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Research Article

Interactive AR Simulation for Pneumatic Systems in Technical Education: A Scalable Low Cost Solution for TVET Institutions

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Pneumatic systems
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Abstract: *Pneumatic system training in TVET institutions Malaysia is constrained by equipment costs above RM 5,000 per station and safety restrictions for student access to pressurized systems. ARpneuma is an interactive Augmented Reality application developed using Unity and Vuforia SDK which can eliminates both barriers using only a printed workbook and a standard Android smartphone. Students scan the printed circuit diagrams to view real-time 3D component models and FluidSIM generated airflow simulations, making invisible pneumatic dynamics fully visible and interactive. Evaluated with Mechanical Engineering students, the application achieved improvements of 15–27.8% across all learning outcomes, offering a scalable, near-zero-cost solution for any TVET institution.*

1. INTRODUCTION

Industrial pneumatic training in Malaysian TVET and polytechnic institutions is constrained by two determined barriers which are equipment costs exceeding RM 5,000 per training station and safety restrictions which limit unsupervised student operation to pressurised systems. These barriers force heavy dependence on static diagrams and infrequent supervised lab sessions. A teaching gap that is directly reflected in poor conceptual outcomes, particularly around airflow visualisation and component sequencing (Kesim & Ozarslan, 2012). Current developments in mobile Augmented Reality (AR) provide a convincing solution to tackle both barriers simultaneously. AR provides interactive digital content from 3D models, animations, and simulation videos into physical world in real time. This enables students to explore the internal behaviour of pneumatic components without access to physical equipment (Phetchakan et al., 2023). Unlike virtual reality, mobile AR requires no specialist hardware but only use Android smartphones. AR also delivers 3D models, embodied interaction that illustrates the hands-on learning experience not like a simulation software in desktop (Sukardjo et al., 2023a). This paper presents the development, implementation, and evaluation of an interactive AR simulation application specifically designed for pneumatic systems education. It built using Unity and Vuforia SDK, and validated against one of the course code syllabus at UiTM Cawangan Permatang Pauh (UiTMCPP). The application is designed as a scalable model deployable across any TVET or polytechnic institution that offers pneumatics-related modules under the Malaysian Occupational Skills Standards (NOSS) framework. The study objectives were to design and develop AR content for key pneumatic components and control circuits and to evaluate the application's effectiveness in improving conceptual understanding within an educational setting.

2. LITERATURE REVIEW

The AR application in technical and vocational education has generated consistent evidence of improvement in engagement and learning outcomes. Kesim and Ozarslan (2012) stated that AR supports visual, auditory, and kinesthetic learning at the same time gives a significant advantage in subjects that need to imagine, visualize and differentiate objects in two or three dimensions. In pneumatics system specifically, the challenge is not theoretical complexity but the invisibility of airflow, valve switching, and pressure dynamics occur inside the components which students cannot observe during normal operation.

The AR interventions have addressed this directly. Phetchakan et al. (2023) developed a marker-based AR application for cylinder control circuits used in Thai vocational education and reported significantly higher post test scores among AR users compared to conventional instruction. Sukardjo et al. (2023a) extended AR application into electro-pneumatic circuits across eight circuit types, integrating voice instructions and interactive animations. Students who practised virtually committed fewer errors in subsequent hands-on sessions. Bajci (2019) paired an AR application with a printed workbook which the closest example to the present project and found it particularly effective for conveying abstract concepts such as signal flow and system timing.

A gap persists across these studies is where the existing AR tools for pneumatics provide either three-dimensional visualisation or circuit logic simulation, but not both. Tools based on FluidSIM (Cojocaru et al., 2021; Rahmat et al., 2019) offer precise logic-based simulation in a 2D desktop environment but lack the spatial, mobile-accessible AR layer. Tools like Ibrahim (2020) portable training kit deliver AR marker-based content on mobile devices but do not incorporate dynamic circuit simulation videos. The present work is the first to systematically combine FluidSIM that generated simulation video content with marker-triggered 3D AR models in a single mobile application. This aligned to a live institutional syllabus which addressing the gap identified across this body of literature.

3. METHODOLOGY

The AR development followed by a structured five-phase (1) needs analysis and content scoping, (2) 3D component modelling, (3) circuit simulation video production, (4) AR application development, and (5) expert verification and student evaluation.

Content scope was determined through structured interviews with the course code lecturer, who identified that students most commonly fail to visualise internal component movements (piston dynamics, valve switching) and to trace airflow through complete control circuits. Six basic pneumatic circuit were selected for coverage which collectively covering the full introductory pneumatics syllabus, Figure 1(a).

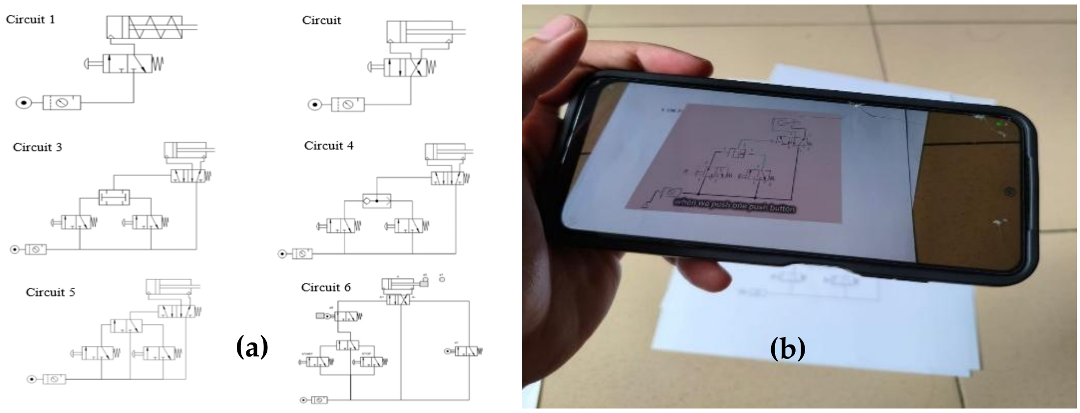

Figure 1 (a) Pneumatic control circuit diagram and (b) Pneumatic control circuit diagram in the AR application

Three-dimensional models of pneumatic cylinders were developed in SolidWorks. Circuit simulations were produced in Festo FluidSIM, capturing animated airflow and sequential component activation as video files. Both assets were integrated into Unity (v6.2.0) with the Vuforia SDK, enabling image marker-based AR triggering: pointing an Android device camera at a printed circuit diagram or cylinder image renders the corresponding 3D model or simulation video in real time on the device screen. The complete application runs offline on standard Android requiring no proprietary hardware. After expert verification by the supervising lecturer, the application was evaluated by the Diploma in Mechanical Engineering students across three groups which are from the students with no prior pneumatics exposure), students with active course code enrolees and students with limited prior exposure. Each session required a brief orientation of 30 minutes on independent AR exploration and completion of pre-test/post-test knowledge assessments alongside Likert-scale usability survey (1 = Completely Disagree, 5 = Completely Agree).

4. FINDINGS

4.1 Functional of the AR application

The function of AR application on all testing sessions which are marker recognition, 3D models rendering and animation playback operated without failure. Airflow direction was represented through colour-coded visual indicators in the simulation videos, enabling students to observe internal system dynamics which are normally hid within physical components. Table 1 presents the pre- and post-AR mean scores for the active course code enrolees, alongside percentage improvements. All values are on a 5-point Likert scale. Consistent patterns were observed across all three groups. Across all three student groups, the post-AR mean scores exceeded 4.0 on every evaluated item, corresponding to 'Mostly Agree' and 'Completely Agree' on the Likert scale. The item 'I would like to use similar applications in other subjects' achieved the highest post-AR mean of 4.7 indicating strong acceptance of AR-based instruction as a general educational mode, not merely a novelty.

Table 1. Pre- and post-AR mean scores and percentage improvement (active course code enrollees, n=10).

Evaluation Aspect	Before AR	After AR	Δ Change	% Improvement
Ease of use/ adequacy of instruction	3.8	4.4	+0.6	15.8%
Faster theoretical learning	3.7	4.5	+0.8	21.6%
Understanding of component operation	3.7	4.6	+0.9	24.3 %

Usefulness of component animations	3.9	4.7	+0.8	20.5%
Usefulness of circuit simulations	3.6	4.6	+1.0	27.8%
Visual display quality	4.0	4.6	+0.6	15.0%

4.2 Usefulness of the AR application for Learning

The developed AR application successfully demonstrates the operation of basic pneumatic systems by providing an interactive learning experience. Figure 2 (a) shows that users can visualize pneumatic components, such as double acting cylinders directly in an augmented reality environment. The application allows users to observe animated cylinder extension and retraction that occur in response to valve actuation, helping learners understand the relationship between control elements and system output. In addition, the direction of compressed air flow is clearly represented through visual indicators, enabling users to more understand internal system behavior that is normally invisible in real systems as shown in Figure 2(b). During testing, all main functions operated as intended. It indicates that the developed system meets the defined project objectives and performs reliably as an educational tool.

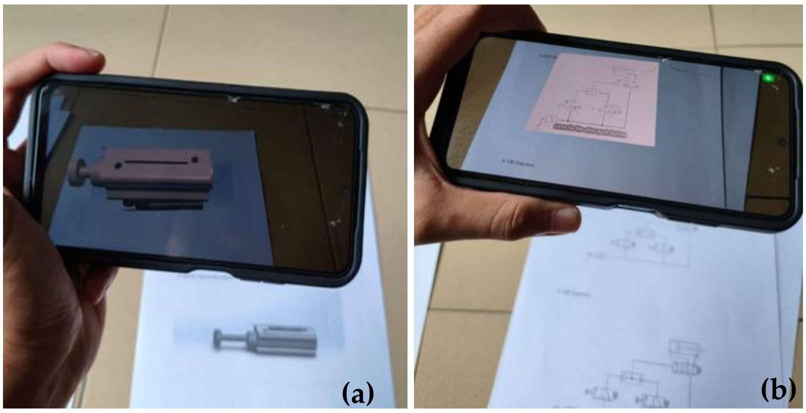

Figure 2 (a) 3D model of the double acting cylinder and view of the device using AR application and (b) Pneumatic circuit diagram simulation from the AR application.

5. DISCUSSION

The results show that this AR application directly impact the cost and scalability of TVET training. Conventional pneumatic training kits for diploma level programmes typically cost between RM 3,000 and RM 8,000 per station, require dedicated laboratory space, and necessitate trained technicians for safe operation. The present AR application requires only a printed workbook and a student owned Android smartphone which a solution that eliminates the hardware cost barrier entirely while delivering measurably superior conceptual outcomes compared to the pre-AR baseline. The differential baseline scores between student groups are instructive. The active course code enrolees students entered with higher pre-test scores (3.6–4.0) reflecting prior formal exposure to the course code content yet still achieved significant post-AR improvement which demonstrating that the application functions as both an introductory tool for beginner learners and a visual reinforcement tool for strengthening prior theoretical knowledge (Šulc, 2023). With this dual functionality, the application reaches a much larger viewer. The highest percentage improvement (27.8%) recorded for circuit simulation usefulness directly validates the core design decision to integrate FluidSIM generated video content. Students can observe the complete airflow sequence, valve actuation, cylinder extension and retraction, pressure release in a single continuous animation anchored to the physical circuit diagram. This provides a level of transparency in static diagrams and 3D models that cannot be achieved. The study acknowledges methodological limitations. Although the n=30 sample allows for descriptive analysis, it is too small for inferential conclusions. Future studies should use larger, more diverse cohorts and paired t-tests to establish statistical significance. While the current version covers six circuit types, incorporating sequential and basic pneumatic circuits, along with integrated formative assessments, would better align the application with advanced curriculum requirements

6. CONCLUSION

In conclusion, this paper successfully developed and evaluated an interactive AR simulation app for pneumatic education. By integrating FluidSIM video content with marker-triggered 3D models in a single, offline Android application, this project delivers a novel, TVET-aligned tool for enhanced active learning. The evaluation by the students of Diploma in Mechanical Engineering has granted percentage improvements of 15.0%–27.8% across all measured learning outcomes with post-AR mean scores consistently exceeding 4.0 on a 5-point scale. Eventually, this application offers a scalable, zero-capital solution to modernize pneumatics training and providing a replicable model for elevating TVET standards across Malaysia. This approach offers a transferable solution for NOSS-aligned pneumatics by providing a framework to overcome learning barriers in industrial systems unseen by hidden internal components. Since industry in Malaysia accelerates in adoption of automation and Industry 4.0 technologies, this solution can close the gap between theoretical classroom knowledge and practical competency. The scale and at near-zero hardware cost achievement can allow a meaningful contribution to national workforce readiness.

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