Scaling Hands-On Learning Principles in Manufacturing through Augmented Reality Disassembly and Inspection of a Consumer Product

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1. Introduction

In recent decades, synergistic advances in materials, automation, and information technology have transformed factories and enabled the globalization of production. As the world's population continues to grow, advanced products use more sophisticated manufacturing processes, and supply chains become more distributed and digitized, manufacturing fundamentals remain critical to increasing numbers of designers and engineers. Manufacturing education is developing digital solutions to scale and meet the growing need. Massive Open Online Courses (MOOCs) on platforms such as edX, Coursera, and Udacity disseminate knowledge at scale to upskill the global lifelong learner, and have reached enrollments of over 100 million [1]-[3]. Online programs such as MicroBachelors, MicroMasters, or the online Masters lead to academia-recognized credentials. Industry-driven training models are also growing to meet the demand for increasing workforce competency. In addition to well-established industry online learning platforms such as ToolingU or NMTA-U, large manufacturing technology firms such as Rockwell Automation and FANUC are collaborating with community colleges to create curriculum on industry-needed technological skills [4]-[5]. Credentialing organizations like NIMS and NOCTI independently assess and award industry-recognized certifications for these skills. These efforts are creating layers of increasingly interconnected, formalized training pathways for the manufacturing learner and worker.

Yet, there are several challenges to scaling manufacturing instruction. Learners must employ highly-developed visual and spatial thinking, yet learning still often relies on two-dimensional boards and screens to render inherently three-dimensional concepts. Engineering courses also often emphasize information and equations, but evidence shows that authentic contexts and hands-on experiences are crucial to effective learning of engineering concepts [6],[7]. Limitations to manufacturing equipment, facilities, geography, and safety considerations also constrain student opportunity to see or perform authentic hands-on activities. COVID-19 further revealed the need for educational tools to enable hybrid models that mix in-person instruction with effective, remote instruction and are flexible under constraints based on public health, scheduling, and facilities.

Instructional activities enhanced by Augmented Reality (AR) provide a compelling opportunity to address these gaps because of AR's inherent three dimensionality, connection to the learner's physical context, scalability, and responsiveness [8]. Unlike Virtual Reality, wherein interactive headsets presently cost hundreds of dollars each, many AR apps are hosted through the ubiquitous smartphone and can therefore increase the feasibility of implementation for a wider range of institutions of higher learning. Further, because of the ever-present physical layer inherent in AR, current research suggests that learning physical concepts through AR requires less suspension of disbelief [9].

Despite growing interest and potential benefits, AR has largely yet to be applied in mainstream engineering education. The majority of funding for developing AR instruction has been invested into pK-12 and earlier AR applications consisted more of location-based AR as opposed to vision-based [9]. In general, mixed reality instruction is a growing research field and the assessment of learning gains has primarily focused on lower-level cognitive skills such as the recall of facts [10].

In this paper we present the pedagogy, iterative design and development, and online course implementation of a vision-based AR app. The app was designed to enable learners to apply their knowledge of manufacturing processes and assembly to analyze and evaluate commercially manufactured products in a scaffolded learning experience. The app presented here focuses on the disassembly and inspection of a low-cost consumer tablet computer. We assess learner reflections through the iterative development of a codebook with the goal of understanding the learning experiences, attitudes, and feedback towards AR-enhanced instructional activities in manufacturing.

2. Pedagogy

The AR-enhanced instruction is modeled after pedagogy developed for 2.008 - Design and Manufacturing II at the Massachusetts Institute of Technology (M.I.T.) using the flipped classroom model [11]. To provide a contextualized and hands-on learning experience, in each weekly class, students are presented with a “Challenge” based on a mass-produced object. The students watch pre-recorded videos that explain the fundamental principles of the associated manufacturing process that is the focus of the week’s Challenge. In class, products are distributed fully-assembled and students inspect, analyze, and/or disassemble them through the Challenge. The activity leads students through a series of guided questions to draft a feasible process plan, evaluate the suitability of different manufacturing processes for the analyzed product, or identify tell-tale visual features to deduce aspects of the manufacturing processes used. Questions also address cross-cutting themes of rate, quality, cost, flexibility, and sustainability. These open-ended activities are designed to mimic the authentic experiences of design and manufacturing engineers.

Two issues face the further development of this type of manufacturing pedagogy. First, manufactured products of pedagogical interest may not be available for learners due to practical issues of availability, size, safety, distance, or costs. For example, it would be difficult or prohibitive to carry out a Challenge activity for windmill turbine blades, a radioactive part in a nuclear reactor, or a Macbook pro. Educational contexts such as COVID-forced distance education or a MOOC also limit or prevent the delivery of physical products to learners. Second, there currently exists no structured way to teach a novice learner expert-level thinking in analysis of a product. A manufacturing expert carries out an extended thought process to evaluate a product. An expert must notice visual features, assess the relevance of features, assign meaning to relevant features, and connect these meanings to deductions of manufacturing assembly and process. Features such as injection gates, machining markings, or a text marking of “ABS” may be relevant to an expert but not a novice. In a flipped classroom, instructors can guide learners in this deduction by pointing out these features or hinting at their relevance in discussion with students engaged in analysis. This interaction is helpful but unstructured and the nature or amount of guidance will vary from instructor to instructor. Further, in a MOOC environment this type of real-time guidance is non-existent. We set out to address product access and guided learning by creating an AR app to disassemble and inspect any manufacturing product in virtual space, and designing scaffolded learning within the structure and functionality of the app.

3. Design and Development

3.1 General Description

The AR app guides the user step-by-step through the disassembly, sub-assembly manipulation and examination of a mass-produced consumer electronics tablet. To begin, the app uses the user’s device camera to recognize a visible marker or “target”, in this case a printout similar to a custom QR code placed on a table or surface. The computer vision engine within the app then calculates in real-time the position and orientation of the target, and superimposes the image of a virtual 3D model of the electronics tablet floating above the target (Figure 1). The 3D model is scaled to an 8.5” x 11” printout of the target, so the objects will appear as life-sized in their physical context--unless the user chooses to use the magnify functionality.

Figure 1. The AR app recognizes the "target" and floats a virtual 3D model on top of the surface. (Pen included for scale.)

The application has three modes: i) Tutorial, ii) Disassembly/Reassembly mode, and iii) Inspection mode.

i) Tutorial: the user enters a practice environment to become familiar with the spatial manipulations (magnify, rotate, and translate) using a simple object (Figure 2). The Tutorial mode is paired with separately-provided instructions that prompts the user to practice these functionalities, and to keep the target fully in the camera view for target recognition.

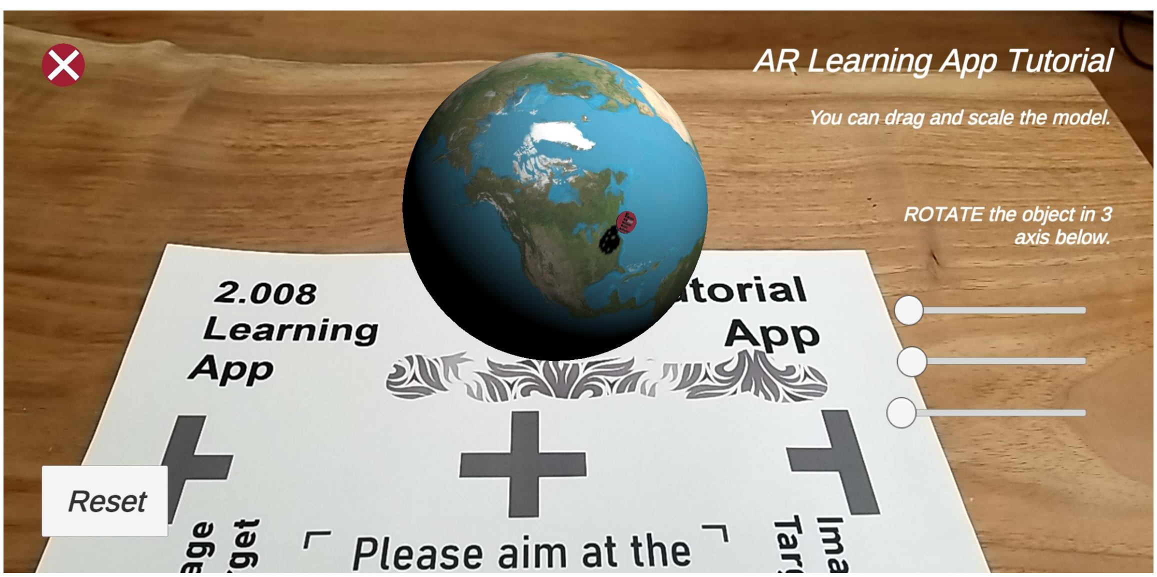

Figure 2. The tutorial gives a user the opportunity to become familiar with basic object manipulations such as magnify, rotate, and translate.

ii) Disassembly/Reassembly mode: the user can disassemble the electronics tablet into six sub-assemblies: front case, LCD screen, internal scaffold, circuit board with speaker, battery, and back case (Figure 3). The order of virtual disassembly is authentic. For example, a user can take out the battery only after the tablet has been opened up, and the sub-assembly of circuit board and battery has first been isolated. Each sub-assembly can be magnified or rotated around one axis to see the back and front.

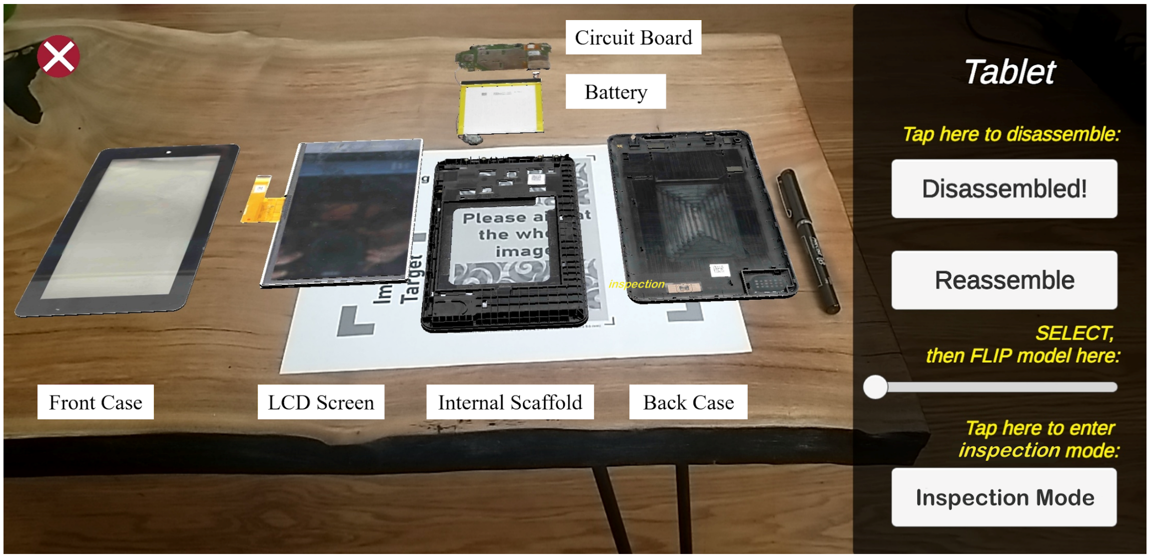

Figure 3. In the Disassembly/Reassembly mode, the electronics tablet can be disassembled into six sub-assemblies: front case, LCD screen, internal scaffold, circuit board with speaker, battery, and back case. (Sub-assembly labels added for reference and pen included for scale.)

iii) Inspection mode: to facilitate closer inspection, the user can isolate each sub-assembly for further examination by selecting the sub-assembly and entering the Inspection mode (Figure 4). The user can toggle on and off a ruler to measure the physical dimensions of the sub-assembly. Each sub-assembly can be magnified or rotated around three axes. The user has the option to turn on visual guides (which appear as yellow boxes in the app), which indicate the locations of relevant information to the product’s material, design, or manufacture. When the user touches the location of one of the yellow boxes on the screen, a pop-up on the right reveals a magnifiable picture of the region and a word hint.

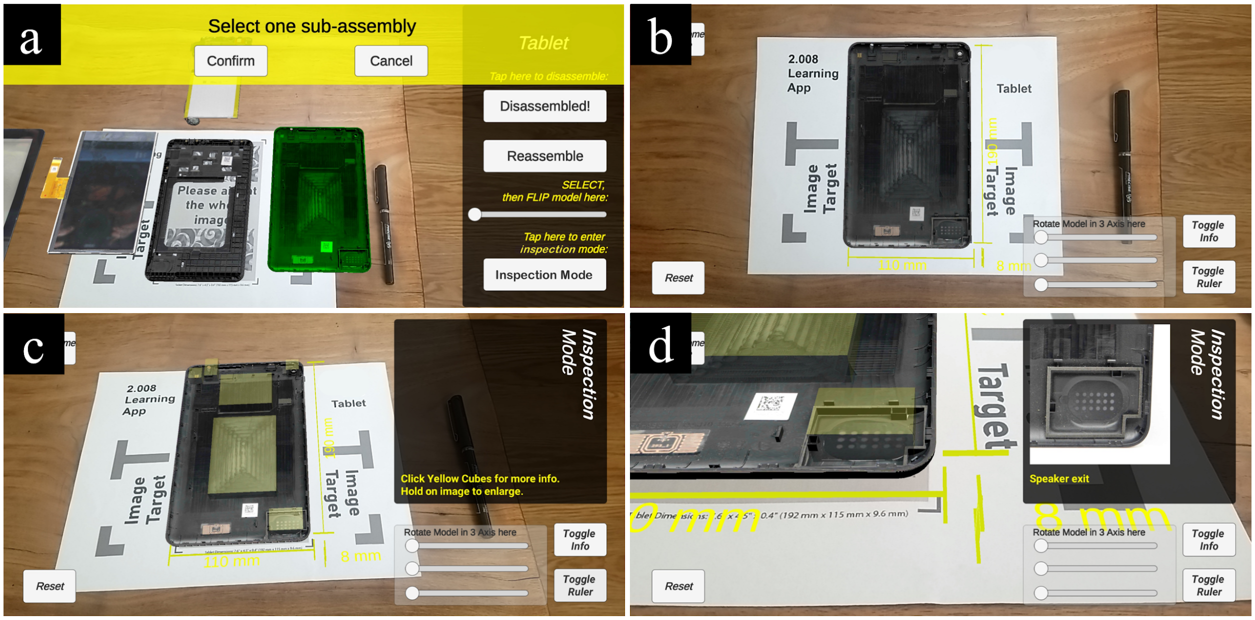

Figure 4. The Inspection mode provides scaffolded learning of manufacturing analysis through examination. Users can a) select one sub-assembly to b) isolate, re-center, and measure the sub-assembly. If the user presses the "Toggle Info" button, a set of yellow highlighted hints appear. d) when pressed, these yellow boxes reveal a magnifiable picture of the region and a word hint. (Pen included for scale.)

3.2 Scaffolding

An expert may analyze a product by 1) noticing visual features, 2) assessing the relevance of features, 3) assigning meaning to relevant features, and 4) connecting these meanings to deductions of manufacturing assembly and process. The app provides scaffolded learning [12] to support the first three stages in the thought process. The yellow visual guides help learners notice the features that are relevant (Stages 1 and 2). If after examining these regions a learner desires additional guidance, the yellow boxes can be pressed to provide an additional photo and text hint to provide physical meaning to the feature (Stage 3).

3.3 Description of UI/UX Design and Software

From the introductory screen, the users first finish the tutorial, and then progress to the tablet app. At any given time after users begin to disassemble the tablet, they can isolate and inspect a sub-assembly (Figure 5).

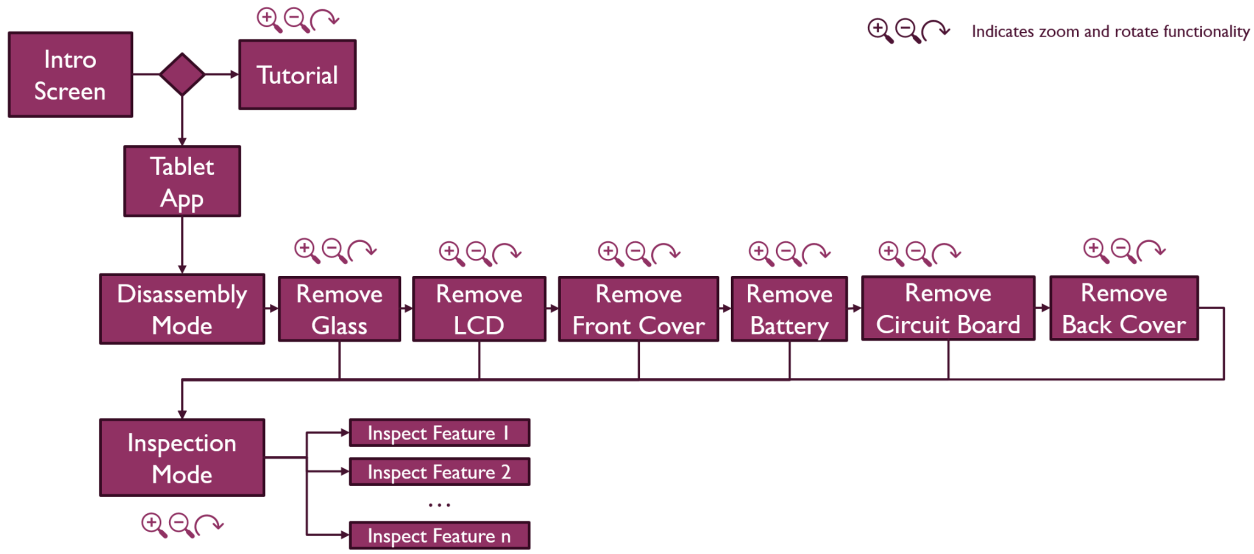

Figure 5. Flowchart of app usage.

We chose to develop the app using two commercial software packages that handle computer vision and provide a 3D software development environment: Vuforia Engine by PTC [13] and Unity [14], respectively. While many technology companies have created their own AR software development kit (SDK) such as ARCore or ARKit [15]-[17], Vuforia Engine is a widely used SDK in the AR community because of its suite of features for AR development, track record of timely and rigorous updates, stability in the market, and compatibility with various devices and operating systems[18].

Unity Engine is a cross-platform game development environment and is the most popular tool for 3D app development for mobile devices because of its compatibility and minimal re-working for different platforms and convenient workflow for user-testing. Compared to other commercial engines, Unity Engine has powerful features for mobile app optimization [19] and is used to develop 3D interactive experiences ranging from games to transportation and manufacturing. The applications made in Unity are object-oriented due to the nature of Unity Engine. All properties and functions were grouped and attached to each one of the 3D models. The UI elements, such as buttons and sliders, trigger the functionality under designated rules.

3.4 High-fidelity 3D Models

Manufacturing processes leave subtle markings and indications on the surface of the finished components. Manufacturing experts can inspect an object and determine what processes were used to make it. Replicating that visual analysis experience in a digital setting requires the creation of high resolution digital reproductions of each part of the subassembly. Optimally the reproduction not only shows visual cues and defects, but also successfully recreates the different surface textures on the object. Our chosen product for the initial AR app, an electronics tablet, has parts with a variety of colors, optical properties, and textures. In particular, smooth and flat, reflective features such as the touchscreen are especially challenging to capture digitally from the physical object.

Our initial method for creating high fidelity scans was 3D scanning (Figure 6a). Scanning can be used to create life-sized 3D models that include realistic colors and textures. However, the scanner we had access to, the Sense 2 from 3D Systems, struggled to retain tracking on the flat surfaces of the tablet components. The resolution produced by the scanner was also lacking. When 3D scanning was unsuccessful, we pivoted to photogrammetry. Photogrammetry has been used successfully to create 3D reconstructions of real world objects for digital applications. However, photogrammetry struggles to successfully create a reconstruction with flat or reflective surfaces. Attempts were made with different photogrammetry packages including Meshroom, COLMAP, and Autodesk ReCap. Yet, all reconstructions produced warped or one dimensional objects with low resolution (Figure 6b). This is due to the photogrammetry software struggling to recognize the very thin sides of the objects in the photosets and failing to correctly determine the 3D shape the object should be in.

a) Unsuccessful 3D scan

b) Unsuccessful photogrammetry attempt

Figure 6. a) 3D scans and b) photogrammetry were explored as methods to produce photorealistic 3D models of tablet components.

After reconstruction attempts with photogrammetry were unsuccessful, the team decided to reproduce the objects in CAD using the most accurate measurements possible. CAD reconstructions of each component were created using SolidWorks CAD software. High resolution images of each object were taken using a high resolution camera and a lightbox. The CAD models were exported to Blender and the high resolution images were overlaid onto the model to produce the finished digital reconstructions. This workflow allowed for the creation of models with accurate dimensions and high resolution surfaces (Figure 7). Surface textures and defects of the objects were not represented in the 3D model but by the 2D photo overlay.

a) SolidWorks CAD Model b) Final model after texture implementation in Blender c) Closeup of Model Details

Figure 7. A comparison between a) a standard CAD drawing of a tablet component, b)the final high-fidelity 3D model used in the app, and c) a close up image of the final model details. Colored box on image b indicates zoom region of image c.

3.5 Iterative Design and App Development

We formed an initial list of app functionalities starting with our observations of how classroom students commonly interact with products in the Challenge: disassembling the product, surveying sub-assemblies, and closely examining specific regions within each sub-assembly. Initial development produced three apps: 1) a tutorial app to teach need users how to use target-based AR, 2) an app to carry out disassembly (each sub-assembly could only be rotated around 2 axes), and 3) an app that only displayed the back case of the tablet with yellow scaffolded hints. The initial apps contained models created using photogrammetry described in Section 3.4.

We conducted user testing of the three apps in January 2020. For user testing, the app was available on Apple iOS through the Apple developer tool called Testflight. Nine test users were recruited from the MIT community, and had a range of comfortability and prior experience with AR applications. Members of the development team were in the room to film the test and observe. The test was conducted in three steps: 1) The tester was given a set of image targets that were used for the app, the instructions, and a Challenge assignment on manufacturing processes, assembly, and cost, all printed on letter sized paper. The testers either brought their own iOS devices or received one with the app pre-installed from the team. 2) The testers followed the instructions to use the app and answered the assignment. 3) An extensive open discussion was conducted right after the testing session.

Feedback from initial user testing gave general consensus that the app could be a positive learning experience after usability and visualization issues were addressed. These issues included loading times, object flickering, text sizing and contrast, touch controls, and object resolution (due to photogrammetry scans). Users confirmed that disassembly and further part inspection were helpful in answering the assignment questions. Feedback also confirmed that the guided hints (Section 3.2) in the Inspection mode would be valuable to help novice learners scaffold their learning.

After the January 2020 test, we developed the full Inspection mode to display close examination and guided hints for all sub-assemblies. The three apps were integrated into one single app and made available on both Android and iOs platforms. We also addressed issues with both the UI/UX design, app performance, and app functionality. Improvements to the UI/UX design were: enlarging the text, changing text fonts and styles, enhancing the user flow so that the app could be self-explanatory, and implementing screen-size adaptation for common mobile devices. The app performance was optimized by: replacing the photogrammetry scans (Section 3.4), upgrading to the newer version of Vuforia Engine and Unity Engine to take advantage of their optimization, enhancing the image targets according to the guidance from Vuforia, and cleaning up and restructuring the code to achieve better performance. Both 3D rotation and magnification of sub-assemblies were introduced into both Disassembly and Inspection mode.

4. Method

4.1 Course Implementation

The AR app was implemented in the Spring 2020 run of Fundamentals of Manufacturing Processes, a MOOC (Massive Open Online Courseware) run on the edX platform. The course is twelve weeks in duration, and the content apportioned to each week covers a particular manufacturing process (e.g., machining, injection molding, casting) or overarching topic (e.g., cost, quality and variation). The course is designed to provide a comprehensive introduction to the principles of manufacturing at scale, in a manner accessible to engineers from many fields related to product development.

Courses on the edX platform can be taken by any edX user anywhere in the world, resulting in highly diverse cohorts. Our data comes from a subsection of 312 learners whose median age was 26; as of their entry to the course, 19% had a high school education or less, 53% had a college degree, and 28% had an advanced degree. These learners were located in 44 countries, with India (30%), US (23%), and Mexico (6%) the top represented. The learners background knowledge of manufacturing ranged from beginners to actively employed manufacturing engineers. This distribution allowed us to see how a diverse range of education levels and backgrounds interacted with the app.

Learners were provided instructions on how to download the app, a tutorial handout, a link to disassembly instructions for the electronics tablet, and offered an alternate set of high resolution pictures of all of the tablet. The app was available on the iOS and Google Play platforms as a free installation to ensure that the app was publicly available and easily accessible. They were then provided with an assignment based on a Challenge consisting of questions on manufacturing assembly and cost of the tablet [Appendix]. Learners were given a week to answer the questions on a platform called CrowdLearn which is designed to facilitate collaborative learning experiences through peer review and grading [20]. The learners then participated in discussion and peer grading over the course of two weeks using CrowdLearn before submitting a reflection at the end of the activity. The reflection prompt was “After participating in the discussion forum, write up a short reflection (50 - 500 words) on what you learned by answering the discussion questions and discussing with your peers. How were your thoughts and ideas about manufacturing costs solidified, pivoted, and/or developed? How was your experience with the AR app?”.

4.2 Analysis

4.2.1 Codebook Development

148 learners wrote reflections. Of this group, 84 learner reflections directly mentioned using the AR app. To perform an analysis of the reflections, we developed a codebook to tag and categorize reflections through an iterative development process [21]. As each of the reflections was at least a paragraph long and included thoughts on the assignment, on the course, and on the AR app, we parsed each reflection into sentences. Sentences and reflections that did not refer to the AR experience were tagged as N/A and were not included in the analysis. The coding system was developed by two of the authors as they reviewed the first 100 reflections together. The coding of the first 20 reflections was done independently with each author developing a coding system. Then the two systems were compared and consolidated into a general hierarchy. The next 20 reflections were then coded independently and compared. This comparison led to a set of rules to govern code use including what distinguished attitudes (general observations) from experience (app-specific observations). Additional tags in the *Attitude* category were created and *Accessibility* and *Visualization* were added as categories. The coders then independently reviewed the 40 reflections that had already been coded for modification and coded the next 40 for comparison. The third round of comparison led to the refinement of rules and definitions.

The final 48 entries were coded separately by two of the authors for the purpose of inter-rater analysis. After the sentences were coded separately, we followed Cohen's kappa method to determine the level of agreement between two raters when agreement due to chance is factored out [22].

4.2.1 Codebook Description

The codebook aimed to capture how learners react and view AR experiences in general (*Attitudes*), how learners felt about our specific app (*Experience*), how the app affected learners visual understanding of the assembly (*Visualization*), if the learners drew conclusions on manufacturing and product design based on their app experience (*Analysis*), any suggestions of improvement on the app or experience (*Feedback*), and any accessibility concerns that learners had (Figure 8).

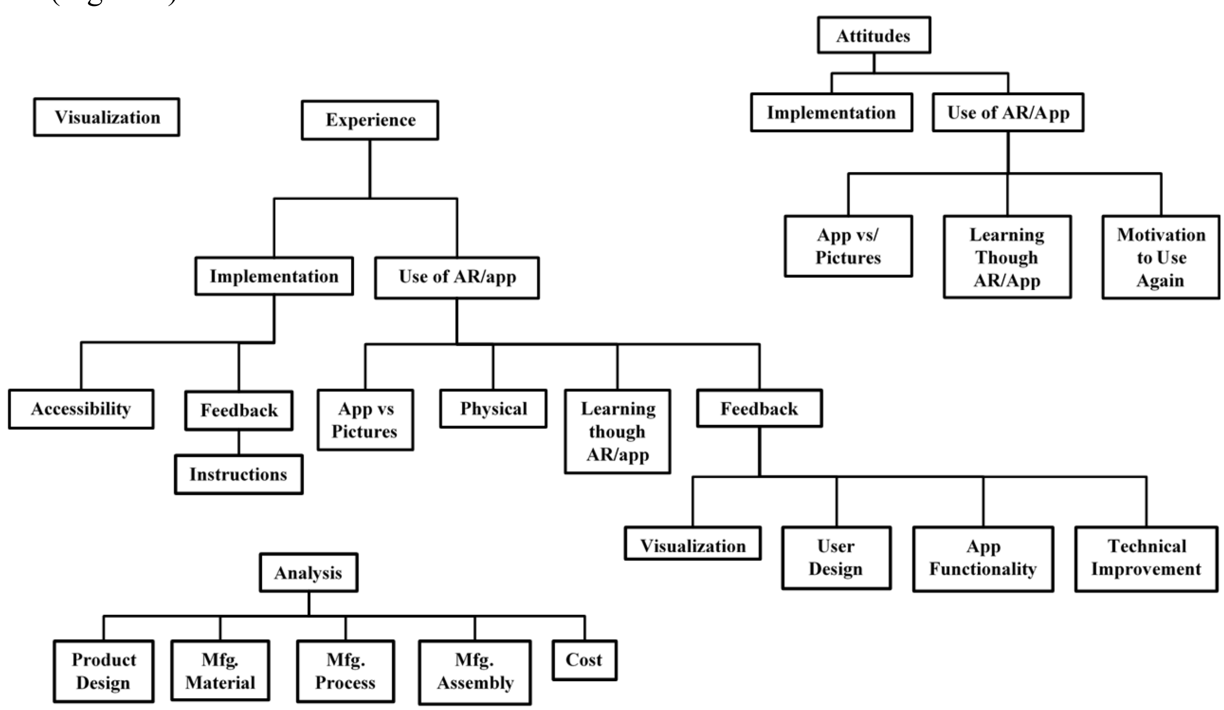

Figure 8. The hierarchy of tags used in coding of statements in learner feedback on the AR app.

Each topic was divided into sub-topics to capture specific areas of interest. The *Attitudes* topic covers general statements that can be applied to AR experiences as a whole rather than our specific app. The *Experience* topic covers statements that are specific to this AR app. When determining if a sentence in the reflections represented *Attitude* or *Experience*, the rule was to default to the specificity of the sentence (i.e. is the sentence and sentence context being specific about the app.) For example, “I really think that the use of technology like this can make the education experience better.” falls under *Attitudes toward Learning Through AR/App* whereas “This application will help learner understand the fine details of object when they do not have the object with them.” falls under *Experience of Learning through AR/App*. To evaluate the overall user attitudes and experience, each user reflection that used an Attitude or Experience tag was coded for the overall tone of the reaction. These were coded at the user level and were coded as positive, positive with caveats, neutral, or negative. *Visualization* was used for items found purely through observation while *Analysis* covered sentences indicating an understanding of the physical properties or engineering design of the object. Terms such as “surface roughness” were evaluated in the surrounding context to determine if the term was being used in a technical nature and qualified as *Analysis*. If not, they were marked as *Visualization*. Descriptive terms used by learners that were given in the assignment itself were not considered the result of a learner’s engineering analysis.

5. Results and Discussion

5.1 Learner Reflections

Overall, 72% percent of learner reflections were “positive” or “neutral” about the app experience covering topics like increased visual understanding or assembly process understanding. These tended to be either short praise of the app or abstract ideas about learning improvements. 28% were negative and tended to be direct feedback related to app design and functionality or the learners preference for other learning methods.

Learner feedback, as measured through the number of tags, was related to *Experience* (57%, 274/478 tags), then *Attitudes towards AR* (18%, 85/478), *Feedback* (13%, 64/478), *Engineering Analysis* (8%, 37/478), *Visualization* (2%, 8/478) and finally *Accessibility* (2%, 10/478). The number of tags by topic and subtopic is given in Table 1.

Topic	Subtopic	Overall Number of Tags	Inter-rater
Attitudes towards AR	Overall tone by user	33	100.00%
	Implementation of app	3	N/A
	Use of AR/app	40	70.82%
	App vs. Pictures	11	83.24%
	Learning through AR/app	13	49.50%
	Motivation to use in the future	18	77.96%
Experience	Overall tone by user	84	44.44%
	Implementation of app	23	70.19%
	Use of AR/app	157	68.09%
	App vs pictures/CAD	23	73.67%
	Learning through AR/app	66	63.54%
	Physical	5	100.00%

Visualization	Object features	8	48.48%
Analysis	Product Design	10	90.22%
	Mfg material	0	N/A
	Mfg process	7	49.00%
	Mfg assembly	18	88.02%
	Cost	2	N/A
Feedback	Instructions	5	100.00%
	Visualization	19	86.83%
	User design	12	100.00%
	App functionality	17	70.10%
	Technical improvement	11	86.07%
Accessibility		10	79.36%
OVERALL		595	85.48%

Table 1. Topics and sub-topics with number of tags and inter-rater.

5.1.1 User Experience

57% of all tags were related to the users experience specifically using this app and 84 of 148 users used the tag. Of these tags, 24% (117/478) were *Use of AR/app*. This category overlapped with multiple other tags (Figure 8) and those sentences will be analyzed in the context of the other tags. When all the *Experience* feedback was analyzed for user tone, 55% (46/84) of users indicated that they had a positive experience, 15% (13/84) had a positive experience with caveats (i.e. "it was a good experience but…"), 11% (9/84) were neutral statements, and 19% (16/84) were negative experiences.

During the analysis, we found that learners often directly compared using the app and using the static pictures they were given. Learners expressed opinions like "The visualization of all the features of the assembly was much more clear than inspection the plain images." or "AR app was really cumbersome to use, and I found static images much more useful.". This feedback was captured in the *Experience of App vs. Pictures* tag which was used 23 times. 8 tags expressed a preference for images, 8 tags expressed a preference for the AR app, and 7 tags expressed a preference for either method or other alternative methods (desktop apps or other). Future interviews and A/B tests may further elucidate the personal and technical factors that influence a learner's preference towards AR.

Experience of Learning through the App was used as a tag 66 times. 69.7% (46/66) of the tags expressed positive learning benefits from the app. One learner expressed "The instructions were simple for a novice like me to get started and most importantly it gave an in-depth understanding of various sub-assemblies and their connections." Another stated "Regarding the AR app, I consider that it was quite useful because it makes me understand better all the internal features, thanks to that, I could do a complete discussion about the majority of internal features of the back and front case." 13.6% (9/66) of the sentences expressed positive benefits with caveats like "I love the concept, but it took some getting used to in order to successfully accomplish the challenge." 4.5% of these tags (3/66) expressed a negative experience with the app. 12% (8/66) tags expressed that they felt the AR was simply unnecessary for their learning.

5.1.2 Feedback for Improvement

Reviewing the Feedback tags led to the following major actionable pieces of feedback.

- *Visualization* feedback was good for items, but assembly details need to be improved.
- Devices with small screens negatively impacted the experience both with visualization and small buttons being hard to interact with.
- The tutorial could be improved to demonstrate zoom and rotation controls more clearly and the app controls overall could be improved to be more responsive.
- The ergonomics of holding the phone or tablet to maintain object tracking, controlling the app, and writing down notes was difficult for learners.
- There were bugs associated with the iOS phones that need to be troubleshooted before further implementation.

5.1.3 Learner Attitudes toward AR

18% of all tags were related to the users attitude towards the concept and use of AR activities. Learners generally expressed positive attitudes towards AR technology and its use in educational contexts. Of the 33 users reflections that were tagged in the *Attitudes* category, 79% were positive, 18% were negative, and 3% were neutral. Learners who expressed positive attitudes cited the novelty of the experience or enhanced visualization, with one learner remarking "A picture can say a thousand words but an AR app can say probably a million words!" Of particular note, the positive attitudes of a number of learners was grounded in excited projections of using the "interesting and upcoming technology" of AR in their own future work contexts: "I personally believe it's the future of CAD and QA/QC". Said another, "But you can use it to augment the capabilities of operators and maintenance workers by providing realistic instructions and remote troubleshooting capabilities directly on site and from a very remote location." Negative attitudes expressed towards AR often shared perceptions that the information conveyed was comparable but was inferior in practical matters: the requirement for another device, the additional time required to install, or inconvenience compared to browser-based pictures. We saw little or no commentary that AR was inferior from the perspective of interaction, learning, or visualization.

5.1.4 Engineering Analysis

Reflections showed learners connecting the AR activity directly with concepts and thought processes necessary in engineering analysis, primarily in the areas of product design, manufacturing processes, and assembly. Some learners commented that the AR application gave them the opportunity to see parts, features, and components of the tablet or appreciate the complexity of the product. One commented that the AR activity put a "twist on the design process". Other learners were able to identify features specific to a manufacturing process: "Even tiny details as injection molding gate were clearly visible and identifiable!" Most learners who reflected on engineering analysis, discussed the experience as helpful to their understanding of manufacturing assembly: how the individual parts come together to form the product, how one would build the tablet, or connections between components: "The AR app has been very helpful as a very practical tool in visualising what a product is and how how maybe it could be built or assembled." One commented that the app did "eventually aid in determining the necessary process stations and the number of workers that are necessary."

These comments reveal that learners are using the AR app to engage with higher modes of cognitive engagement such as apply, analyze, and evaluate. A reflection activity or survey composed of specific questions may reveal a more representative picture of how this AR-enhanced activity impacts learning engineering analysis.

5.1.5 Other

Accessibility was represented by 2% of the tags; while this is a small fraction, this topic is important to be addressed. Concerns were focused on the technology accessibility; some learners did not have a printer to print out the target or a device capable of running the AR app. These issues of accessibility may be economic in nature and could remain an issue for a portion of the MOOC population whereas in a residential course it is easier to distribute needed equipment to learners. Therefore, in MOOCs alternative materials such as high resolution pictures must always be offered as an alternative to app use.

5.2 Inter-rater Reliability

The measurement of overall agreement (Cohen's kappa) between two independent raters is 83.1%, demonstrating strong reliability of the coding scheme (Table 1). Cohen's kappa was strong for most sub-topics, but sub-topics that were tagged three times or less yielded less consistent agreement. Also, three sub-topics did not include any sentences in the portion of the data set used for inter-rater analysis. We therefore could not calculate an inter-rater for these sub-topics and have marked them as "N/A" in the *Inter-rater* column of Table 1.

6. Conclusion and Future Work

AR-augmented instruction is a cost-effective and promising approach that makes time- and resource-constrained hands-on activities accessible through virtualization. We presented the design and development of an app where users can learn about manufacturing processes through disassembling and examining a consumer electronics tablet. The app scaffolds the learning of key stages in an expert-like analysis: the noticing of manufacturing features, and assigning relevance and meaning to these features. Initial app development took time, but initial development hurdles have paved the way for an easier development process in the future. MOOC learner feedback indicates that the AR-enhanced activity was well-received overall with 70% (59/84) of users indicating an overall positive experience using the app. Some learners perceived improvement to learning through enriched visualization, directed disassembly, and scaffolded hints. Reflections confirmed that learners not only recalled or described manufacturing concepts introduced in the course, but were engaged with higher levels of cognitive engagement such as interpreting visual artifacts and evaluating the product design, manufacturing processes, and assembly of the tablet. The codebook was developed to organize learner reflections and resulted in a high overall inter-rater reliability of 85.48% between two independent raters. We presented the app's implementation in a MOOC context but the app could also be used for in-person learning when there is a large number of students and limited funds to purchase tablets for hands-on disassembly.

Ongoing and future work entails further developing scaffolded learning within the app, open-ended disassembly of products, introducing additional products and high-detail single components into the app, refinement of the app design based on learner feedback, and developing and disseminating a post-activity reflection and survey that includes greater specificity and guidance. We will carry out A/B testing to compare learning outcomes and attitudes when students use static pictures versus AR. We are also interested in developing the app to analyze learner actions to study how novices learn manufacturing analysis for the purpose of deriving learning strategies and AR education design principles.

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8. Appendix

Manufacturing Cost Assignment

1. Examine the front and back case, and also the ProtoMold quotes for both molds [links removed]. Discuss how the complexity of the internal features and surface finishes would influence the mold cost.

2. Observe the six major sub-assemblies of the tablet.

- Which connections (physical, electrical, audio) between the sub-assemblies did you observe?
- Write out a flowchart indicating how you would configure an assembly line for the tablet, assuming these are the only six sub-assemblies. How many distinct assembly steps does this require?

3. According to the process that you outlined in Question 2, calculate the total manufacturing cost (material + assembly cost) for producing 1,200,000 tablets in one year. **State any assumptions you make to complete these calculations.**

Assume the following, and state any additional assumptions:

- Assembly time: 15 seconds per operation
- Cost of an assembly station (assume each worker has a dedicated assembly station, and each assembly station only performs one operation): $500
- Hourly cost of a worker: $60/hr (inclusive of wages, benefits, taxes, etc.)
- Facility overhead: $100/day
- Unit cost of other subassemblies at stated volume:
    - Case cost (front / back): $1.90
    - Front glass: $1.53
    - LCD touch screen: $3.00
    - PCB + speaker: $1.00
    - Battery: $2.47