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Construction Knowledge Transfer Through Interactive Visualization

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Abstract. Changing population demographics and infrastructure demands are having a significant impact on the average level of worker expertise in the North American construction sector. Experienced employees with specialized knowledge are leaving the workforce, and their replacements are required to install and maintain a broader variety of complex systems. Because of this, it is imperative that construction knowledge be quickly and effectively transferred to practitioners through educational processes. However, recent history has demonstrated that traditional techniques may not be effective at transferring sufficient knowledge to eliminate many common mistakes. It has been suggested that new forms of knowledge transfer may be more effective and result in fewer construction errors, especially those which result from installing components out of sequence. In this paper, the authors describe efforts to adapt a traditional paper-based best practice guide into an interactive 3-D tool that can be used on a variety of devices, from laptop computers to commercially available entertainment systems.

Keywords: Construction knowledge, knowledge transfer, visualization

1 Introduction

Canada, like many other developed nations, is facing a dramatic change in demographics, where experienced workers are reaching retirement age, and being replaced by less experienced members of the workforce. In the construction sector, this trend is illustrated by the fact that there is expected to be a shortage in nearly all classifications of skilled trades [1]. To meet the expected demand, new workers, combined with increased productivity of existing workers will be required.

Errors made by practitioners come in many forms, but most common errors fall into three broad categories, errors in sequence, position, and material. Errors in sequence occur when there is a discrete set of steps that must happen in a particular order and one or more of these steps occur out of order or omitted. Position errors are generated by components that are installed in the correct sequence; however, they are in an incorrect location or orientation, such as a one-way membrane being installed backwards, or an air vent being improperly located. Material errors occur when the materials used in the design are replaced, as a cost-cutting or supply availability measure, with substitutes lacking the same performance characteristics. An example of this would be the use of lower-than-expected grade fasteners.

One set of case studies, where each of these sets of errors can be seen, is the “leaky condo” crisis in British Columbia, Canada. From approximately 1982 to 1999, a housing boom in Vancouver led to numerous high rise condominiums being built and occupied. After occupancy, many owners and tenants began having mold and other moisture-related problems. According to reports [2,3], between 50,000 and 75,000 units may be affected with severe moisture damage, and more than 40,000 still require significant repairs, with one estimate of $696 million in financing required for the 10,000 units that can be repaired by 2012.

In a report to the government of British Columbia, the Commission Of Inquiry Into The Quality Of Condominium Construction In British Columbia found numerous systemic issues with the design and construction of these condominiums. For example, in one case, an owner reported:

"In our case, the concrete on a number of floors was poured incorrectly, resulting in some window openings being as much as 3/4" too small from floor to ceiling. Rather than disassembling the window units, cutting pieces smaller and reassembling the window to the correct dimension the window installer trimmed 3/4" off the bottom of the window. Moreover, instead of cutting the glass to fit, the contractor crammed the window into the opening, making it impossible to remove the glass without completely disassembling the window unit" L.L. Wright, Condo Owner [2].

In this example, the errors of the window installer (altering materials, and presumably changing the positioning of components) compounded apparent sequence errors (failure to inspect that openings were poured correctly) that happened earlier in construction. Since the proper techniques had not been effectively communicated to the labourers, errors were compounded, and the result was a poor structure.

Given the drivers above, there is a need for alternative approaches that can be used to communicate construction knowledge and provide training and evaluation materials. Some of the requirements would be the ability to update information and best practice scenarios, give users defined access to views and information, and have a mechanism for testing their understanding of the information being conveyed. In this paper, the authors describe their work with interactive visual training software and validating its effectiveness for transferring construction knowledge.

2 Current Knowledge Transfer

Before looking at improving communication, it is important to first consider some of the primary methods of knowledge transfer in the construction sector. Tools come in many forms in this sector. In Canada, the most fundamental of these are the Provincial building codes. These are a set of legal requirements that guide the minimum standards that any new building must meet, in terms of structural, electrical, and plumbing performances. While the building code specifies performance, even to the point of describing what a finished structure must be like, it does not specify how to construct a building to meet that performance, nor does it specify the details that are required. For this reason, many organizations provide best practice guides that are a step-by-step set of instructions on how to build something that will meet the building codes, and provide good performance.

One example of a best practice guide was a direct result of the aforementioned "leaky condo" crisis. The Homeowner Protection Office, British Columbia, Canada created a book called the **Building Envelope Guide for Houses**. This is a reference book that gives step by step instructions for many construction tasks, each illustrated with color drawings to help a practitioner avoid errors, particularly sequence ones.

Unfortunately, these guides also have typical drawbacks. While they are usually illustrated for added clarity, often several steps are combined in a single drawing. This can lead to ambiguity, and even when only a single element is being represented, static, isometric drawings do not always allow the practitioner to see the element they are interested in. For this reason, they may not be as effective in reducing position and material errors. Also, because these guides are static, they can be used for years, and are not necessarily updated when there are revisions to the codes, changes in accepted best practices, or when a new material comes to the market.

Formal learning practices in the construction sector are based on "hands on" experience as typified by apprenticeship programs. Initially, the student, with the supervision of an instructor or mentor, assimilates the information by reinforcing the knowledge through continuous practice of individual tasks. This learning mechanism is related to the behaviourism theory and provides feedback to the student in the form of positive and negative reinforcement. Once the student acquires enough experience and independence, project-based learning and problem-based learning are used to instruct and to coach the student to overcome challenging, open-ended problems with multiple solutions. A project-based learning scenario requires that the student have specific content knowledge or skills to produce an end-product. A typical example is the installation of a window, which involves the understanding and the implementation of a multi- step process. A problem-based learning scenario provides the student with a challenge they must solve or improve. A typical example is the installation of the electrical wiring, which requires the students to exercise their own judgment to find a good solution to the problem. These learning mechanisms are related to the constructivist model of human cognition and rely on dynamic interactions with the environment [4,5].

Conventional training is performed by formal classes and on-the-job training, however, this may not be sufficient to train and retain new workers who are used to accessing digital information. For these workers, there are likely better ways of transferring the knowledge. The subject and the related content are often not the issue, however the way the information is conveyed nowadays could deter acceptance by the younger generation immersed in visual, social and communication technologies. Conversely, the baby boomer generation working in the construction sector may find video games unrealistic and a frivolous way of learning. A middle ground is possible, Michael Zyda [6] describes a Serious Game by: "a mental contest, played with a computer in accordance with specific rules that uses entertainment to further government or corporate training, education, health, public policy, and strategic communication objectives." Traditional VR training systems are very efficient at providing problem-based learning and project-based learning scenarios focusing onjob training. Concrete applications, using "what if" scenarios, are successfully used in space and aviation, military, medicine, manufacturing etc. These simulations allow the trainees to comprehend the consequences of their actions, improve their confidence and prevent exposure to unnecessary danger until the task familiarity is acquired [2,7].

In addition to conventional practices, other forms of knowledge transfer have been considered. Video - based guides are becoming popular, and while they have a high degree of realism, once they are delivered, they cannot be modified, and they do not always show a practitioner sufficient detail for a given step or process. Furthermore, videos are difficult to consult on site, and can be awkward to search through to review a particular operation or task. Perhaps, most importantly, these tools also do not necessarily allow a practitioner to test their understanding, so they must wait until they physically try to perform an installation before they know if they understand the material.

Many researchers have reported that advanced visualization and Virtual Reality (VR) environments assist and enhance users learning experience [8,9,10,11,12,13]. Also, it is realized and widely accepted that effective training is important both for learning and to prevent accidents and disasters due to faulty workmanship [14]. To address these issues, interactive training systems [15] are being developed. With the help of these systems the users can visualize and have appropriate interactions with the computer-generated models, thus minimizing physical training requirements and avoiding costly and hazardous mistakes. Research has shown that visualization and VR techniques enhance communication among stake-holders and allow them to visualize design and constructability errors earlier in the project [16]. The implementation of visualization and VR systems is expected to greatly increase alongside the construction industry's adoption of computers and the emergence of a new generation of students. Recent studies have shown that if advance technologies such as visualization and VR are integrated appropriately within built environment academic curriculums, they will provide a good foundation for the new workforce [17]. A recent report [18] on the VR Roadmap "A vision for 2030 in the built environment" suggests the training of workers is a big challenge and needs significant R&D. The report also emphasizes the fact that hardware and software technologies used should be intuitive in order to cater to the new generation workforce.

For some jobs, there have been examples of highly immersive training environments which are very efficient for skills training and allow the students to learn "by doing" and "by feeling" through multiple tactile feedbacks from the simulation environment. Similarly, the technology is very efficient for situation training which allows the students to learn "by seeing", "by experimenting" and "by socializing" through feedback from other team members in the scene, supported by a greater degree of coordination between team members. However, several challenges remain when implementing advance simulation and visualization technologies into the construction industry depending on the focus of the training. The classical one is cost; a traditional VR environment requires significant financing with the consequence that the potential return on investment may only be appropriate for highly skilled and potentially dangerous tasks like operating heavy equipment. However, commercial video game platforms are mature enough to take the lead in more common skills and situation training. The second problem is how to move the simulation and visualization technology from the secure place of an office to where the construction workers need the technology i.e. the work site. The third would be to develop applications with the construction industry specificities in mind, i.e. education background, generation differences, multiple ethnicities and languages [19].

Work towards the development of training systems, especially involving visualization and VR, are fast progressing as the technology becomes more affordable. Researchers in Australia [20] have developed an Augmented Reality Training System (ARTS) that trains the novice operators in a real worksite environment populated with virtual materials and instructions. The developed system assists the user to operate the heavy equipment, previously limited to off-site training programs that restrict the novice's experience of real working conditions. It is to be noted that, on-the-job operator training is not only costly but also prohibitive due to requirements for specialized equipment and an on-the-job trainer. Additionally, in environments where the climate is harsh, learning on-site is difficult and the probability of making mistakes is high and the resulting consequences can be significant. A review of literature, specifically in the context of the Canadian construction industry, shows that very few researchers are working in the areas of developing the workforce, their productivity and safety [21,22,23].

3 Approach

While the previously described technologies all contain promising elements, and do much to advance the state of knowledge transfer, they may not have the combination of effectiveness, affordability, and flexibility that will be required to address the challenges the construction sector faces on a day to day basis.

The construction knowledge transfer framework proposed in this paper consists of a step-by-step software tool that combines interactive visualization, audio cues, and feedback mechanisms, all displayed on a commercial entertainment system. The goal is to allow the practitioners to have a better understanding of the installation sequences and make fewer errors when they are at the worksite. Though 100% perfection may not be expected by following this framework, the practitioner will certainly have a better understanding of the process and hence become more productive. Figure 1 shows screenshots illustrating the few steps that are involved in the virtual window assembly, using the developed system.

The initial applications that are considered are those that can be described as a series of discrete steps, where, in a given step, one or more tasks are performed until a certain level of performance is achieved. Typically, these tasks are the installation of a proper component combined with any inspections needed to ensure that the component is in the correct location. These types of step-based applications are especially suited, because they can be easily represented by format independent model languages, such as XML, and lend themselves to implementation using object-oriented software.

The second element of the framework is an interactive visualization where the user can move, rotate, and focus the viewpoint to better understand the context of the current step compared to the existing assembly. In the visualization, the current step instructions are presented. These instructions can be provided as some combination of text, audio, or images.

To advance from one step in the sequence to the next, the framework supports several options. In addition to allowing a user to directly cycle from one step to the next, there is also a context-sensitive palette that displays multiple tools or parts. The user is required to interpret the text and choose the palette object that best represents the current task. When the correct palette object is selected, the animation continues, and the user sees an animation of the step being performed. If needed, the user can adjust the viewpoint during or after the sequence, and view the part being moved in real-time. This provides a useful feedback mechanism to force the user to consider the instructions, which studies have shown, greatly increases comprehension and retention.

The developed tool contains several epistemological objectives. First, the pedagogical material defines the process to assemble the window based directly from the guide. Second, the conduit to provide the knowledge uses interactive visualization, which is more appealing to the new generation. The dynamism, the interactivity and the realism of the simulation allows the student to learn by exploring the potential solutions. Once the ludic aspect of the simulation has passed the inhibition stage, the older generations are not reticence about using the technology. Third, the tool can be used for beginners or experts, depending on the configuration. For a novice, the goal is to acquire the skills required from the pedagogical material and the understanding behind the task. He will be assessed by how he follows the rules. For an expert, the goal is to acquire the understanding of the overall context and potentially propose alternative solutions for doing the tasks. His assessment is based on self-evaluation and by his peers [24,25].

Figure 1: Components of the developed system

4 Implementation

To demonstrate the proposed framework, the authors have constructed two interactive guides and have applied them to describe the assembly of windows on an airtight drywall with an air barrier. The guides present the same content as found in the guide but in 3D, in an interactive challenge-based format where the users can not only review the material to be learned but assess their knowledge. It is important to remember for these initial applications that the content being conveyed is limited to sequences of steps. Future work could consider training for more elaborate problem solving applications where multiple solutions might be applicable.

As an example, the steps for the assembly of a window on an airtight drywall, were taken from Section 3.3.08 of Reference [26]. In total, there are 26 individual steps described, the first 5 of which are provided in Table 1.

Step No.	Description for Airtight Drywall Air Barrier, Simple Window on Exterior 2x6 Stud Wall
1	Complete the rough framing for the window opening.
2	Ensure adequate space is provided between the rough framing and the window to accommodate sealants between the window and the rough opening, and to facilitate drainage of the sub-sill region.
3	Apply compatible sealant to framing connections between the sub-sill and the jamb as well as the framing connections where the jamb meets the head.
4	Install a stripping ply of sheathing membrane
5	Install a waterproof membrane to the sub-sill, continuous up the jamb of the rough framing.
etc.	

Table 1: Assembly procedure to install a window assembly on an airtight drywall

A hierarchical description of the necessary elements is shown in Figure 2. As can be seen, the data required to create the virtual environment and run the assembly sequence interactively is large and can be time consuming, especially for a scenario with many steps, such as: the description of the components, the geometry details, the rendering details, the sequence of performing the task, assembly rules, sequences, all must be provided for each sequence. To address this issue, simulation rules have been integrated into a MS Excel-based planning process. This tool assists the user to build a data set required for simulation quickly and error-free. This has been implemented in XML for the current work.

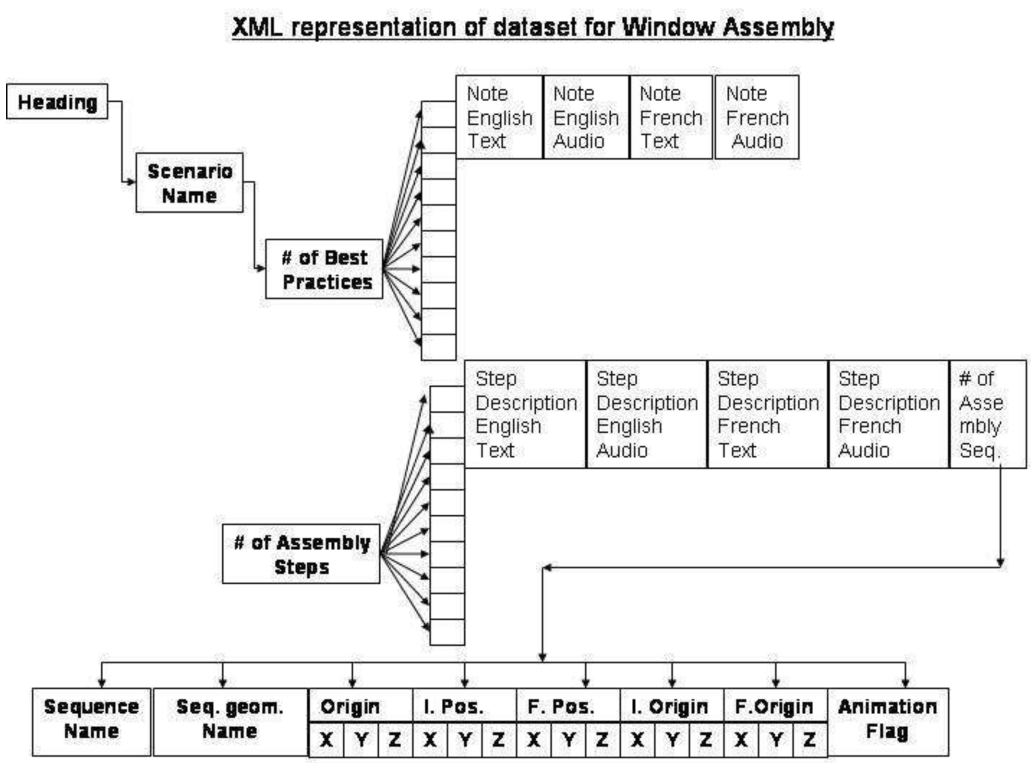

Figure 2: Hierarchical view of scenario representation.

One of the guides was built for the Windows PC platform and one was built for the Xbox360 gaming system. These two platforms were chosen to allow the authors to investigate the potential of two platforms in common public use. The guides developed share significant similarities and offer the same basic functionality but in ways typical to their respective platforms. The basic functionality of both platforms includes:

- Start with an introduction to the challenge at hand
- A navigable 3D rendered environment allowing the user to move their viewpoint around the window assembly and review its current state close up or from further away
- Text instructions state the objective of each step
- Text based best practice notes can be triggered
- Audio recitation of the text instructions can also be triggered
- All audio and text are available in two languages
- Audio feedback for making correct and incorrect choices is included

Both versions also share the XML representation of the scenario, so that content only needs to be developed once, and can be used on either of the two implementations.

The Xbox360™ version of the guide was built to examine how easily, and naturally a best practice guide could be implemented on a gaming system, which is naturally rich in graphics and audio interaction and generally perceived to be simpler to own and operate than a computer. The Xbox360™ was picked for the development platform, as its development environment is open and free in comparison to other common gaming systems. Nevertheless, it is envisaged that what was built for one platform can likewise be implemented on other platforms. Due to the fact that games are controlled using controllers with multiple pads, joysticks and buttons compared to a PC, the interaction of the user with the guide is a little different than the PC version. Superficially, control of navigation and selection of actions was implemented with common gaming platform elements like trigger-toggled menus and joysticks for navigation. As shown in Figure 3 and 4 the interface also has a look more consistent with gaming systems.

Figure 3: The Xbox360™ version of the guide

Figure 4: Screenshot from the Xbox360™ version of the guide

Some more significant differences were implemented based on feedback from education specialists. First, more configuration options were given, including settings for playing at a difficult or easy level, which toggles step to related clues such as instructions, step number, score and time feedback on and off. Second, the option to play the game in reverse was enabled to allow an alternative approach to learning the sequence material, much like how people problem solve. Third, ambient audio, appropriate to a construction zone was included and audio feedback was made more appropriate for the application, i.e. a breaking window sound for incorrect steps and active construction noises for correct choices. Finally, steps can be skipped or redone to enable people already quite familiar with construction practices to review only sections they wish to brush up on. This is consistent with the goal of making a tool useful for new workers as well as seasoned veterans wishing to review the latest recommended practices.

The Windows PC implementation is intended to be accessible to as large a segment of new and experienced construction practitioners as possible. It was decided that the visual elements of the tool be built around a game engine and if possible to use freely available tools. After considering several options, the version 1.5 of the Panda3D game engine was chosen. This engine was originally developed as a commercial tool, however it is currently maintained by Carnegie Mellon University, who makes it freely available (with certain requirements, such as attribution) under a modified version of the common BSD license [27]. While this implementation is intended to be usable for knowledge transfer, a prime consideration is the capacity to use it to conduct research into the effectiveness of knowledge transfer. For this reason, it has been built with internal diagnostic tools that are transparent to the end user. These diagnostic tools will allow researchers and educators to gather data on the behaviour patterns of end users, such as task timing, choice, and button presses. These can be correlated with studies of student's behaviour of practical tests to help validate learning hypotheses. Unlike the Xbox 360 implementation, the Window PC version does not require content to be pre-compiled. For this reason, it is expected that models and scenarios will be much more easily updated and tailored to end users.

These applications remain simple but provide an important dynamic to the learning process where self-evaluation is possible, and where learning is reinforced by active participation in the training program. Experts can quickly test if their knowledge allows them to intuitively understand new practices or products without reading whole guides, while novices can learn from the ground up with extra available embedded learning material relevant to understanding why operations are done in certain ways. Computers are especially good platforms for showing cause and effect through dynamic mechanisms like embedded videos or animations to illustrate points.

Future extensions of these applications can include tracking of individual student performance or class performance, logging of tasks that cause particular difficulties and extensions to include an entire curriculum of content. Initial feedback for educators suggest most significantly would be the expansion of content in multiple ways to better teach the material in question. For example: 1) providing links to other learning material, reference manuals and product documentation. 2) making better use of the multi-media -rich capabilities of today's computers and gaming systems to include video of current content related to the material being learned (e.g. interviews of people studying the BC condo crisis) 3) allow the user to make mistakes and then show the consequences of their mistakes (e.g. leaky windows or lack of space to install a window).

5 Future Work and Conclusions

This paper reports the ongoing work on developing an interactive visualization guide for best practices for performing the assembly of windows. Introduced is a new concept of advanced interactive system. The prototype described in this paper demonstrates a system that can be used to train in an economical way. The implementation of planning rules from the best practice guides assists the user and prevents possible errors which normally occur during the construction phases.

Knowledge transfer in the construction industry through visually-orientated tools needs not be limited to training applications. More complex knowledge, included in things like design guides, is often most useful in software tool form. The goal is to automate tedious or difficult calculations or table look ups and create a friendly interface that guides less experienced users through, and supports more experienced users during, a process or decision. For example, the authors have been working on a sound insulation design guide for multi-residential wood frame buildings. The guide encapsulates significant knowledge typically found in tables and product specifications and presents possible choices and their impact in a very visual way (Figure 5). There is a very real potential for interactive training tools and games and guides to converge into singular applications supporting all uses. As a rule though, these tools will only be as useful as long as their content is kept fresh and relevant.

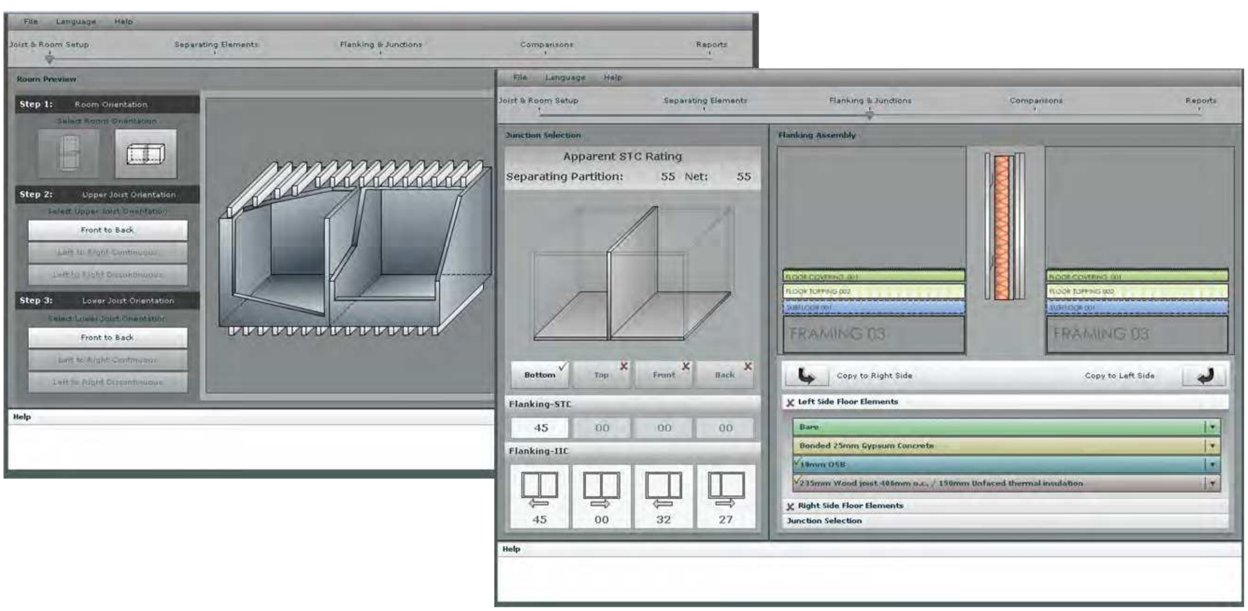

Figure 5: Screenshots from the Flanking Sound Transmission Guide in Development

The authors are planning significant future work including the development of more sophisticated systems, and conducting systematic research into which elements of interactive guides are the most effective at eliminating construction errors.

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