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Student Learning Through Engineering Design: Developing a Safe Recoil Indication System for Military Applications

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Abstract
This paper details a student-led research project, supervised by faculty and funded by the Civil-Military Innovation Institute (CMI2), to develop a Safe Recoil Indication System for military training. The system addresses the dangers associated with the 350-pound recoil of a breech block, replacing it with a safer alternative designed for training purposes. The design emphasized simplicity, ease of use, manufacturability, maintainability, and performance. Students gained hands-on experience in CAD design, electric circuit design, programming, laser scanning, and iterative refinement. The system utilizes vortex tube technology to produce cold and hot air streams, with careful attention to component placement and performance. This project allowed students to apply theoretical knowledge to practical challenges, enhance problem-solving skills, and refine designs through continuous feedback, offering a significant educational experience.

Keywords: Student-Led Research, Engineering Education, Safe Recoil Indication System, Breech Recoil Replacement.

Introduction

Design principles serve as essential guidelines that influence the creation and execution of systems, ensuring they achieve their goals efficiently and safely. In military training systems, certain key principles are often emphasized. These principles help ensure that systems are durable, dependable, and designed to prevent accidents while minimizing risks. In the following, we address seven key design principles that are essential to developing military training systems : 1) fail-safe, 2) safety margins, 3) defense-in-depth, 4) observability-in-depth; 5) inherently safe design, 6) training engagement, and 7) near-miss management.

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Fail-Safe Principle
The fail-safe principle plays a fundamental role in military training systems. It ensures that systems revert to a safe state when a failure happens. For example, in military training, simulations are built to stop or switch to a safe mode if a significant issue arises, safeguarding trainees from potential harm[1,2].

Safety Margins Principle
Safety margins play a crucial role in both fields by accounting for uncertainties and variations in system performance. Including adequate safety margins allows designers to ensure systems remain secure, even in unexpected situations. In military training, this could mean applying conservative limits to exercises to avoid injuries or overexertion[1,2].

Defense-in-Depth Principle
The defense-in-depth principle focuses on using several layers of safety measures to guard against potential failures. This approach is especially important in military training, where safeguards like redundant communication systems and backup power sources are used to maintain safe and uninterrupted operations[1,3].

Observability-in-Depth Principle
Observability-in-depth involves the continuous monitoring of systems to detect and respond to any deviations from normal functioning. In military training, this could mean tracking trainees' performance and health metrics in real-time to offer immediate feedback and take action when needed.[1,3]

Inherently Safe Design
Inherently safe design aims to remove hazards at their origin, instead of managing them with additional safety measures. This concept is essential in military training, and it could involve structuring exercises to avoid risky scenarios altogether[1,2].

Training Engagement and Transfer
Providing effective safety training is essential to ensure that safety principles are understood and applied properly. Studies emphasize the need to engage trainees emotionally, mentally, and physically to help them retain and use safety knowledge in practice. In military training, this requires creating realistic, relevant scenarios that help soldiers transfer their skills to actual situations[4].

Near-Miss Management Systems
Near-miss management systems (NMS) play an essential role in learning from incidents that almost caused accidents but were avoided. These systems allow for identifying and addressing the underlying causes of near-misses, helping to prevent future accidents. In military training, NMS can be used to examine training incidents and improve safety measures[3].

This paper highlights a design focused on inherently safe design by removing the danger posed by the 350 lb. breech recoil and substituting it with a significantly safer option. The system is intentionally designed to eliminate the risks associated with real recoil, ensuring safer training without requiring extra safety measures. Three female engineering students completed this project under the guidance of two mechanical engineering faculty members.

Problem Statement

This project tackles the significant risk posed by the recoil of a 350 lb. breech system, which can result in serious injuries to military personnel during use. The existing recoil systems are unsafe for training, highlighting the need for a safer alternative that still preserves operational effectiveness. Additionally, the project sought to boost the involvement of female engineering students by offering hands-on research opportunities, an important step in fostering diversity and promoting innovation in the field.

Student Brainstorming and Team Structure

At the start of the project, students participated in weekly brainstorming meetings with faculty supervisors to develop practical solutions for the Safe Recoil Indication System. These sessions included concept mapping, feasibility assessments, and multiple rounds of idea refinement. Through this process, students explored various technical approaches, such as LED-based visual indicators and vortex tube air recoil systems, before deciding on a hybrid solution.

Three female mechanical engineering students actively contributed to the project. The team worked as a cohesive unit, with responsibilities divided among members for CAD modeling, circuit design, system assembly, and testing. While collaboration was central to the project, tasks were assigned based on each student's strengths and interests, ensuring they gained hands-on experience in different aspects of the design and development process.

Design Process

The Safe Recoil Indication System is designed around several important criteria, including: 1) simplicity; 2) ease of use; 3); ease of manufacturing; 4) maintainability; and 5) performance. Next, we discuss these factors in detail.

Simplicity

Simplicity was a central focus in the design process of this system. Every part of the indication system was purposefully chosen to ensure efficient and effective operation. By keeping the design straightforward, potential issues were minimized, making both manufacturing and maintenance easier. When problems did arise, they were quickly identified and resolved due to the system's simple design.

Ease of Use

A major factor when designing this system was that it was easy to use. The point of this system was to indicate when the breech would recoil to warn the soldiers to clear the area. Because of this, it was important to ensure that there were no additional steps outside of what the user must do to run the breech system itself. A simple switch was used so the system would activate when the rope was pulled to deploy the breech. This was important to make the simulation as similar to the M109A6 Paladin Breech as possible.

Ease of Manufacturing

The team prioritized making the design as easy to manufacture as possible without compromising efficiency or performance. We created simple yet effective components that can be easily added, removed, or adjusted to fit the user's needs and the layout of the breech. Each component was designed to simplify the manufacturing process while still fulfilling its intended function.

Maintainability
The design was made so that any parts that could need work or to be replaced are easily accessible. Every component of the ring is in a case that protects the important hardware, but also is easily removed for replacement of wires or repairs. The wiring of the LEDs was done in a way that they can be replaced easily as they will eventually burn out. The design of the ring also allows the LEDs to be easily removed when the time comes for them to be replaced.

Performance
The final key criterion for this design is performance. Every component needs to handle continuous use for an extended period. When selecting the power source and LED lights, the team made sure they were compatible, which helped maximize the lifespan of the lights and improve the overall system performance.

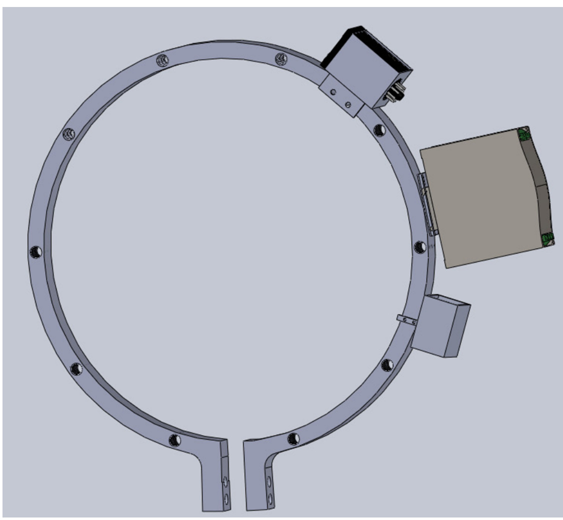

Figure 1: Recoil System Ring with Components Attached

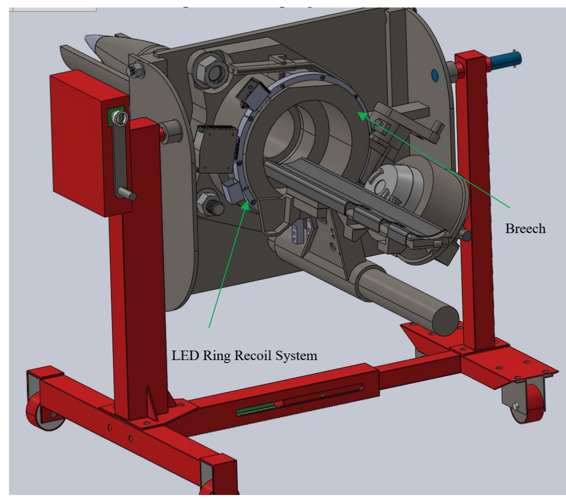

Figure 2: Finished breech model with LED Recoil Indication System

Design of the LED Recoil Indication System
The first idea for the Recoil Indication System was to attach LEDs around the breech that would be triggered when the rammer was pulled back. This would allow the LEDs to remain on for a specified amount of time when the risk for recoil was present. The first task that arose from this idea was to create a way to attach the LEDs to the breech in a way that was minimal and out of the way of the breech's functions. The material for this ring would also need to be flexible enough to fit over the circumference of the breech without breaking, to allow for easy removal and installation. This material would also need to be nonconductive as it will be in contact with the LEDs and several forms of wiring. To make the LEDs functional, a few other components were needed. The ring would need to be able to hold a power supply to power the LEDs, a switch to trigger the LEDs to turn on, and a timer to leave them on for a specified amount of time. These components would need attachment points to be able to attach to the system.

Approach to Design Process
To initiate the design of the physical ring, detailed information about the breech system was required. Using 3D scan data, the team extracted precise dimensions to begin the design process.

This work was carried out in SolidWorks, where the breech and associated components, including the rammer, were modeled. The ring was designed to fit securely around the breech's outer rim and fasten at the bottom for easy removal, as depicted in Figures 1 and 2. The next phase involved incorporating the necessary components to enable LED functionality. By analyzing the breech model, the team identified optimal points on the ring for attaching these components without interfering with other elements. Using CAD tools, cases were created to securely mount the power supply, switch, and timer onto the ring.

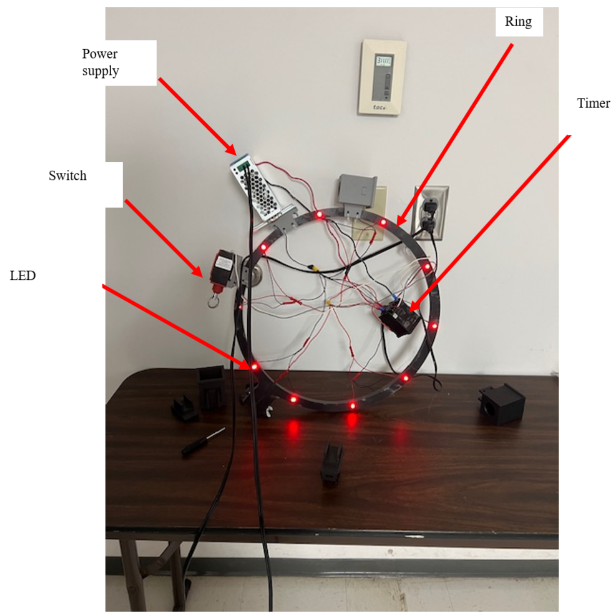

Figure 3: LED Recoil Indication System.

Figure 4: Components of the LED Recoil Indication System.

LED Ring Indication Circuit

Figures 3 shows the initial design of the metal ring with the electronic components connected to it and Figure 4 list the critical electronic components used in the design. : a metal ring, power supply, timer, LEDs, and a switch as shown in Figure 3. The metal ring is positioned around the breech and serves as a structural element of the system. The selected LEDs were rated for 24V DC, while the timer required 120V AC for operation.Thus, a power supply is used to provide the necessary energy to operate the LEDs, which are activated by a switch.

The N terminal of the power supply is connected to the neutral terminal of the AC power source, and the L terminal is connected to the live side of the AC input. The V- terminal 1 of the converter is linked to the negative side of the LEDs, while the second V- terminal connects to terminal 5 of the timer. The V+ terminal of the converter is connected to terminal 3 of the timer, supplying the necessary positive voltage for the timer to control the circuit.

The negative terminal of the switch is connected to terminal 6 of the timer, and the live wire is connected to terminal 8. Regarding the LED connection, its positive side is connected to terminal

4 of the timer, and the negative side is connected to the V- terminal 1 of the power converter. When the switch is engaged, the timer controls how long the LEDs remain illuminated. These LEDs are used to provide a visual indication when the system is in recoil.

Throughout the circuit, AWG male and female connectors are used to ensure secure and reliable electrical connections. These connectors allow for easy assembly and disassembly during maintenance or component replacement. While butt clamp connectors were initially used to join the wires, the final setup employs screw terminals for the timer, switch, and power converter to provide a more robust and long-lasting connection.

The Omron H5C5A timer is set up to control the 24V LEDs, keeping them on for 30-second intervals in countdown mode. It operates in ”H” output mode, which ensures the LEDs stay lit for the full countdown. To start the countdown, it uses an NPN input. To avoid any accidental adjustments, the timer’s settings are locked with a key lock (kP-1), and its display shows important info like the remaining time. There’s also an alarm set to trigger after 100 output cycles, and a safety cap is in place to make sure the timer doesn’t run past 35 seconds. This setup helps keep everything running smoothly and safely.

With these components integrated together, the ring indication system enhances safety by providing a clear, immediate visual signal that the breech has recoiled after firing, thus preventing premature actions by the crew. This visual feedback helps mitigate the risk of crew members approaching the breech area before it is safe. Additionally, the system serves as an important tool in training scenarios, offering clear, visual feedback to operators about the recoil process, allowing them to better understand and respond to potential hazards. This improvement not only increases operational safety but also enhances the learning experience by ensuring the crew is aware of the breech’s status during training and live operation. The traditional recoil of 350 pounds poses significant risk during training, as it can lead to serious injury if operators are not fully aware of the timing and extent of the recoil. This alternative system minimizes that risk, ensuring a safer training environment for all personnel.

Design of Hybrid LED and Air Recoil Indication System

The team decided that another type of indication system should be designed since the soldiers may be in conditions where the lights are not visible, and the air was the most functional option for the given circumstances. Rather than just simple compressed air, the team decided that cold air would be a better option to be noticeable in all conditions and clothing types. To achieve this, a vortex tube is used to convert the compressed air into cold air. For the air to be noticeable from at least 6 feet away, the ideal velocity out of the nozzle needs to be 1.5-2 m/s. Because of this, a 100 SCFM EXAIR vortex tube was used for this design. The breech simulation already uses an air compressor for the other operations, so a branch hose will be taken off the compressor to provide air for the vortex tube.

With the original visual recoil system already finished, the team decided that for not only ease of use but also ease of manufacturing, the ring would be modified to fit the vortex tube and components needed.

Vortex Tube Technology

A vortex tube, shown in Figure 5, is a mechanical device that separates compressed air into a hot and a cold stream, without any additional energy sources needed. The tube itself is made of a cylindrical chamber with a tangential inlet and then an outlet for both the hot and cold air. The compressed air enters the tube at a high velocity, which generates a rapid rotating vortex. While inside the tube, the air spins and creates a centrifugal force that forces the hot air molecules to the outside and the cold air molecules to the inside of the chamber. They then exit at their respective outputs with substantial temperature differences down to -50°C and up to 100°C. The simplicity of this design allows for the tube to be easily incorporated into the team's design, while also producing the air temperatures that are needed.

The main component of the air system is the vortex tube which allows the system to produce cold air to exit the nozzle by using the principle of forced vortex flow. Because the environment that this simulation is used in may vary, cold air ensures that in any condition and with any amount of clothing on, the air will be felt by the user.

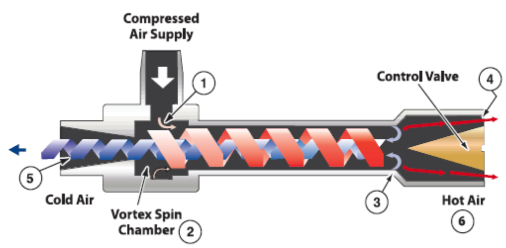

Figure 5: The Theory of the Vortex Tube.[5]

Approach to Design Process

To begin the design of the air recoil indication system, the team had to factor in all the components that would be needed and any parts of the breech that would need to be worked around. Because of the setup of the breech where the ring would be located, all the components attached to the ring would have to be on the left side. The number of air nozzles was also a consideration that changed throughout the design portion of this system. The team started with a sketch of the original design which included the original LED indication system as well as the additional components needed to accommodate the air, which included places for multiple nozzles.

After the original design, the team decided to use the vortex tube rather than just normal compressed air which changed the design. After the correct vortex tube was purchased, the team concluded that one tube would be enough to satisfy the needs of this system. The same ring is used in this design, however the places for the air nozzles and LEDs were removed. A 3D printed clamp was designed to hold the vortex tube on the ring.

As the team continues to create this system, moving forward testing will be run to find proper hosing needed to give the air velocity needed. A valve will be purchased and incorporated into a timer system. This component will allow the air to flow for a specified amount of time when the switch is activated and then stop after the timer runs out. The team will continue to improve

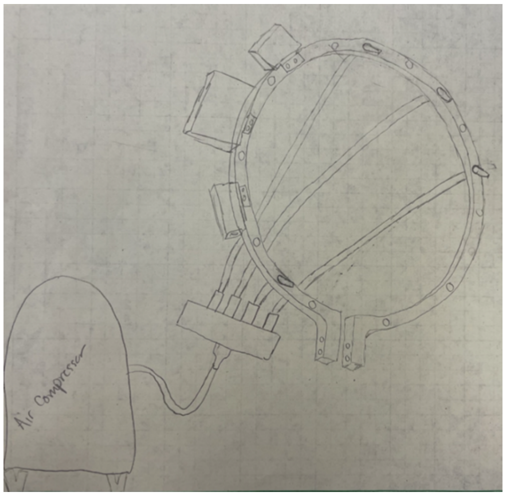

Figure 6: Sketch of Air Recoil Indication System.

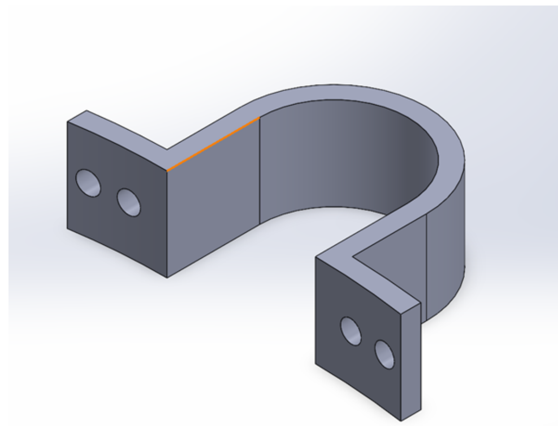

Figure 7: CAD Model of Clamp to Hold Vortex Tube on the Ring.

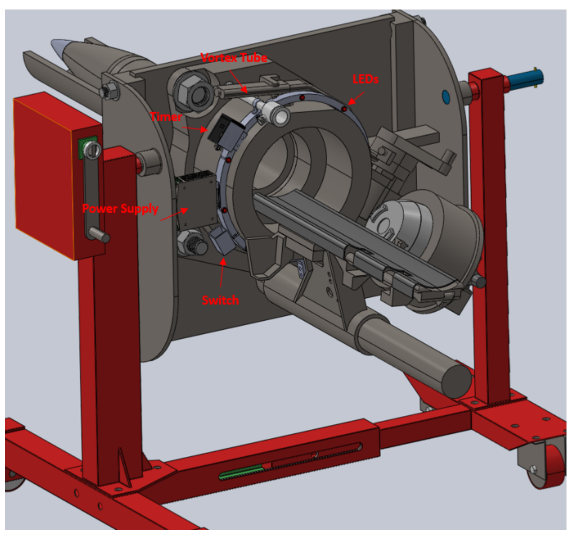

Figure 8: Finished Hybrid LED and Air Recoil Indication System.

and modify this design until it is functioning and meets the specifications that they placed for the system.

Results and Evaluation

With the help of industry to manufacture a second breech that simulates the feeling of the rammer opening and closing the team was able to successfully create a Recoil Indication System using the LEDs Ring mechanism. With the breech, rammer, and cylinder all mounted on the mobile breech stand the system is easily transportable for training purposes. As a soldier operates the rammer and closes the breech door the switch will be triggered, turning on the red LEDs to indicate that the recoil would take place at that time, the LEDs would then remain on for 30s to show the affected area.

However, the team recognized that the LED system gave only visual inputs and depended on the light conditions of the environment which was a weakness for the system. This led us to the introduction of the Air Recoil Indication system, which created two-factor security. The flexibility of the two-method approach ensures that the system is more resistant to outside factors making it an overall more effective and reliable system. Overall, the project successfully balanced innovation with practicality, ensuring that soldiers could rely on the system in real-world conditions. Future testing and iteration will only improve the system further, allowing it to become a more robust and reliable safety tool.

Challenges and Lessons Learned

Throughout the design process the team faced many challenges in the design, assembly, and programming of the Recoil Indication System.

The first challenge to the design process was to find a way to quickly manufacture the concept that was drawn in SolidWorks in an inexpensive manner. The solution was to partner with local industry to collaboratively produce the ring. Marshall's Advanced Manufacturing Center (MAMC) would use the student team's CAD drawings and dimensions to water jet the ring in a quick and cheap fashion. The student team would then help hand tap the LED holes into the ring and perform the rest of the assembly themselves. All individual component holders would be 3D printed with a strong polycarbonate PLA.

The next challenge arose when installing the LEDs into the ring in neat and physically appealing way. The Ring Recoil System includes 12 LEDs all with individual wires that need to be connected to a power supply. The solution was to follow the path of the ring and use multiple wire connectors to make all wires fit seamlessly against the ring. Through this challenge the team learned to tackle problems one step at a time.

Another challenge with the LED system was programming the timer and making it stay on for the specified time. This problem was approached by first figuring out to make the switch trigger the LEDs through the power supply, but this only allowed the LEDs to remain on as long as the switch was pulled. To make the timer stay on for 30s the team had to be diligent by trying different settings and reiterating the inputs into the timer until the desired output was obtained. Through many different trials the proper program settings were found, and the timer sent a signal to the LEDs to remain on for the allotted time frame.

After the LED system was designed, the vortex tube design offered its own range of challenges.

The first of these being finding the correct vortex tube to fit the needs of the project. Though vortex tubes are not a recent technology, there is not a lot of information regarding different applications like the one the team needed it for. Because of this, the team spent a lot of time researching and rejecting varied sizes that would not output the proper velocity needed. After extensive research and calculations, the team was able to select the correct vortex tube that would be ideal for the application.

Once the team found the vortex tube that was needed, the next challenge was the size of the tube itself. To get the velocity needed for the constraints of this project, the vortex tube was much larger than originally accounted for. Though this was an unexpected hurdle, the team worked quickly and diligently to change the original design to one that would work with the larger tube. Through this challenge, the team learned to be adaptable and work quickly to change the design.

System Validation and Deployment Feasibility

The system has undergone extensive validation through both functional testing and direct user feedback, including two Soldier Touchpoints—one at the Army National Guard in West Virginia and another at Central Florida Tech Grove, Florida. Testing focused on verifying that the LED's light was bright enough for soldiers to clearly recognize when the breech was in the recoil state. The vortex tube system was assessed to confirm that the airflow effectively reached soldiers positioned at the back, providing a clear warning of the recoil process. Additionally, the switch mechanism was evaluated to ensure it was durable enough to withstand the demands of military use. Feedback from military personnel indicated that the combination of visual and tactile alerts greatly enhanced awareness of the recoil process, helping to minimize the risk of injury.

Results from testing confirmed that the LED system provided a strong visual signal, though its visibility was somewhat limited in certain lighting conditions. To improve this, brighter and more noticeable lights have been incorporated. The vortex tube system effectively produced a cold air stream, but adjustments were needed for better control. To synchronize the system's operation, a valve was installed to automatically release air whenever the LED activates, ensuring both alerts function simultaneously. In addition, a second compressor was incorporated to generate a stronger airflow for enhanced effectiveness. Additionally, the switch location was repositioned to better align with the layout and operation of the Paladin M109A6, ensuring smoother activation during training exercises.

In terms of long-term deployment feasibility, the system has been designed with scalability and adaptability in mind. The modular construction allows for easy integration into various training environments, while the use of standardized components ensures cost-effective manufacturing and maintenance.

Conclusion

This project led to the successful creation of a Safe Recoil Indication System, addressing major safety concerns for military personnel who work with heavy breech mechanisms. By providing a clever solution that reduces injury risks without compromising realistic elements in training, this system is a game-changer. Instead of using the standard 350 lb. breech recoil, it employs a safer indication mechanism that strikes a careful balance between operational realism and personal safety.

Students involved in the project gained valuable hands-on experience, particularly in CAD modeling, circuit design, and iterative development, allowing them to put their engineering skills into practice. The system combines LED visual indicators with vortex tube air recoil, offering dual-sensory feedback for improved effectiveness. This dual-sensory setup not only enhances user experience but also proves that cost-effective safety measures can be applied practically within military training environments.

The involvement of female students in this project emphasized the importance of diversity in engineering, fostering inclusive learning experiences, and improving the overall outcomes of training system design and development. Female participation in engineering research is vital for closing the gender gap in STEM fields and enhancing retention by reducing dropout rates, particularly in male-dominated environments through supportive and collaborative settings[6]. Creating gender-aware courses that promote participation across technical and managerial roles and introducing role models can build STEM self-efficacy, encouraging young women to pursue and remain in engineering careers[7,8]. Addressing unconscious bias and providing fair role assignments further enable female students to confidently take on technical responsibilities while fostering a strong sense of community and professional commitment[9,10].

Ultimately, this project highlights how practical, student-led initiatives in engineering education drive real-world skill development and meaningful safety advancements for professional applications.

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