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Web-based Proton Magnetometer Simulation System: Architecture, Implementation, and Teaching Practice

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Abstract

Within the framework of the "New Engineering" reform, engineering education has gradually shifted toward closer integration of theoretical understanding and operational competence. In geophysical exploration courses, this objective is often constrained by the limited availability of precision instruments, high maintenance costs, and strict spatial-temporal requirements associated with field training. To address these challenges, this paper presents the design and application of a web-based simulation platform for proton magnetometer instruction, developed using the Vue.js framework and a progressive Nuxt.js architecture. The platform implements a high-fidelity 1:1 virtual model of a proton magnetometer, accurately reproducing the instrument's interface layout, menu logic, parameter configuration process, and measurement workflow. Through a visualized interactive console and real-time data feedback, the system establishes a closed instructional loop consisting of principle verification, operational training, and result analysis, thereby supporting a blended teaching mode that combines virtual simulation with physical experimentation. The platform has been deployed in geophysical exploration teaching since 2021 and has served over 600 individual users during its operational period. Usage statistics and instructional observations indicate that the simulation significantly improves students' familiarity with instrument operation, reduces procedural errors during field practice, and alleviates dependence on limited laboratory resources. Overall, the observed outcomes indicate that web-based instrument simulation can support a level of instructional fidelity comparable to physical devices, while offering a sustainable option for experimental engineering education.

Keywords

Online simulation; Proton magnetometer; Geophysical exploration; Web-based instrumentation; Engineering education

1. Introduction

With the rapid development of information and communication technologies, digital transformation has become a defining trend in higher education, particularly within engineering disciplines. In China, the "New Engineering" initiative advocates a shift from knowledge-centered instruction toward competency-oriented education, emphasizing practical skills, problem-solving ability, and experiential learning outcomes. For geophysics-related programs, this transformation poses distinct challenges, as experimental teaching remains strongly dependent on specialized instruments and field-based training environments [1].

Magnetic prospecting is a core component of geophysical exploration education, requiring students to integrate theoretical knowledge of geomagnetism with precise operational skills [2]. Proton magnetometers, such as the GSM-19T, are widely used in both teaching and production practice. However, effective operation of these instruments depends on familiarity with multi-layered menu systems, parameter tuning strategies, and real-time interpretation of measurement feedback [3]. In traditional laboratory settings, limited instrument availability often restricts students' opportunities for repeated hands-on practice, resulting in observational learning that weakens skill acquisition.

The limitations of conventional experimental teaching became particularly evident during the COVID-19 pandemic, when physical access to laboratories and field sites was severely restricted. While theoretical courses were able to transition smoothly to online platforms, instrument-based experimental courses faced significant obstacles due to their reliance on physical equipment [4, 5]. This situation highlighted the need for alternative instructional approaches capable of overcoming spatial and temporal constraints without compromising professional authenticity.

Online simulation technology offers a viable solution to these challenges. By virtualizing both the interface behavior and operational logic of field instruments, simulation platforms can provide students with a safe and repeatable training environment, enabling independent practice and error correction without the risk of equipment damage [4][5]. Within this teaching context, we developed a web-based simulation platform specifically aimed at proton magnetometer instruction. Based on a high-fidelity digital replica of the GSM-19T console, the platform aims to support experimental teaching by bridging the gap between theoretical learning and field operation, while offering a scalable and resource-efficient model for geophysical education.

2. Related Work and Educational Context

2.1 Development of Virtual Laboratories in STEM Education

Virtual laboratories have been increasingly adopted in science, technology, and engineering education as a means of expanding access to experimental resources and improving learning efficiency [5, 6]. Early virtual laboratory systems were often constrained by proprietary software environments, limited interactivity, and poor scalability. As web technologies such as HTML5 and modern JavaScript frameworks have matured, contemporary platforms have shifted toward browser-based deployment, real-time interaction, and modular system design.

Previous studies indicate that the educational effectiveness of virtual laboratories depends not only on graphical realism but also on the extent to which operational procedures are faithfully reproduced. In engineering education, simulations that merely visualize physical processes without replicating actual control logic tend to have limited impact on skill acquisition. Consequently, recent research emphasizes procedural authenticity and user interaction as key design principles for virtual experimental platforms.

2.2 Limitations of Digital Tools in Geophysical Instrument Training

In the field of geophysics, most existing digital teaching tools focus on data interpretation, numerical modeling, and post-processing workflows, while comparatively little attention has been given to instrument operation itself [2]. This imbalance creates a gap between theoretical understanding and field readiness. In practice, many operational errors during geophysical surveys arise not from conceptual misunderstandings but from incorrect parameter settings, unfamiliarity with instrument menus, or misinterpretation of measurement feedback.

For proton magnetometers, improper configuration of survey parameters—such as station intervals, line indexing, or signal-to-noise thresholds—can significantly degrade data quality or invalidate an entire survey. However, opportunities for systematic training in instrument operation are often limited by equipment availability and teaching schedules. Simulation-based instruction that directly targets these operational skills remains underdeveloped within geophysical education, despite its clear pedagogical relevance.

2.3 Outcome-Based Education and Simulation-Oriented Training

The design philosophy of the present platform aligns with Outcome-Based Education (OBE), which emphasizes demonstrable competencies rather than passive knowledge acquisition. From this perspective, the primary objective of instrument training is not only to understand measurement principles, but also to perform correct operational procedures under realistic constraints.

Simulation environments provide a "safe failure" context in which students can explore instrument behavior, test parameter boundaries, and observe the consequences of operational decisions without risking equipment damage or data loss [8]. By supporting repeated practice and self-directed exploration, simulation-oriented training can effectively complement traditional laboratory instruction and enhance the transfer of skills from virtual environments to real-world fieldwork.

3. System Architecture and Technical Framework

3.1 Overall Architecture and MVVM Design Pattern

The simulation platform is developed using a web-based architecture centered on the Model–View–ViewModel (MVVM) design pattern, implemented through the Vue.js framework (Figure 1). This architectural choice facilitates a clear separation between data logic, user interface rendering, and interaction control, which is essential for accurately simulating the behavior of complex geophysical instruments.

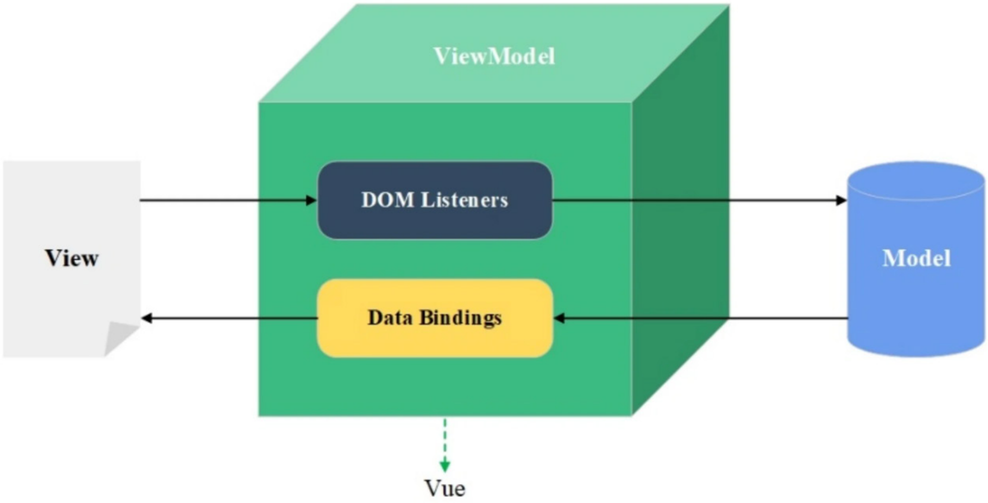

Figure 1. Schematic diagram of the MVVM mode of the Vue framework.

The Model layer functions as the logical core of the system, encapsulating the internal state of the instrument and its associated computational processes. This includes parameter management, measurement state control, and the generation of simulated magnetic field data based on user-defined settings.

The View layer is responsible for rendering the visual representation of the magnetometer console. High-resolution graphical assets are used to reproduce the layout of the physical instrument, including the multi-line LCD display and the 16-key keypad. The display area is treated as a dynamic rendering region that reflects real-time changes in instrument status.

The View Model layer serves as the interaction mediator, linking user inputs to the underlying instrument logic. Through reactive data binding and event listeners, user actions—such as keypad operations or menu navigation—are translated into state updates within the Model, which are then immediately reflected in the View. This mechanism enables real-time synchronization without direct manipulation of the Document Object Model (DOM).

3.2 Platform Scope and Academic Use Statement

The simulation platform is modeled specifically on the GSM-19T proton magnetometer [3], which is widely used in geophysical teaching and field practice. The system was independently developed at the China University of Geosciences (Beijing) as a non-commercial academic project intended solely for educational purposes. The virtual interface is a schematic and instructional representation designed to support teaching objectives.

No proprietary firmware, source code, or commercial software components from the instrument manufacturer are incorporated into the platform. The simulation aims to replicate operational behavior and interface logic under academic fair-use principles, serving as a pedagogical bridge between theoretical instruction and practical field operation.

4. Technical Implementation and Software Engineering

4.1 Progressive Development with Vue.js and Nuxt.js

The platform is implemented using Vue.js in combination with the Nuxt.js framework to support progressive development and structured routing. This technical approach enables the simulation to be deployed as a browser-based application with minimal access barriers, while maintaining a clear and maintainable project structure.

Nuxt.js is used to organize complex instrument menus into modular routes, allowing different functional interfaces—such as survey setup, parameter tuning, and data review—to be dynamically loaded while preserving the overall console state. This routing mechanism mirrors the hierarchical menu logic of the physical instrument, ensuring continuity of user interaction across interface transitions.

4.2 Modular Design Based on Single-File Components

To improve maintainability and extensibility, the simulation adopts a modular design based on Vue Single File Components (SFCs). Core functional units, including the LCD display module, keypad controller, and signal processing logic, are encapsulated as independent components.

This design decouples visual rendering from interaction logic. For example, the LCD display component is solely responsible for visual output, while keypad input handling is managed independently. Such separation simplifies debugging and allows individual components to be reused or adapted for other simulated instruments. In practice, the keypad component supports configurable key–function mappings through external configuration files, enabling rapid adaptation to instruments with similar control layouts.

4.3 High-Fidelity Interface Rendering

To enhance realism and facilitate field familiarity, the visual interface of the magnetometer is rendered using a high-resolution image of the physical instrument panel as the base layer (Figure 2). Interactive elements, including the LCD display region and control buttons, are overlaid and dynamically updated according to instrument state.

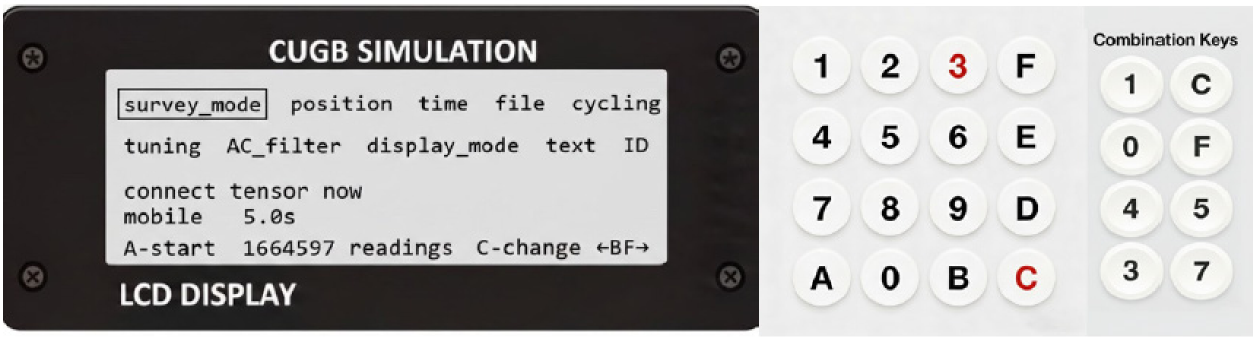

Figure 2. Virtual Simulation Instrument: UI & Controls.

The LCD area functions as a real-time rendering zone, where measurement results, system prompts, and parameter values are updated through reactive data binding. This approach allows students to visually associate operational outcomes with specific interface elements, reinforcing spatial memory of the instrument layout encountered during field practice.

4.4 Menu Logic and Finite-State Machine Control

The internal operational logic of the simulation is governed by a finite-state machine (FSM), which replicates the menu structure and functional transitions defined in the GSM-19T user manual [3] (Figure 3). Each menu screen corresponds to a discrete state, such as the main menu, survey configuration, or tuning mode.

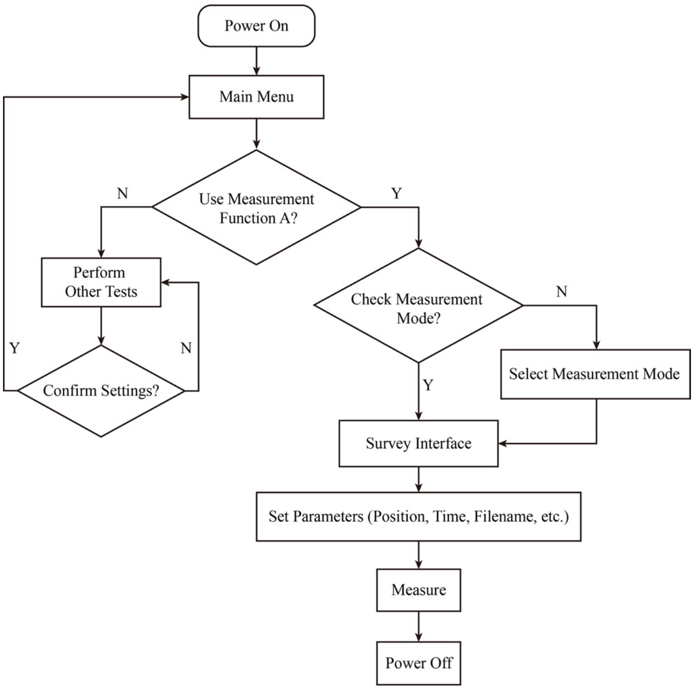

Figure 3. Logic Flowchart of the Virtual Simulation Instrument.

State transitions are triggered by keypad events and mapped to corresponding system responses, including measurement initiation, parameter modification, or data clearance. By strictly adhering to the documented operational logic of the physical instrument, the FSM ensures that user interactions in the simulation produce behavior consistent with real-world device operation.

4.5 Keypad Simulation and Composite Key Handling

The GSM-19T magnetometer features a 16-key physical keypad, including several composite key combinations that require simultaneous input. Simulating this behavior in a web environment presents practical challenges, particularly for mouse-based interaction.

To address this issue, the platform introduces a composite key (CKeys) module that abstracts dual-key combinations into dedicated virtual inputs. This design preserves the functional logic of the original instrument while ensuring usability for desktop users. For users operating with physical keyboards, native keybinding listeners are also supported. Auditory feedback is implemented using the Web Audio API to reproduce the characteristic confirmation tones of the instrument.

4.6 Emulation of Measurement Latency

Actual proton magnetometer measurements involve a polarization phase that introduces unavoidable time delays. To reflect this constraint, the simulation incorporates asynchronous behavior using JavaScript Promises and async–await patterns.

When a measurement command is issued, the interface enters a temporarily locked state and displays a polarization message. This enforced delay prevents premature input and helps students develop an intuitive understanding of measurement timing, which is essential for planning efficient field surveys.

4.7 State Management and Data Persistence

Instrument configuration parameters and survey states are managed through a centralized Vuex store. The store maintains key variables such as tuning parameters, station indices, and measurement modes, ensuring consistency across different interface modules.

To support continuity of learning, the platform integrates browser-based local storage for data persistence. Upon initialization, the application restores the previous session state, allowing students to resume interrupted simulations without reconfiguring parameters.

5. Teaching Practice and Effectiveness Evaluation

5.1 Platform Deployment and Usage Statistics

The simulation platform has been integrated into geophysical exploration courses at the China University of Geosciences (Beijing) since 2021. During its operational period, the platform recorded 636 unique users and a total of 5,499 page views (Figure 4).

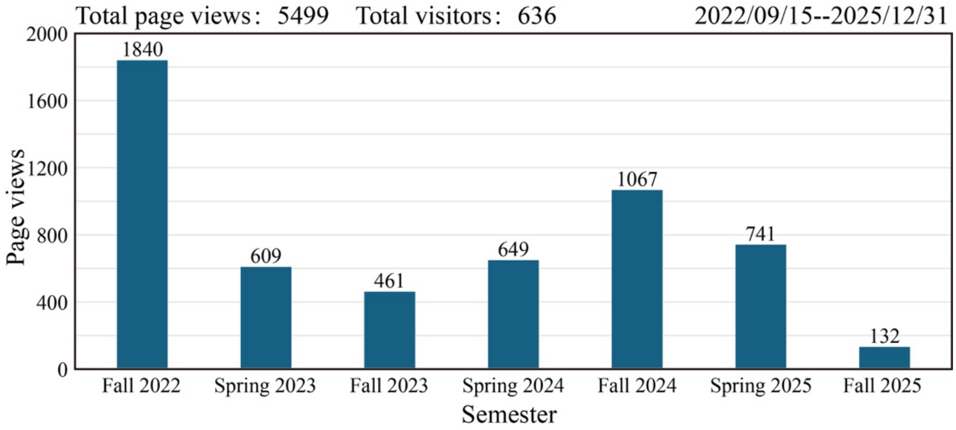

Figure 4. Statistics of platform access frequency (PV: 5499, Visitor: 636).

Backend logs indicate that students frequently revisited the survey configuration module, often spending extended time adjusting parameters before initiating simulated measurements. This usage pattern suggests that the platform is not merely accessed for demonstration purposes, but is actively used for exploratory learning and skill rehearsal [8-10].

5.2 Observed Learning Outcomes

Analysis of access logs and instructional observations reveals several notable trends. First, repeated use of the platform led to a marked reduction in redundant menu navigation, indicating improved familiarity with the instrument’s hierarchical control logic. Second, students demonstrated greater accuracy in configuring core survey parameters, such as line numbering and station spacing, during subsequent field training sessions.

Instructors also reported that students who had engaged extensively with the simulation exhibited improved hand–eye coordination and faster response times when operating physical instruments. When operational errors occurred, these students were generally able to identify and correct mistakes independently, drawing on prior simulation experience.

6. Discussion

Based on classroom use and deployment experience, a high-fidelity web-based simulation was found to be a practical supplement to traditional experimental teaching in geophysical education. By virtualizing instrument operation rather than focusing solely on data visualization, the platform addresses a critical gap between theoretical instruction and field readiness.

One limitation observed during early deployment was the abstract nature of a keyboard-driven interface for first-time users. To mitigate this issue, a visual guidance mode was introduced to highlight recommended key sequences during initial sessions. This adjustment improved usability without compromising operational authenticity.

From a technical perspective, the Vue-based architecture offers strong scalability. By re-abstracting the Model layer, the same framework can be extended to simulate other geophysical instruments with comparable interaction patterns, supporting broader application across experimental curricula.

7. Conclusion

This work reports the development and instructional use of a web-based simulation platform designed to support proton magnetometer training. By combining a high-fidelity interface with accurate operational logic, the platform provides students with continuous access to instrument training while reducing reliance on limited physical resources.

The results demonstrate that browser-based simulation can achieve instructional effectiveness comparable to hands-on laboratory training, particularly in terms of operational familiarity and error reduction. Beyond its immediate application in magnetic prospecting courses, the platform offers a transferable framework for the digital transformation of experimental teaching in engineering education.

As web technologies and immersive tools continue to evolve, future work will focus on extending the platform to additional geophysical instruments and exploring enhanced interaction modes. These efforts aim to further integrate simulation-based training into the broader ecosystem of engineering education under the “New Engineering” reform.

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