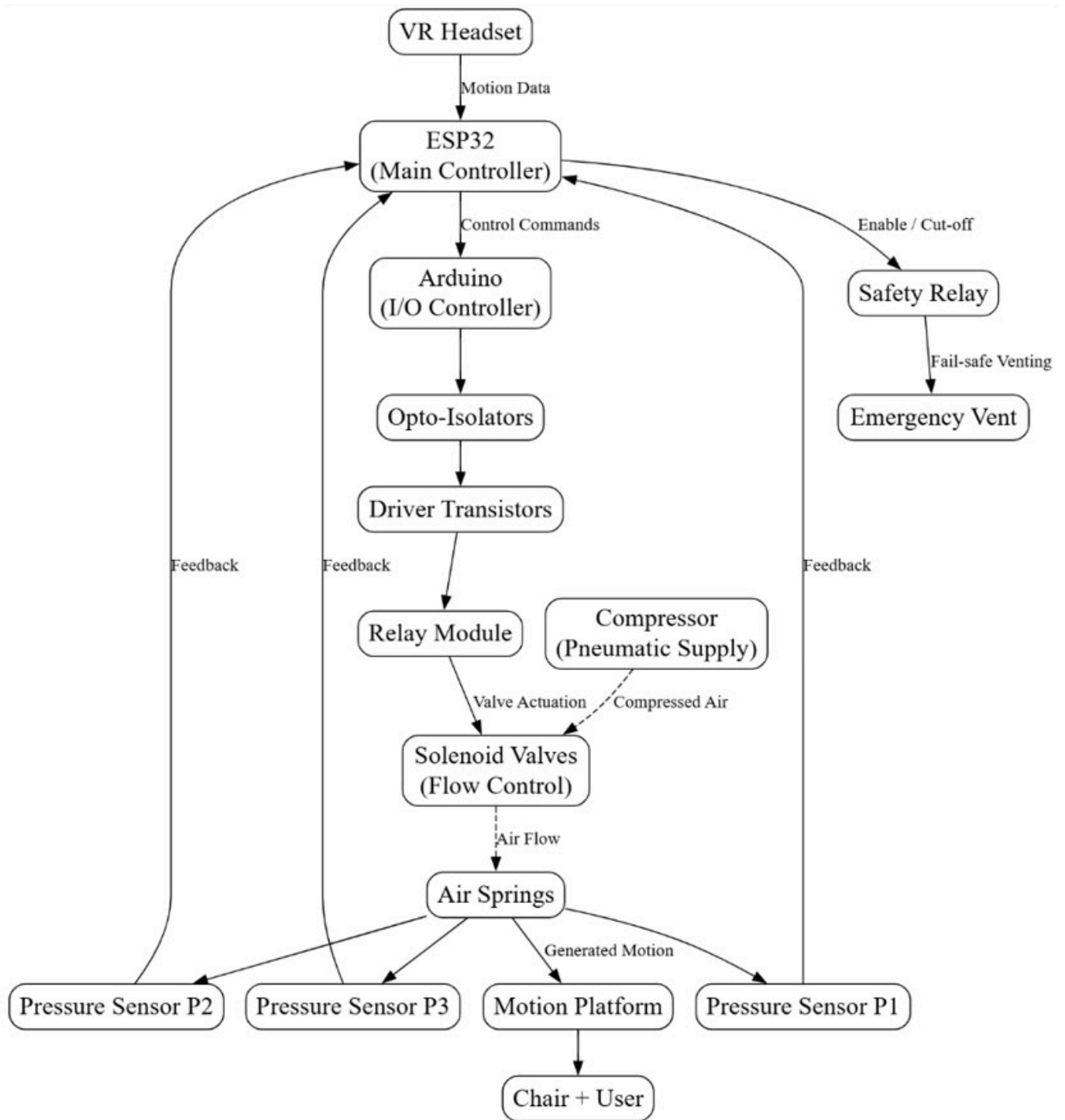


Figure 3

Architecture of the Proposed Model

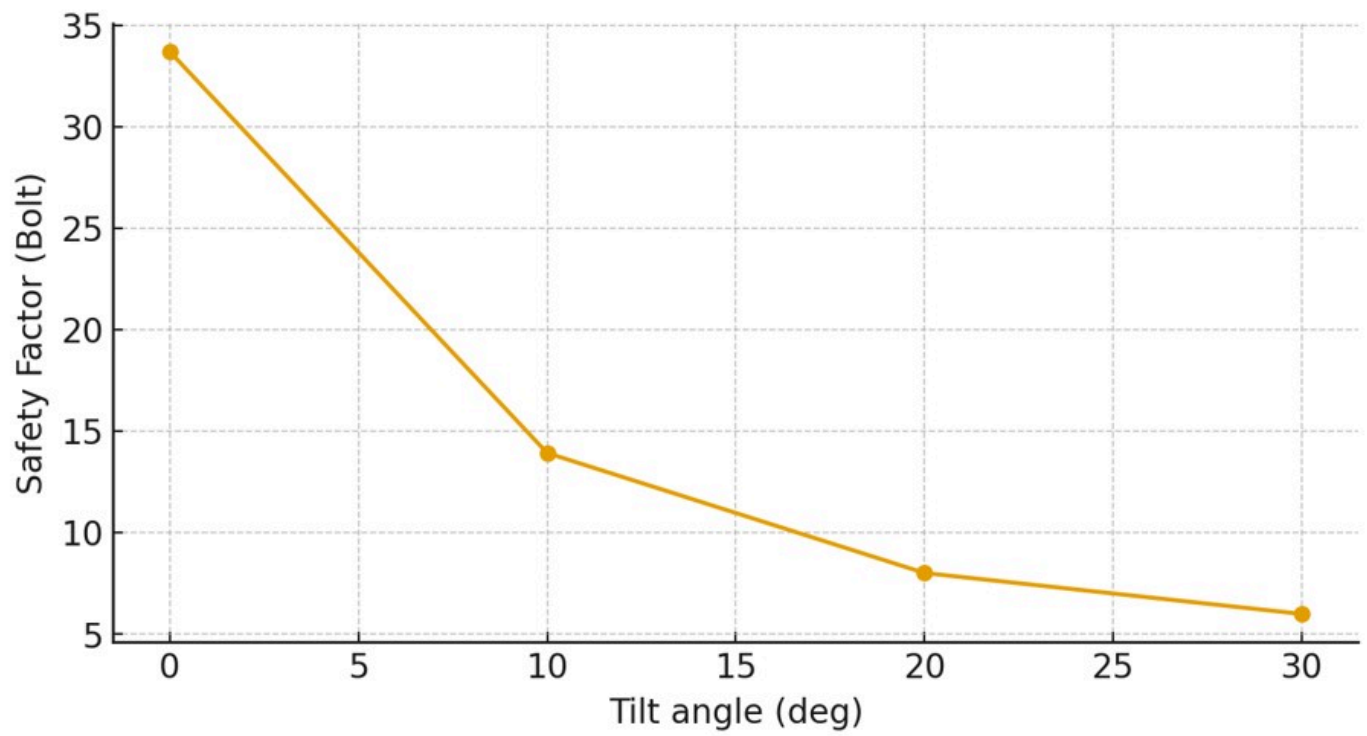


Figure 4

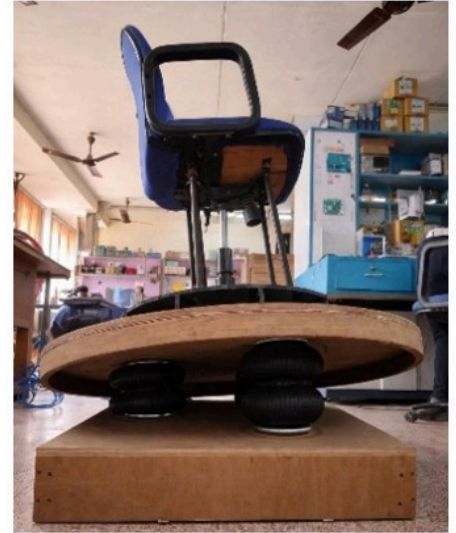
Safety factor variation with tilt angle.



Pitch



Heave



Roll



Figure 5

Realized Pitch, Heave, and Roll Motions of the Pneumatic VR Chair