The MARVLS of Flight: An Augmented Reality Intervention for Engineering Education

Fasiha Khaliq, Siena College

Fasiha Khaliq is a senior undergraduate student in Applied Physics (Mechanical Track) at Siena University. Her work involves developing augmented reality (AR) applications to enhance students' understanding of abstract and three-dimensional concepts. She also works on designing and 3D printing physical targets for integration into AR-based educational projects.

Michele W. McColgan, Siena University

Dr. Michele McColgan is a Professor of the Physics & Astronomy Department at Siena University, a small liberal arts university in upstate New York. She spearheaded developments in the realm of augmented reality (AR) smartphone applications to enhance the learning experience for physics and engineering students (MARVLS). These tools serve as a bridge, enabling students to connect abstract concepts and 3D models with the traditional 2D representations and equations found in textbooks. By immersing students in a visually engaging and interactive learning environment, these applications facilitate a deeper understanding of complex physics and engineering principles. Dr. McColgan focuses on physics education research, investigating the impact of augmented reality applications on students' conceptual understanding of physics and their spatial visualization skills. She explores how manipulating 3D models and establishing connections between 2D representations, physics equations, and the real-world counterparts can enhance students' comprehension and problem-solving abilities.

Dr. Jason W Morphew, Purdue University – West Lafayette

Dr. Jason Morphew is an assistant professor at Purdue University in Engineering Education and serves as the director of undergraduate curriculum and advanced learning technologies for SCALE, and is affiliated with the INSPIRE research institute for Pre-College Engineering and the Center for Advancing the Teaching and Learning of STEM. Dr. Morphew's research focuses on the application of principles of learning derived from cognitive science and the learning sciences to the design and evaluation of learning environments and technologies that enhance learning, interest, and engagement in STEM. Morphew earned his Ph.D. from the University of Illinois Urbana-Champaign in Educational Psychology from the Cognitive Science of Teaching and Learning Division where he examined self-regulated learning of engineering students enrolled in introductory physics courses.

©American Society for Engineering Education, 2026

WIP: The MARVLS of Flight: An Augmented Reality Intervention for Engineering Education

Abstract

This Work-in-Progress paper describes the design and development of augmented reality (AR) scenes for visualizing aerodynamic concepts related to lift. The AR environment enables students to explore flow behavior, pressure distributions, and velocity fields through interactive three-dimensional representations. The instructional design emphasizes connections between conservation principles and physical interpretations, while addressing common misconceptions associated with Bernoulli-based explanations of lift. Assessment of learning outcomes is planned as future work.

Introduction

Reasoning about aerodynamics and the generation of lift is conceptually challenging, and a substantial body of research has documented both the complexity of these phenomena and differing instructional approaches [1–11]. Research on embodied cognition suggests that coordinating abstract conceptual understanding with physical representations can be supported through perceptuo-motor engagement, particularly for spatially complex phenomena [12]. Students frequently struggle to develop spatial understanding of three-dimensional concepts in physics and engineering, particularly when instruction relies heavily on two-dimensional representations. This challenge is especially pronounced for abstract topics such as Bernoulli's principle and aerodynamic flow around airfoils.

To support learning of abstract scientific concepts, the MARVLS smartphone applications provide interactive three-dimensional visualizations using augmented reality and Merge© cubes. These visualizations include integrated guidance that links labeled features directly to elements of the model, and they allow students to physically manipulate virtual objects, rotating, translating, and examining them within real space helping bridge mathematical expressions, two-dimensional diagrams, and three-dimensional representations [12,13-17].

This paper describes the development of AR scenes designed to support student visualization of three core aerodynamic concepts: aerodynamic forces, pressure and velocity distributions, and flow behavior as a function of angle of attack. These concepts are foundational to aerospace engineering yet difficult to reason about using static, two-dimensional representations, as they involve invisible, spatially distributed, and dynamic phenomena. Airfoils, representations of aircraft wings, provide a compact and representative system in which small parameter changes produce qualitatively different physical outcomes, making them well suited for inquiry-based exploration.

Instructional explanations of lift often rely heavily on simplified Bernoulli-based reasoning, which can lead to persistent misconceptions. One common misconception is the “equal transit time” argument, in which fluid elements traveling over the upper surface of an airfoil are assumed to recombine with those traveling below at the trailing edge. This reasoning incorrectly suggests that the higher velocity above the airfoil results from a longer path length. In reality, fluid elements do not recombine in this manner, and the velocity distribution is not determined by path length considerations. Instead, the pressure and velocity fields around an airfoil are established by the global flow structure, including geometry, boundary conditions, and streamline curvature. Bernoulli’s equation (Equation 1), in which P represents fluid pressure, ρ the fluid density, v the flow velocity, and h the elevation relative to a reference level, relates pressure and velocity changes along a streamline under appropriate assumptions. For flow around an airfoil at a fixed orientation, variations in elevation are typically small, so the gravitational term (ρgh) can be treated as approximately constant, reducing the relationship primarily to a tradeoff between pressure and velocity.

$$P + \frac{1}{2}\rho v^2 + \rho gh = constant \qquad (1)$$

To make aerodynamic interactions explicit, vectors representing velocity, lift, and drag are overlaid on the airfoil, illustrating both the magnitude and direction of forces and flow. The AR environment, developed in the Unity game engine, enables students to visualize flow fields, pressure variations, and velocity vectors from multiple perspectives, while simulations animate these quantities in real time, linking mathematical variables to physical behavior. As the angle of attack increases, airflow over the upper surface of the airfoil can become unstable, leading to flow separation and the formation of vortices near the trailing edge, effects that are difficult to convey with static representations but readily explored within the AR environment.

This Work-in-Progress paper focuses on the design of these AR learning environments and the instructional framework guiding their development. Assessment of student learning outcomes is beyond the scope of this paper and will be addressed in future work.

Design of AR Learning Environments for Aerodynamics

This section describes the instructional design and implementation of the AR scenes.

Scope

This Work-in-Progress paper focuses on the design and development of augmented reality (AR) scenes for visualizing fundamental aerodynamic concepts related to lift. The primary goal is to describe the instructional design and implementation of these AR environments. Systematic assessment of student learning outcomes is planned as future work.

Instructional framing and Bernoulli-related nuances
Instructional explanations of lift often rely on simplified Bernoulli-based reasoning that can lead to misconceptions, such as the equal transit time argument. The AR environment is designed to address these issues by enabling simultaneous visualization of velocity fields, pressure distributions, and streamline behavior.

Instead, the pressure and velocity fields around an airfoil are established by the global flow structure, including geometry, boundary conditions, and streamline curvature. Bernoulli's equation, applied in its steady, incompressible, inviscid form along a streamline, does not determine the origin of velocity differences; rather, it relates pressure and velocity changes once the flow field is established. The AR environment is designed to address these nuances by enabling students to simultaneously visualize velocity fields, pressure distributions, and streamline behavior in three dimensions.

AR instructional scenes
The AR scenes are designed to support student understanding of lift through multiple complementary physical frameworks, including conservation of mass, energy, and momentum, as well as viscous effects.

1. Continuity and velocity-area relationship.
Students explore conservation of mass using a pipe with varying cross-sectional area. The visualization demonstrates that as the cross-sectional area decreases, flow velocity increases, reinforcing the inverse relationship between area and velocity for steady incompressible flow.

2. Pressure-velocity relationship along a streamline.
Using the same pipe geometry, students observe how changes in velocity correspond to changes in pressure along a streamline. This scene introduces Bernoulli's equation and emphasizes its validity along individual streamlines under appropriate assumptions.

3. Momentum change and Newton's third law.
An airfoil scene illustrates how the wing deflects airflow downward (downwash). The AR visualization highlights the resulting change in momentum of the air and connects this to the upward force on the airfoil through Newton's third law, providing a force-based interpretation of lift.

4. Boundary layer and viscous effects.
The AR model visualizes the development of the boundary layer along the airfoil surface, showing how velocity increases from zero at the surface to the free-stream value. This scene highlights the role of viscosity in shaping the flow field, including its influence on flow attachment, separation, and the resulting pressure distribution that contributes to lift.

Together, these scenes support coordinated reasoning across conservation of mass, energy, and momentum, while also introducing the role of viscosity. The AR environment enables visualization of three-dimensional flow features such as velocity gradients normal to the surface, streamline curvature, and spatial pressure variation that are difficult to represent in traditional two-dimensional diagrams.

These scenes are intended to support coordinated reasoning across multiple representations, an aspect that will be investigated in future work using the Mathematical Sensemaking (MSM) framework [19, 20] to analyze how students coordinate mathematical and physical representations, as demonstrated in prior AR-based studies [14].

Future Work

Assessment of the AR intervention is beyond the scope of this Work-in-Progress paper. Future work will include both quantitative and qualitative measures of student learning, including concept inventories, surveys, and analysis of student reasoning during AR interaction. Qualitative analysis will be guided by the Mathematical Sensemaking (MSM) framework [19,20] to examine how students coordinate mathematical, visual, and physical representations during AR interaction.

Methodology

The AR scenes were developed using the Unity game engine with custom C# scripts to control interactivity, parameter changes, and visual feedback. Unity was selected for its cross-platform deployment, real-time rendering capabilities, and support for augmented reality development.

Fluid flow and aerodynamic behavior were visualized using Unity's built-in particle system in combination with the *Aerodynamic Objects* asset from the Unity Asset Store. This asset provides configurable aerodynamic functions, including geometric airfoil models, lift and drag calculations, uniform flow fields, and particle-based flow visualization [18].

The visualization design prioritized making invisible quantities explicit through multiple coordinated representations, including vector arrows for lift, drag, and velocity; animated path lines and flow particles for air motion; and adjustable parameters such as wind speed and angle of attack. These representations were selected to support qualitative reasoning about aerodynamic relationships rather than numerical prediction.

Users can modify parameters such as angle of attack and wind speed in real time, allowing direct observation of resulting changes in force vectors, pressure-related flow behavior, and wake structure.

The AR models are intended as conceptual visualizations rather than high-fidelity computational fluid dynamics models, with the goal of supporting qualitative reasoning about aerodynamic relationships.

AR Scene Implementation and Examples

This section presents the three augmented reality (AR) scenes developed in this work, which visualize aerodynamic forces, flow behavior, and angle-of-attack effects associated with airfoil operation within an interactive 3D environment.

Three AR scenes were created using Unity to support students in coordinating abstract fluid mechanics concepts with spatial, visual representations. Together, these scenes illustrate how forces acting on an airfoil relate to airflow velocity, pressure distributions, and changes in angle of attack.

The first AR scene focuses on the vector forces acting on an airfoil. Students can rotate the airfoil in three dimensions to observe how lift and drag vectors change as a function of the airfoil's orientation relative to the oncoming airflow. Figure 1(a) shows the airfoil aligned with the airflow, represented by a blue velocity vector, producing a drag force (red vector) and negligible lift. In Figure 1(b), the relative airflow results in a downward lift vector (green) along with the drag force. Figure 1(c) illustrates a configuration in which the airflow produces both upward lift and drag. Through manipulation of the airfoil orientation, students can directly observe how changes in angle of attack alter the magnitude and direction of these vector quantities.

Figure 1. AR Scene showing how the velocity (blue), drag (red) and lift (green) vectors change with angle of attack.

The second AR scene in Figure 2 allows students to explore the relationship between air velocity and pressure around the airfoil through interactive sliders linked to Bernoulli's equation. Students independently vary velocity and pressure values and observe the corresponding changes in real time. In Figure 2 students observe that regions of higher velocity along the top surface correspond to regions of lower pressure, consistent with Bernoulli's relationship along a streamline. Students observe that air particles above the airfoil move faster than those below, while particles beneath the airfoil move more slowly and appear closer together, corresponding to a higher pressure region. The resulting pressure differential between the top and bottom surfaces produces a net upward force on the airfoil. This scene explicitly connects visual flow behavior to the mathematical relationship described by Bernoulli's equation.

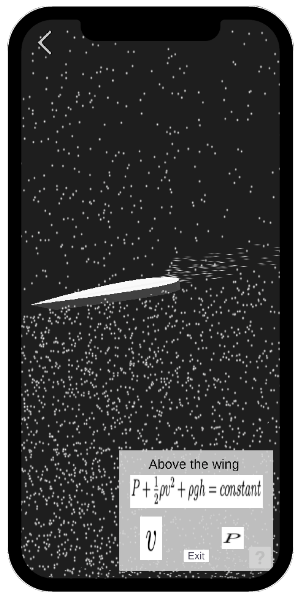

Figure 2. Bernoulli's equation AR scene with slow velocity airmass below the airfoil and large pressure below the airfoil and faster air particles above the airfoil and lower pressure above the airfoil.

The third AR scene in Figure 3 examines the effect of angle of attack on airflow behavior and pressure distribution around the airfoil. Students rotate the airfoil to increase or decrease the angle of attack. As the angle approaches a critical value, the airflow transitions from smooth flow to turbulent behavior and no longer follows the contour of the upper surface of the wing. This transition is visualized through the formation of vortices above and toward the trailing edge of the airfoil, representing flow separation. By observing these changes, students can connect angle-of-attack variations to turbulence, loss of lift, and stall-related aerodynamic effects.

Figure 3. (a) Airfoil through the airmass below the critical angle with the air flowing around the airfoil. (b) At and above the critical angle, the air mass becomes turbulent as shown by the vortices at the lower left edge of the airfoil.

Collectively, these AR scenes provide students with an interactive means to link vector representations, mathematical relationships, and physical flow behavior, supporting a coordinated understanding of airfoil aerodynamics.

Conclusions and Future Work

This work describes the development of three augmented reality (AR) scenes designed to support student learning of foundational aerodynamic concepts related to airfoil operation. The AR scenes visualize vector forces, airflow velocity and pressure relationships, and angle-of-attack effects within an interactive three-dimensional environment. By enabling students to manipulate airfoil orientation and flow parameters in real time, the scenes provide a means for linking abstract mathematical relationships and vector representations with spatial and physical intuition.

This work illustrates how AR can make otherwise invisible aerodynamic phenomena visible and interactive, supporting coordinated reasoning across multiple representations. These visualizations provide opportunities for students to explore how changes in velocity, pressure, and angle of attack influence lift generation and flow behavior, reducing reliance on static two-dimensional representations.

Future work will extend both the instructional and research impact of these AR scenes. First, structured lesson materials will be developed to guide student exploration, prompt prediction and reflection, and explicitly connect AR interactions to mathematical models, vector representations, and traditional problem-solving approaches.

Second, qualitative research will investigate how students use the AR scenes to make sense of aerodynamic concepts. Semi-structured interviews will examine how students coordinate visual, mathematical, and conceptual resources during AR interaction. These data will be analyzed using the Mathematical Sensemaking (MSM) framework [19,20] to identify patterns in how students construct meaning and reconcile multiple representations, informing iterative refinement of both the AR scenes and accompanying instructional materials.

Together, these efforts will contribute to understanding how AR-supported visualizations can promote mathematical sensemaking in aerodynamics and support learning of complex spatial phenomena in physics and engineering.

References

[1] J. G. Leishman, *Aerodynamics of Airfoils*. Eaglepubs.erau.edu, *31*, 2022. https://doi.org/10.15394/eaglepub.2022.1066.n23

[2]F. Genz, & K. Falconer, "Naïve concepts of aerodynamic lift – data lessons from different (learning) cultures". Paper presented at *Physics Education Research Conference 2021, Virtual Conference.*

[3] E. Regis, "No One Can Explain Why Planes Stay in the Air", *Sci. Am*. 51, 1, 2020. https://www.scientificamerican.com/article/no-one-can-explain-why-planes-stay-in-the-air.

[4] K. Weltner, "A Comparison of Explanations of the Aerodynamic Lifting Force", *Am. J. Phys.* 55, 50, 1987.

[5] D. McLean, "Aerodynamic Lift, Part 1: The Science", *Phys. Teach.* 56, 516, 2018. https://doi.org/10.1119/1.5064558.

[6] D. McLean, "Aerodynamic Lift, Part 2: A Comprehensive Physical Explanation", *Phys. Teach*. 56, 521, 2018. https://doi.org/10.1119/1.5064559.

[7] D. Auerbach, "On the Problem of Explaining Lift", *Am. J. Phys.* 56, 853, 1988. https://doi.org/10.1119/1.15444.

[8] C. N. Eastlake, "An Aerodynamicist's View of Lift, Bernoulli, and Newton", *Phys. Teach.* 40, 166, 2002.

[9] K. Weltner, "Bernoulli's Law and Aerodynamic Lifting Force", *Phys. Teach.* 28, 84, 1990. https://doi.org/10.1119/1.1466553.

[10] E. L. Houghton, P. W. Carpenter, S. H. Collicott, and D. T. Valentine, *Aerodynamics for Engineering Students*, 6th ed., 2012. ISBN: 9780080966335

[11] F. Genz, K. Falconer, L. Möhring, and A. Bresges, "Flight Physics Concept Inventory - A Multi-Cultural Concept Inventory for Flight Physics", *AAPT SM19,* 2019. http://dx.doi.org/10.13140/RG.2.2.21476.71044.

[12] J. A. Bennett, J. W. Morphew, & M. W. McColgan, "Embodied Learning with Gesture Representation in an Immersive Technology Environment in STEM Education", *Paper presented at 2024 ASEE Annual Conference & Exposition*, Portland, Oregon. http://dx.doi.org/10.18260/1-2--47233

[13] M. W. McColgan, G. E. Hassel, K. Pashayi, and J. W. Morphew, "Seeing Electromagnetic Induction: Student Sense Making with Augmented Reality," *Proceedings of the 2026 ASEE Annual Conference*, 2026 (accepted).

[14] M. W. McColgan, G. E. Hassel, K. Pashayi, J. W. Morphew, & J. A. Bennett, "MSM Framework: Augmented Reality Models of 3D Vectors", *Paper presented at 2025 ASEE Annual Conference & Exposition*, Montreal, Quebec, Canada. doi:10.18260/1-2--56981

[15] M. W. McColgan, G. E. Hassel, and K. Pashayi, "MSM Framework: AR Model of the Force on a Charge Moving in a Magnetic Field", 2*024 PERC Proceedings* [Boston, MA, July 10-11, 2024], edited by Q. X. Ryan, A. Pawl, and J. P. Zwolak, doi:10.1119/perc.2024.pr.McColgan.

[16]M. W. McColgan, J. W. Morphew, G. E. Hassel, J. A. Bennett, & M. C. Kelly, "Board 415: Understanding Magnetism Concepts Through Augmented Reality: A Qualitative Analysis", *Paper presented at 2024 ASEE Annual Conference & Exposition*, Portland, Oregon. doi:10.18260/1-2--47004

[17] M. W. McColgan, G. E. Hassel, N. C. Stagnitti, J. W. Morphew, and R. S. Lindell, "Augmented Reality to Scaffold 2D Representations of 3D Models in Magnetism", *2023 PERC Proceedings* [Sacramento, CA, July 19-20, 2023], edited by D. L. Jones, Q. X. Ryan, and A. Pawl, doi:10.1119/perc.2023.pr.McColgan.

[18] *Aerodynamic Objects* Unity Assets: https://www.aerodynamicobjects.com/

[19] J. Gifford, N. Finkelstein, "Applying a mathematical sense-making framework to student work and its potential for curriculum design". *Phys. Rev. Phys. Educ. Res.*, 17(1), 010138, 2021. https://doi.org/10.1103/PhysRevPhysEducRes.17.010138

[20] J. Gifford, N. Finkelstein, “Categorical framework for mathematical sense making in physics”. *Phys. Rev. Phys. Educ. Res.*, 16(2), 020121, 2020. https://doi.org/10.1103/PhysRevPhysEducRes.16.020121