AN AUGMENTED REALITY TOOL FOR FACILITATING ON-SITE INTERPRETATION OF 2D CONSTRUCTION DRAWINGS

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ABSTRACT: *Two-dimensional drawings are the only type of design document that is legally approved for construction. For large construction projects, because of the drawings' high level of abstraction and because of the very large number of drawings, interpretation and correct understanding of drawings is identified by some construction firms as their greatest single challenge. To do the building work as designed, the builder must understand the meaning of the drawings, and this comes from establishing a visual correspondence between the abstract 2D drawings and the physical environment. Unfortunately, that correspondence may not be easy to obtain when the structure of interest is not clearly visible from the user's position (occlusion, differences between the model and the actual building, etc.). In this paper, we propose a technique that enables the display of 2D drawings into the real world using augmented reality in a way that can overcome those kinds of limitations. The tool enables users to "browse" the real world in search of drawings, or to request the real location that a specific drawing represents, and to view each drawing within a context composed of a combination of captured photographic reality and designed virtual modeling. Augmentation is achieved by displaying the drawing using either an animated sliding plane that shows it being "inserted" into the real building, or a clipping technique that displays the drawing inside a clipped 3D model which in turn is inside the real building. The 2 techniques were implemented and tested in a situation where section drawings are visualized from the outside of the building. Our results show that those visualization techniques provide good 3D perception in a representation that is easy to understand visually. They also enable quick localization of the drawing in its environment, and provide a better understanding of the drawing with respect to its context: the 3D model and the built environment.*

KEYWORDS: *Augmented reality, panorama, construction, 2D drawings, design, 3D model.*

INTRODUCTION

Construction is a complex process involving a large number of complex tasks aimed at the development of physical infrastructure (the built environment). To ensure that infrastructure is safe for human use, design and construction firms comply with regulation, like building codes, and conduct their work within a legal framework that holds engineers and architects responsible for the communications they issue and certify. In the whole construction process, each team (designers, architects, builders, engineers, surveyors) is legally responsible for their part of the work. For that reason, information between the teams must be transferred in a clear and unambiguous way. Certification helps define the legal bounds of responsibility. For instance, by putting his seal on a drawing, or a set of drawings, an architect asserts and claims his own responsibility and accountability for that statement, or set of statements. Furthermore, drawings, by their nature, contribute to the definition of legal boundaries of responsibility in an essential way that makes certification possible. Because drawings are location-specific, they are finite in number. Because of the finiteness of a set of drawings, describing only representative locations, and only implying the rest of a project, as a practical matter, architects and engineers have adequate control over these representations.

Infrastructure, however, is inherently 3-dimensional. Designers propose a 3D building concept, and ultimately builders create the 3D object that corresponds to the designer's idea. Yet, the only design document that is legally approved for construction is the 2D drawing. Consequently, even though designers may have produced a 3D model of their design, drawings, because of their location-specific review and certification, are the only form of visual design communication that satisfies the legal framework required for construction. Since the process

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forces designers, architects and engineers to take one dimension out of their 3D design, drafting consists of a complex set of tasks aimed at accurately representing a 3D object with 2D representations. For large infrastructure projects, the process may lead to the production of a very large number of drawings (e.g. thousands), each one referring to other drawings, through symbols that indicate their relative spatial relationship. The process is complex and must be done with great care, to ensure that when the builders read the drawings, they will be in a position to build the 3D building as it was designed.

Because of the large number of drawings and their high level of abstraction, the transmission of information between the designer and the builder is not easy. Three main difficulties arise from the process:

- Because drawings are 2D representations of a 3D object, and because each drawing refers to several other drawings in the set, by way of special symbols, understanding the meaning of any drawing is a complex task that takes sustained continuous effort from the builder to continually keep and update a mental representation of the project by putting many related drawings together in space, by imagination, and projecting their implied 3-dimensional continuities.
- Drawings are often arranged in groups. This is illustrated in Figure 1, where 4 sections of the same wall are displayed on the same sheet. When building that wall, the builder must therefore carefully select and use the corresponding section of the drawing. Many drawings in a set are similar. The builder must be careful to associate each drawing with its correct actual location in the proposed real environment of the project, its actual location in reality, to build the right things in the right place.
- The builder may not always notice that there is a drawing that represents some physical location of interest in the building, as this would require familiarity with the whole document set, which requires continuous long-term effort and meticulous attention. Consequently, some drawings of the set may inadvertently go unnoticed.

Because of those difficulties, errors can be made, both in the preparation of those drawings and in their interpretation, and in any case, the task of understanding the meaning of the drawings may be said to be more difficult than necessary; that is, visual communication could certainly be made more effective than is provided for today by either of the two conventions, drawing or modeling.

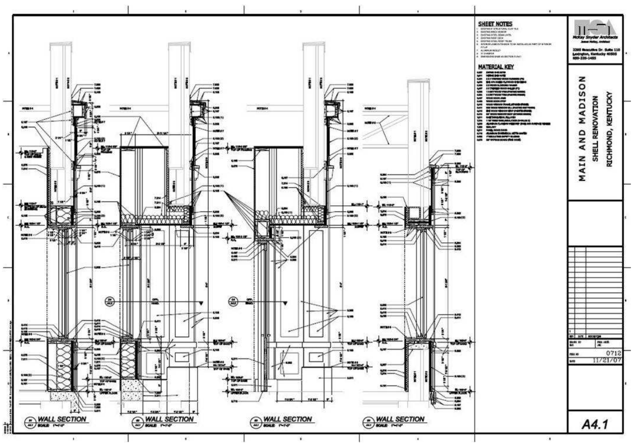

Fig. 1: A typical drawing showing 4 sections of the same wall.

To decrease ambiguity and errors that can be caused by working only with 2D drawings, or with 3D models and 2D drawings separately, a few years ago Bentley® proposed a new concept, commercially released in 2012, and referred to as “Hypermodeling”. Using 3D model clipping, 2D drawings are displayed automatically inside the 3D model, on demand, at the exact location they represent (see Figure 2). The spatial relationship between various drawings is then much more clearly represented, as each drawing is graphically represented *in-situ* in a 3D model.

The Hypermodeling technique is very useful for improving communication between designers and builders, as it indicates exactly the location of the certified drawings in the building model and helps both designer and builder more fully, correctly, and quickly understand the meaning of the lines and other graphic elements in each drawing. The technique also helps build trust in a 3D model, because it makes clear the difference between “just any location” (which may or may not be complete enough), and specific locations that are

certified as graphically complete enough. Although it is very useful, that solution is not complete for construction, as a builder must still establish a visual correspondence between the 3D model and the real environment of the building. That correspondence, essential for doing his work at the right location, may not be clear when the environment is very different from the model, for instance early in the construction process, when the building is fully built, or when construction material or furniture is in the way.

To address the problems faced by builders to interpret drawings on-site because of their large number and because of the fact that their spatial location is only specified relative to the other drawings in a symbolic and abstract way (within a set of drawings), or virtually (within the hypermodel), what would be needed is a way for the builder to see exactly the correspondence between the certified drawings and the locations they represent in the real environment – in other words, a system that would visually indicate the relationship between a 2D drawing and the 3D real environment. This, we hope, might decrease the number of construction errors caused by drawings misinterpretation, and may save the time it normally takes to search for the right drawing. That problem is an excellent candidate for augmented reality.

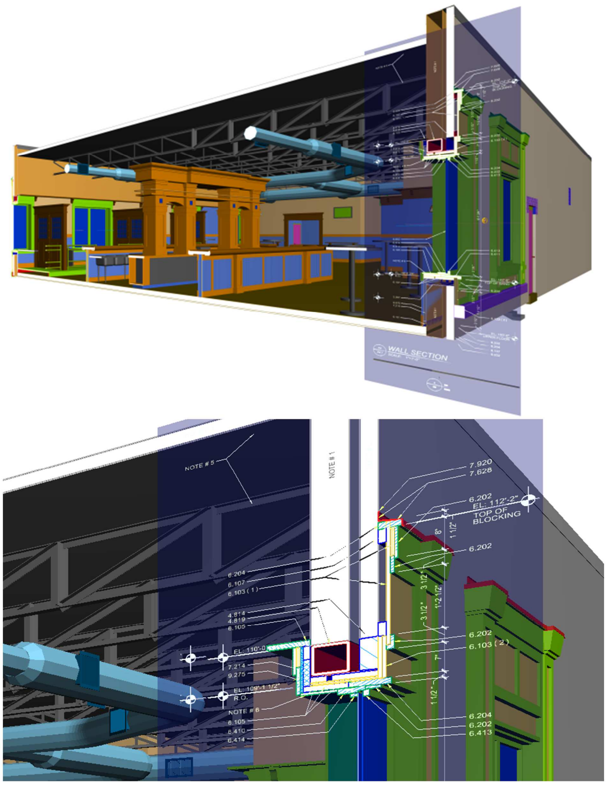

Fig. 2: Two views of a clipped 3D model showing the exact location of a section 2D drawing aligned in place.

In this project, we propose a new visualization technique based on augmented reality (AR) that renders 2D drawings at the exact physical location they represent, in a way that is visually compelling, informative, and helpful for their interpretation, on-site, by construction and maintenance workers.

RELATED WORK

The use of 3D CAD building models in an augmented reality context has been studied many times and shows high potential. For instance, Woodward et al (2010) described an AR system aimed at displaying BIMs in their physical world context. Hammad et al. (2002) described a case study in which a bridge inspector visualizes a bridge CAD model based on his location and orientation. In their user evaluation, Olsson et al. (2012) confirmed the usefulness of mobile AR for visualizing urban plans. Golparvar-Fard et al. (2011) described a system for the automated acquisition of point clouds from photos and their use for comparing with 4D BIMs in an augmented

environment.

The specific problem we are trying to solve is different, as it is mainly related with spatial perception and 2D drawings. Spatial perception is a fundamental issue in the CAD software industry. In their work, Dunston et al. (2002) discussed the importance of considering spatial cognition issues in the validation of AR CAD systems.

The specific use of 2D CAD drawings in AR was also studied. For instance, the works of Mackay et al. (1995) and Fiorentino et al. (2010) focused on using 2D drawings as an interface to visualize the corresponding 3D model using AR. In our study, our purpose is different: we want to display 2D drawings at the exact location they represent in the 3D world. The works that are conceptually closest to ours are the ones of Navab's team (1999 & 2002) where a floor plan drawing is draped onto the corresponding real floor in an industrial context. However, their study was limited to floor plans, where the physical floor (used as an augmentation surface) is visible during the augmentation session. In another investigation, Gimeno et al. (2011) described an AR system that displays 2D floor plans and elevations overlaid onto live or static images or building floors or facades. In our study, we wanted to focus on drawings that are arbitrarily located in space (e.g. section drawings) and for which the corresponding real world location might not be visible nor represent a good projection surface for augmentation.

Augmentation in the presence of occlusion is a problem that was often explored. For instance, when augmenting a scene with an object that is normally hidden (for instance a cable hidden behind a wall), it is well known that simply overlaying that object on top of the occluding surface (in this case: the wall surface) alters perception (Kalkofen et al., 2007). To display the augmentation at its true location, parts of reality that normally occlude that object must first be hidden, for instance using techniques used for Diminished Reality (DR) (Mann et al., 2001). In this work, we propose a technique inspired from the Magic Lens metaphor (Bier et al., 1994), where the portion of the scene that is removed is replaced by a clipped 3D CAD model, which helps preserving perception.

PROPOSED SOLUTION AND RESULTS

The visualization of 2D construction drawings in an AR context is hard. To display the drawing at its exact physical location, a "physical context" is ideally needed to display the drawing into. For instance, a floor plan would be easy to understand in an augmented scene if it were displayed on the surface of an existing physical floor. The floor would, in this case, be used as a context for displaying the drawing. The problem is that on construction sites, the ideal physical context may be invisible, either because it has not been built yet, or because of occlusion by other parts of the building. The main problem is therefore one of perception: how to display a 2D drawing in its physical context when that context is not visible.

To alleviate the problem, we proposed 2 techniques: sliding plane, and model clipping. The 2 techniques are described below.

Since we concentrate on the visualization aspect of the augmentation problem, a simplified augmentation environment was used. The system we used is based on the augmentation of static panoramic images that are used as a representation of reality and captured prior to the augmentation session (Côté, 2011) – this is described as a "fixed configuration" by Lee et al. (2005). The 3D model, used for augmentation or clipping, was aligned with the panoramas at the beginning of the session, using the method described in Poirier's thesis (2011). Used on the field, the augmented scene can be viewed on a portable (tablet) device, that displays the portion of the augmented panorama that corresponds to the user's instantaneous orientation, estimated using an orientation sensor. Used at the office, the remote augmented scene can be viewed on a personal computer and navigated using a mouse. Although this only produces an emulation of AR, it has the advantage of offering jitter-free augmentation, as no live video tracking is involved. Consequently, the system is not very demanding in terms of computing resources. However, it has the disadvantage of providing no real-time augmentation, and is based on images that are, by definition, out of date. Yet, the system is ideal for some types of applications, for instance where accuracy is very important (Côté, 2011), where access is not easy because of distance or safety issues, for preparing site visits, and also very generally in common situations in which authored, instructive, directive, actionable, and certified visual statements are to be well and correctly understood, and where contextualization improves their intelligibility.

In this experiment, all 3D models and drawings were designed by McKay Snyder Architects, James McKay, Architect, using MicroStation®. Panoramic images were obtained from individual photos captured with a

standard digital camera and stitched using Microsoft ICE. Augmentation experiments were run on a standard 2-core laptop computer with 2 Gb of RAM. However, since the prototype requires very little CPU power, it could easily be ported to tablet devices. Augmented scenes were viewed using a prototype based on Ogre3D. 2D drawings and clipped models were rendered in MicroStation and imported into the Ogre3D application as jpeg images. Models for occlusion were exported in Collada format from MicroStation®.

Sliding plane

We first proposed a solution to the problem of finding the location that a drawing represents, in the presence of occlusion. Considering, for instance, the situation where a drawing represents a section of a wall that is already built. The user holds a tablet that displays a drawing where 4 sections are displayed. The user wants to know the location that one of those 4 sections represents. Upon selecting the section, the system displays it in an animation, showing it inserted into the wall, at the exact location it represents (see Figure 3). The drawing is first displayed outside of the building, then progressively inserted into it, until it reaches its correct location, and then moved out again. The drawing insertion, played a few times, is aimed at catching the user's attention, and at showing the physical location that the drawing represents. During the insertion process, the drawing is clipped by the building model, revealing only the portion of the drawing that is physically outside of the building. The drawing was displayed on a semi-transparent virtual sheet for display clarity.

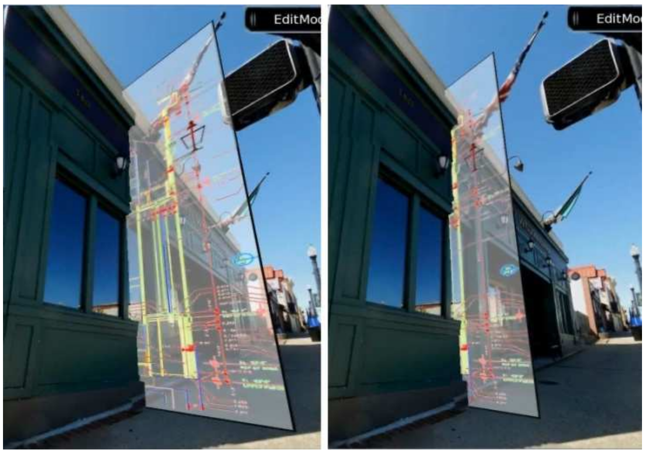

Fig. 3: Example of a 2D drawing being inserted into a building.

Model clip

The sliding plane technique appears very useful for highlighting the physical location that a drawing represents, and for attracting the user's attention. However, the proposed technique has a major disadvantage: when the drawing is fully inserted in the building, positioned exactly at the location it represents, its content is occluded by the wall. To let the user see the drawing in its context, it would be interesting to apply the concept of "virtual excavation" (Schall et al., 2010) to those walls. However, the problem would then be about knowing what to display inside the excavation: the 2D drawing needs an appropriate intelligibility-providing context within a 3D environment, and an empty hole would provide no such context. As a solution, we proposed a technique based on hypermodeling: the outside wall of the building is virtually replaced with a clipped version of a 3D model revealing the inside of the building. The 3D model is further augmented by the 2D drawing, displayed within the clipped model section, in a hypermodeling fashion (see Figure 4).

In the prototype, 2 methods were used to help the user locate drawings: handles and thumbnails. Drawings thumbnails are displayed at the bottom of the view – when the user clicks on one of them, the system automatically displays the corresponding drawing in the real environment with its pre-selected model clip (resulting in a scene similar to Figure 4). Handles are small icons displayed into the scene, which the user can click on to get the same result. Those tools were implemented to provide the user with 2 ways to navigate drawings: spatially or drawing-based.

Our experiment was not limited to panoramic images. The main advantage of panoramic images is that they are

a faithful representation of the physical world that can be easily understood by users. It turns out that point clouds are also faithful, and they have the additional advantage of being 3D. We hypothesized that augmenting point clouds with 2D drawings could bring the same kind of visualization and intelligibility benefits. A point cloud was therefore captured inside and outside the building, clipped, and augmented with a 2D section drawing as well as some clipped elements of the 3D model (see figure 5). Our results show that not only is the augmented representation visually clear, but it has the advantage of being viewable from any orientation, as both sets of data are fully 3D.

To get an idea of the potential of such visualization technique, our prototype was demonstrated to and/or used by about 30 CAD users. They all confirmed that potential, confirming they understood the purpose of the drawings better. Several users also pointed out that a large number of 2D drawings exist for our infrastructure, and those drawings are never used, either because they are not easy to access, or because once accessed, deciphering them requires great effort due to their decontextualized abstraction. Some also mentioned that their format (paper drawings) is not appropriate for use on site, or because they are generally out of date with the current state of the infrastructure asset. Such visualization techniques could bring those drawings back to life, enabling users to take advantage of their data, but also would offer the possibility to update and correct them more easily.

CONCLUSION & FUTURE WORK

In this project, we tried to address the problem of interpreting 2D engineering drawings on-site, for construction work. Drawings are abstract and numerous, and a wrong interpretation may lead to mistakes in the construction process. Our contribution consists of proposing 2 AR visualization techniques that can be used to browse a stack of drawings, searching for their corresponding location in the world, or to browse the physical world, in search of corresponding drawings.

Our results suggest that by providing a visually clear and intelligible way of displaying the drawing in the 3D scene, the techniques could potentially be useful for:

- Reducing the time required for searching for specific drawings;
- Reducing the risk of using the wrong drawing when doing the construction work.
- Reducing the risk of a drawing going unnoticed.
- Helping users more correctly, thoroughly, and easily understand the meaning of 2D drawings and their 3D spatial relationships.
- Helping users clarify the locations in a 3D model at which there exists reliable and certified graphical information.
- Generally improving the intelligibility of complex information of several types mutually when combined: drawings, virtual models, and captured reality, both photographic and point cloud.

Other studies will be required to confirm those advantages.

In construction work, drawings are essential, as they provide instructions on how to build. 3D models are also very important, as they provide a global understanding of how all the 2D drawings are aligned together to form a 3D object. Finally, the physical reality is also essential, as that is where the infrastructure is built. All 3 components, taken individually, have some value. Our results suggest that the value of aligning all 3 media together is greater than the sum of the individual values of its parts. Indeed, the alignment seems to provide the user with an improved understanding of each media, understanding that is long and difficult to obtain when using each media separately. On the design side, media alignment could also prove to be very useful, as the combined environment becomes the place within which to conceptualize, develop and deliver both the design itself, and the certified communications that serve ultimately to convey essential ideas and instructions to builders. In addition to providing a set of 2D drawings, engineers and architects could also deliver a rich, intelligible, directive, and actionable visual information environment that would enable builders to better understand the work they are doing, and will do, and therefore to better understand the whole of a project and its parts.

The proposed method is in its infancy, and could be vastly improved. The method could first be improved in terms of the quality of the rendering. Adding a semi-transparent plane behind the drawing proved to be useful for the sliding plane technique, and should also be tried for the model clipping technique, as it might improve the drawing's visual appearance. Some attention should also be put on the drawings' line thickness, to improve

readability in an augmentation context at varying zoom level. A 2D view inset could also be used to display the selected drawing in 2D, when the angle of the clip does not allow easy readability.

Fig. 4: Top: non-augmented scene. Middle: scene augmented with a clipped 3D model, revealing the inside of the building, which is further augmented with a 2D drawing. Bottom: detailed view.

Fig. 5: Point cloud augmented with 2D section drawing and some clipped 3D elements.

In terms of applicability, the method has been tested on simple cases of section drawings for a building that is completely built. Other studies should be conducted in situations where:

- The building is not completed yet, or nonexistent.
- The built infrastructure was not perfectly built according to specifications, and is therefore different from the 2D drawings and 3D models.

- The drawing is a floor plan.
- The drawing represents an area that is hard to access physically, for instance a high level floor seen from the ground, or a twice-occluded area (for instance by 2 layers of walls).

Our results are only a beginning, and let us envision several other applications of AR in the construction field.

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