Situated Visualization of Photovoltaic Module Performance for Workforce Development

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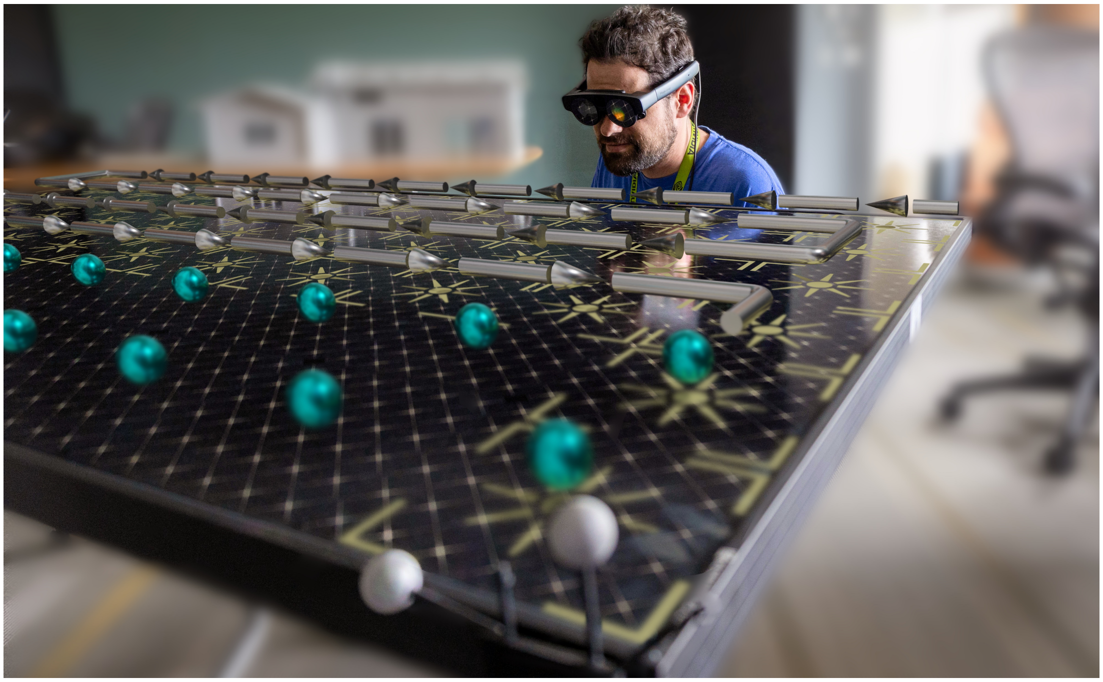

Figure 1: A simulated image of the situated visualization of photovoltaic module performance, mimicking the view of the augmented reality projection. In this figure, a simulation has been run; power flow across the cells are shown as arrows and pipes. Shaded cells are highlighted in yellow. As a portion of the module is in shadow, diodes have bypassed certain cells; these are marked by spheres. Note the optical tracking marker in the foreground, used to relay physical panel orientation to the rest of the system. *All photos provided by authors.*

Abstract

The rapid growth of the solar energy industry requires advanced educational tools to train the next generation of engineers and technicians. We present a novel system for situated visualization of photovoltaic (PV) module performance, leveraging a combination of PV simulation, sun-sky position, and head-mounted augmented reality (AR). Our system is guided by four principles of development: simplicity, adaptability, collaboration, and maintainability, realized in six components. Users interactively manipulate a physical module's orientation and shading referents with immediate feedback on the module's performance.

Index Terms: Augmented Reality, Situated Visualization, Photovoltaics, Workforce Development, Education

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1 Introduction

The growing deployment of renewable energy, particularly solar power, has created a significant demand for workforce development [28]. However, many aspects of solar energy remain unfamiliar to learners, as the technical processes are often invisible and challenging to explain. Situated visualization places data visualizations in their relevant environments, linking data to the physical locations or entities they represent [7]. Incorporating AR for situating educational visualizations is an increasingly popular approach, empirically shown to improve both the "learning gains" and "motivation" of students [16].

We present an educational system design that combines a photovoltaic (PV) module simulation with situated visualization using head-mounted augmented reality (AR). This approach provides hands-on experience with the devices in a non-energized setting, making the typically unseen operations visible and helping learners build intuition about system operation and performance.

We embed a visualization of power flow on the PV module. The system allows users to interactively manipulate the module's orientation, tilt, and shading. In response, the visualization reflects the simulated PV performance in real-time, visualizing the current flow and the operation of bypass diodes directly on the module. Further, IV curve plots (representing the relationship between the current I and the voltage V output of a PV module) are situated near the module. This approach makes understanding complex concepts (such as irradiance effects) more accessible, bridging the gap between theoretical knowledge and practical application.

2 RELATED WORK

The application of immersive visualization technologies to analyze renewable energy data highlights the technology's practical value in the industry. Engineers and planners have used immersive technologies to evaluate renewable energy deployments from individual solar panels [23] to campus microgrids [10], from city-wide analyses [21] to national-scale investigations [9]. Combining immersive visualization with tracked objects has enabled the analysis of worker-machine interaction to increase workforce productivity in construction environments [25] and the construction of large concentrating solar collectors [18]. Situated visualization has been used to visualize solar resources on tangible building models [12] and visualize reliability data on specific components of a hydrogen fueling dispenser [30].

There is a significant and growing body of work using AR for education. A 2020 bibliometric analysis identified 3,475 studies on AR in education over a 25-year period (1995-2020) [15]. Generally, AR has been found to improve learning outcomes [16], and found to improve university students' laboratory skills and attitudes towards laboratory work [1]. AR in education has been integrated through a variety of methods. In many instances, AR has been used to situate visualizations in the environment. Some examples include utilizing hand-held devices to visualize processes on physical circuits [6, 22], using spatial AR to experiment with optical interferometry [14], and visualizing magnetic fields on student-built audio speakers using head-mounted displays to teach electromagnetism concepts [26]. Despite the widespread interest in educational AR, we have found no literature that includes its use in solar education. The closest related work involves virtual reality (VR) for solar education, creating a separate digital visualization rather than situating or augmenting the physical world with visualizations.

A 2024 systematic review [3] identified a total of 15 articles that focused on the application of VR in PV education. Similar to many AR studies, VR has been shown to improve student engagement in learning PV system design concepts [2]. A few VR applications, have illustrated various aspects of PV panel performance in relation to adjustments in tilt angle [13, 11] environmental conditions [5], and more technical visualization of electron transport through the layers of a PV cell [17]. Our work introduces a novel combination of situated visualization through head-mounted displays (HMD) and tracked objects, such as PV modules and shade-producing objects, integrated with a real-time simulation of the PV module. Unlike previous applications, our system dynamically situates the visualization of power flow and resulting performance directly within the physical context of actual PV modules. This real-time, interactive experience allows users to physically manipulate the PV module and the shading on the module with immediate feedback on the module's performance.

There are multiple models of situated visualization. Willett et al. [31] present a foundational model of placing data in a physical context to enhance understanding and interaction. Satriani et al. [27] extend this model by incorporating proxies for physical referents, capturing scenarios where users interact with proxy representations instead of the actual physical objects. Both models have the concept of spatial indirection, referring to the degree of separation between a physical referent (the real-world object) and its visualized data. Spatial indirection can range from *immediately situated* with the visual representation directly embedded in or on the physical referent to *indirect* with the visual representation distantly separated from the physical referent. Several design patterns [19] have emerged from these models for creating visualizations in mixed-reality environments.

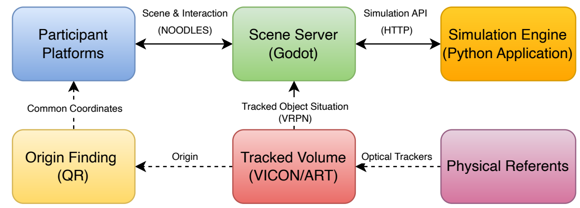

Figure 2: Diagram of the six interacting components of the system. The Scene Server builds the situated visualization using simulation and tracked object information. Participant platforms link their independent coordinate systems and place the visualization over real-world objects. Solid lines indicate network connectivity. Dashed indicates optical or inferred information (for obtaining common coordinates).

3 SYSTEM DESIGN

Our primary goal is to provide an intuitive, interactive visualization of power flow on select PV modules, allowing users to manipulate orientation, tilt, and shading of the modules, with feedback on module performance embedded on the physical elements. To this end, our system features a PV module mounted on a motorized tilt table as the physical referent. This aligns with Willett et al.'s model of situated visualization by embedding interactive elements within a real-world context [31]. The classroom setting serves as the physical world location. We use proxies described by the extended model [27], defining a proxy environment with a sun position based on latitude, time of year, and time of day, and proxy objects (buildings and trees) used to interactively shade the module. Users can manipulate the module's orientation to the proxy sun by physically rotating the table or adjusting the tilt. As the user manipulates the module, embedded markings are immediately situated on the module (*glyph* design pattern [19]), representing the current flow and diode operation. Simultaneously, an IV curve chart with low spatial indirection is displayed (*panel* design pattern [19]). Users can cast shade onto the module by defining a shadow-casting object in the proxy environment or interactively by moving a proxy referent—-a tracked object with an immediately situated visualization of a block or a tree that casts shade on the module.

The design of this situated mixed reality system is guided by a set of core principles aimed at balancing complexity with usability, ensuring future-proofing, and facilitating educational effectiveness: **(D1) simplicity in management:** we prioritized simplicity in our system design, removing extraneous interactions and emphasizing easily-configurable and disruption-resilient components; **(D2) adaptability to evolving hardware:** given the rapid evolution of VR/AR headset technology, our system must be easily adaptable; **(D3) multi-user heterogenous collaboration:** the curriculum requires group exploration, with participants using both headsets and traditional 2D monitors; and **(D4) maintainability for evolving educational content:** educational content will evolve, as new modules are added, or the overall configuration may change, requiring our system must be maintainable and extendable. We implemented this system as a collection of six components: the simulation engine, physical referents, tracking, origin finding, visualization engine, visualization platforms (see Figure 2).

3.1 Simulation Engine

The Simulation Engine component serves scenario simulation requests. This component is implemented as a Python application using the PVlib library [4], a well-tested production library for photovoltaic energy system exploration. The simulation provider takes inputs such as module type, module positioning, sun position, PV module occlusion, and temperatures. It then calculates metrics such

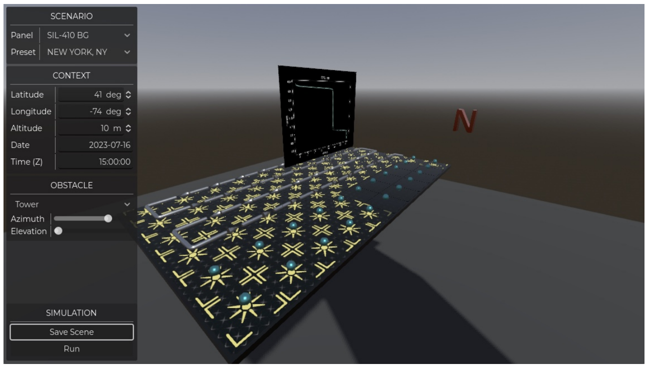

Figure 3: User interface for the Scene Server, developed in the Godot Engine. This application constructs the content (but not the view) that all clients must present. Users may select from different modules and preset locations, introduce obstacles to shade the panel (optionally overriding the physical referent), and launch simulations automatically or on demand. The scene can also be saved for later analysis.

as flow, current, and voltages. Additionally, this component provides conversions between geo-coordinates and time into sun-sky position, which is used by other components for a graphical representation of the sun and shadow casting. Communication with this component is managed over HTTP using the Flask library.

The simulation engine achieves sub-second wall-time processing, even on lower-end hardware, ensuring scalability for future scenarios. The use of a minimal-state HTTP API promotes simplicity (D1), and Python was chosen for this component due to its robust ecosystem of existing libraries and to align with our maintainability goals (D4).

3.2 Physical Referents

The simulation engine can simulate various PV modules and their characteristics, providing flexibility and depth in educational settings. For our classroom setup, we have incorporated three types of PV modules: a full-cell, a half-cell, and a bifacial module. We have mounted these on mobile, motorized tilt tables, which serve as the physical referents in our system. The tables feature controls that allow the tilt to be adjusted from 0 to 90 degrees and rotate the table relative to the proxy sun, providing a comprehensive range of configurations to study and allowing users to understand the impact of different sun angles and positions.

In addition to the PV modules, we have incorporated a shade referent proxy. This is a tracked stick that can simulate a building or tree when placed between the PV module and the proxy sun. By casting a shadow or partial shadow onto the module, users can observe the effects on the module's performance, such as the engagement of bypass diodes. The use of referent proxies and real-world control for the tilt table allow for simple modification of complex scenarios, adhering to our principle of simplicity (D1).

3.3 Tracked Volume

We utilize an optical motion tracking system to monitor the classroom volume. This system tracks the position and orientation of all physical referents. While this represents another component to maintain (D1), the alternative would require that there always be a headset active and all referents be frequently within the field of view. Additionally, tracking eliminates the need to reconcile referent positions between different HMDs. This optically based tracking, with calibrated systems, offers an accuracy of less than 2 mm [24], ensuring precise monitoring of all movements and interactions.

We transmit the referent information through the VRPN (Virtual Reality Peripheral Network) messaging interface [29]. VRPN a device and network-agnostic open-source framework that allows us to integrate across various hardware and software configurations. Since we are using a commercial optical tracking product, these VRPN messages are served through a separate server application. This setup ensures robust tracking, enhances user experience and system functionality, and is adaptable to future HMD tracking capabilities or limitations (D2).

3.4 Origin Finding

All mobile devices operate with an independent coordinate and reference system. To provide a cohesive coordinate space registered to the room for all participating AR/VR devices, we implemented a system using a QR code placed at the origin of the tracker's coordinate system. Most mobile hardware provides native APIs for scanning and reporting QR code positions and orientations. The QR code includes metadata, specifically the URL of the graphics scene server. This allows mobile devices to establish the root of the graphics scene by simply observing the code once. We chose this approach to overcome the limitations of coordinating between different AR/VR devices and tracking systems. Using a device-agnostic method with QR codes, we can accommodate various devices without relying on brand-specific solutions limited to small groups of similar devices (D2). QR codes are simple to deploy and maintain (D1).

3.5 Scene Server (Visualization)

The visualization server enables the creation, distribution, and interaction with a 3D scene populated with information from the tracked volume and simulation provider. To construct the 3D scene, we utilize the open-source Godot graphics engine [20]. The Godot scripting language, GDScript, closely resembles Python and is accessible and editable by end users (D4). This choice lowers the development requirements and avoids potential licensing challenges associated with other engines.

The visualization server provides a graphical user interface (GUI) designed for instructors. This interface allows for setting up and modifying various scenarios, such as changing the proxy environment's geo-coordinates or time of day. The server connects to the simulation provider and listens for VRPN messages to build and update the scene in real-time.

We stream the scene using NOODLES, a collaborative visualization protocol that synchronizes scenes between disparate platforms and software packages [8]. This protocol provides a decoupling of platforms, supporting augmented reality views for on-site educational activities, traditional web-based views for broader accessibility, and immersive VR views for off-site collaboration (D2, D3). Any new hardware, such as a new headset, would need a small client adapter to join the scene. Using readily accessible technologies, this client adapter is simple to build. This approach allows the server and clients to be modified or replaced without affecting other system components; critically any changes to the scene (adding or removing graphical elements) need only take place on this server application–no client needs to be modified (D1).

We display the simulation results using a veriety of glyphs and graphical elements (Figure 3). Power flow across modules is shown as tubes with arrows. For modules with no flow, we use spherical glyphs to indicate inactivity. Modules receiving sunlight (unshaded) are given a yellow overlay. We further generate a real-time IV plot and situate it above other visual elements. The server can also render proxies of the physical referents (i.e., 3D models of the PV modules) for users interacting with the scene using desktop or other devices (Figure 4).

3.6 Participant Platforms

Our system supports a variety of platforms for viewing and interacting with the simulation, including desktop, mobile, and VR/AR displays such as the Magic Leap 2, Apple Vision Pro headsets,

Figure 4: Captures of the system in action on a variety of participant platforms. From left to right; web interface for projection of scene on large-scale displays, Apple Vision Pro with situated visualization, Magic Leap 2 with the same, presentation of scene in an immersive virtual reality environment. Heterogeneity is a key requirement for this system.

browser-based clients, and immersive clients (D3). We add clients to the system by building a client-side application capable of understanding the NOODLES protocol and translating it into graphical content.

For the Magic Leap 2, we developed the client in Unity. Unity was chosen due to its flagship status on this platform, offering the best support and user experience. For the Apple Vision Pro, we created a native Swift application using RealityKit, the flagship API for this platform. The web-based client was built using Three.js in JavaScript to leverage web-first technologies, ensuring a lightweight and responsive user experience across different browsers. For the immersive client, we developed a client adaptor in C++/Qt to integrate with our custom immersive engine. Note that these clients are general, and can be used outside of this specific project with any NOODLES-speaking server.

By adopting the NOODLES protocol and developing clients in a generalized manner, our approach abstracts the scene and content management to the server side, simplifying client-side development. This abstraction ensures that any modifications or updates are centralized, enabling greater flexibility and ease of maintenance without the need to alter individual clients, providing consistent updates across all supported platforms (D1) and (D4).

3.7 Operational Workflow

The scene server, the simulation provider, and the tracking server can be contained on one physical node and scripted to start sequentially. Once started, the system is ready for clients. Headset users don their equipment and start the NOODLES client application, which searches for the QR code and connects to the server over NOODLES. The client application then syncs the scene and establishes the origin at the QR code. Meanwhile, web users can easily access the system by pointing their browsers to the provided URL.

4 Discussion

We present a novel and first-of-its-kind implementation of a system for situated visualization of photovoltaic module performance through six interacting components. Guided by our four design principles, our system provides a simple, easily maintained, device-agnostic collaborative educational tool designed to help train the next generation of engineers and technicians in the growing solar industry.

We evaluated a number of technical options and alternatives during the project's development. We examined other popular graphics engines, such as Unity and Unreal, to be used as the scene server. However, these other engines ran into conflict with our ease of maintenance and content management (D1) and (D4) priorities, as they implement logic in C# and C++, demand larger development environments, and may bring potential future licensing challenges. A fully unencumbered engine with a simple Python-like language coupled with an editor was better aligned with our goals. We initially considered using WebXR for all clients. This approach was soon dismissed due to poor support across devices and the burdensome deployment process. Likewise, Godot has uneven support for headsets. We implemented a Unity client for the Magic Leap 2. For the Vision Pro, however, Unity support is still in its early stages and does not align well with the platform's interaction paradigms. Instead, we used an existing Swift and RealityKit client. For the web, we made use of a lightweight and simple pre-existing web-first client. We envision future devices will either use the Unity or Swift clients, with minor modifications as needed. We also considered alternatives to collaboration, such as Nvidia's Omniverse product. This was discounted due to a combination of hardware requirements, licensing, ease of modifications, and setup complexity. NOODLES is unencumbered, has no hardware requirements aside from networking, and is simple to implement.

This system has a number of opportunities for improvement and future work. First, the use of QR codes introduce new challenges. The position and orientation of QR codes are determined optically, and due to the limited resources of mobile hardware, the resolved position and orientation of the codes tend to fluctuate, disturbing the scene. Small corrections also must be made on a per-headset basis. In the future, we are considering the use of ultra-wideband or geo-coordinated systems to improve accuracy. The use of a whole room tracker adds complexity, but is needed to capture the situation of all the referents. We will continue to explore other options, such as headset-relayed positioning, or an angle-aware tilt table to excise this component. Another aspect is in lighting. In our situated visualization, a virtual light source is used to act as a sun and cast shading on the module. Modern headsets use complex environment lighting schemes to better integrate content; our 'artificial' light can easily be washed out or de-emphasised, and our shading can be confused with added shadows from the headset's environment.

Our system represents a significant advancement in solar education by providing real-time, interactive visualization of photovoltaic module performance in a classroom setting. This approach enhances understanding of solar energy principles and prepares students for practical applications in the renewable energy industry. Compared to traditional methods, which rely either on static diagrams or purely virtual simulations lacking real-world context, our system bridges the gap between theoretical knowledge and practical application. By situating visualizations directly on physical PV modules, learners gain hands-on experience that enhances their comprehension and retention of complex solar energy concepts. Further, our system holds promise for other applications beyond education. Some possibilities include PV manufacturing, materials analysis, and cell design. Other possible extensions include the integration with related equipment, such as inverter installation and whole-house renewables.

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