Visualization of Construction Progress Monitoring with 4D Simulation Model Overlaid on Time-Lapsed Photographs

Mani Golparvar-Fard1; Feniosky Peña-Mora2; Carlos A. Arboleda3; and SangHyun Lee4

Abstract: The ability to effectively communicate progress information and represent as-built and as-planned progress discrepancies are identified as key components for successful project management that allow corrective decisions to be made in a timely manner. However, current formats of reporting (e.g., textual progress reports, progress curves, and photographs) may not properly and quickly communicate project progress. Current monitoring methods also require manual data collection and extensive data extraction from different construction documents, which distract managers from the important task of decision making. Therefore, to facilitate progress monitoring, this paper proposes visualization of performance metrics that aims to represent progress deviations through superimposition of four-dimensional (4D) as-planned model over time-lapsed photographs in single and comprehensive visual imagery. As a part of the developed system, registration of the 4D model with photographs, augmenting photographs, and occlusion removal for progress images are presented. While contextual information is preserved, the as-built photographs are enhanced and augmented with 4D as-planned model in which the performance metrics are visualized. The augmented photographs provide a consistent platform for representing as-planned, as-built, and progress discrepancies information and facilitate communication and reporting processes.

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Introduction

Accomplishing desired performance during construction is a challenging task. Most construction projects or their individual work phases are relatively short duration and are performed at variable locations by a temporary alliance among multiple organizations (Slaughter 1998). Operations are generally conducted outdoors and are subject to interruptions and variations in site conditions and other difficulties such as unforeseen weather conditions (Oglesby et al. 1989). These circumstances cause errors and changes within a project and their corresponding results are difficult to understand the situation clearly and quickly. It is even nor do they intuitively and simultaneously reflect information pertaining to the as-planned and as-built spatial and visual aspects of construction as well as their associated complexities [as stated by Lee and Peña-Mora (2006), Poku and Arditi (2005), Korde et al. (2005), Song et al. (2005), Kamat and Martinez (2002), and Koo and Fischer (2000)]. These representations result in significant amount of information to be inefficiently presented in meetings and as a result, time is spent on describing existing problems and explaining the rationale of decisions rather than evaluating alternatives and discussing what-if scenarios and corrective actions (Golparvar-Fard et al. 2006). With textual representations, it is difficult to understand the situation clearly and quickly. It is even

schedule delay and cost overrun which challenge construction operations productivity Peña-Mora et al. 2008).

For the purpose of effectively managing project development, a systematic and comprehensive approach for progress monitoring needs to be developed so that discrepancies between as-planned and as-built progress are identified and reported to the project managers as early as possible (Lee and Peña-Mora 2006). In this paper, monitoring is defined as collecting, recording, and reporting information concerning any or all aspects of project performance which highlights presence of progress discrepancies and facilitates project managers and decision makers to take corrective actions in a timely manner (Meredith and Mantel 2003).

Today, decision making for corrective actions and schedule revisions usually takes place in coordination meetings where a wide range of individuals (e.g., from the owners to subcontractor organizations) with diverse expertise and interest attend the meeting. In these face-to-face communications, progress information needs to be easily and quickly communicated among the participants. Currently, none of the existing reporting methods (e.g., progress $S$ curves, schedule bar charts, and photographs and textual reports) effectively present and visualize multivariable information (i.e., schedule, cost, and performance) in a holistic manner nor do they intuitively and simultaneously reflect information pertaining to the as-planned and as-built spatial and visual aspects of construction as well as their associated complexities [as stated by Lee and Peña-Mora (2006), Poku and Arditi (2005), Korde et al. (2005), Song et al. (2005), Kamat and Martinez (2002), and Koo and Fischer (2000)]. These representations result in significant amount of information to be inefficiently presented in meetings and as a result, time is spent on describing existing problems and explaining the rationale of decisions rather than evaluating alternatives and discussing what-if scenarios and corrective actions (Golparvar-Fard et al. 2006). With textual representations, it is difficult to understand the situation clearly and quickly. It is even
more troubling when the need for frequent remote and quick decision making in construction is considered (Lee and Peña-Mora 2006). Besides, most organizations do not have standardized reporting procedures or employ different control systems which create miscommunication in progress reporting. In this case, the ability to effectively communicate progress information and represent the discrepancies is a definite prerequisite for a successful project management.

Visualization of progress through visual imagery has been recognized by a number of researchers as an effective way to communicate progress monitoring metrics (Lee and Peña-Mora 2006; Poku and Arditi 2006; Kerzner 2005; Song et al. 2005; Abed et al. 2003). For the purpose of progress monitoring, this requires both as-planned and as-built information to be integrated and visualized to provide a holistic view of all processes during construction progress. Therefore in this paper, a visualization technique for progress monitoring is presented that visualizes progress deviations through superimposition of four-dimensional (4D) as-planned model on real time-lapsed photographs in single and comprehensive visual imagery.

Visualization of the as-planned progress in 4D environment enables project participants and clients—regardless of their level of construction knowledge and expertise—to understand spatial constraints and explore design and construction alternatives before construction starts. It provides a consistent visual platform and a common language of as-planned construction that could be extended to the monitoring phase (Song et al. 2005).

In addition, visualization of as-built progress in photographs not only has the advantage of being understandable to those who are not well versed in studying written material or numerical data analysis or even those who question verbal or written reports (Oglesby et al. 1989), but also allows large amount of data to be understood and absorbed quickly. Compared with progress reporting techniques which generate words and numbers, techniques such as time-lapse photography and videotaping provide a rich data set that can be a good source for as-built data collection and act as good communication tools for progress monitoring among the project participants.

Considering these advantages, the presented visualization model integrates the 4D model and time-lapsed photographs within an augmented reality (AR) environment where progress discrepancies are identified and visualized. To present this model, this paper begins with introducing the challenges of progress monitoring followed by the proposed methodology that visualizes discrepancies between the as-planned and as-built progress. In the subsequent sections, three important steps for the augmented photograph are explained in details: (1) 4D simulation as the underlying context for representing visualized metrics; (2) Time-lapse photography and real-time filming for as-built progress data collection; and (3) visualization techniques to represent performance metrics on augmented photograph. As a part of the system, registration of the 4D model with photographs, augmenting photographs and occlusion removal for progress images of the building structure and façade are presented. While contextual information in photographs is preserved, the real-world image is enhanced and augmented with 4D simulation model where performance metrics are visualized. The augmented photographs provide a consistent platform for representing as-planned, as-built, and progress discrepancies information and facilitate communication and reporting processes.

Challenges with Construction Progress Monitoring

Project managers require a robust monitoring system that ensures most up-to-date design, schedule, cost, and progress performance data are delivered and represented in a timely and a comprehensive manner so that control decisions could be made as quickly and easily as possible. Proper implementation of such a system reduces the time for routine decision makings and in turn overall project cost and duration. According to Barrie and Paulson (1992) such a system should have these characteristics:

1. To provide an efficient and effective means of measuring, collecting, verifying, and quantifying as-built data reflecting the progress and operations with respect to schedule, cost, resources, procurement and quality.
2. To accurately convert as-built progress data from construction operation into information. The system should be realistic and should recognize means of processing the information, the skills available, and the value of information compared with the cost of obtaining it.
3. To identify and assess the critical information from a given progress situation.
4. To report the information to managers in time and in a form which can best be interpreted by management, and at an appropriate level of detail for the individuals who will be using it so that corrective action could be taken on the progress situation that generated the data in the first place.
5. To record the control action taken; to represent the as-built performance of the project.

Without data collection, thorough comparison of the planned and as-built performance and a proper communication and recording, there may be no basis for proper project control and decision making. This requires progress data to be analyzed and maintained in a desired level of detail (i.e., according to decision maker’s needs) so that understanding the progress would be easier (Jung and Kang 2007); however the process of monitoring is faced with a series of challenges such as

1. Current progress monitoring is time consuming and labor intensive. Projects are not constantly monitored making it very difficult to take corrective actions in a timely basis. Current methods require manual data collection and also extensive data extraction from construction drawings, schedules, and budget information produced by project teams in which none is independent (Navon 2007). Field staffs collect progress data from the construction site, analyze, and deliver them to project managers in a format specific to their areas of expertise, e.g., construction drawings, spreadsheets, bar charts, critical path method (CPM), or progress site photographs or videos. Such discrete and exhaustive reports could be produced but do not explicitly convey level of performance, problems, and their causes and impacts on construction situation (Song et al. 2005). Consequently, project managers need to devote significant amount of time and effort to sort out, prioritize, and interpret these data.
2. Quality of manually collected and extracted progress data are low. Manual collection of progress information—usually acquired by field staff—is dependent on the status seen on site and the information collected, which in turn makes it subjective and may not reveal the impact of site circumstances on construction (personal communication with field staffs on five different projects (9/2006–6/2007); Navon and Sacks 2007). This may affect the quality of the collected data and makes it error prone since the ability of anticipating possible
outcomes based on the collected information, depends on the ability and expertise of the project manager.

3. Existing methods of measuring progress are nonsystematic and generic. Accurate measurement of the progress performance usually poses the most difficult data gathering problem as there may be a tendency to let project inputs serve as surrogate measures for output (Meredith and Mantel 2003). For example, a concrete subcontractor reports to the project manager that they have completed 60% of their work or reached 60% of their performance goal. Does it mean 60% of the planned area/volume of concrete pouring is finished? Is it 60% of the planned concrete that has been used? Or is it 60% of the planned man hour that is spent? If the item being referenced is a small work unit, it may not have a significant difference; however, in case where the references are to the whole task or project, assumption of input/output proportionality could be very misleading (Meredith and Mantel 2003). Thus, the most commonly used methods to monitor progress are: (a) Monitoring physical progress in percentile: used in most construction fields that heavily relies on experience and knowledge of the project management personnel. This metric is used subjectively and is inefficient at presenting progress due to its abstract nature representation of physical progress (Song et al. 2005); (b) Budget based monitoring: based on percentage of the budget paid to contractors according to the schedule-based inspections. This method of monitoring creates time lag between progress estimations and schedule updates; besides, judgments are usually subjective and misleading especially if a field manager makes any erroneous decision (Shih and Wang 2004). Without a specific comparative analysis on construction plan, resources, and cost data, wrong assumption and inaccurate measurement on the progress status could be made. Mistakes such as over paying and overlook of expected delay might appear.

4. Progress monitoring reports are visually complex. Kerzner (2005) argued that 30 to 40 different data representations are currently being used in construction industry. These graphical representations can serve several functions such as showing data, analysis methodology, and communication means (Oglesby et al. 1989). These methods require drawing, sketches (to show layout and physical details), and graphs and charts (which present numerical data and the results obtained by observation) to represent schedule, cost, and performance. The choice among them is dependent on the intended audience. For example, upper level management may be interested in costs and integration of activities with very little detail; hence summary-type charts normally suffice for this purpose. Daily practitioners, on the other hand, may require as much detail as possible in daily schedules. In addition, understanding the situation only based on the schedules may be difficult as they lack information relating to spatial context and complexities of project components (Koo and Fischer 2000). None of the existing reporting methods effectively present multivariable information (i.e., schedule, cost, and performance) in a holistic manner nor do they reflect the spatial and visual aspects of as-planned and as-built construction and their associated complexities simultaneously. Consequently it affects the ability of communicating effective progress information which is a definite prerequisite for successful project management.

Based on the deficiencies mentioned and considering challenges with current reporting formats and communications, the visualization of progress monitoring is presented. In the following section, components of the visualization technique which results in augmented photographs are discussed.

### Visualization of Progress Monitoring

Visualization techniques have been widely adopted in construction, from visualizing construction management data (e.g., Korde et al. 2005; Songer and Heys 2003) to the physical artifacts that are to be built to facilitate constructability reasoning or workability of the operation methods selected for its construction (e.g., Kamat and Martinez 2003). However the focus of the visualization techniques in this paper is on their application of as-planned 4D simulations to augment as-built progress photographs with the purpose of project monitoring and control. In this context, Song et al. (2005) introduced project dashboard as a three-dimensional (3D) model visual representation to show a holistic picture of a project by applying the multiple project data sets to the geometric attributes (e.g., shape, faces, and edges) of the building product model through color-tone variations and motion. It was suggested that consistent application of colors would allow project performance metrics to be represented easily. This would also purge visual complexities which could be caused by complexities associated with large and sophisticated building product models. Nonetheless in their presented system, as-built progress was not visualized using photographs or any other means different from that of as-planned model. Rather, geometric attributes of the building product model were used to communicate progress. Based on the same concept of consistent visual representation, Lee and Peña-Mora (2006) superimposed planned product models with photographs and initiated a new paradigm on visualization of construction progress monitoring where deviations between planned and as-built performance models were conceptually represented in an AR environment. AR is an environment wherein virtual and real world are combined to enhance user’s experience of the virtual world through contextual information (Wang and Dunston 2005; Azuma 1997). It gives the user the ability of observing the background environment and superimposes virtual model over the real-world background. Considering the benefits of visualization techniques and AR environment for visualization and automation of progress monitoring specifically assisting project managers, a new approach is presented which integrates three different modules.

1. **4D Simulation as the as-planned progress information,**
2. **Time-lapse photography and videotaping as the as-built progress data collection, and**
3. **Visualizing progress through augmenting the as-built photograph with the as-planned data**

### 4D Simulation as the As-Planned Progress Data

4D simulations have been developed for the main purposes of detecting spatial and temporal conflicts, understand construction logistics, coordinate the construction with subcontractors and trades, and demonstrate the planned progress to the owners (Tabesh and Staub-French 2006; Kamat and Martinez 2003; Kam and Fischer 2002). This kind of a time-based monitoring focuses on a preconstruction study that will allow for better management of a site afterward (Haymaker and Fischer 2001). So far, 4D tools have not been used for project progress management through as-built data collection during the construction phase (Chin et al. 2005). Currently 4D applications are able to detect some scheduling errors in the construction and enable project participants and
clients, regardless of their level of construction knowledge, to understand the spatial constraints and explore design and construction alternatives before construction starts. However, a pre-construction simulation cannot necessarily take into account every incident that might occur to the parts of a building under construction but could be used as a base for the as-planned information. 3D and 4D models can provide realistic visual expression, a consistent visual platform, and a common language of as-planned information for all parties involved within a project (Song et al. 2005). Specifically, an industry foundation classes (IFC)-based 4D system that contains all the information of the as-planned parts and their relationships, not only can serve as a complete as-planned database but also serves as the underlying structure for monitoring progress where deviation between the as-planned and as-built progress could be visualized. Fig. 1 demonstrates snapshots of a 4D simulation superimposed on time-lapsed photographs.

**Time-Lapse Photography and Videotaping as the As-Built Progress Data Collection Techniques**

Photography and filming have proved for many years to be very useful means for recording site progress photo logs and work-face activities (Brilakis et al. 2005). With the advances of digital photography and webcams, these methods of information gathering are more cost-effective, practical, and acquiring a substantial footage is not costly. They have all the advantages found in time studies without the disadvantage of high data gathering costs. Owners and contractors usually acquire construction site time-lapsed photographs from a fixed location or capture videos for a series of functions (1) to create a photo log for dispute resolutions and litigation purposes and (2) permanently record certain field operations of an individual or a crew or a machine and the interactions among them for progress monitoring records and reports. Fig. 2 shows four construction progress photographs out of a time-lapsed photograph collection for a construction site over a two year period.

Table 1 demonstrates the advantages/drawbacks of time-lapse photography and videotaping. Despite their various advantages, photographs may not demonstrate construction site information in very severe weather, illumination and shadow conditions. For example, Figs. 3(a–c) demonstrate the construction site under fog, rain and snow weather conditions respectively and shows how weather conditions can affect the quality of time-lapsed photographs in a construction site.

Shadow is another problem which is caused by adjacent buildings or elements (temporary or permanent) and affects visual quality of photographs. Figs. 4(a–c) show three photographs that are selected out of a working day photo log. These photographs show how shadow affects the visibility of the work site and how these effects may reduce visibility of the elements on a photograph. However since a full set of photographs are collected during working hours, different zones and locations on the jobsite could be studied at different times.

Since progress is usually measured within weeks or even days (not hours), this allows the selection of more visible photographs for the purpose of analysis and representation. Furthermore, application of robust image analysis and pattern recognition tech-
niques such as Gaussian filters (Forsyth and Ponce 2003) allows the photographs to be enhanced which in turn reduces and/or neutralizes these effects.

Overall, compared with techniques that generate only words and numbers, photography has the advantage of being easily understandable and believable to those who are not well versed in studying material or numerical data analysis or who question verbal and written reports (Oglesby et al. 1989). This technique is particularly useful when the activities depicted are not going as smoothly as they might, since it is difficult for anyone to argue successfully that the photographs do not portray the as-built work situation.

Visualizing Construction Progress

Considering the existing generic progress monitoring methods, earned value analysis (EVA) can provide a monitoring basis and allows the future performance to be forecasted. Although EVA has some limitations as referred in Kim and Ballard (2000), but since in EVA, all the construction work is planned, scheduled, and budgeted in time-phased planning value increment, it can constitute a performance measurement baseline (Abba 1997) which is useful for comparison. EVA provides information in terms of as-built conditions, potential issues, prior concerns, and future scenarios in one construct. Along with time photography as an automated data collection method, 4D model and cost database, for every decision making, EVA performance metrics needs to be calculated and visualized. The scheme of using this methodology is further explained in the subsequent section.

Progress Monitoring Visualization System Scheme

Visualization process consists of a series of modules which results in color coded time-lapsed AR imageries. Fig. 5 summarizes the information action-representation-environment perspectives for the proposed system. As represented in Fig. 5, raw data are collected from two different sources: the as-planned and the as-built performance environments. The collected information represents

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Drawbacks</th>
</tr>
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<tbody>
<tr>
<td>Easy to obtain progress images</td>
<td>Distortion of images—make it challenging to superimpose images</td>
</tr>
<tr>
<td>Inexpensive</td>
<td>Show what is not obstructed by objects such as construction machinery or scaffoldings</td>
</tr>
<tr>
<td>Time-lapsed photography continuously records and yields benefits of filming without diminishing understanding of the operations that is recorded</td>
<td>Show what is within range and view field</td>
</tr>
<tr>
<td>Easily understandable by any visually able person</td>
<td>Various illumination, shadows, weather and site conditions makes it difficult for image analysis</td>
</tr>
<tr>
<td>Provide more detailed and dependant information</td>
<td>Storage of digital photographs/videos</td>
</tr>
<tr>
<td>Making possible review and study by analysts, management, or other groups away from hustle and bustle of the work site</td>
<td>Suitable for progress monitoring and productivity analysis</td>
</tr>
</tbody>
</table>

Table 1. Advantages and Drawbacks of Time-Lapsed Photography and Videotaping

Fig. 3. Different weather conditions during a construction project: (a) fog; (b) rainy; and (c) snow (Photograph subject: Institute of Genomics Biology, UIUC. Source: Information, Technology and Communication Services, College of ACES, UIUC.)

Fig. 4. Effect of shadow on a single working day (Photograph subject: Institute of Genomics Biology, UIUC. Source: Information, Technology and Communication Services, College of ACES, UIUC.)
product models, i.e., IFC 3D as-planned model and site photographs (Fig. 5, 1-A and 1-C), process models, i.e., working schedule and operation process (Fig. 5, 3-A and 3-C) and cost modules, i.e., estimated and performed costs (Fig. 5, 4-A and 4-C).

Collected information from these two environments is merged to produce a 4D as-planned simulation and time-lapsed photographs (Fig. 5, 2-A and 2-C, respectively). For any given time, the as-planned model is superimposed on the as-built performance model (i.e., site photograph) (Fig. 5, 2-B). This process involves proper registration of the 3D virtual world and photograph coordinates. The superimposed imagery would allow discrepancy to be either manually or automatically detected and quantified (Fig. 5, 3-B and 4-B). At this stage, cost values are extracted from estimated and actual construction cost modules and are integrated to the system (Fig. 5, 4-A and 4-C). This would allow cost information required for EVA to be derived. This information is appended to the known as-planned and as-built information and allows the budget spent to be properly assessed and the cost discrepancies to be understood.

The next step is to monitor progress against the performance measurement baseline, or the planned value. The physical earned value performed is then related to the actual costs spent to accomplish the physical work performed, providing a measure of the project’s cost performance. To establish the guideline for the proposed system, the IFC as-planned model and the work breakdown structure in the schedule are considered as the basis of monitoring (Fig 5, 2-A). The level of details is based on the product and process work breakdown structures and cost estimating scheme in the as-planned model. For example if a general contractor schedule is provided, only major activities associated with building elements are visualized in the 4D model and monitoring system only involves that level of details in the schedule as the baseline for measurements. If a detailed daily schedule is available, the 4D as-planned model may further visualize the dynamics of the construction operations and the site, such as temporary structures and site layout. In this case, a more detailed progress measurement is possible. However, visualizing detailed construction activities such as electrical rough-ins may not be possible and therefore at this stage, the proposed model only incorporates construction schedules with a visible physical progress level in terms of the building structure and façade. Based on the guideline set during the planning phase and generation of the as-planned model, interpretation and assessment of the data would be performed in the subsequent steps.

At the following step, a series of visualization techniques is applied to visualize EVA metrics (Fig. 5, 5-B); i.e., according to the status of the progress, the as-planned model would be color coded and superimposed on top of the photograph. Once the status of the progress is represented on the superimposed image, any occlusion and blockage caused by the superimposition should be removed. Therefore depth and perspective integrity of the virtual and actual environments is maintained (Fig. 5, 6-C). The final imageries are represented for decision making and are kept as a record for progress monitoring photo log.

This reporting process is repeated for every coordination cycle where control actions are taken and the construction schedule is revised and updated by project participants. For example, if architectural/engineering/construction teams have coordination meeting every other week, this report would provide progress information from the last meeting to the current meeting considering the same time period for future activities that may have been performed in the project. In this section, an overview of the data collection, comparison baseline, and assessment processes have been discussed. In the sections that follow, each of the steps

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**Fig. 5.** Information action-representation-environment perspectives for visualization of construction progress monitoring

<table>
<thead>
<tr>
<th>Information Action Perspective</th>
<th>Data Representation Perspective</th>
<th>Information Environment Perspective</th>
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<tbody>
<tr>
<td>Collect</td>
<td>Product Model</td>
<td>As-planned Progress Model</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AR Model</td>
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<tr>
<td></td>
<td></td>
<td>As-built Progress Model</td>
</tr>
<tr>
<td>Interpre</td>
<td>Product Model</td>
<td>Site Photograph</td>
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<tr>
<td></td>
<td>+ Process Model</td>
<td>(1-C)</td>
</tr>
<tr>
<td>Collect + Assess</td>
<td>Process Model</td>
<td>4D Simulation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Product+ Process)</td>
</tr>
<tr>
<td>Collect + Assess</td>
<td>Cost Module</td>
<td>Schedule and Work Breakdown</td>
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<tr>
<td></td>
<td></td>
<td>Structure</td>
</tr>
<tr>
<td>Represent</td>
<td>Visualization Module</td>
<td>Detect Deviation</td>
</tr>
<tr>
<td>Record</td>
<td></td>
<td>(Product Components + Process</td>
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<tr>
<td></td>
<td></td>
<td>Activities)</td>
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<td></td>
<td></td>
<td>Quantify Physical and Monetary</td>
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<td></td>
<td></td>
<td>Deviations</td>
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<td></td>
<td></td>
<td>Actual Schedule</td>
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<td></td>
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<td>Visualize Deviation on Superimposed</td>
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<td></td>
<td></td>
<td>Image</td>
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<tr>
<td></td>
<td></td>
<td>Remove Occlusion/Blockage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Final Representation</td>
</tr>
</tbody>
</table>

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any point in the 3D model such as \( P(x,y) \) needs to be precisely related to image coordinates \( p(u,v) \). In the case of time-lapsed photographs, the camera location is fixed on the construction site, therefore, ideally, if camera is registered once, the correspondences between the photographs and the virtual model would be set for all subsequent images; i.e., with the same correspondence relationship, all the images of the 4D environment could be superimposed on the photographs. However, photographic cameras, webcams, and/or video recorders similar to any surveying camera are subject to displacement and vibration caused by gravity and lateral forces such as wind. Fig. 7 shows the camera registration error. A deviation in camera angle can make a major error in registration. As seen, perspective views A and B are seen from the same location with different view angles.

Due to these potential registration errors, the camera needs to be regularly adjusted. In this scenario, it is assumed that the location of the camera will be regularly fixed at all times and the same correspondence relationship between the 3D virtual world and the photograph coordinates could be applied to all time-lapsed photographs.

Then after knowing the camera is fixed, correspondence between the 3D model and photograph needs to be set. The photograph and camera coordinate systems are related by a set of physical parameters, such as the focal length of the camera lens, the size of the pixels, the position of the principle point (of the lens), and the position and orientation of the real world (Forsyth and Ponce 2003). In order to register the camera, these intrinsic and extrinsic parameters of the camera should be defined. Intrinsic parameters relate the camera coordinate system to the idealized coordinate system (i.e., effective focal length, aspect ratio, image center coordinates, and radial distortion coefficient) and extrinsic parameters relate camera’s coordinate system to a fixed camera coordinate system and specify its position and orientation in space (i.e., rotation matrix and translation vector) (Forsyth and Ponce 2003). Estimating these parameters of a camera is called geometric camera calibration (Forsyth and Ponce 2003). If we consider \( p = (u,v,1) \) and \( P = (x,y,z,1) \) to be the homogenous coordinates of the points in the photograph and the virtual world, the relationship between these points in general terms can be represented as

\[
p = \frac{1}{z} M P
\]

where \( M_{3 \times 4} \) is the projection matrix and \( z \) is the depth of the point.

To solve Eq. (1) for \( M \), a set of features (i.e., points) with known positions in the photograph and the 3D environment are required. In order to achieve good and predictable results for \( M \), there is a certain amount of preparation that needs to be done manually. This preparation consists of two main areas: (1) Identifying “matchable” features in the photograph and (2) associating 3D features (from the virtual model) to the features chosen in the photograph.

It is extremely important for setting correspondences and solving the equation to choose accurate features (points) within photograph and 3D model. However, since photographs are formed in pixels, finding the accurate positions for features could be a very challenging task. For example, let’s assume that the selected feature to be the top corner of two converging concrete walls. In a low quality photograph, this point could be located in-between pixels and it affects the quality of the preferred location for registration purposes which affect preciseness and quality of registration. An alternative to increase the accuracy for solving this equation is to extract more features from the photograph. Therefore, by selecting more features to establish the correspondence, the error in a single feature selection would not significantly af-
fect the overall registration outcome and therefore the cumulative error in feature selection would be minimized. Fig. 8 shows an example of feature selection and setting correspondence relationships for three points. As shown in Fig. 8, the points extracted from photograph pixels with plus symbols (+) are related to 3D world coordinates indicated with cross symbols (×).

In this situation where more than minimum required features are selected, instead of directly solving the equation, camera calibration [Eq. (1)] would turn to an optimization process for the error function where the discrepancy between image features and their positions in the virtual world with respect to the camera’s intrinsic and extrinsic parameters is minimized. It is also imperative to have features spread out evenly throughout the photograph—which represent the space from foreground to background as well as the side-to-side and up and down distance—to allow a more accurate calibration. To automatically perform the registration, Autodesk Viz (2007) camera matching toolbox has been used. This toolbox requires at least five points to calculate a solution based on aforementioned error function; however, it is better to choose more features to refine the matching through the iteration. Fig. 9 shows how feature selection and the correspondence setting is performed for a photograph. In this case, surveying information of the site (location of the benchmarks) is not known and the matching needs to be performed given the photograph information and the 4D model. Therefore, first, an IFC-based model of the building at an early stage of the 4D environment is imported to Autodesk Viz (2007). A photograph of the same time frame of construction in which various features of the construction entities could be detected is placed as the background in the matching window. Now a set of features are selected from the photograph and will be matched to their correspondence in the 3D model. Particularly, corners of converging entities (e.g., top and bottom corners of converging foundation walls) would be a good choice. Despite diminishing effects of shadow with reducing visibility of the images, shadow could be very helpful in camera calibration, since it would allow corners of any selected entity to be easily chosen. To increase the accuracy of registration and minimize the effect of pixelized photographs, fifteen features are selected from various surfaces and different elevations within the photograph (i.e., top and bottom corners of converging foundation walls and converging walls/columns). The number of features required to achieve a precise registration (in this case 15 features) is selected through an iterative process in which a desired visual registration is achieved, i.e., a minimal error in the matched figure visually resides. Fig. 9(c) shows some of these selected features where the plus sign shows the location in the photograph and the cross sign, the location of those features within the 3D model. In this case, a cumulative registration error of 1.45 pixels is achieved which has resulted in a visually precise registration. The superimposed 3D on the photograph is shown in Fig. 9(d).

Progress Assessment on the Superimposed Imagery

Once the camera is registered, the as-planned model can be superimposed on the photograph. At this step, discrepancies between the as-planned model and the photograph (as-built) can be easily identified. Given the deviations observed, EVA metrics are obtained (compared to schedule or cost information, Fig. 5) and a color (depending on the progress status) is assigned to the planned model. Fig. 10 shows the assessment of the schedule deviation on a building project. Before a coordination meeting, a series of actions are performed to prepare the visualized progress monitoring status. A photograph of the basement level of a building taken on December 2, 2006; 1:13 p.m. and a registered snap-

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**Fig. 8.** Feature selection and setting correspondences between a part of a photograph and 3D coordinate system. Plus symbols (+) in (a) show the pixels correspondences of cross symbols (×) within the 3D coordinate system in (b).

**Fig. 9.** From top to bottom: (a) Site photograph superimposed with 3D model in Autodesk Viz environment; (b) site photograph; (c) close view on feature selection and matching between the photograph and the 3D model; and (d) superimposed 3D model on the site photograph (Photograph subject: College of Business Instructional Facility; Facilities and Services, UIUC; Application: Autodesk Viz).
shot of the 4D as-planned model taken on the same time are represented in Figs. 10(a and b), respectively. Based on the visual comparison between the photograph and the as-planned model, discrepancies are identified. These discrepancies have been manually analyzed and the physical components of the basement level that are behind or on-schedule are identified. The schedule deviation is quantified by the management team based on the construction schedule and based on the EVA analysis performed. Then, different colors (light green for on schedule and red for behind schedule) are assigned to each of the components depending on its progress status.

It is clear that as more components are constructed or install on the site, the number of 3D model components in the 4D environment increases and as a result visual representation could potentially become more complex. Given the identified deviations, a consistent visual scheme is required to simplify and facilitate its

**Fig. 10.** From top to bottom: (a) the site photograph taken on December 2, 2006, 1:13:27 p.m.; (b) snapshot of the 4D model at the same time as the photograph; (c) superimposed image; (d) schedule deviation detected and color coded according to the schedule in (e); and (f) color-coded superimposed 3D model on the site photograph (Photograph subject: College of Business Instructional Facility, UIUC. Source: Facilities and Services, UIUC.)
interpretation. Therefore, in order to effectively and consistently use these visualization techniques, a single color spectrum ranging from dark red to dark green for all possible EVA monitoring and project performance metrics based on an underlying metaphor of a traffic light is proposed (Fig. 11). This metaphor can manually or automatically visualize various project metrics with discrete values. For example it categorizes building elements based on their schedule deviations in three distinct categories: ahead of schedule, on schedule, and behind schedule (Fig. 11). According to Fig. 11, light green is used to represent those components that their performance is “as-expected,” dark green for those components that are performing “above expectation,” and they need the least management effort, while red color represents components that need corrective action. Once the status of progress for each building component is identified, these colors are assigned to the 3D components and the color coded 3D as-planned model is superimposed on the photograph. Fig. 12 shows the site and superimposed photographs representing as-built and progress status respectively. As seen in Fig. 12(b), behind-schedule 3D entities that are color coded in red, on-schedule 3D entities in light green and ahead of schedule in dark green. In Fig. 12(d), behind schedule steel members along with parts of the foundation components are color coded in red which represent that these components may need corrective actions in order for the project to be on schedule. The application of color gradients and color quadrangles to visualize multiple progress parameters together or ranges values for a progress situation has also been considered [please refer to Golparvar-Fard et al. (2007)]. Authors have implemented a “MouseOver” action on these augmented photos to make these imageries are interactive and provide progress status information associated with the colors. This potentially allows the user to also extract progress monitoring data from the visualization system.

**Static Feature Extraction**

Some visual features, such as excavation profile, fixed components on the site such as light towers and/or trees are static on the

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<th>Color Spectrum</th>
<th>Poor</th>
<th>As Expected</th>
<th>Excellent</th>
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<td>On-Schedule</td>
<td>Ahead of Schedule</td>
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**Feature Extraction (Occlusion Removal Techniques)**

Once the augmented photographs are generated, in order to keep the realism of the scene and perspective integrity of the virtual and actual environments, the occluding objects needs to be placed on the original depth in which they appear from the perspective of the viewer (Fig. 5, 6-C). This requires two types of features to be extracted: (1) Static features and (2) dynamic features. These features are explained as follows.

**Fig. 11.** Critical information sets for project managers during construction phase and the color spectrum

**Fig. 12.** From top to bottom: (a) the site photograph taken on January 3, 2007; 12:35:13 a.m.; (b) the color-coded superimposed photograph at the same time as the photograph (a); (c) the site photograph taken on January 8, 2007; 4:08:21 p.m.; and (d) the color-coded superimposed photograph at the same time as the photograph (c) (Source of the photographs: Univ. of Illinois, Facilities and Services)
time-lapsed photographs, i.e., the shape or location of these features, do not change rapidly. Once the superimposition of the colored as-planned model on the site photograph is performed, some of these features are overlaid with the color coded 3D model, while in camera’s line of sight, these features are located in front of the as-planned 3D model and should not be occluded by the model. Hence these features need to be extracted from the original site photograph and overlaid on the superimposed image. Since these static features do not frequently change throughout the period of construction, once they are recovered, the same process could be applied to the rest of the time-lapsed photographs. In computer vision, there are many different edge detection techniques that could help in finding these features within a photograph. These methods include but are not limited to Canny, Sobel, Robert, Laplacian of Gaussian, and SUSAN (smallest univalue segment assimilating nucleus) edge detection techniques (Shin et al. 2001; Smith and Brady 1997). All these methods could be used to detect corners of the features and localize them. Among these methods, SUSAN edge detector had been applied in this research due to its good detection, localization, response, and speed to be usable for image processing systems compared to the rest of the mentioned edge detection techniques (Shin et al. 2001; Smith and Brady 1997). In this method, nonlinear filtering is used to define image parts that are closely related to each individual pixel. These pixels are associated with their local regions within the photograph that have similar brightness to that pixel. Feature detectors are based on minimization of local regions and noise reduction. The detail of this method is not scope of this paper and could be found in Smith and Brady (1997); rather the applicability of the method to extract static features is described in the AR model. Fig. 13 shows the result of applying the SUSAN edge detection in recovering the excavation line, light poles, and some machinery located on the construction site. The recovery of the information below excavation line in the photograph has been done in a supervised manner, i.e., the required recovery section is manually selected and it is automatically applied to subsequent time-lapsed photographs.

Another possible way to overcome static occlusion problem is to model the static occluding objects in 3D model and have them hide the geometry of the augmented images just as any real object hides the background in photographs. (The writers would like to acknowledge that this idea was suggested by one of the anonymous reviewers of the paper.) However this method may increase the level of details required for 3D modeling and would not be suitable for cases where the occluding objects, themselves needs to be detected and/or tracked.

Dynamic Feature Extraction
Along with aforementioned static features, dynamic features also exist within photographs such as construction machinery, temporary structures, and work crew. These features also need to be extracted to be overlaid back on the photograph to preserve depth and perspective within the superimposed photograph. The same feature detection technique i.e., SUSAN are applied to dynamic feature extraction. As seen in Fig. 13 the truck in front of the foundation wall is also recovered. This method required manual supervision and could be time consuming while other techniques such as identification of moving objects between consecutive images or using different points of view that do not have the machinery crossing their field of view could also be considered for future implementations to reduce such overheads. (The writers would like to acknowledge that this idea was suggested by one of the anonymous reviewers of the paper.)

Visualized Progress Report
Fig. 14 illustrates a visualized report of progress monitoring. In this figure, the photographs and 4D snapshots are presented and based on the work schedule and the comparison performed, deviations are identified and are color coded. The deviations are also quantified based on the number of days according to the schedule and are reported. Finally, based on the actual cost occurred and the planned costs, cost performance index (CPI) and schedule performance index (SPI) are calculated and presented [Fig. 14(f)]. These forms of reporting can facilitate the coordination process by reducing the time to inform the participants as to what the situation is. Once the superimposed photographs are ready, the report table could be generated. This sort of representation does not require the observer to have any expertise or knowledge about construction operations.

Based on the positive feedback received from the professionals and executives of the five construction case studies in this research as well as other executives from leading construction companies, writers believe the visualization will facilitate progress monitoring process.

Conclusions
This preliminary method has shown that AR environment can successfully represent progress monitoring information in forms of as-planned, as-built information along with their comparison in a holistic manner. The superimposed images retain all the con-
struction site information while the planned information along with the status of progress is enriching the contextual information within these photographs. The registration method gives the opportunity for image processing to be applied to specific regions within the photograph to assess the status of the progress based on material and shape recognition techniques. Color-coding metaphors give the end users of the superimposed photograph the opportunity of grasping progress status based on a single representation form and could facilitate the communication of progress status within a coordination meeting, allowing more time to be spent on control decision making. Moreover preliminary results of applying feature detection technique preserves depth and perspective within the superimposed photograph allowing a more realistic picture of the progress status to be represented. The overall methodology and reporting addresses the issues related to data collection and reporting steps of a robust progress monitoring.

**Future Work**

This work is part of a larger project that aims to automatically generate superimposed photographs for progress monitoring. Overall, the aim is to develop methods and processes within an AR environment that automatically and distinctively recognize visual construction content within site photographs, compare with the as-planned 4D model and visualize the status of progress using visualization and project management techniques. Considering application of time-lapsed photographs for visualization of as-built data collection, two major challenges are identified.

**Challenges with Time-Lapsed Photographs for Visualization and Assessment of the As-Built Data**

**Occlusion/Proximity Problems for Data Collection**

Type of structures (e.g., steel, concrete, and composite), camera location for taking time-lapsed photographs (e.g., ground level versus upper levels, proximity of components to the camera), horizontal and vertical obstacles (e.g., static objects on site or blockage of the view of one element by the others), and outdoor versus indoor monitoring are all among the challenges of visualizing as-built data. Fig. 15 shows two different scenarios on horizontal and vertical occlusions and the challenges of visualizing progress only on a single view. As seen in Figs. 15(a and b), a column is occluded since there is another column which is blocking camera’s line of sight toward to the specific column under study. This situation has been solved by moving the camera to a...
new location. The vertical occlusion case is also shown in Fig. 15(e) where the slab has blocked the view toward the beam. There is a need for finding the optimum locations of a network of cameras both for outdoor and indoor progress monitoring to make sure all the elements could be monitored and data required for as-built progress is collected. In addition, authors suggest using an unordered set of registered photographs that are taken from various viewpoints to tackle the occlusion issue, and/or using a remote helicopter to capture photographs in order to avoid angle and line of sight issues for higher elevations.

Automatic Photograph Analysis for Progress Monitoring
Considering all the challenges with shadow and illuminations, a series of image processing and pattern recognition techniques is required to make sure progress of any type of element regardless of the material used or the texture of the surface could be detected under nonsevere noise in the photograph.

Challenges with As-Planned Data
Although the baseline for progress monitoring would be the as-planned model, the correspondence between the schedule information and a product model on one side and the level of details within the 4D model on the other side, creates two major challenges for its application as a baseline for monitoring: (1) Activities with no correspondence in the 4D model: The 4D as-planned model does not represent all the information within the schedule. It may not show activities within schedule that do not have correspondence in the 4D model on the other side, creates two major challenges for its application as a baseline for monitoring; (2) Level of details in the 4D model: The major challenge with the as-planned data are mostly related to the level of detail for progress monitoring. Most of the 4D models can be viewed only in one level of detail. For example, it may only communicate schedule information within the general contractor’s interest and it may not include all the shop drawing details, however for progress monitoring these details could affect the decision made on the progress observed. For instance, considering a steel structure, the level of details within joints between columns and beams could be modeled but it may not be possible to perform the comparison in that level of details. The applicability of a 4D model with such level of detail depends on the robustness of image processing techniques in overcoming data collection problems and considering the occlusions.

Based on these challenges, the future work and automation of the visualization falls in four categories: (1) exploring more visualization techniques and perform testability and applicability of these techniques in communication of progress monitoring information on concurrent representation of performance metrics and work sequence visualization; (2) exploring time-lapsed photographing for data collection, optimum locations for exterior and interior data collection considering all the challenges discussed; (3) addressing measurement, quantification, and assessment of progress status using effective image processing and computer vision concepts along with using edge detection techniques from one side and on the other hand, formalizing a database for the system based on IFC; and (4) applying the technique on various construction projects. Ultimately, an all-inclusive methodology will be developed that not only visualized progress status, but automatically collects data, analyses the photographs, compares them to as-planned model database and visualizes progress status.

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