Facilitating the Communication of Rework Information to Craft Workers Using an Augmented Reality Process

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Abstract

Pipe spool fabrication is still highly dependent on skilled craft labour and thus is subjected to the productivity issues, such as rework, that plague the construction industry. Rework is a major challenge and is estimated to account for up to 12% of the total cost of a major project. Identifying geometric non-conformance that requires rework is done by pipe fitters and inspectors and its impact is commensurate with the stage in the assembly process at which the non-conformance is detected. Thus, improving the frequency and effectiveness of this process can reduce rework and help mitigate its impact. It is proposed to replace the traditional process with an augmented reality process, where a 3D as-built point cloud can be superimposed on the 3D BIM model of the design, facilitating the communication of rework information. An experiment was conducted to compare the time required to convey rework information using an augmented reality feedback process compared to a traditional feedback system. Participants were given a PVC pipe spool to assemble with either the augmented reality process or with a two-sided isometric drawing. The time spent conveying the rework and the iterations of rework that were completed in each instance were evaluated to compare how the use of visualization technology affects the communication of rework.

Keywords –

Rework; Pipe fitting; Augmented Reality; point cloud; 3D BIM; modular

1 Introduction

Modular construction has become an increasingly popular means of construction as it allows for greater automation and allows for more work to be completed in a controlled fabrication shop environment as opposed to on a construction site. Shifting construction from an exterior activity where it is impacted by the elements to an interior activity has helped reduce rework. Currently, rework is believed to account for 6 to 12% of the cost of a typical construction project [1]–[3]. However, not every task can be automated. This is particularly true for the piping industry, leaving it susceptible to project delays and cost overruns caused by rework.

The focus of this work is on piping elements, since they can account for up to 50% of the total cost of an industrial construction project and of module fabrication [4]. This is largely due to the nature of piping work and its dependence on skilled craft workers, as most components in a piping project are custom-made based on the design, by cutting and welding sections of pipe, elbows, reducers and tees. The raw materials coupled with the extensive hands-on time from craft workers makes piping portions of projects costly to complete and critical with respect to the project schedule. Additionally, current quality control methods for piping are time consuming, requiring use of conventional measuring tools and utilize traditional paper based drawings to convey information. This method is inefficient, as it is not conducive to the sharing of information regarding an assembly's fit for use amongst project stakeholders [5]. While this study is focusing on pipe elements, the general concept could be applied to other construction project components.

Craft workers conduct routine checks as they assemble to verify their progress thus far. The technology traditionally used to complete this work consists of hand tools tailored to measure the geometry of the pipe assembly. These include callipers, measuring tapes and spirit levels. Following the completion of an assembly, quality control personnel complete a final check before the assembly is deemed complete. Should an instance of non-conformance requiring rework be detected, the quality control personnel must take note of the issues and explain them to the craft worker. The craft worker will be responsible for remedying the situation through interpreting the information presented by the quality control person and comparing it with the design information presented on the isometric drawing. The work proposed in this study would facilitate the self-checking during the assembly process by the craft workers by providing them with quick visual feedback regarding their work in addition to assisting quality control personnel with conveying information to craft workers.

In a traditional industrial project, pipe fitters are given isometric drawings containing all the information pertaining to the assembly they are fabricating. These drawings represent the pipes as a single straight line using a 45°, 90°, 45° projection system [6]. These drawings provide information about assembly geometry, welds and components such as elbows and flanges. Isometric drawings can be hard to interpret depending on the geometric complexity of the assembly and the worker's experience and level of comfort with the drawing format. Studies have found that using a two-sided isometric drawing, one which contains a traditional isometric drawing on one side and then a two dimensional (2D) projected rendering of a three dimensional (3D) model increases productivity by making the design easier to interpret [4]. Studies have also shown that providing a worker with a 3D model has a similar effect [6], [7]. With the technology used to acquire 3D spatial data becoming increasingly more affordable, and the ubiquity of 3D models for construction projects, it is now possible to show craft workers the rework that needs to be completed by overlaying the 3D as-built scan over the 3D design model, simplifying the process of conveying this information.

2 Literature Review

2.1 Rework

Rework is responsible for losses of both resources and time in the construction industry and is a major contributor to projects being completed behind schedule and over budget. In an industrial project, measured rework is believed to be approximately 2.4% of the contract value, representing millions of dollars in losses [8]. Normal process iteration is not considered part of rework. In general, minimizing rework and its impact on a project's ability to meet its budget and schedule is viewed as the key in improving construction productivity [9].

It has been found that craft workers believe that 32% of their negative productivity is caused by the insufficient quality of the information they are provided, and this insufficient quality of information was deemed to contribute to reduced morale within the group of workers [10].

In addition to the direct costs of rework in construction, which may total up to 25% of the contract value, rework has an impact valued at 3 to 6 times its direct cost given the impact it has on workers and the decreased site moral experienced when workers are asked to redo work that was previously completed [11].

2.2 Augmented Reality

In recent years, enhanced digital reality has become increasingly prevalent as technological advances allow for higher quality digital environments at lower price points. There are two areas of enhanced digital reality: virtual reality and augmented reality. Virtual reality consists of an immersive environment while augmented reality is an enhancement of the existing surroundings by overlaying digital information [7]. Augmented reality is preferable to virtual reality for applications in the construction industry as it does not inhibit a user's awareness of their physical environment in the way that virtual reality does, making it a safer option for hazardous construction sites.

2.3 Information Formats

A number of studies have been conducted showing the impact of different information formats on the productivity and quality of work performed by craft workers.

In 2015, Hou et all [7] focused on improving productivity and performance through lowering the cognitive load experienced by craft workers using augmented reality. The study was executed on graduate students in construction, computer science, architecture and engineering. Students were tasked with assembling a PVC pipe system. Half of the students were given a 2D isometric drawing while the other were given a 3D model on a TV display. The model could be rotated by moving a hand-held remote sensor in the direction they wanted to move the model. This study found that the use of 3D models reduced the cognitive load experienced by the participants and reduced the time required to complete the assembly by 50%

In 2016, Goodrum et al [4] completed a study in which 54 pipe fitters were given different formats of information to assemble a pipe assembly. One group was given a traditional 2D isometric drawing. The second group was given a two-sided isometric drawing, which consists of a 2D isometric drawing with a 2D projection of the corresponding 3D model on the back. The third group was given a 2D drawing with a 3D printed model of the assembly. The latter two groups both benefitted from the additional information; however, the second group, the one with the two-sided isometric drawing, was the fasted group. The results of this study were the main motivation behind providing the participants who did not use the augmented reality application with a two-sided isometric instead of a standard isometric drawing in the current study as two-sided isometrics are now an industry best-practice.

In 2014, Dadi et al [6], recruited 26 individuals, both engineering professionals and craft workers to assemble a 3D structure. The individuals were separated into three groups and each group was given the design in a different format. One group had a 2D set of drawings, the second a 3D computer model of the assembly and the third had a 3D printed model of the assembly. The study found that 3D printed models increased direct work and lowered the required mental work load more than 3D computer models and 2D drawings.

While studies focused on the impact of information formats on a craft worker's ability to complete an assembly have been completed, this study will instead focus on how the information format affects a craft worker's ability to identify and correct errors in their own work.

2.4 3D BIM

The increased prevalence of 3D Building Information Modeling (BIM) over the last two decades is a major contributor to the feasibility of the process being investigated in this work, as the process is contingent on having access to accurate, updated 3D models. Utilizing BIM offers many benefits to project stakeholders. Projects that utilize BIM are able to achieve increases in productivity of up to 30% while reducing the Requests for Information and Change Orders by a factor of 10 [12]. With design errors and omissions having the highest impact on the project cost for industrial projects, adopting 3D models to better integrate the different aspects of the design can help reduce the cost of a major industrial project [13]. Project managers believe that 3D modeling is a worthwhile investment and, specifically for the piping industry, that failing to create a model will increase the cost of piping project by 10% [14].

2.5 3D Spatial Data Acquisition

The use of laser scanners to acquire 3D spatial data is well established in construction management [15]. Laser scanners have been used for automated progress tracking [16], [17] and for compliance checking of fabricated elements [18], [19].

While laser scanners are able to provide highly accurate and broad range data, the data requires processing to be used, often requiring that multiple scans be stitched together, making it difficult to incorporate the technology into real time processes. For this reason, portable structured light scanners present a unique opportunity to acquire 3D spatial data that does not require processing and can thus be used in real time. For this reason, a structured light scanner is being utilized in this work.

2.6 Research Motivation

In countries with high labour costs, it is imperative to incorporate new technologies to maximize productivity. With the strict tolerances provided on most projects and the lack of skilled labour in countries like Canada and the United States [20], finding the means to minimize the impact of rework once it is encountered on a project is critical.

While work has been done to assess the impact of rework on a project's schedule and budge, and studies have been competed to determine how the format used to convey design information impacts productivity, there has been no work done in assessing how the communication of rework helps reduce the impact of rework on a construction project.

3 Methodology

As part of a larger study being conducted by the University of Waterloo and Aecon Industrial West, an application was developed with the aim of increasing productivity and reducing rework in pipe spool assembly through the use of augmented reality. This same application was utilized to assess how using an augmented reality process assists quality control personnel in conveying information pertaining to rework that must be completed on an assembly to the craft worker creating the assembly.

3.1 Participants

Currently, the recruited participants are all engineering students. Participants were split into two groups, with one completing the experiment with a two-sided isometric drawing and having corrections verbally conveyed. The other group utilized the augmented reality process to complete the assembly and were actively involved in the quality control, utilizing the augmented reality process to obtain feedback on their work. As such, a total of 2 groups of participants were utilized in the experiment: engineers with drawings and engineers with the application.

A total of 30 students were used, 15 in each subcategory. There are plans in place to recruit craft workers to further this study and this effort is currently in the coordination stage.

3.2 Experiment Assembly

It was deemed infeasible from a financial, logistical and safety perspective to conduct the experiment using a welded metal pipe assembly as would be the normal use scenario for the augmented reality process once it is deployed. Thus, a spool utilizing 1.5" diameter black PVC pipes was designed for this experiment. To help simulate the act of tack welding, the team purchased flexible couplings shown in Figure 2. The connections require the participant to use a screwdriver to tighten the metal connector. This penalizes a participant for creating an incorrect assembly since the connection must be loosened, the components moved and then the connection reconnected.

The nature of these socket-based connections prevents some of the challenges pipe fitters typically experience in assembling components to be flush with one another. This prompted the design of a spool with a more challenging geometry than normally experienced in an industrial piping project to help create an assembly that requires the level of planning and attention to detail that assembling a proper metal pipe spool would require. This design was then shown to an engineer at Aecon Inc. who said that while the spool was more complicated than a typical spool assembly seen in their shop, it was not an unreasonable design.

The two-sided isometric drawing that was given to participants to convey design information is shown in Figure 1.

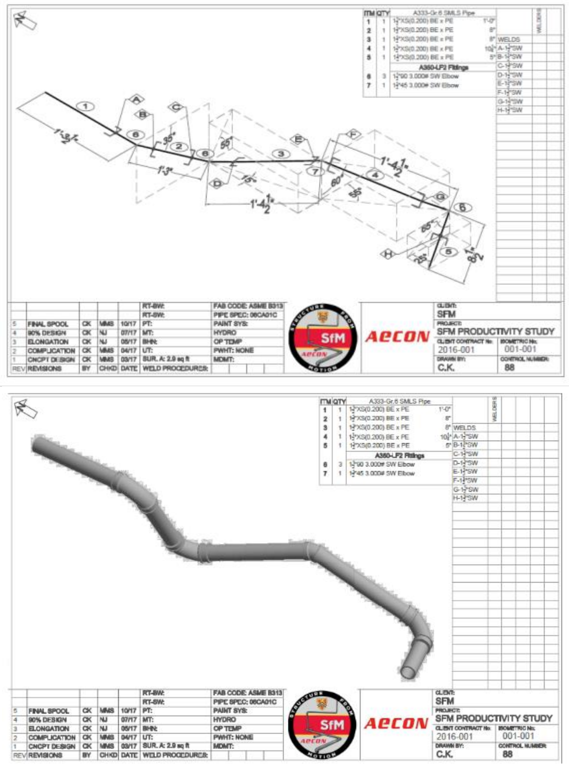

Figure 1. Both sides of the two-sided iso used in the experiment

Figure 2. Flexible elbow coupling used to simulate socket welds

3.3 Experiment Process

The participants were divided into two groups: one group working with a standard two sided isometric drawing and the other group working with the augmented reality process. Both groups were instructed to complete the same assembly. Figure 3 shows the set-up participants who used the augmented reality process were given to begin the experiment.

Figure 3. Initial set up of experiment

Figure 4. Structure IO, structured light scanner used for experiment mounted on an iPad

The workflow associated with both iterations of the experiment is shown in Figure 5. The steps enclosed in the red boxes are the main focus of this work. Both groups were given the same two-sided isometric drawing and assembled the same PVC pipe spool, however, the augmented reality group had rework identified by showing errors through overlaying a scan of the as-built assembly over the 3D design model while the group working with only the two-sided isometric drawing had their rework identified without the aid of the visual contrast comparing their erroneous assembly with the design model.

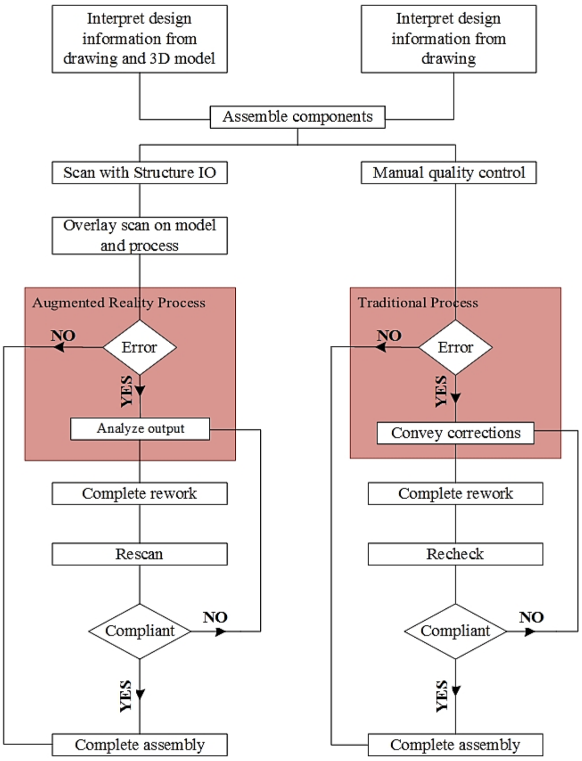

Figure 5. The workflows associate with both iterations of the experiment

Both groups were given the same traditional measuring tools and the same two-sided isometric drawing. In addition to the resources given to the participants who had information presented on only a static drawing, the participants using the augmented reality process had access to the 3D design model during the assembly process and were able to use a structured light scanner shown in Figure 4 to scan the assembly as they build it. This scanner is accurate up to 0.5 millimetres (mm) depending on how close the scanner is to the object being scanned [21]. A tolerance of 5 mm was set as the threshold for acceptance through multiple trials of scanning prefabricated components and comparing the scans to their actual dimensions. These participants were able to overlay the assembly, as they completed it, on the 3D design model to verify that what they had completed to that point was correct. These participants were also actively involved in the quality control process as they were the ones scanning the assembly, overlaying it on the model and doing the processing required to check if their assembly was compliant.

For participants using the static drawing, required rework was articulated and gestured to the participant by the experiment administrator who completed the quality control on the assembly.

3.4 Participant Assessment

Participants were administered two spatial cognition tests: a Card Rotation Test and a Cube Rotation Test created by Educational Testing Service (ETS) in 1976 [22]. This was done primarily to ensure that participants with higher spatial cognitive skills were not all grouped into the same category and inflating the results by comparing a group with higher spatial cognition against a group with lower spatial cognition. Participants were then grouped into 3 groups: having either low, medium or high spatial cognition. The groupings were determined by averaging the scores of the two tests. A fairly even distribution of scores was found across all the participant groups as is shown in Table 1.

Table 1. Distribution of spatial scores of participants

Score	App Participants	Drawing Participants
High (0.8-1.0)	3	3
Med. (0.6-0.79)	6	4
Low (0-0.59)	6	6

3.5 Data Analysis

Participants were filmed while assembling the pipe spool. The videos were watched and segmented into activities and durations to assess the participants' progress during the experiment. Figure 6 illustrates the average time spent on each activity for experiment participants who only had the drawing. Figure 7 shows the average time sent on each activity for participants who used the app.

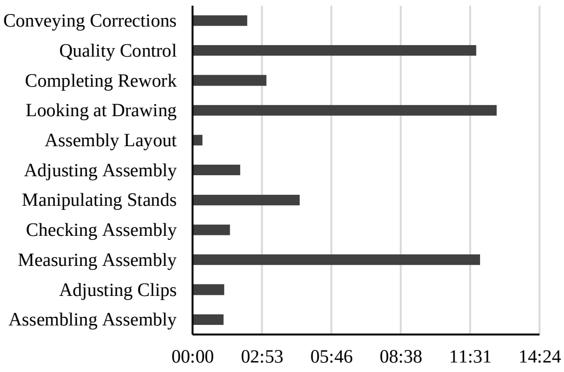

Figure 6. Average time spent on each activity for experiment participants using only the drawing

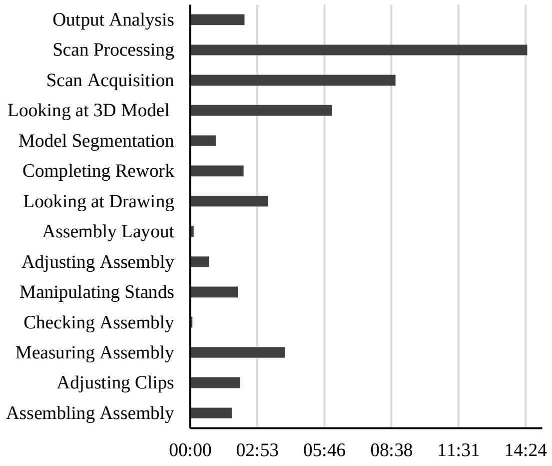

Figure 7. Average time spent on each activity for experiment participants using the app

In evaluating the videos, emphasis was placed primarily on tracking the activities of conveying the rework to be done and completing rework. Conveying rework was deemed to be any time where the administrator explained to the participant how their assembly failed to meet the required specifications in the case of participants using a traditional assembly and the time the participant spent assessing their own mistakes based on the overlay of the as built scan on the 3D model for a participant using the application. In both cases completing rework was deemed to be any time where the participants were modifying components that failed to meet the required specifications.

For both activities the time and cycle count were tracked. In the case of conveying rework, cycle count referred to the number of cycles of feedback that were completed. In the case of completing rework, cycle count considered the total number of times a participant modified an assembly component based on the feedback they were given regarding the work that had been completed thus far.

4 Results

The participant categories were divided into three clusters based on spatial cognition: low, medium and high spatial cognition as shown in Table 1 to compare how using the augmented reality application to convey rework affected participants of varying levels of spatial cognition. A total of 30 trials were run on engineers, 15 using the augmented reality process and 15 using the traditional drawing. Two participants had to be remove from the data pool that used the drawing as those two did not have any rework associated with their trials.

4.1 Conveying Rework

The times that were spent conveying the errors to the participants were totaled. An average of 2:26 was spent conveying corrections to participants with traditional formats while an average of 1:50 was spent conveying corrections to participants with the augmented reality process, a 25% reduction in the time required. Table 2 shows a summary of the time spent conveying corrections to the three groups. The use of the augmented reality process seemed to have the biggest impact on participants who fell into the medium spatial skills category. A number of the participants who fell in the low spatial skills category were unable to complete the assembly and eventually gave up, meaning that the times spent conveying corrections to them are lower than they should be as they do not represent the total time required.

Table 2. Average times spent conveying rework to participants based on spatial skill groups

Cognition Score	App Participants	Drawing Participants
High (0.8-1.0)	2:01	2:14
Med. (0.6-0.79)	1:47	3:07
Low (0-0.59)	1:33	1:54

4.2 Completing Rework

The time spent by participants completing rework was computed. The average time spent by participants using only the drawing and traditional quality control practices was 4:21 compared to 2:09 for participants who used the augmented reality process to assess their correctness. Using the technology led to a 50% decrease in time spent completing rework. Table 3 presents a summary of the time taken by each spatial group to complete the rework required for their assembly.

Table 3. A summary of the time taken to complete rework by both groups of participants

Cognition Score	App Participants	Drawing Participants
High (0.8-1.0)	1:27	4:30
Med. (0.6-0.79)	1:17	4:33
Low (0-0.59)	3:21	3:58

The number of rework cycles completed by each participant was also totaled. It was found that the average person using the augmented reality application had 11.73 cycles of rework while the average person using the drawing had 18.77 cycles of rework, a decrease of 37% when the augmented reality process was used. Table 4 presents a summary of the number of rework cycles by each group.

Table 4. Average number of rework cycles by both groups of participants

Cognition Score	App Participants	Drawing Participants
High (0.8-1.0)	10	13
Med. (0.6-0.79)	7.33	15.25
Low (0-0.59)	17	24

5 Conclusions and Discussion

It was found that using the augmented reality process reduced the time required to convey the required rework to participants by 25% and that it reduced the time they required to complete the rework by 50% with a 37% reduction in the number of rework cycles needed.

The data samples collected thus far were all using engineers, many of whom lacked experience working with hand tools and assembling products based on drawings. While their spatial skills and ability to interpret information was a factor in their work, the rework cycles could have likely been reduced if the participants were more experienced with working with the hand tools they were presented.

Somewhat surprisingly, the augmented reality process seemed to have the greatest impact on the group with medium spatial skills. From a qualitative assessment of the participants, the reason appears to be that the medium spatial skills participants were more likely to confuse themselves. They were fairly confident in their own interpretation of the information and were noticeably flustered when presented with information that did not align with their expectations. Participants with low spatial skills were more likely to accept what the experiment administrator told them at face value and didn’t question the rework they were told to complete. The augmented reality process had the lowest impact on participants who had high spatial skills, likely because most of the rework these participants had was linked to their ability to perform the tasks of assembling and measuring the assembly, that is their ability to complete craft work, and was not as dependent on their ability to have the general correct assembly shape.

5.1 Participant Habits

It was observed that participants who had access to the augmented reality app utilized the app as a measuring tool in favor of actually measuring. It appears that participants realized that they would be able to verify the assembly with the application quicker than they would be able to actually perform the measurements with traditional measuring tools.

Participants with the application also appeared more comfortable checking assemblies they were less confident in. Participants with the drawing were more inclined to spend time checking the assembly before telling the experiment administrator that it was complete, whereas participants using the application were more likely to check it and modify the same piece multiple times. This may be because for the participants using the application the feedback on the rework to be done was self-given whereas the participants who had only the drawing to complete the assembly were being told by someone else that their work was wrong, lowering their morale.

5.2 Feedback from Participants

At the end of the experiment, participants were briefly presented the format of the other version of the experiment. Participants with the drawing often expressed that they would have found the visualization of the rework to be more conducive to their ability to complete it while several participants who used the augmented reality process expressed that they did not think they would be able to complete the assembly without the aid of the 3D model.

6 Future Work

At this time, experiment trials still need to be completed, particularly with craft workers. The intention was to evaluate 40 engineering students and 40 craft workers. At this time 30 engineering students and 4 craft workers were recruited. The sample of 4 craft workers was deemed too small to include in the work at this time.

The participants’ skills working with their hands must also be taken into account. Additional trials could be conducted with engineering students who were more experienced working with their hands or they could be evaluated in groups based on their experience working with hand tools and assembling things. To help offset the impact of participants’ skills, the participants could be recruited to complete a second spool of comparable difficulty with the alternate experimental procedure. Participants who used the traditional methodology could use the augmented reality process and those who used the augmented reality process could use the traditional methodology.

Additionally, using a more realistic spool could give participants a greater sense of purpose in completing the assembly. Finally, statistical analysis of the significance of the variance must be completed.

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