# Design and Development of an Interactive and Intelligent Wood Harvester Machine Operator Simulator

Barve Pranjali Ramesh[a], Ian Backus and Raffaele de Amicis[b]
*Oregon State University, Corvallis, U.S.A.*
{*barvep, backusi, deamicisr*}*@oregonstate.edu*

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Abstract: This paper presents the design and development of a virtual reality (VR) forestry harvester simulator, optimized for the untethered Meta Quest. The simulator offers an immersive training environment where users can practice essential harvester operations such as navigation, tree processing, and control of the harvester head and boom. A comprehensive functional evaluation was conducted using 20 black-box test cases to ensure the simulator functions as intended, with testing performed in both standalone and PC-tethered configurations. The results confirmed the simulator's reliability, highlighting differences in responsiveness and graphical performance across configurations. With the portability and accessibility of the Meta Quest, the system provides a flexible, cost-effective solution suitable for both training and educational applications. Future work will focus on evaluating the usability of the system and validating its effectiveness within formal educational settings by integrating the simulator into forestry curricula.

## 1 INTRODUCTION

Worldwide, forestry contributes to economic development, environmental sustainability, and social well-being. As of 2023, the global forestry sector was valued at over $1 trillion, providing millions of jobs and essential resources, such as timber, paper, and bioenergy (Lippe et al., ). A key component of this industry is the use of harvesting machines, complex and powerful tools designed to efficiently cut and process trees. Over time, these machines have evolved from basic mechanized tools into highly advanced systems equipped with with semi-autonomous features.

As harvesting technology advances, so does the complexity of operating these machines. Modern harvesters, while capable of performing many autonomous tasks, still require human oversight, placing greater demands on operators. Operating these machines involves managing challenging terrain, adapting to weather conditions, and processing large amounts of real-time data tasks comparable to those performed by fighter jet pilots (Burman and Löfgren, 2016). This level of complexity highlights the need for effective training, where operators must develop precise control and adaptive decision-making skills.

Traditionally, heavy equipment operators have been trained on-site, which is costly and resource-intensive. In response, many industries are turning to simulators for cost-effective and controlled training environments. With the rise of Virtual Reality (VR) technology, simulators have become even more effective, offering immersive environments for training operators of complex machinery (De Crescenzio et al., 2011). In the forestry industry, where operators face high physical and cognitive demands, VR solutions are particularly valuable.

VR-based simulators provide several key advantages for forestry training. They enable training sessions without disrupting actual harvesting operations, improving both time and cost efficiency. Physical fatigue, particularly in the neck, arms, and shoulders, is a common issue for operators, and VR simulations can help alleviate such strain. Mental fatigue from managing complex control interfaces and navigating off-road environments also increases the risk of accidents (Wei-Sheng Wang and Huang, 2024). VR simulators address these challenges by providing a safe, controlled environment to enhance operator skills and proficiency.

[a] https://orcid.org/0009-0008-1103-0252
[b] https://orcid.org/0000-0002-6435-4364



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## 2 BACKGROUND AND RELATED WORK

Early studies established the feasibility of using VR for training forestry operators. (Lapointe and Robert, 2000) designed a VR system that simulated the control of a harvester's manipulator arm and processing head through a workstation and two-axis joysticks. This system replicated the physical environment operators encounter, demonstrating that VR could significantly increase harvesting productivity while reducing maintenance costs. Similarly, (Lopes et al., 2018) found that participants with no prior experience in forestry operations could quickly develop the necessary skills using a Harvester Virtual Reality Simulator (HVRS).

Over the years, simulator technologies have advanced, integrating increasingly sophisticated hardware and software components. (Zheng et al., 2018) developed a training system featuring a steering wheel, pedals, a shifter, and control handles, with visual feedback rendered through Unity3D. This system demonstrated the importance of creating realistic driving interfaces to enhance operator immersion and skill acquisition. Similarly, (Luecke, 2012) developed the GREENSPACE VR simulator to train combine operators in precision farming. By incorporating authentic operator controls, GREENSPACE offered a realistic driving experience and promoted the adoption of precision farming methods.

Innovative input technologies have also been explored to enhance user interaction with virtual training environments. (Nainggolan et al., 2020) evaluated the Leap Motion Controller as an input device for controlling virtual joysticks and levers. Their research highlighted the potential for novel, gesture-based input systems to improve user satisfaction and control precision, pointing to future directions for immersive training systems.

Because of the heavy dependency on physical hardware like steering wheels, pedals, and joysticks the costs and complexity of setting up training environments increases, making it less accessible for institutions with limited resources and funds. These setups also restrict flexibility, as new or updated training modules would require modifications to physical setups, rather than being adaptable entirely through software updates.

US companies like JohnDeere (Deere, 2024) and CM Lab Simulations (Labs, 2024), Finnish companies Ponsse (Ponsse, 2024) and Mevea (Mevea, 2024) have developed a virtual training platform for logging harvesters with high immersion, good stability and real-time interaction. However, these simulators are likely to come with significant development and maintenance costs. This can make it challenging for smaller educational institutions or training centers to adopt such advanced simulators.

Addressing these shortcomings could significantly enhance the efficacy of VR training systems for harvester and logging machinery by improving their immersion, accessibility, and ability to accommodate a range of learner needs.

The collective body of research and industry efforts underscores the growing importance of VR technologies in forestry training. As these technologies continue to evolve, they are poised to play a central role in equipping operators with the skills required to manage increasingly complex machinery. VR-based simulators offer a cost-effective and accessible solution for initial training.

## 3 VIRTUAL REALITY AND DICE FRAMEWORK

Traditional training methods often struggle to keep pace with the evolving needs of industries such as forestry, where technological advancements demand more specialized skills. With VR systems becoming more affordable, portable, and accessible sometimes costing less than a typical smartphone the question arises: when is it time to shift from traditional methods to next-generation VR solutions?

The DICE framework, proposed by Bailenson (Bailenson and Lesher, 2024), provides valuable criteria to determine when VR is the appropriate training medium. DICE stands for: Dangerous, Impossible, Counterproductive, and Expensive situations where VR offers significant advantages over conventional practices. A VR-based training simulator for forestry harvester operators aligns well with the DICE framework by addressing each of these dimensions:

**Dangerous:** Operating forestry harvesters involves maneuvering heavy equipment across uneven terrain and navigating dense forest environments, which can pose risks, especially for novice operators. Training in a virtual environment mitigates the risk of accidents and injuries, offering users a safe space to develop their skills without exposure to real-world hazards. VR allows trainees to practice critical maneuvers repeatedly until they achieve proficiency, reducing the likelihood of mishaps during live operations.

**Impossible:** Simulating rare or extreme scenarios in real life, such as operating in severe weather conditions, handling equipment failures, or responding to falling trees, can be impractical for safety reasons. VR enables operators to experience and prepare for these uncommon situations, equipping them with the decision-making skills necessary to respond effectively when such challenges arise in the field.

**Counterproductive:** Traditional on-site training often requires taking expensive equipment out of service, slowing down productivity, and diverting skilled operators from their regular duties to mentor trainees. Moreover, forestry operations are seasonal, with busy periods leaving little room for in-depth training. VR eliminates these disruptions by allowing operators to train at any time without impacting ongoing operations. This ensures that essential training does not interfere with crucial harvesting windows, helping to maintain productivity throughout the year.

**Expensive:** On-site training involves considerable costs, including machinery operation, maintenance, fuel, and the risk of equipment damage during practice. VR simulators offer a cost-effective alternative by reducing reliance on physical machinery. Operators can practice as many times as needed without incurring additional costs, minimizing the financial burden associated with real-world training.

VR enhances training with consistency and scalability, allowing standardized modules to be replicated across locations and schedules, ensuring uniform skill development. This promotes safety and efficiency in forestry operations.

Aligned with the DICE framework, VR simulators provide immersive, repeatable, and risk-free training scenarios, essential for mastering complex machinery. Integrating VR into forestry training reduces costs, minimizes disruptions, and prepares operators for the challenges of modern forestry.

# 4 SIMULATOR DESIGN

## 4.1 Software Stack

The software stack for this project is built around Unity 2022.3.23f1, which serves as the primary game engine. Unity is selected for its versatility and robust tools for creating immersive 3D experiences. The project makes use of Unity's built-in physics engine to simulate real-world interactions with high accuracy. It also helps to enable realistic physical behavior and interactions within the virtual environment. The built-in 3D rendering capabilities are used to guarantee optimal performance and visual quality which allows complex models and environments to be rendered smoothly. The project is developed using C#, which is the preferred programming language in Unity for its ability to handle object-oriented programming and efficient manipulation of game objects. Visual Studio 2022 is selected as the Integrated Development Environment (IDE). Git and GitHub Desktop are utilized for version control and code management throughout the development process. To support extended reality (XR) functionality, the project integrates the Oculus XR Plugin along with Unity's XR Plugin Management. These packages are critical for managing and deploying the application to various XR platforms, ensuring compatibility with devices like the Meta Quest series, and providing users with a smooth and immersive VR experience. Together, this suite of technologies forms a cohesive and efficient framework for the development, testing, and deployment of the VR project.

## 4.2 Meta Quest

Unity supports development and deployment on the Meta Quest (Quest, 2024), making it ideal for the simulator.

The Meta Quest 2 and 3s are more affordable than other VR devices. For training environments, especially in educational or industrial contexts, budget constraints often necessitate selecting a solution that balances performance with cost. Its affordability made it an ideal choice for prototyping and validating the system's functionality.

Therefore, the simulator has been developed and optimized for the Meta Quest 2 and 3s standalone VR headset. With Six Degrees of Freedom (6DOF) the headset provides full immersive experience to the user in a virtual space. The headset also features built in 3D positional audio.

The Meta Quest controllers are used as the primary user input. The controllers are programmed through scripting, allowing users to manipulate scene objects within the virtual environment. During the development phase, we used the the quest link cable to connect the headset to the computer. This allowed us to test and debug the changes made in the VR environment instantly, making it easier to iterate quickly without having to repeatedly build and deploy the application to the headset.

The controllers are also made visible to the user in the virtual environment using a prefab model. The prefab for the Meta Quest controllers are sourced from Meta Horizon. The controller models are available in .fbx format which makes it easy to import and use in Unity.

### 4.3 Harvester Model

The simulation utilizes the John Deere - 959MH Tracked Harvester model integrated into the VR environment which has been sourced from (CGTrader, ) and developed by Markos 3D. The virtual harvester (Figure 1) closely resembles the real one capturing its complexities in detail.

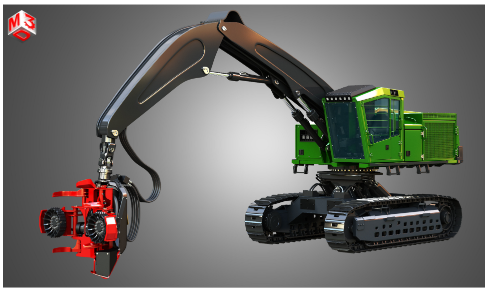

Figure 1: Virtual John Deere Harvester model.

The 4 main components of the harvester are - tracks (Figure 2), cabin (Figure 4), harvester arm (Figure 5) and harvester head (Figure 6). The tracks consist of three wheels - front, middle and rear along with a crawler on both the right and left side.

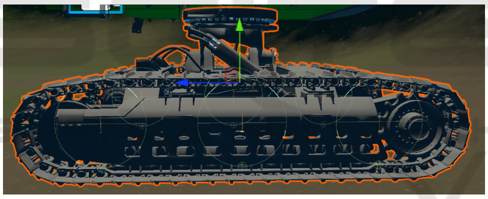

Figure 2: Harvester track.

The operator's cabin features components like the seat, control panel, buttons, joysticks, pedals, monitors, and windows (Figure 3 and 4). We removed the front glass pane from the original model to improve visibility, as it obstructed the view.

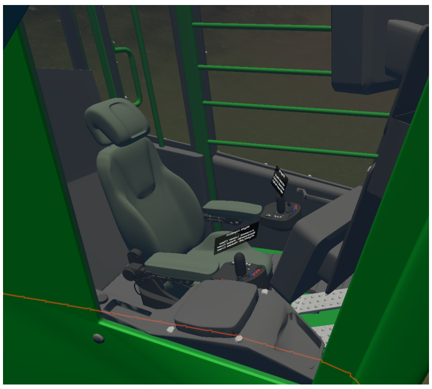

Figure 3: Operator Seat.

Figure 4: Inside the cabin.

The harvester end and the harvester base make up the harvester arm (Figure 5), sometimes referred to as the harvester boom. Retraction, extension, lowering, and raising of the arm are all made possible by the Unity scripts.

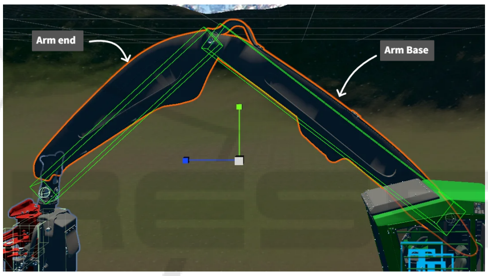


Figure 5: Harvester arm.

The harvester head (Figure 6) consists of inner and outer claws to grasp trees. It also consists of inner and outer wheel components which process the grasped tree. Apart from this it also features a blade to cut trees and an arm that connects the harvester head to the boom.

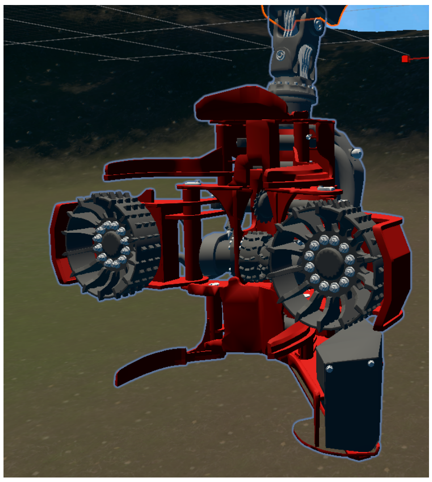

Figure 6: Harvester head.

## 4.4 Scenario Creation

The virtual scenario, as shown in Figure 7 is designed in Unity platform. Starting with the ground, it was created using the game object terrain. Various heights were applied at different locations to replicate the contours of mountain terrain. To provide a more natural look, we also applied grass and dirt textures to its surface.

Figure 7: Harvester model and the virtual forest in Unity.

We modeled the trees in Unity with ProBuilder. The tree prefab consists of a trunk and branches as its child game objects. This modular design approach treats each part, such as the trunk and branches, as separate units or components. This allows flexibility in creating a variety of tree types and adapting the simulator to different use scenarios.

## 4.5 Simulator Design

The VR simulator, developed in Unity with C#, runs as an Android APK on the standalone Meta Quest headset. The Quest controllers enable intuitive interaction and precise control of the harvester within the simulation.

Upon entering the VR simulator, users find themselves positioned inside the harvester cabin, seated in the operator's chair. For a better experience, the user may also choose to sit on a physical chair while using the simulator. The headset dynamically adjusts the view as users move their heads. Movement within the simulator is restricted to the cabin area, as all operational procedures must be conducted from the seated position. Each button of the controller has a certain action associated with it, for example, cutting, tilting, processing, etc. The cabin also features virtual joysticks on the front panel that can be manipulated using the controllers to perform specific functions. The Meta Quest controllers and virtual joysticks, shown in Figure 8, are labeled for easy function identification.


Figure 8: Labelled controls.

The virtual joystick once grabbed using the controllers, switches its color to blue to give a visual cue, indicating that they have been grabbed. The harvester operates within a training field where trees are strategically placed, allowing users to practice various operational techniques. Figure 9 provides a high level overview of the system architecture.

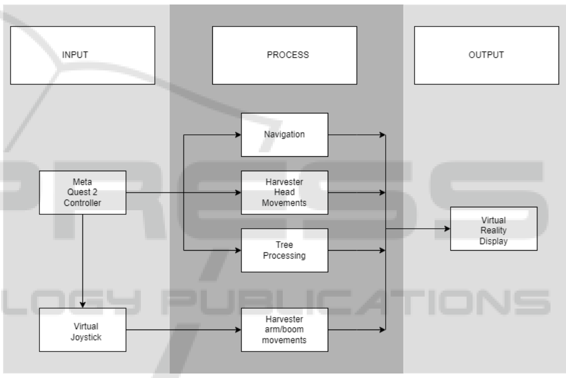


Figure 9: System architecture.

The design of the system was guided by feedback from subject matter experts in the forestry department at Oregon State University, ensuring that it aligns with industry requirements. The main goal of the system is to create a tool that is portable, accessible, and cost-effective, making advanced training solutions available to a wider range of users and settings.

## 4.6 Tasks

The training sessions are divided into different modules of increasing complexity ranging from simple navigation of a harvester to cutting and processing a tree. These modules are divided based on the principle of task simplification and part-task training (Wickens et al., 2021), wherein complex tasks are divided into smaller parts and trained individually before being reintegrated. Each part is a simpler version of a complex task. As the proficiency develops, the difficulty of the task gradually increases.

**Module 1 - Driving the, Harvester (Navigation):** The primary objective of this initial module is to enable the user to navigate the harvester to a designated location. This is achieved by manipulating the thumbsticks on the controllers. Specifically, pushing the thumbstick on the left-hand controller forward or backward moves the harvester in the corresponding direction, while pushing the thumbstick on the right-hand controller left or right allows for lateral movement.

**Module 2 - Harvester Head and Boom Movements:** In this module the user has to learn correctly how to control the movements of the harvester's head and arm. This involves manipulating virtual joysticks and using specific controller buttons to achieve precise actions. To tilt the harvester head, the user has to press the trigger button on the left-hand controller. Pressing the grab buttons on either the right or left controller allows the user to grip the respective virtual joystick. Once the virtual joysticks are grabbed, the movement of the harvester boom and harvester head can be controlled. For lowering and raising the harvester boom, the left virtual joystick needs to be pushed forward and pulled backward respectively. Similarly, to retract and extend the harvester boom, the user needs to operate the right virtual joystick. Pulling the joystick backward retracts the harvester arm, whereas pushing it forward extends the arm. The user can also adjust the harvester head by rotating it, to align it properly with the tree. For rotation, pushing the right virtual joystick to the right rotates the harvester head clockwise, and pushing it to the left rotates it counterclockwise.

**Module 3 - Processing Tree:** The objective of this module is to instruct users on the various actions required for effectively processing trees with the harvester. Users should be able to grab, release, process, and cut a tree. Once the harvester head is appropriately positioned in front of a tree for a secure grip, the user can press the B button on the right-hand controller to close the harvester claw and grasp the tree. To release the tree, the user must press the A button on the right-hand controller. Pressing the trigger button on the right-hand controller will cut the tree. Additionally, users learn to position the tree for further processing. To process the tree upward or forward, the X button on the left-hand controller is utilized, while processing the tree downward or backward is achieved by pressing the Y button on the left-hand controller. Demonstrations of these interactions are recorded and can be accessed through YouTube video (XX, 2024b).

# 5 BLACK BOX TESTING

To thoroughly evaluate the functional capabilities of the harvester simulator within the virtual reality (VR) environment, we designed and conducted a series of black-box tests. Black-box testing, which focuses on the system's outputs in response to a variety of user inputs without examining the internal code, was chosen to assess how effectively the simulator handles real-world usage scenarios. A comprehensive suite of 20 test cases was developed, covering a wide range of interactions to validate the key functionalities of the application and ensure it could handle both typical and edge-case user behaviors (XX, 2024a).

The primary objective of these tests was to evaluate the simulator's ability to perform as intended across multiple scenarios, as well as to assess its resilience when exposed to unexpected or erroneous inputs. These cases were designed not only to confirm that the simulator functions correctly under normal conditions but also to identify any potential flaws or vulnerabilities that could emerge during atypical usage.

To ensure the pertinence, comprehensiveness, and ethical soundness of our testing methodology, the entire process underwent a rigorous review by the Institutional Review Board (IRB) of our institution. The IRB approval was a critical step, as it confirmed that the study adhered to the highest ethical standards for research involving human participants. This approval also enabled us to engage with practitioners from the AR/VR field, allowing us to gather meaningful feedback and insights from experts actively involved in the development, application, and optimization of immersive training systems.

By combining comprehensive functional testing with ethical oversight, we ensured that the simulator not only meets technical requirements but also aligns with best practices for responsible research. This approach allowed us to validate the simulator's readiness for deployment while gathering valuable input from practitioners, further informing the iterative development and refinement of the system.

## 5.1 Participants and Methods

The testing group consisted of 8 Computer Science students, evenly split between 4 males and 4 females at both graduate and undergraduate levels. The participants' ages ranged from 20 to 26 years, with a mean age of 22.0 years and a standard deviation (STD) of 2.24 years. All participants had prior experience using VR headsets but were unfamiliar with the internal workings of the harvester simulator. This ensured that their interactions with the system were unbiased, focusing purely on functionality from an end-user perspective.

The decision to involve computer science students as participants in this process supported the verification of the system. These participants, with their familiarity with VR systems, were well-positioned to identify technical issues, assess interaction mechanisms, and provide actionable feedback on the system's functional aspects without requiring extensive onboarding. This approach allowed us to efficiently validate the system's design and development during the early stages.

The test setup was designed to simulate realistic conditions under which the simulator might be used. As shown in Figure 10, participants were seated in a physical chair to mimic the posture they would assume during an actual training scenario.

Figure 10: A participant trying out the harvester simulator on standalone VR headset.

The participants were given verbal instructions to perform specific tasks within the simulator. Since most participants were familiar with the naming conventions for buttons and triggers on the VR controllers, commands such as "Cut the tree using the trigger button on the right-hand controller" were easily understood. However, additional guidance was sometimes needed to help students identify the less commonly used buttons, such as the grab and trigger controls. More familiar buttons, such as X, Y, A, B, and the thumbsticks, were easily identified by participants without further assistance.

Each testing session lasted approximately 10 to 15 minutes. We conducted black-box testing on both a standalone version of the simulator and a PC-tethered version. Four students (2 male, 2 female) tested the standalone version, while another four students (2 male, 2 female) tested the PC-tethered version. This dual approach allowed us to evaluate the simulator's performance under different configurations, assessing how it functioned independently on the VR headset and how it performed when connected to a PC. We specifically looked for differences in responsiveness, graphical quality, and overall user interaction between the two setups.

In the standalone configuration, students were solely responsible for confirming whether the simulator behaved as expected based on their interactions. For the PC-tethered version, the instructor monitored and verified the simulator's real-time behavior through Unity's game view. This observation ensured the simulator met the desired functional requirements on both platforms.

### 5.2 Result

The black-box testing revealed that the harvester simulator responded correctly to most user inputs. However, 2 out of the 8 participants encountered issues while understanding the exact operation of pushing the left virtual joystick forward or backward, indicating a potential intuitivity issue. They also reported that the pushing of the virtual joystick required more effort, indicating a potential input sensitivity issue. Most participants reported that the interaction felt intuitive, though feedback suggested the need for more visual feedback for familiarizing with the controls.

Students quickly became familiar with the basic harvester operations. The instructor's verbal instructions helped the participants understand how the controllers worked. By the end of the session, most students were capable of performing the complex task of processing a tree without any guidance.

The harvester simulator substantially satisfies user expectations with its intuitive control responses, according to the findings of the black-box testing. However, the identified sensitivity issues suggest a need for calibration of the input mechanisms to ensure smooth interactions. Addressing these issues will likely enhance user satisfaction and make the simulator more effective for training purposes.

## 6 DISCUSSION AND CONCLUSION

In this paper, we present the design and development of a virtual reality (VR) forestry harvester simulator, specifically optimized to run on the untethered Meta Quest. The simulator offers users an immersive platform to practice essential harvester operations, including navigation, tree processing, and precise control of the harvester head and boom. By leveraging the portability and accessibility of the Meta Quest, the simulator eliminates the need for external hardware, making it more flexible and accessible for training in various settings.

As part of this study, we conducted a thorough evaluation of the simulator's functionality using 20 carefully crafted test cases. This rigorous black-box testing ensured that the system performed as intended, providing a reliable and accurate experience across all core operations. To further validate the system, we assessed its performance both as a standalone application on the Meta Quest and when tethered to a PC, comparing differences in responsiveness, graphical quality, and user interaction.

In future work, we will focus on evaluating the usability of the system and validating the effectiveness of the training simulator in formal educational settings. This will involve collaboration with academic institutions to integrate the simulator into forestry curricula, allowing us to measure its impact on students' learning outcomes and practical skill development.

One current limitation lies in the restricted number of interactions, constrained by the limited buttons on standard VR controllers. To address this, future research will explore innovative interaction methods that reduce reliance on physical controllers. Hand gesture recognition, for example, could be used to manipulate the virtual model's control panel, offering a more natural and intuitive way for users to interact with the system

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## SUPPLEMENTAL MATERIALS

Supplemental materials are available at https://bit.ly/2025-GRAPP

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