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Enhanced PBL Through AR for Early-Stage Manufacturing Design: Supporting Brainstorming and Low-Fidelity Prototyping

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Augmented Reality for Early-Stage Manufacturing Design: Supporting Brainstorming and Low-Fidelity Prototyping

Abstract

Augmented Reality (AR) has the potential to support early-stage manufacturing design education by enhancing students' ability to visualize and sketch before modeling or physical prototyping. In this work, AR is integrated as a targeted visualization tool within a freshman-level course to support the low-fidelity (lo-fi) stage of a semester-long project-based learning (PBL) activity. Short AR-based sketching assignments were introduced during the early design phase of a comprehensive manufacturing design project to complement traditional brainstorming and hand sketching practices.

The AR application was designed to allow students to visualize simplified mechanical and electromechanical components, such as motors and switches, within a physical context and to sketch orthographic and isometric views without access to physical parts. Rather than serving as a training or fabrication tool, AR functioned as a cognitive aid to support spatial reasoning and early concept communication. These activities were integrated alongside low-fidelity prototyping tasks to reinforce the non-linear nature of the engineering design process and to prepare students for subsequent medium- and high-fidelity design stages.

This paper presents the structure of the manufacturing design project, details the development and deployment of the AR application, and describes how AR-based assignments were incorporated into the lo-fi stage. Preliminary observations indicate that AR activities had great potential, as they were engaging during early sketching and ideation. This work builds on the authors' prior research on extended reality (XR) in manufacturing education, which has primarily focused on assembly training and later-stage design tasks, and extends XR integration into the conceptual and early design phases. Ongoing efforts aim to expand the AR activities and conduct systematic evaluation of their impact on future course offerings.

Keywords: AR, manufacturing education, conceptual design, sketching, design process

1. Introduction

For over two centuries, the manufacturing sector has served as a cornerstone of the United States economy, playing a role in sustaining economic growth [1], [2]. Manufacturing drives commercial innovation, provides high-wage employment opportunities, and contributes to reducing the U.S. trade deficit [3], [4]. According to reports from the U.S. Department of Defense, manufacturing activities account for approximately 35% of U.S. economic growth and nearly 60% of U.S. foreign trade through exports [5], [6]. In addition, manufacturing organizations generate over half of U.S. patents and support nearly 70% of national research and development spending [5]. These metrics show the importance of preparing an engineering workforce capable of advancing modern manufacturing processes.

Manufacturing, however, extends beyond production and assembly. It represents a connected pipeline that begins with conceptual design and progresses through modeling, prototyping, fabrication, and final assembly [7]. Decisions made during the earliest stages of this pipeline affect the final product's cost, safety, and performance. Among all stages of the manufacturing process, the early stages, including conceptual designs, have a great influence on the final outcomes [8]. Choices made at early stages define part count, assembly complexity, tolerance requirements, and production feasibility. Designers repeatedly move between ideas, constraints, sketches, and feasibility assessments as concepts evolve. Helping students understand and manage this non-linear process remains a central challenge in manufacturing-focused engineering education [9].

Freshman-level solid modeling and design courses often represent students' first exposure to formal design thinking within a manufacturing context. These courses commonly rely on project-based learning (PBL) [10] and competition-based learning (CBL) [11] to engage students in open-ended problems that resemble real-world design tasks. Through PBL, students define requirements, generate concepts, evaluate alternatives, and gradually refine designs under realistic constraints. These instructional approaches expose students to the design process, supporting experiential learning. However, they rely heavily on effective visualization skills, as students need to communicate ideas through sketches and reason about motion, scale, and assembly before developing detailed models.

Studies showed that many students encounter difficulties during the low-fidelity stage of the design process, due to the lack of reasoning skills [12], [13]. One study with 219 freshmen engineering students indicated that poorer modeling performance is measurably associated with students' weaker reasoning/visualization skills [14]. Translating abstract ideas into sketches requires spatial reasoning skills that are still developing at the freshman level. Students struggle to visualize how components interact, how motion occurs, or how a design fits within physical and manufacturing constraints. While physical prototyping in PBL can help address these challenges, it introduces additional cost, time, and resource demands that limit iteration, particularly in early coursework.

These challenges motivate the use of instructional tools that support visualization without increasing cost or complexity. Augmented Reality (AR), an extended reality (XR) technology, could be a powerful tool when used during early-stage design, allowing students to project digital objects into their physical environment. AR would help students externalize ideas, examine spatial relationships, and reason about motion and assembly before committing to detailed geometry.

The author's prior research on XR in manufacturing education has demonstrated benefits in areas such as assembly training, safety awareness, and procedural understanding [15], [16], [17], [18], [19], [20], [21]. XR environments have improved student engagement and comprehension during the learning of complex assembly tasks, focused on later stages of manufacturing, where procedures and geometries are already defined.

This paper builds on and complements the author's prior research on XR by examining the integration of AR into early-stage manufacturing design education. The study investigates the impact of integrating short AR-based assignments into the final project of a freshman solid modeling and design course on students' understanding of the non-linear nature of the design process.

The rest of this paper is organized as follows. Section 2 presents background on the use of AR as an instructional tool in manufacturing education, highlighting current challenges and our proposed approach. Section 3 describes the PBL activity centered on the final course project, The Arm-propelled Robot, and outlines the major design stages along with representative student outcomes at each stage. Section 4 presents the development and integration of the AR application and introduces the AR-based short sketching assignment, noting that additional AR activities are currently under development. Section 5 presents preliminary results and reflections on the project and on the integration of AR during the lo-fi design stage, as this implementation is still under evaluation. Finally, Section 6 concludes the paper and outlines future directions for expanding the use of AR in early-stage manufacturing design education.

2. Augmented Reality: An Instructional Tool in Manufacturing Education

AR can be defined as a spatial medium that embeds digital geometry and constraints within the user's physical environment via display-based devices [22]. Unlike Virtual Reality (VR), which replaces the physical world with a fully virtual environment, AR overlays digital content onto real surroundings using devices such as smartphones, tablets, head-mounted displays, or projection-based systems, while preserving the user's awareness of the physical context [23]. This capability makes AR a powerful educational tool for engineering design tasks that require reasoning about scale, geometry, motion, and physical constraints.

In manufacturing education, AR has the potential to support spatial augmentation, real-time interaction, and contextual visualization, all of which play a critical role during early-stage manufacturing design [24]. AR enables students to place digital components within a physical workspace and examine them from multiple viewpoints. Students can observe how parts align, move, and interact before committing to detailed geometry or fabrication. Unlike static sketches or 2D screen-based CAD models, AR allows learners to reason about designs in relation to their body, tools, and surrounding space. This spatial visualization tool reduces the cognitive effort required to mentally transform 2D sketches into 3D structures and supports more effective communication among team members during brainstorming and concept evaluation.

Students would use AR to project simplified component representations, sketch directly over augmented views, and explore motion and configuration without defining full geometry. AR will help bridge the gap between abstract ideas and formal solid models by enabling students to visualize and manipulate concepts within a physical context.

When integrated into PBL and CBL, AR supports the non-linear nature of the design process by allowing students to revisit ideas, test alternatives, and refine concepts before committing to detailed designs. Thus, this work proposes integrating AR into a freshman-level Solid Modeling design project to help students understand the non-linear nature of the design process while developing spatial reasoning skills. The project requires students to work in teams to design a arm-propelled robot under defined manufacturing and performance constraints, progressing from low-fidelity concepts to high-fidelity designs. Short AR-based assignments were designed and integrated alongside the other project activities to reinforce brainstorming, visualization, and early feasibility assessment before design selection and detailed modeling.

3. Overview of the Arm-propelled Robot Project

The Arm-propelled Robot Project focused on designing a legged motion mechanism, intentionally selected over wheeled motion to introduce mechanical complexity, motion planning challenges, and manufacturability considerations. The project aimed to expose students to the non-linear nature of the design process and its associated phases within an engaging educational context.

The project was implemented as part of a freshman-level course and accounted for 30% of the overall course grade. The course was offered across more than nine sections within the Mechanical Engineering Department; however, the project was conducted in seven sections taught by the authors of this work. Each section enrolled between 16 and 18 students. Students were organized into teams of four to five, resulting in a total of 24 project teams. Team formation was completed using CATME, a web-based team management and assessment tool, which allowed the instructors to form balanced teams based on customized criteria, including CAD experience, hands-on skills, and sketching proficiency.

Students worked within their teams to design an arm-propelled robot capable of racing along a wooden branch through a sequence of consecutive project assignments completed throughout the semester. The project progressed through three structured design stages, shown in Figure 1: low-fidelity (lo-fi), medium-fidelity (med-fi), and high-fidelity (hi-fi), each divided into multiple mini assignments. Each stage focused on different aspects of the manufacturing design process and required students to reflect on performance, feasibility, and design limitations before moving to the next stage.

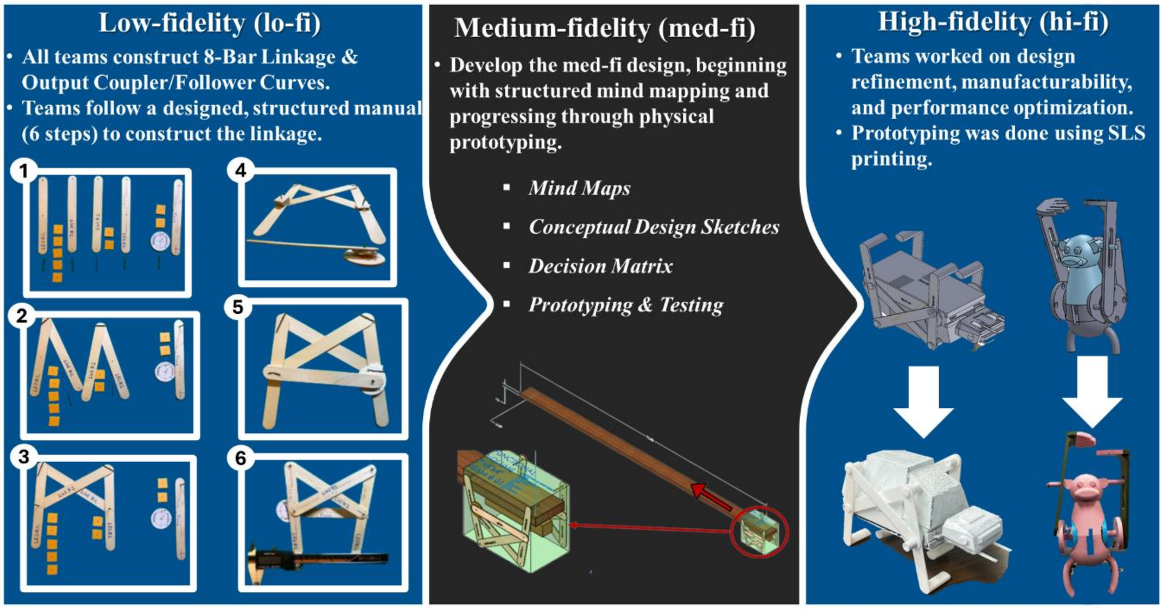


Figure 1. Diagram illustrating the three basic stages of the project (lo-fi to med-fi to hi-fi).

3.1. Low-Fidelity Design Stage

The lo-fi design stage was structured to expose students to early mechanism understanding about legged motion and linkage behavior before any CAD design was introduced. This stage allowed students to construct a parallel four-bar–based eight-bar linkage mechanism that served as the foundational walking structure for the toy robot. The linkage was constructed using simple, low-cost materials, like tongue depressors, cardboard spacers, cotter pins, and basic hand tools, following a standardized construction manual (see Figure 2). This stage focused on introducing students to kinematic behavior rather than fabrication precision, while still exposing them to alignment, tolerance, and assembly challenges.

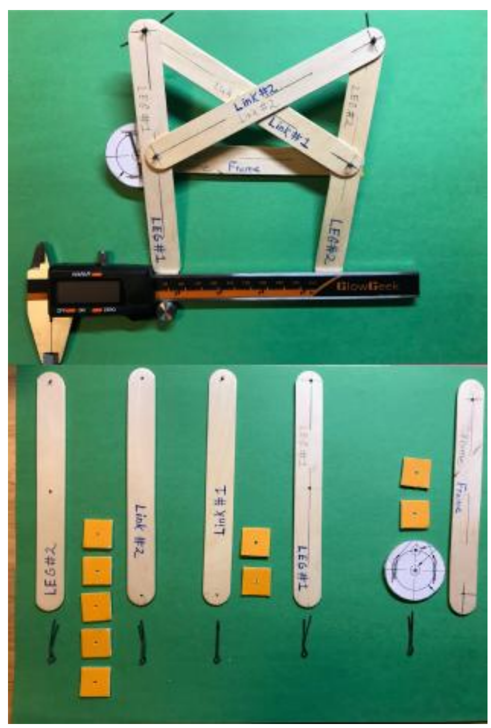
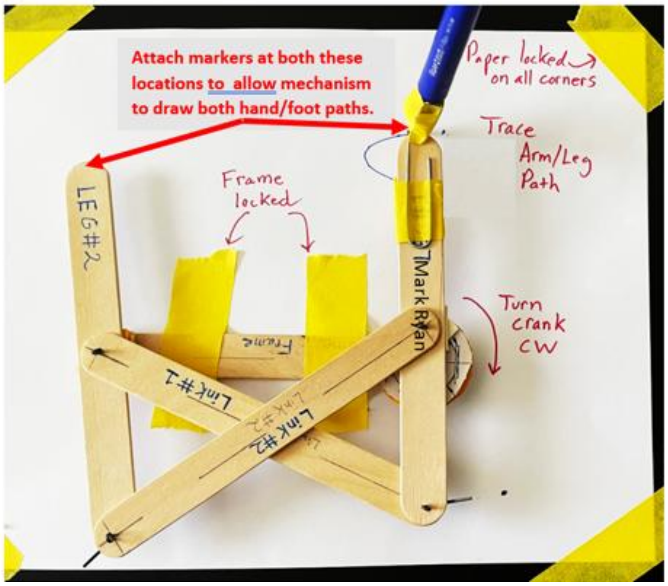


Figure 2. The assembled four-bar–based leg mechanism (top) and the corresponding individual linkage components and hardware (bottom).

The main objective of the lo-fi stage was to help students understand how linkage geometry affects leg motion and ground interaction. After assembling the mechanism, students traced the trajectory of the output coupler by attaching markers to the "feet" of the linkage and manually rotating the crank through a full cycle, as shown in Figure 3. This motion path tracing activity allowed students to analyze step height, stride length, and motion smoothness without relying on simulation tools. Students studied the impact of small geometric changes on walking performance by physically observing and recording trajectories.



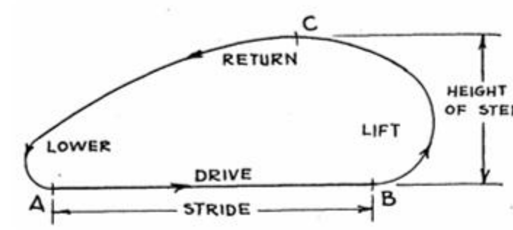


Figure 3. Motion-path exploration during the low-fidelity design stage. The left image shows a sample-constructed linkage mechanism instrumented with markers to trace the leg and foot trajectories during manual crank rotation. The right image illustrates a representative footpath, highlighting characteristics such as stride length, step height (lift), and return phase.

After building the lo-fi prototype, the next step was to allow students to identify its limitations, including friction at joints, lack of rigidity, and sensitivity to misalignment. These observations would help students make decisions on material selection, joint design, and tolerancing during the medium- and high-fidelity stages.

From a manufacturing education perspective, the lo-fi stage introduces students to the idea that early design is not about producing a "working product," but about learning how a system behaves. The structured manual ensures consistency across teams while still allowing room for observation, questioning, and reflection. As a result, students would enter the subsequent brainstorming and conceptual design phase with a shared mechanical reference point and a clearer understanding of how physical constraints shape feasible design solutions.

3.2. Medium-Fidelity Design Stage

The med-fi design stage allowed students to transition from exploratory low-fidelity mechanisms to functional prototypes. This stage focused on structured ideation, concept evaluation, and early manufacturability considerations. The following subsections outline the steps involved in developing the med-fi design, beginning with structured mind mapping and progressing through physical prototyping.

Mind Maps

The med-fi stage starts with structured brainstorming activities that guide students in expanding and refining their lo-fi design ideas. This stage allows Teams to develop mind maps (see Figure 4) to identify key functions and features required for the arm-propelled robot, such as motion stability, motor housing, battery placement, and structural support. This process reinforces the students' divergent thinking, helping them explore multiple ways to satisfy design requirements and constraints before converging on a single solution. This teaches the students the difference between distinguishing what the system must do and how it could be implemented.

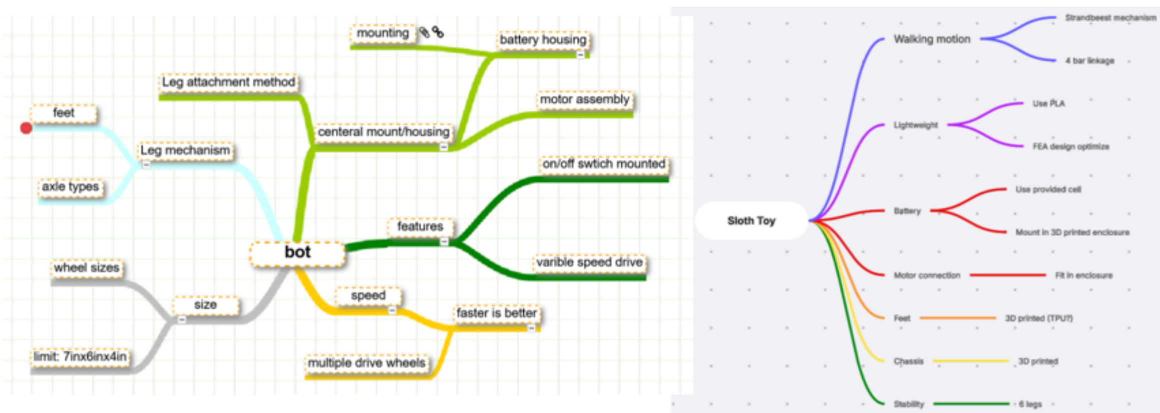


Figure 4. Sample of the students' developed mind maps

Conceptual Design Sketches

Following brainstorming, it is required that each team generate multiple configuration concepts through engineering sketches (see Figure 5). Each student will contribute at least one design concept, ensuring a range of ideas within the team. Sketches illustrate both the primary walking motion and a proposed secondary motion mechanism, allowing students to explore how multiple subsystems could be integrated within a compact toy-scale design. Students sketch primary components, such as motors, batteries, switches, and linkages, and use simple geometric representations to communicate design intent clearly. This stage emphasizes visual communication and early system-level thinking prior to detailed modeling.

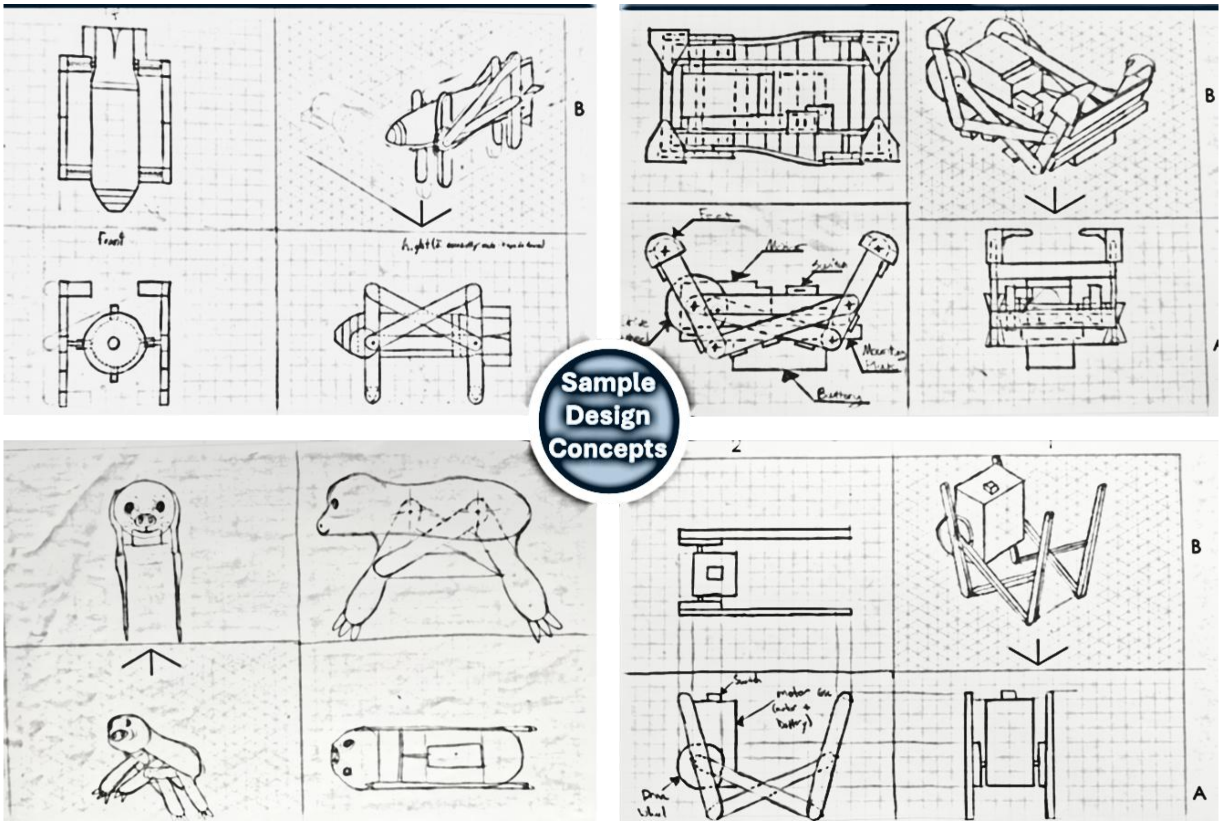


Figure 5. Some samples of the developed engineering sketching.

Decision-Making through Decision Matrix

Teams will then evaluate their design concepts using decision matrices (sample shown in Figure 6). They are asked to develop decision matrices for the primary walking mechanism and the secondary motion. Evaluation criteria included manufacturability, assembly complexity, robustness, expected performance, and feasibility within project constraints. Students weighted these criteria and ranked each concept accordingly, then reflected as a team on whether the highest-ranked design required modification before advancing. This structured evaluation process encouraged critical thinking and prevented premature convergence on a single concept.

Weight Scale for Selection Criteria			
Scale	0	3	5
Description	Lower Impact on Project Success	Medium Impact on Project Success	Higher Impact on Project Success

Concept Ratings on Ability to Meet Selection Criteria			
Scale	0	3	5
Description	Worse than Baseline	Equivalent to Baseline	Better than Baseline

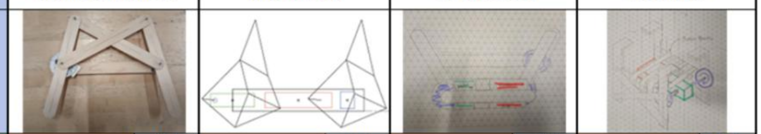
		Description	Baseline/Current Product		Jansen's Linkage		Clip-on Enclosure		Rubber Bands	
		Concept Image								
		Criteria Weights	Rating (0-5)	Mult. Score	Rating (0-5)	Mult. Score	Rating (0-5)	Mult. Score	Rating (0-5)	Mult. Score
Design Criteria	Weight	5	3	3	2	2	4	4	4	4
	Speed	35	2	14	4	28	3	21	3	21
	Design simplicity	15	4	12	1	3	4	12	5	15
	Manufacturing simplicity	15	4	12	2	6	4	12	5	15
	Low cost	5	5	5	5	5	5	5	5	5
	Reliability	25	1	5	3	15	3	15	2	10
Total Score			51		59		69		70	

Figure 6. Sample of one of the decision matrices developed by one of the teams.

Prototyping & Testing

After selecting the optimal concept using decision matrices, teams will develop detailed CAD models and engineering drawings using SolidWorks. Components will be fabricated using fused deposition modeling (FDM) and assembled with basic electrical elements, including DC motors and battery packs, to produce functional medium-fidelity prototypes. Figure 7 illustrates a representative med-fi prototype developed by one team, showing the integration of the linkage-based walking mechanism, motor mounting, and body structure, along with the corresponding CAD drawings used to guide fabrication and assembly.

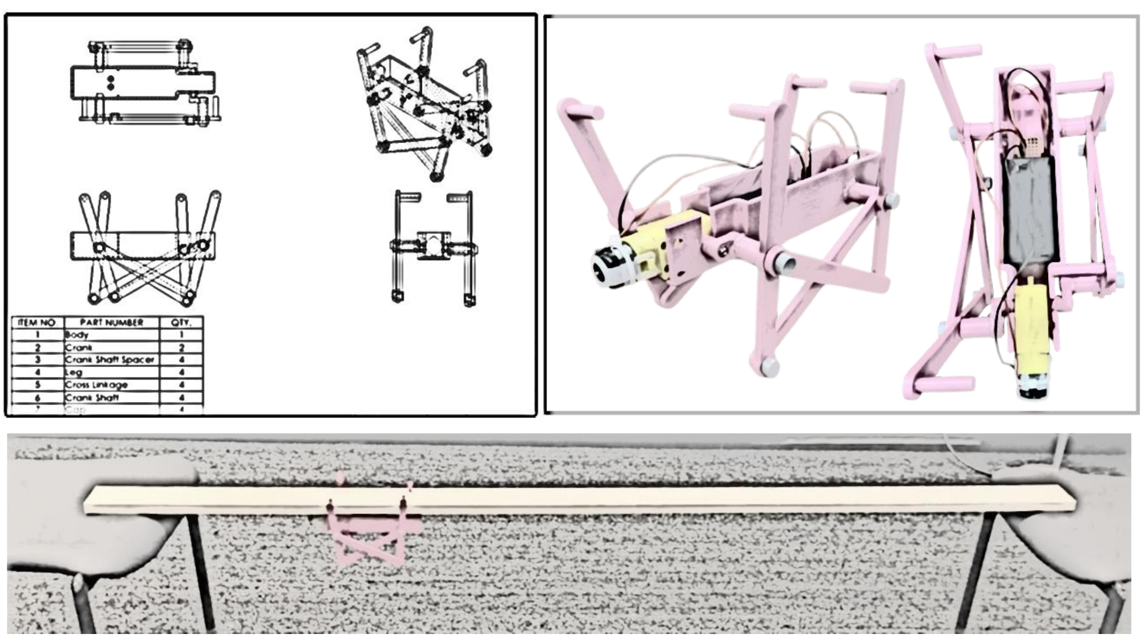


Figure 7. Med-fi design for one of the teams.

The assembled prototype will be tested on the wooden branch to evaluate walking performance and system behavior under realistic operating conditions. This initial physical testing during this stage might reveal some/several practical design limitations, including insufficient motor torque, joint misalignment, tolerance-related fit issues, and inefficient motion paths. Rather than treating these outcomes as failures, students will get the chance to document these observations and use them as design inputs to guide structural reinforcement, linkage refinement, and motor and joint redesign in subsequent stages.

Therefore, the med-fi stage plays a critical role in linking early ideation to manufacturable outcomes. Students will explore the correlation between design decisions and manufacturing constraints through structured brainstorming, visual communication, concept selection, and physical testing. This stage reinforces the iterative and non-linear nature of the design process and prepared students for the refinement and integration tasks required in the high-fidelity stage.

3.3. High-Fidelity Design Stage

The hi-fi design stage represents the final phase of the Arm-propelled Robot Project, during which teams will transform their validated med-fi prototypes into fully integrated functional systems. This stage focuses on design refinement, manufacturability, and performance optimization, requiring students to treat their designs as engineered products rather than experimental prototypes. All design decisions during this phase were led by observations and limitations identified during med-fi testing.

Teams began the hi-fi stage by finalizing the complete CAD model of their toy robot using SolidWorks, including both a functional assembly used for motion evaluation and a separate print-ready assembly configured for additive manufacturing. This distinction requires students to consider not only how components function together, but also how they would be fabricated, assembled, and maintained. Teams refined component geometry to address issues such as misalignment, excessive friction, insufficient stiffness, and inefficient motion paths observed during earlier testing.

The hi-fi components will then be manufactured using selective laser sintering (SLS), an additive manufacturing process selected for its ability to produce strong, durable, and dimensionally accurate parts suitable for moving mechanical assemblies, as shown in Figure 8. The figure shows printed structural parts, linkage components, and fasteners prior to final assembly. It illustrates the transition from med-fi prototypes to manufacturable, dimensionally accurate parts designed for durability, repeatable assembly, and integrated motion. Compared to fused deposition modeling (FDM), SLS enabled students to fabricate thinner features, tighter tolerances, and more robust joints without the need for support structures. However, because SLS produces fully dense parts, students will then be required to redesign components to reduce unnecessary mass by hollowing bodies, adding internal ribs, and incorporating powder removal openings. These requirements reinforced principles of lightweight design and material efficiency.

Figure 8. High-fidelity SLS-printed components and subassemblies from the Arm-propelled Robot Project (for two different teams).

From a manufacturing perspective, the hi-fi stage focused on fastening strategy, joint design, and assembly sequence. Temporary fastening methods used in earlier stages were replaced with screws, shafts, bearings, and insert-based joints to improve durability, repeatability, and ease of assembly. Students evaluated clearance requirements, fit types, and tolerance accumulation to ensure that moving components functioned reliably after fabrication. In several cases, students redesigned joints and interfaces multiple times to balance manufacturability with mechanical performance.

Besides the primary motion (walking mechanism), the hi-fi stage involved a secondary motion. Students incorporated additional motion elements, such as body articulation or coordinated limb movement, increasing system complexity and requiring careful synchronization between subsystems. This requirement encouraged students to consider system-level behavior, interference between moving parts, and the impact of added complexity on reliability and manufacturability.

Following fabrication, teams assembled their SLS prototypes, as shown in Figure 9, presenting some examples of student-developed arm-propelled robot prototypes. The figure shows a range of legged configurations, body designs, and integrated mechanisms that resulted from iterative design, manufacturability considerations, and system-level refinement under common performance and fabrication constraints.

Teams then tested their prototypes under realistic operating conditions on the wooden branch track. Testing focused on evaluating walking stability, structural integrity, and motion consistency. Rather than seeking a single optimal outcome, students analyzed tradeoffs between performance, complexity, and manufacturability. These evaluations reinforced the iterative and non-linear nature of the manufacturing design process, exposing students to how early design decisions influence final system behavior.

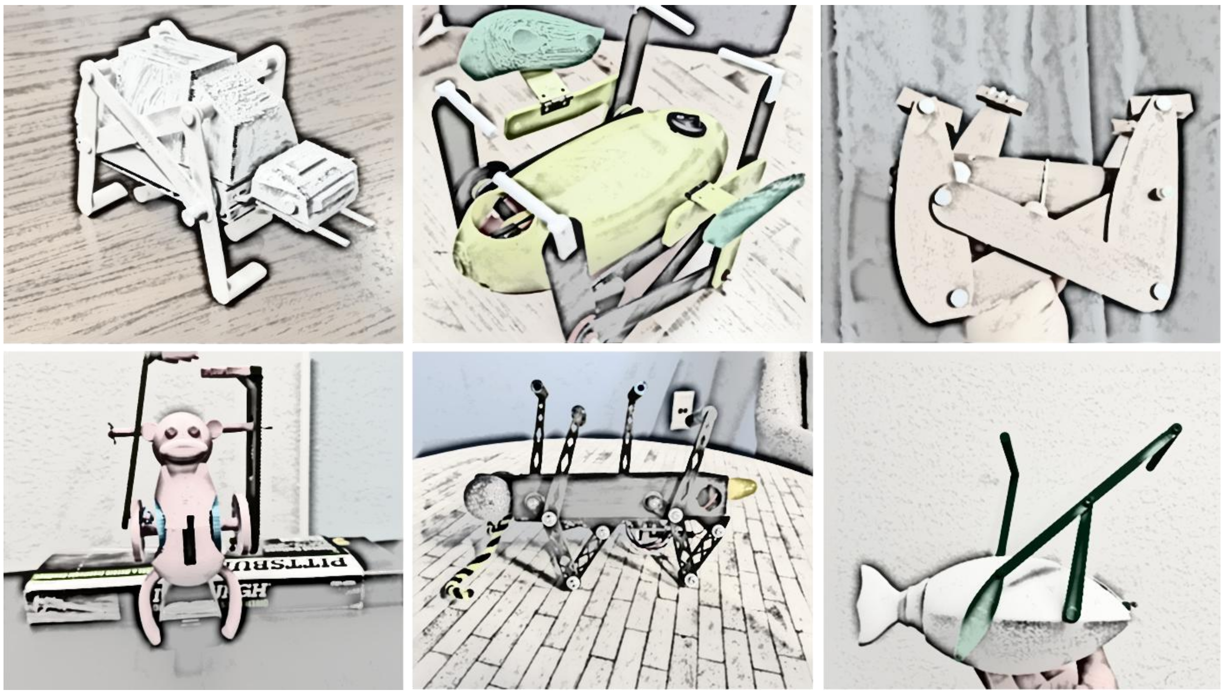


Figure 9. Sample examples of student-developed arm-propelled robot prototypes from the seven sections.

Thus, the hi-fi stage served as the culmination of the semester-long project by connecting early ideation, structured concept selection, and physical testing to manufacturable outcomes. This stage strengthened the students' understanding of design iteration, system integration, and engineering decision-making in manufacturing contexts by requiring students to refine and integrate multiple subsystems under realistic constraints.

4. Integrated AR Short Assignments into the Lo-fi Stage

AR was integrated into the Arm-propelled Robot Project during the early stages of the design process, primarily within the lo-fi phase. AR served as a cognitive visualization tool to support early ideation, spatial reasoning, and concept communication. The AR application was specifically designed to allow students to visualize and sketch mechanical and electromechanical components used in the project, such as motors, switches, and LEDs, within a physical context prior to detailed modeling. This integration aligned with the project's emphasis on early-stage design exploration, complementing the PBL activities.

Then, using the AR application, short AR-based assignments were developed to run in parallel with the lo-fi design tasks. Although these assignments were not graded as direct project deliverables, they aimed to help the students visualize the project components, understand geometry and orientation, and improve sketching accuracy before committing to detailed CAD models. The following subsections present the technical development of the AR application and introduce one of the designed AR-based sketching assignments. The AR application and associated assignments represent ongoing work and are currently being refined for expanded implementation in the Spring 2026 semester.

AR Application Development

The AR application was developed and deployed on an Android device using the Niantic Lightship ARDK toolkit integrated within Unity, as illustrated in Figure 10Figure 11 [25]. Mechanical and electromechanical components relevant to the Arm-propelled Robot Project, such as DC motors, switches, and structural elements, were first modeled in SolidWorks. These CAD models were then optimized and prepared for real-time visualization, exported as FBX files, and imported into Unity to create virtual representations compatible with the AR environment.

Once imported, the FBX assets were organized within the Unity scene as individual game objects and positioned relative to a physical reference image to support consistent spatial alignment during AR visualization. The Niantic Lightship SDK, along with AR Foundation, was used to configure spatial tracking and anchoring, allowing the digital components to be accurately overlaid within the user's physical environment. Custom Unity scripts were developed using the *UnityEngine* and *UnityEngine.Events* libraries to manage object placement, scaling, and basic interaction, enabling students to inspect components from multiple viewpoints during sketching and visualization tasks.

This development workflow enabled the augmentation of simplified component geometry within a mobile AR interface and supported the creation of a lightweight user interface tailored for early-stage design activities. After configuration and testing within Unity, the AR application was utilized for developing short AR-based assignments during the lo-fi design phase.

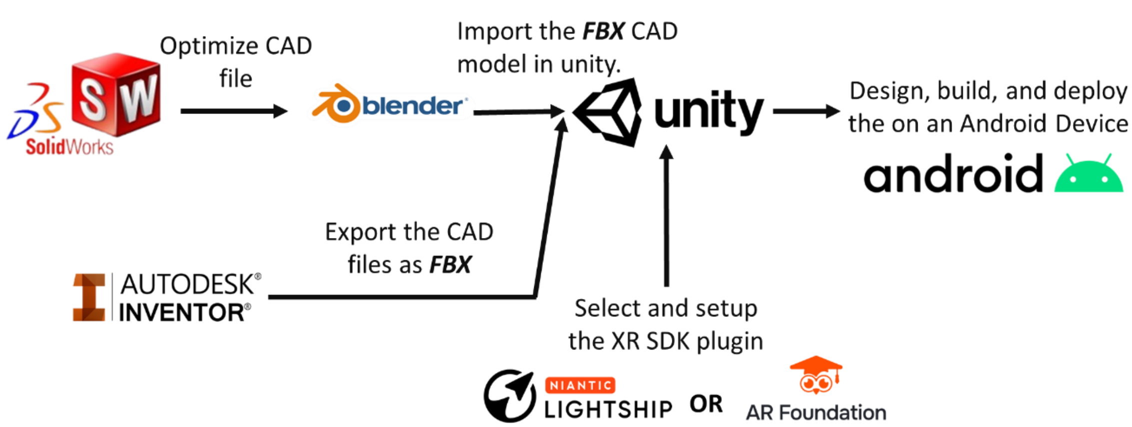


Figure 10. AR application development workflow.

Short AR-Based Sketching Assignments

After developing the AR application, short AR-based assignments have been designed, focusing on visualizing and sketching the mechanical components, i.e., 5V DC motor, toggle switches, LED, and other elements, prior to engaging in detailed CAD modeling. Such assignments require the students to use the custom-developed mobile AR application to view virtual representations of these components overlaid on a physical reference image, without access to the actual components. The developed AR models allow the students to examine each component from multiple viewpoints, including top, front, and side views, while maintaining awareness of relative scale, orientation, and spatial relationships. Figure 11 illustrates an example from one of the AR-based sketching assignments provided to students during the lo-fi stage of the project. The example presents a virtual representation of a 5V DC motor augmented within the student's physical workspace and annotated with explicit orientation cues for top, front, and side views. Embedded sketching guidelines encourage students to approximate the component geometry using basic primitives, such as rectangular prisms, cylinders, and through-holes, while intentionally omitting fine geometric details.

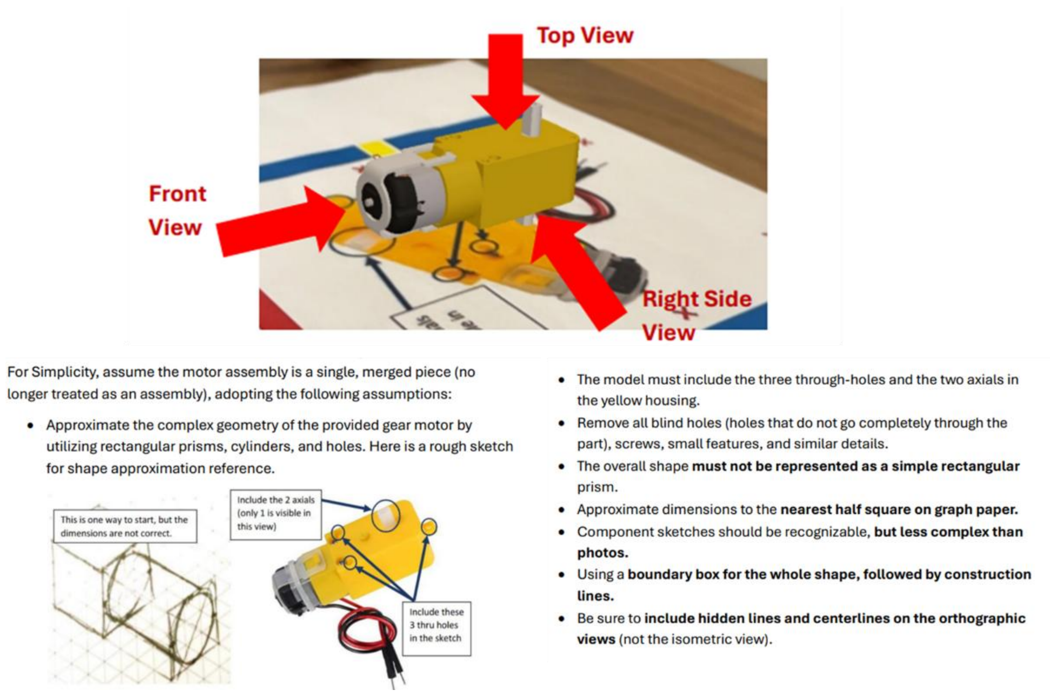


Figure 11. AR-based sketching assignment used during the low-fidelity design stage.

For this activity, students need to augment the virtual motor into their physical space and produce three orthographic sketches followed by a corresponding isometric view. The assignment requires students to rely on spatial reasoning, visual interpretation, and geometric abstraction, skills that are central to effective lo-fi design. Rather than copying geometry from a physical object, students must interpret 3D form through observation and mental reconstruction, mirroring the type of reasoning required during early conceptual design.

This example from the AR-based sketching assignment, like other examples, guides students to approximate the motor geometry using simplified primitives such as rectangular prisms, cylinders, and through-holes, rather than reproducing detailed features. This aligns with the goals of the lo-fi stage, where understanding form, proportion, and functional interfaces is more critical than dimensional accuracy. Students practice decomposing complex components into basic geometric elements, a skill directly transferable to early mechanism layout, motor placement, and enclosure design in the arm-propelled robot project.

The AR-based sketching assignments are intentionally integrated into the lo-fi phase of the project, when students begin sketching linkage mechanisms, exploring motor placement, and defining overall body layouts. Although the assignment did not require immediate incorporation of the sketches into the project deliverables, it served as a preparatory cognitive tool. This represents one of the designed AR-based assignments; additional assignments are currently under development and will be incorporated in the upcoming semester.

5. Preliminary Observations & Students' Reflection

This section presents preliminary observations drawn from informal reflections. Because the integration of AR into the lo-fi stage represents ongoing work, no formal experimental data were collected to quantitatively assess its impact on student performance. This section focuses on descriptive indicators of student engagement, project completion, and early qualitative feedback related to both the overall project and the AR-based activities.

5.1. Design Process Understanding

Throughout the semester, students encountered a range of engineering challenges, particularly during the med- and hi-fi stages. During early physical testing in the med-fi stage, many teams identified issues related to friction, insufficient motor torque, and inefficient walking mechanisms. These challenges often required teams to revisit earlier design decisions, modify linkage geometry, or adjust motor selection. Similarly, during the hi-fi stage, teams experienced issues related to additive manufacturing, including broken components, tolerance mismatches, and the need for reprinting SLS parts. These issues required students to iterate on geometry, revise fastening strategies, and refine assembly approaches.

Rather than viewing these challenges as failures, students took them as part of the design learning process. This perspective was revealed in their final reports and presentations, where teams explicitly discussed how testing outcomes led subsequent redesign decisions. Across teams, students demonstrated an improved understanding that engineering design is non-linear and iterative, with frequent transitions between conceptual design, prototyping, testing, and refinement.

5.2. Preliminary Student Reflections on AR Integration

Although no formal assessment was conducted to evaluate the impact of AR on project outcomes, informal student reflections indicated a positive response to the AR-based sketching activities. Students reported that interacting with the AR application during the lo-fi stage was engaging and enjoyable, particularly during at-home sketching tasks. Several students noted that the ability to view virtual components in their physical space helped them better understand orientation and spatial relationships when producing orthographic and isometric sketches.

Students also described the AR-based assignments as a helpful supplement to traditional sketching instruction, especially during the early stages of the project when they were beginning to explore motor placement, linkage layout, and overall body configuration. From an instructional perspective, the AR activities appeared to lower barriers to early sketching by allowing students to explore component geometry without needing immediate access to physical parts. This was particularly valuable during the lo-fi stage, when abstraction and spatial reasoning are more critical than precision.

5.3. Limitations and Ongoing Work

The preliminary observations presented indicate that AR has the potential to support early-stage design thinking in manufacturing-focused courses; however, they are subject to several limitations. First, the AR integration was implemented on a limited scale and focused on a small number of short assignments. Second, no control group or pre/post assessment was used to measure changes in spatial reasoning, sketch quality, or design performance attributable to AR. Finally, student feedback was collected informally rather than through validated survey instruments.

The authors are currently seeking additional resources to expand the AR activities and explore the integration of MR technologies in future offerings of the course. Given the author’s prior experience with XR technologies in manufacturing education, future work will focus on systematically evaluating the impact of AR and MR on early-stage design learning outcomes using more rigorous assessment methods.

6. Conclusions & Future Work

This paper presented the integration of AR into the early stages of a freshman-level manufacturing design project to support brainstorming, visualization, and lo-fi prototyping. AR was introduced as a cognitive visualization tool during the lo-fi phase of the Arm-propelled Robot Project, complementing existing PBL activities without altering fabrication or testing workflows.

The Arm-propelled Robot Project provided a structured, flexible context that exposed students to the non-linear nature of the engineering design process. Through iterative progression from lo-fi to hi-fi design stages, students engaged with realistic manufacturing constraints, reflected on testing outcomes, and refined their designs accordingly. Preliminary observations from informal feedback indicate that the targeted use of AR during early design stages was well received and supported student engagement and spatial reasoning during sketching and ideation.

Future work will focus on expanding the scope of AR-based assignments and systematically evaluating their impact on student learning outcomes. Planned efforts include developing additional AR activities focused on mechanism layout, component integration, and spatial reasoning, as well as exploring the integration of MR technologies to support collaborative early-stage design. Future course offerings will incorporate formal assessment instruments, such as pre- and post-surveys and rubric-based sketch evaluations, to quantitatively examine the effects of AR and MR on students' understanding of the non-linear design process and their ability to transition from conceptual sketches to manufacturable designs.

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