Research in Visualization Techniques for Field Construction

Vineet R. Kamat, M.ASCE[1]; Julio C. Martinez, M.ASCE[2]; Martin Fischer[3]; Mani Golparvar-Fard, M.ASCE[4]; Feniosky Peña-Mora, M.ASCE[5]; and Silvio Savarese[6]

Abstract: Field construction can be planned, monitored, and controlled at two distinct levels: (1) the activity or schedule level; and (2) the operation or process level. Graphical three-dimensional (3D) visualization can serve as an effective communication method at both levels. Many research efforts in visualizing construction are rooted in scheduling. They typically involve linking activity-based construction schedules and 3D computer-aided design (CAD) models of facilities to describe discretely evolving construction product visualizations (often referred to as four-dimensional CAD). The focus is on communicating what components are built where and when, with the intention of studying the optimal activity sequence, spatial, and temporal interferences. The construction processes or operations actually involved in building the components are usually implied. A second approach in visualizing construction is rooted in discrete-event simulation that, in addition to visualizing evolving construction products, also concerns the visualization of the operations and processes that are performed in building them. In addition to what is built where and when, the approach communicates who builds it and how by depicting the interaction between involved machines, resources, and materials. This paper introduces the two approaches and describes the differences in concept, form, and content between activity level and operations level construction visualization. An example of a structural steel framing operation is presented to elucidate the comparison. This work was originally published in the proceedings of the 2002 IEEE Winter Simulation Conference. This paper expands on the original work by describing recent advances in both activity and operations level construction visualization. **DOI: 10.1061/(ASCE)CO.1943-7862.0000262.** © *2011 American Society of Civil Engineers.*

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Introduction

Although the planning and control techniques used in planning construction at the project and operation levels are different, both can benefit substantially from dynamic three-dimensional (3D) visualization. Different people in construction thus understand different things by the term "visualization." As a result, the term has been used in the literature to refer to any kind of series of sequential computer frames without taking into account their origin or contents. In effect, numerous computer-based visual activities that can be directly or indirectly used for construction planning may be appropriately termed visualization. These activities include, but are not limited to, the animation of construction schedules [i.e., four-dimensional computer-aided design (4D CAD)], design analysis of construction equipment in physical simulation environments (e.g., Working Model), visualization of assembly sequences and real-time virtual interactive modeling of construction equipment (e.g., IV++), scenario creation and animation for interference analysis (e.g., Bentley Dynamic Animator), construction site model-based information access over the internet using VRML (Campbell 2000), and dynamic 3D visualization of discrete-event operations simulations (Kamat and Martinez 2001). This paper elucidates the differences in concept, form, and content between two notions of visualizing construction i.e., 4D CAD and 3D visualization of discrete-event operations simulations. This work was originally published in the proceedings of the 2002 IEEE Winter Simulation Conference (Kamat and Martinez 2002). This paper expands on the original work by describing recent advances in both activity and operations level construction visualization.

Activity Level versus Operations Level Construction Visualization

Visualization research efforts at the project or activity level are motivated by the shortcomings of traditional scheduling and control techniques such as bar charts and critical path method (CPM) in being able to represent all aspects of construction necessary for project level planning (Skolnick 1993; Koo and Fischer 2000). Visualization is achieved by linking a 3D CAD model representing the design of the facility and a construction schedule (Cleveland 1989). This form of visualization has popularly become known as 4D CAD. 4D CAD focuses on the visualization of the construction product over the period of its construction. As time advances, individual components (CAD elements) of the facility are added to the visual model in their final position and form as dictated by the schedule. 4D CAD models thus convey what physical components are built where and in which time frame. Numerous research

[1]Associate Professor, Univ. of Michigan (corresponding author). E-mail: vkamat@umich.edu

[2]Associate Professor, Purdue Univ.

[3]Professor, Stanford Univ.

[4]Associate Professor, Virginia Tech.

[5]Professor, Columbia Univ.

[6]Associate Professor, Univ. of Michigan.

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studies have explored and exploited such dynamic project level 3D visualization and documented its advantages and benefits.

In contrast, visualizing construction at the operations level, in addition to visualizing the evolving product, involves being able to view the interaction of the various resources as they build the product or perform a support service. These resources include, but are not limited to, temporary structures, materials, equipment, and labor as they create the product. At this level of detail, visualization of the evolving construction product can be achieved as a by-product if the operation visualized is of long duration.

To visualize an operation it is necessary to see, in addition to the physical components of the facility, the equipment, personnel, materials and temporary structures required to build it. Moreover, it is necessary to depict the movements, transformations, and interactions between these visualization elements. The movements and transformations must be spatially and temporally accurate. To depict smooth motion, visual elements must be shown at the right position and orientation several times per second. Issues such as trajectories in 3D space, speed, and acceleration need to be considered.

Visualizing construction operations also encompasses construction procedures that do not necessarily involve the assembly of a tangible product such as a building or a bridge. For instance, construction operations such as paving, tunneling, quarrying, and earthmoving can obviously be simulated and visualized at the operations level. However, at the project level, construction of this nature can typically only be planned in terms of the desired production rate, because the tangible product (e.g., pavement) is rarely decomposed into chunks suitable for 4D visualization. Some researchers have started to combine discrete-event simulation and 4D CAD by automatically creating 3D "chunks" of constructed products with geometric transformations (Akbas 2003).

Construction operations of any duration and complexity can be visualized dynamically in 3D by linking together discrete-event simulation models and CAD models of the infrastructure, construction equipment (i.e., machines), temporary structures, and other resources (Kamat and Martinez 2001). The results are smooth, continuous 3D animations of simulated construction operations that not only describe what is built where and when, but also convey who builds what and how they build it. Visualization of construction at the operations level allows us to see, graphically on the computer, the operations being carried out in the same way as they would in the real world. Such 3D animations of simulated construction operations facilitate rapid verification and validation of the underlying discrete-event simulation models. In addition, the practical and educational benefits of being able to visualize construction at this level of detail are tangible.

While being focused on project level planning and visualization, researchers and industrial proponents of 4D CAD have developed approaches to convey a subset of operational details in activity level visualization. For example, this is demonstrated by research works that aim to convey operations planning information about construction space requirements through 4D visualizations (Akinci and Fischer 2000; Riley 1998). The planning information that 4D visualization synthesizes is however derived from project level planning tools (i.e., CPM schedule and CAD model of the infrastructure). Therefore, it is not possible to visualize the actual construction operations that lead to the construction of the end product using the sources of 4D CAD (Adjei-Kumi and Retik 1997; Fukai 2000). In other words, 4D CAD can depict the evolution of the construction product, but not the interaction of the resources that build it. Activity level and operations level visualization, therefore, differ significantly in concept, content, and usage. The following sections will clarify and further elucidate these differences using an example of a structural steel frame erection operation.

Structural Steel Erection Example

Fig. 1 presents a typical framing plan for a multistory steel-framed building. The small rectangular formations in the middle of the building frame are typically provided for accommodating openings for elevators, stairways, and mechanical shafts. Erection of a multistory steel building frame starts with the first tier of framing. Each tier typically spans two building stories. Erection of the steel components begins with a crane that starts erecting the columns for the first tier. The columns are usually furnished in sections that are slightly taller than two stories to facilitate the splicing of column sections for subsequent tiers. The columns are picked up from organized piles on the site and lowered carefully over the anchor bolts and onto the foundation. After the first tier of columns has been erected, the beams and girders for the first two stories are similarly picked up, lowered, and bolted in place. The two-story tier of framing is then plumbed up using diagonal cables and turnbuckles. Erection of the subsequent tiers then proceeds much like that of the first.

Scheduling and Visualizing Steel Erection Activities

A scheduler may choose to represent the erection of the entire steel frame as a single activity in the planned construction schedule. Depending on the size of the building (and the frame), such an activity could span multiple days. In addition, erection of the frame may also be planned by dividing it into zones based on how wide the structure spans horizontally (Sawhney et al. 1999). A more elaborate schedule may also break up the erection operations into multiple subactivities such as (1) erect first tier columns; (2) erect first floor girders and beams; and (3) erect second floor girders and beams. Fig. 2 presents such a possible schedule for erecting the frame shown in Fig. 1. For simplicity, the subactivities of conveying and installing bundles of decking and/or installing and maintaining a safety net are omitted.

Based on the level of detail incorporated into the schedule, an activity level visualization involves depicting the state of the completed facility at the end of each unique activity (or subactivity). In the present example, a 4D CAD visualization would represent the

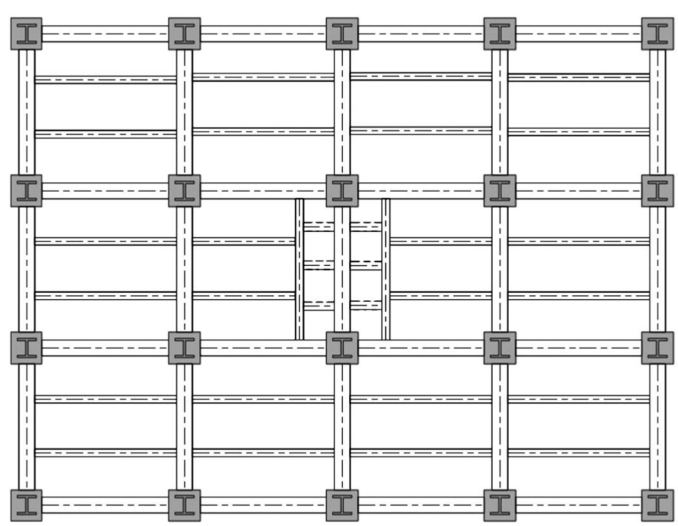

Fig. 1. Typical framing plan for a multistory steel-framed building (reprinted with permission from Kamat and Martinez 2002)

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Fig. 2. Possible steel frame erection schedule (reprinted with permission from Kamat and Martinez 2002)

status of the completed steel frame at the end of each of the subactivities, however detailed the level of subactivities. For example, the highest level of detail in erecting a steel frame is a single steel shape. However, a separate activity for erecting each frame is unnecessary from a scheduling point of view. Fig. 3 presents snapshots of a 4D CAD visualization corresponding to the schedule in Fig. 2.

The snapshots depict the state of the completed construction facility at the end of each uniquely identifiable activity in the construction schedule. These snapshots or series of snapshots allow project teams to coordinate the work of several subcontractors more easily, determine the weekly quantities of materials needed, and explain the flow of work at this level of detail. Static CAD models of cranes, temporary equipment, and materials may be included in such snapshots to help identify space and layout constraints and to increase the visual impact. However, the interaction of these resources and the processes involved in erecting the steel shapes themselves are not depicted in such visualizations. Furthermore, the duration of activities displayed in 4D CAD models is deterministic.

Designing and Visualizing Steel Erection Processes

Designing construction processes involves comparing and choosing among alternative construction methods, pieces of equipment, labor levels, and operating strategies for accomplishing the planned activities. The focus is on planning construction at the field (i.e., production) level.

Fig. 4 presents a Stroboscope (Martinez 1996) process model that simulates the processes involved in erecting the steel frame depicted in Fig. 1. A tower crane is used to erect the steel shapes. The schematic model presented in Fig. 4 is simple and self-explanatory. The model, however, exploits Stroboscope's concept of characterized resources and its programmability to simulate the operation in great detail.

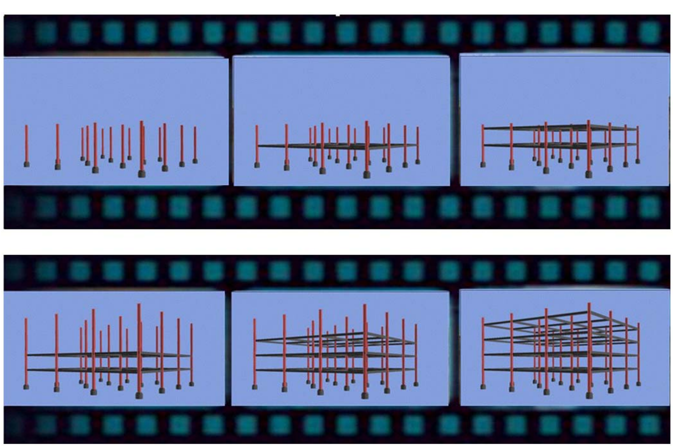

Fig. 3. Snapshots of 4D CAD visualization (reprinted with permission from Kamat and Martinez 2002)

Stroboscope characterized resources allow each steel shape to be uniquely identified. This fact is exploited in determining the durations of each involved erection task. For each steel shape (column, beam, or girder), the amount by which the loaded crane cable must be raised, the amount by which the boom must swing, and the amount by which the tower crane trolley must slide are all functions of the materials' starting locations and their final in-place configuration as part of the erected steel structure. For example, the amount by which the crane operator must swing the boom is different when erecting a near column on tier 1 than the amount of swing necessary for erecting a far girder on tier 2. When sampling the durations of each erection task, Stroboscope accesses and considers the in-place configuration of the shape that is currently being processed. The duration of each erection task is thus a function of the particular shape that is being erected, as it would be in a real erection operation.

In addition to simulating the operation and obtaining the statistical parameters of interest, the simulation model can generate a dynamic 3D visualization of the steel erection processes. This is accomplished by using the Vitascope visualization system (Kamat 2003). Using CAD models of the site, the tower crane, and each unique steel cross section (not individual shapes), Vitascope can recreate the entire frame erection operation in a 3D virtual world. Such a visualization depicts the tower crane erecting each member of the frame using the same logic and constraints that are embedded in the underlying simulation model.

Vitascope has a language that allows simulation models to communicate dynamic, time-stamped events and geometric transformations to an ASCII text animation trace file. The file can contain references to the CAD models of the involved resources. Using the information recorded in the trace files and the preexisting CAD models, Vitascope recreates a faithful representation of the simulated (and recorded) operation. The simulation models are instrumented to write (to the trace file) the relevant time-stamped animation instructions on each pertinent simulation action event (e.g., ONSTART of activities and/or ONFLOW of links). Fig. 5 presents a short segment of an automatically generated trace file that, when processed, will depict the erection of a column on tier 2.

Fig. 6 presents a snapshot strip depicting a few frames that are visualized when the animation trace file segment presented in Fig. 5 is processed. The continuity and the smoothness of the animated processes are not apparent by looking at the snapshot strip. Only the animation can convey that information.

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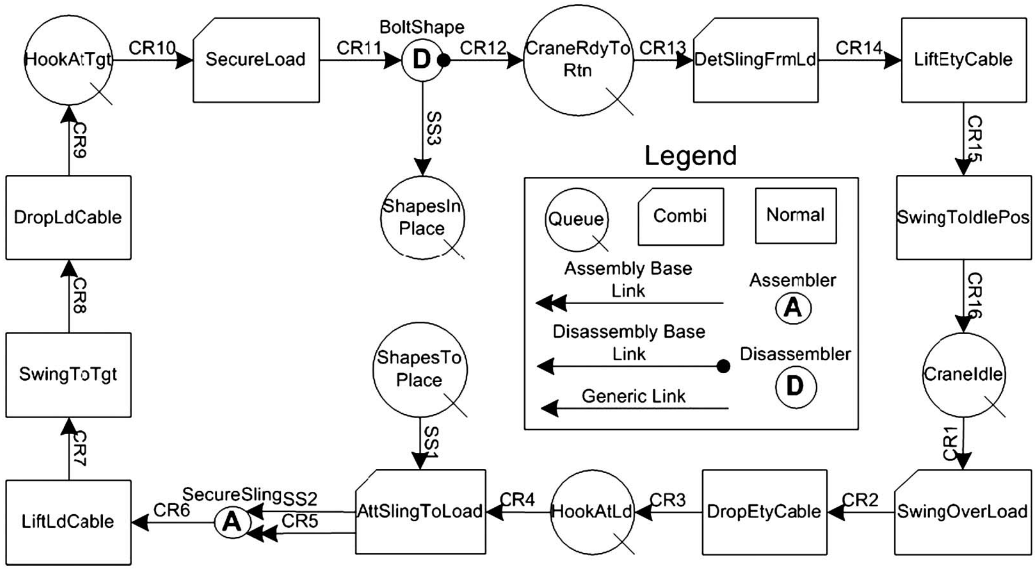

Fig. 4. Simulation model of steel erection processes (reprinted with permission from Kamat and Martinez 2002)

```
TIME 6760.000000;
CREATE Shape65 Column;
TGTSCALE Shape65 (1,9.00,1) 0;
PLACE Shape65 AT (-14.00,0.00,8.00);
TIME 6770.000000;
ATTACH Shape65 TheHook (0,-0.5,0);
TIME 6770.000000;
SCALE TheCable (0,-30.00,0) 15.00;
SLIDE TheHook (0,30.00,0) 15.00;
TIME 6785.000000;
TGTROTATE TheBoom HOR 151.93 20.00;
TGTSLIDE TheTrolley (17.00,0,0) 20.00;
TIME 6805.000000;
TGTSCALE TheCable (1,16.30,1) 15.00;
TGTSLIDE TheHook (0,-16.30,0) 15.00;
TIME 6805.000000;
ROTATE Shape65 HOR 28.07 15.00;
TIME 6830.000000;
DETACH Shape65;
PLACE Shape65 AT (0.00,18.00,0.00);
HORIZORIENT Shape65 0.00;
```

Fig. 5. Segment of generated animation trace file (reprinted with permission from Kamat and Martinez 2002)

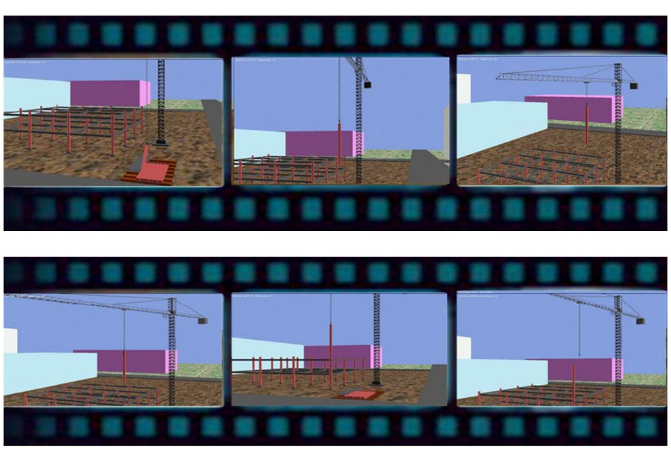

Fig. 6. Snapshots of steel erection processes (reprinted with permission from Kamat and Martinez 2002)

Advances in Activity Level Construction Visualization

4D CAD is extended in the following ways:

1. Simplifying the linking between activities and 3D components;
2. Parameterizing 4D CAD models;
3. Automatically calculating quantities and other metrics from 4D models;
4. Extending the temporal and spatial scales beyond the daily/weekly/monthly and building focus typically found in 4D CAD models; and
5. Extending 4D CAD models beyond construction applications.

Linking activities and 3D components is simplified through graphical drag and drop interfaces. A 4D modeler can select a set of 3D components and drag them onto a corresponding activity, or the modeler can select a set of 3D components and define an activity for these components. Some construction firms are starting to replace CPM and bar-chart scheduling tools with 4D modeling.

Parameterizing 4D models further reduces the tedious task of connecting 3D model components and activities by enabling schedulers to define the starting point of an activity, the direction of the work [e.g., using Riley's (1998) taxonomy of construction workflows], the production rate, and factors affecting the production rate, e.g., proximity of other work, and then creating the 4D model (and other schedule views) automatically (Akbas 2003). The combination of location-based scheduling and 4D models further enhances the functionality of this method (Jongeling and Olofsson 2007).

The development scenario simulator (DSS) calculates time-space quantities automatically from 4D models (Langhoff et al. 2009) to complement the visualization of a project's progress with corresponding metrics (e.g., money spent, concrete placed, and CO2 emitted). Jongeling et al. (2008) report on a 4D modeling approach that calculates construction parameters like available work space, amount of available work space used, distance to the closest other activity, amount of scaffolding, and formwork needed from a project's 4D model.

The range of temporal and spatial scales of 4D models is being expanded from the typically day to month long activities and primary building components to smaller and larger scales. On one end of the spectrum, 4D models show the installation of rebar by a crew

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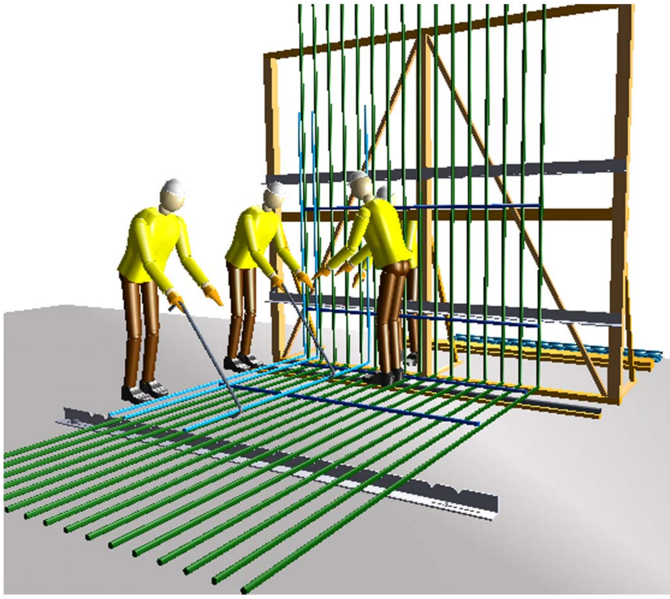

Fig. 7. 4D model showing the production of a rebar cage by a crew (image courtesy of Strategic Project Solutions, Inc.)

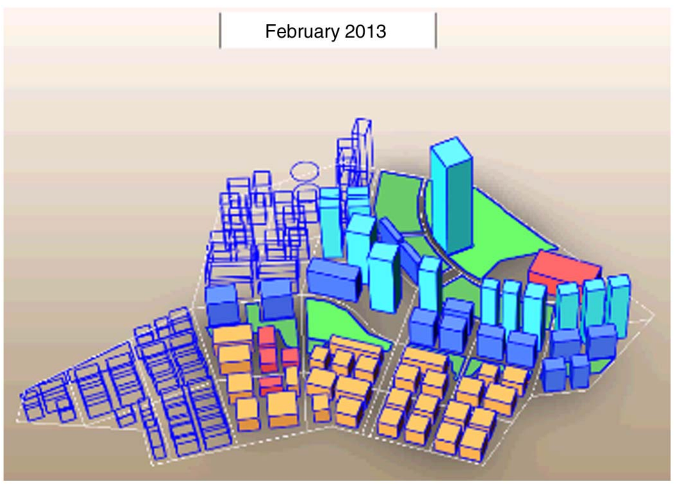

Fig. 8. Snapshot of 4D model showing the development of a city over a decade

(Fig. 7). On the other end of the spectrum, they show the development of an entire city (Fig. 8).

Zhang (2009) extended 4D models beyond construction to show maintenance activities, predict structural performance, update the condition of the facility, and track environmental conditions over time. Eisenhower et al. (2010) use 4D models to show energy consumption of buildings at different temporal and spatial scales.

Advances in Operations Level Construction Visualization

Discrete-event simulation and virtual reality are technologies that can be of significant utility in construction engineering. Until now, these technologies have been based on separate concepts and used for different purposes. Recent research led to the synergistic combination of both into what Rekapalli and Martinez (2009) call discrete-event simulation based virtual reality (DES-Based-VR). DES-Based-VR promises to be more than the sum of its parts, because it makes it possible to turn sophisticated discrete-event simulation models that have been instrumented to produce 3D animations, as described previously, into virtual reality environments where (1) experts can extensively validate the logic of the underlying DES model; (2) decision makers can gain high credibility in the DES study; and (3) others can effectively learn about complex construction operations.

Discrete-event simulation models are a representation of a real world or imaginary system. These models should consider the logic of the system, including dynamic strategies that specify the choices that are possible at various situations and how these choices are made. A multitude of nontrivial choices exist in any complex construction operation. Creating DES models that accurately capture these choices and the process by which they are made is a difficult task where mistakes can be made easily. Most importantly, experts and decision makers understand the difficulty of capturing the choices and dynamic decisions, and tend to take the results of simulation models with a grain of salt. Animation of DES models, both in 2D and 3D, has been used to communicate DES models so that experts and decision makers can see that when choices present themselves in the course of an operation, the model makes the choices that would be made in real life in the same situation. The problem is that the universe of choices that are possible in the complete plan of a construction operation is very large, and only a handful of them actually take place during a single execution of the plan. As a consequence, animation improves credibility, but an extraordinary number of independent animations need to be fully observed to validate all possible choices that may be part of a plan.

Virtual reality is a sensory-immersive computer-generated environment that responds to, and is to some extent controlled by, users. In DES-Based-VR, the user can theoretically control anything that is part of a DES model. If a machine can break down during a simulation, the user can break it at will while immersed in the virtual operation. If the performance of activities slows down during bad weather, the user can make the weather bad. In either case, if the underlying DES appropriately models the choices that follow a breakdown of the machine or the sudden change in weather, the user will immediately experience the subsequent choices made by the DES. These choices will contribute to the credibility of the model as they would in the real operation, or will provide feedback for the correction of the underlying DES model if they disagree with the plan.

The NovoScope and VitaScope++ DES-Based-VR systems (Rekapalli 2008) implement the research that makes it possible to create discrete-event simulation based virtual reality environments. Although the typical animation of a simulated construction operation takes place after the simulation has run to completion, in a DES-Based-VR system the discrete-event simulation and its animation run concurrently and synchronized. This allows any interaction of a user experiencing the animation to affect the state of the concurrently running discrete-event simulation, which can in turn change its course and be immediately reflected in the animation.

Advances in Construction Visualization Methods

A newer visualization paradigm called augmented reality (AR) is also emerging, and is based on the idea of generating an environment where virtual models, representing expected construction, and real objects, representing actual construction, are jointly represented in a shared environment. Unlike virtual reality modeling, the application of AR allows the observer to completely interact with both actual and virtual objects (Behzadan and Kamat 2009).

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The recent advances in these visualization methods are primarily motivated by: (1) visualization of activity and operation level construction within the actual context in which the operation is happening; and (2) visualizing expected and actual construction performance, enabling automated tracking, analysis, and visualization of progress discrepancies.

In a broad sense, AR is a multisensory technology that blends virtual contents with the real environment. AR has distinct advantages over other forms of visualization in at least three aspects: (1) from the perspective of visualization, the real world can significantly mitigate the efforts of creating and rendering contextual models for virtual objects and provide a better perception about the surroundings than pure virtual reality, e.g., visualization of construction simulations (Behzadan et al. 2008), and visualization of architectural designs (Thomas et al. 1999); (2) from the perspective of information retrieval, AR supplements users' normal experience with context-related or georeferenced virtual objects, e.g., looking through the walls to see columns (Webster et al. 1996) and looking beneath the ground to inspect subsurface utilities (Roberts et al. 2002); (3) from the perspective of evaluation, authentic virtual models can be deployed to measure the physical condition of real objects, e.g., evaluation of earthquake-induced building damage (Kamat and El-Tawil 2007), and automation of construction progress monitoring (Golparvar-Fard and Peña-Mora 2007).

The successful application of AR for construction or any other engineering problem should typically possess the following properties concluded by (Azuma et al. 2001) that real and virtual objects should (1) coexist in the augmented space; (2) run in real-time; (3) register real and virtual objects with each other. Each property corresponds to a field of research challenges, e.g., the coexistence of real and virtual objects leads to occlusion and photorealism problems. Recent applications of AR in construction attempt to address these challenges to enable richer, integrated, and more informative visualizations both at the activity schedule level and the operations and process levels.

Mobile Computing Framework for Construction Visualization in Augmented Reality

The mobile computing framework described in this section provides a complete hardware and software solution for centimeter level accuracy AR tasks in both spatial and temporal domains. The effectiveness of the framework has been validated in several construction visualization applications, including visualization of the simulated steel erection processes described earlier (Fig. 9) (Behzadan and Kamat 2009), and for visualizing buried underground infrastructure in AR for collision avoidance and planning in urban excavation (Fig. 10) (Talmaki et al. 2010).

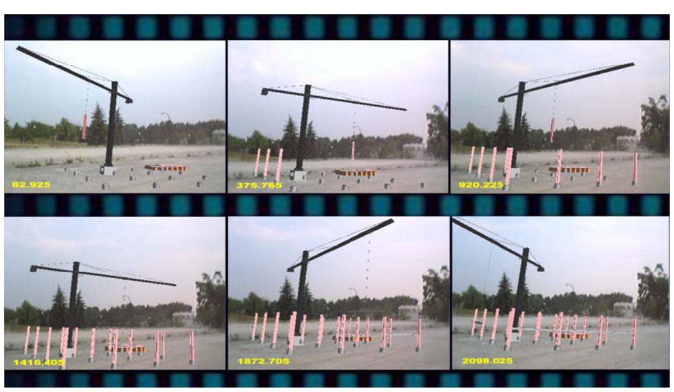

Fig. 9. Visualization of simulated steel erection processes in outdoor augmented reality (reprinted with permission from Behzadan and Kamat 2009)

Augmented Reality Mobile OpeRation platform (ARMOR) evolves from the ARVISCOPE hardware platform (Behzadan et al. 2008). ARMOR improves the design of ARVISCOPE from two aspects, rigidity and ergonomics, by (1) introducing high accuracy and lightweight devices; (2) placing all tracking instruments rigidly with full calibration; (3) renovating the carrying harness to make it more wearable. Scalable and Modular Augmented Reality Template (SMART) builds on top of the ARVISCOPE software platform (Behzadan et al. 2008). The primary motivation of ARVISCOPE is exporting some basic modules communicating with peripheral hardware as a dynamic link library that can be later imported into other potential AR applications. SMART takes advantage of these modules and constructs an AR application framework that separates the AR logic from the application-specific logic. This extension essentially creates a standard structured AR development environment.

The in-built registration algorithm of SMART guarantees high accuracy static alignment between real and virtual objects. Some preliminary efforts have been made on dynamically reducing misregistration: (1) to reduce synchronization latency, multiple threads are dynamically generated for reading and processing sensor measurement immediately upon the data arrival on the host system; (2) a finite impulse response (FIR) filter applied on the jittering output of electronic compass leads to filter-induced latency, therefore an adaptive lag compensation algorithm is designed to eliminate the dynamic misregistration (Dong and Kamat 2010).

As a prototype design, the ARVISCOPE hardware platform succeeded in reusability and modularity, and produced sufficient results for proof-of-concept simulation animation. However, there are two primary design issues that are inadequately addressed: accuracy and ergonomics. ARMOR (Fig. 11) is a significant upgrade over the ARVISCOPE hardware platform. The improvements can be categorized into four aspects: (1) highly accurate tracking devices with rigid placement and full calibration; (2) lightweight selection of input/output and computing devices and external power source; (3) intuitive user command input; (4) load-bearing vest to accommodate devices and distribute weight evenly around the body. A comparison between ARVISCOPE and ARMOR is listed in Table 1. Together, SMART and ARMOR allow the creation of complex AR visual simulations in construction or any other engineering domain.

D^4AR Models: Integrated As-Planned and As-Built Visualization

D^4AR (4D AR) models that integrate expected (as-planned) and actual (as-built) visualizations can be of significant utility in monitoring and controlling construction performance. These models are based on the concept of utilizing (1) building information models (BIMs) as a baseline for monitoring performance of a project; and (2) daily construction photographs as a source for modeling and representing as-built status of a project and also tracking progress.

The motivations behind using these photographs are cheap and high resolution digital cameras, low cost of memory, and availability of internet on most construction sites, which enables their capturing and sharing on a truly massive scale. These photos are usually collected by all project participants and capture detailed information on progress, productivity, safety, quality, and constructability, and even serve as a record of the past history on a project. Based on the way they are captured, these photos are categorized into (1) time-lapsed imagery and videos, which represent construction activities from the same viewpoints; and (2) unordered daily photos; the availability of large number of these photos

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Fig. 10. Visualization of buried utilities in augmented reality for excavation planning and collision avoidance (reprinted with permission from Talmaki et al. 2010)

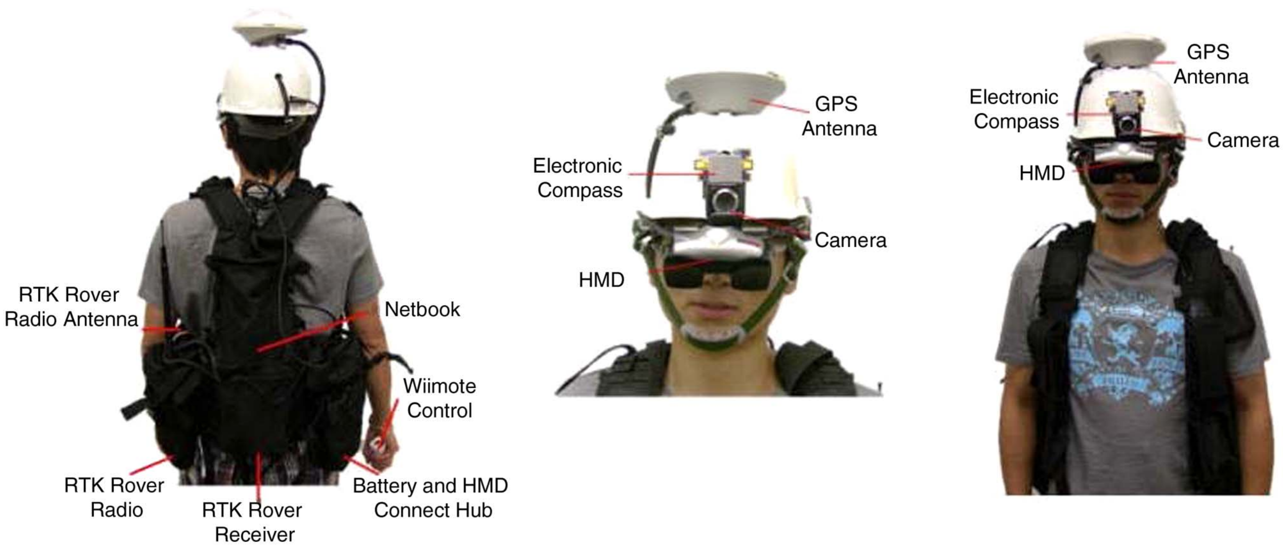

Fig. 11. ARMOR: mobile hardware platform for AR construction visualization

Table 1. Comparison between ARVISCOPE and ARMOR Hardware Configuration

Device	ARVISCOPE	ARMOR	Comparison
Location tracking	Trimble AgGPS 332 using OmniStar XP correction for differential GPS method	Trimble AgGPS 332 using CMR correction broadcast by a local base station Trimble AgGPS RTK Base 450/900	OmniStar XP provides 10–20 cm accuracy; RTK provides 2.5 cm horizontal accuracy and 3.7 cm vertical accuracy
Orientation tracking	PNI TCM 5	PNI TCM XB	The same accuracy, but ARMOR places TCM XB rigidly close to camera
Video camera	Fire-I digital firewire camera	Microsoft LifeCam VX-5000	LifeCam VX-5000 is lightweight, small in volume, with smaller wire connection
Head-mounted display	*i*-Glasses SVGA Pro video see-through HMD	eMagin Z800 3DVisor	Z800 3DVisor is lightweight with stereovision
Laptop	Dell Precision M60 notebook	ASUS N10J netbook	ASUS N10J is lightweight, small in volume, and equipped with NVIDIA graphics card
User command input	WristPC wearable keyboard and Cirque Smart Cat touchpad	Nintendo Wii remote	Wii remote is lightweight and intuitive to use
Power source	Fedco POWERBASE	Tekkeon myPower MP3750	MP3750 is lightweight and has multiple voltage outputs, charging both GPS receiver and HMD
Backpack apparatus	Kensington contour laptop backpack	Load-bearing vest	Extensible and easy to access equipment

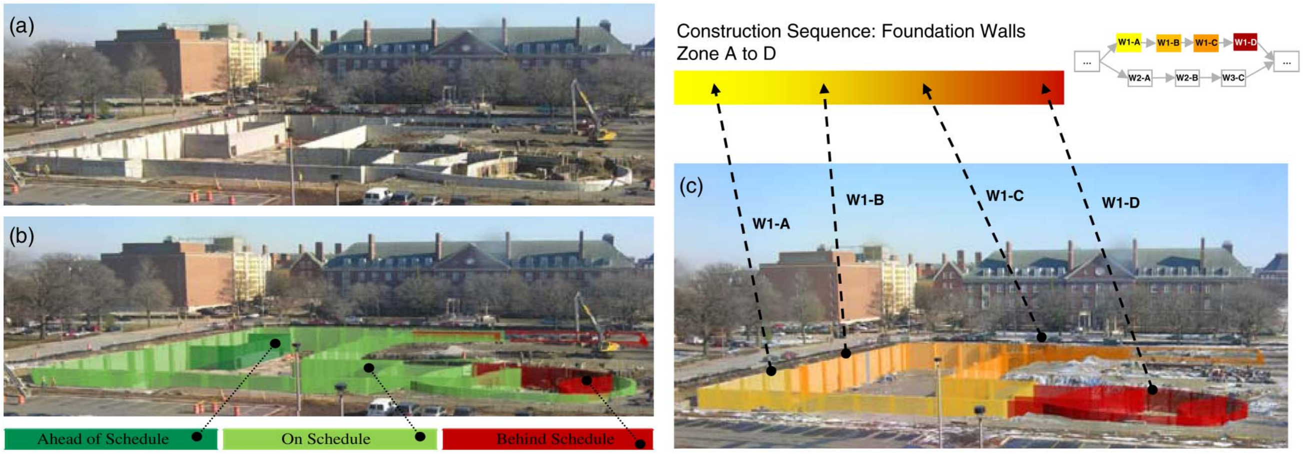

Fig. 12. Augmented time-lapsed imagery visualizing different performance metrics (reprinted with permission from Golparvar-Fard et al. 2007): (a) original image; (b) progress discrepancies color-coded over the augmented image; (c) visualized work sequence

enables ongoing construction progress and operations to be documented from every conceivable viewing position and angle during the construction phase.

Using time-lapsed photos, Golparvar-Fard et al. (2007, 2009a) presented an AR environment wherein BIMs are superimposed over time-lapsed imagery, providing a clear comparison between expected and actual performances on construction sites. Not only do these augmented photos and time-lapsed videos represent what is expected to be built where and when, but they also communicate the actual status of the construction along with the interactions among construction machinery, personnel, and materials.

In this research, a series of color and color gradient spectra are introduced to visualize and communicate progress discrepancies, construction sequence, cost, and schedule performance indices and floats. Fig. 12 represents three examples in which progress discrepancies are color-coded over the augmented image [Figs. 12(a) and 12(b)] and the expected work sequence is visualized [Fig. 12(c)].

Using daily site photos taken by different cameras in different conditions, Golparvar-Fard et al. (2009b, 2010) created and developed a new modeling technique that takes these unordered and uncalibrated photos, automatically reconstructs a dense 3D point cloud model of the construction site, and automatically computes each photo's viewpoint. Using different photo collections, this approach automatically reconstructs different 3D point cloud models, automatically registers those over one another, and ultimately generates 4D point cloud models. Finally, BIMs that are linked with construction schedules, visualizing what is expected to be constructed on the site, are superimposed with the point cloud models generating the D^{4}AR models. The resulting D^{4}AR models jointly visualize actual and expected performances. In this sense, the application of BIMs that are typically used during design development and preconstruction stages is extended to the construction phase and serves as a baseline for visualizing and comparing expected and actual performances.

Using D^{4}AR models, project participants can remotely access and visualize actual and expected 3D models of the project, conduct virtual walkthroughs on the construction site, and assess progress, productivity, safety, constructability, and quality and site logistics. These models facilitate quick and remote construction control decision-making, minimize the time required to discuss construction performance during contractor coordination meetings through quick and intuitive access to actual construction information, and significantly cut travel time and cost for project executives, architects, and owners. Fig. 13(a) represents an as-built point cloud model that is reconstructed with 160 photos collected along the site

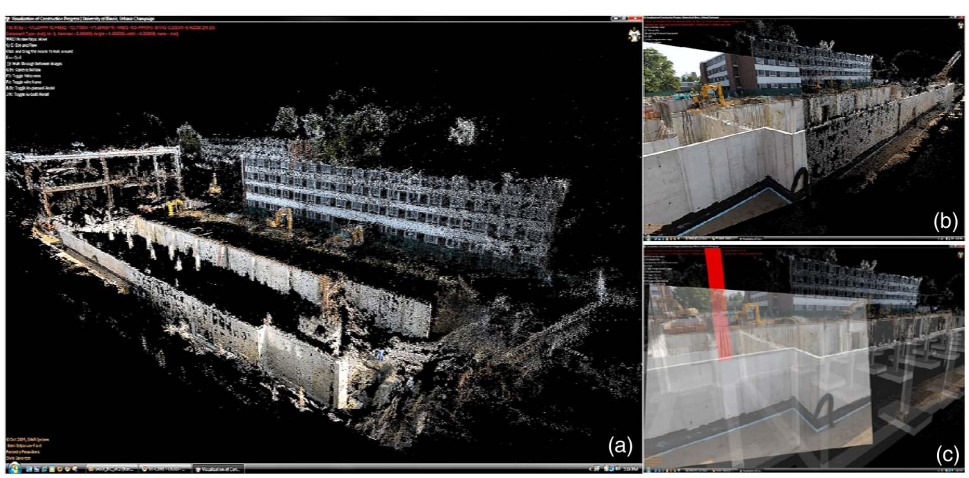

Fig. 13. An example of a D^{4}AR model generated with 160 photos (2 megapixels in quality) (reprinted with permission from Golparvar-Fard et al. 2010): (a) as-built cloud model collected along the site walk of the basement area; (b) one site photo rendered over the camera frustum visualized the construction site through joint 3D point cloud and image representation; (c) BIM superimposed with point cloud model

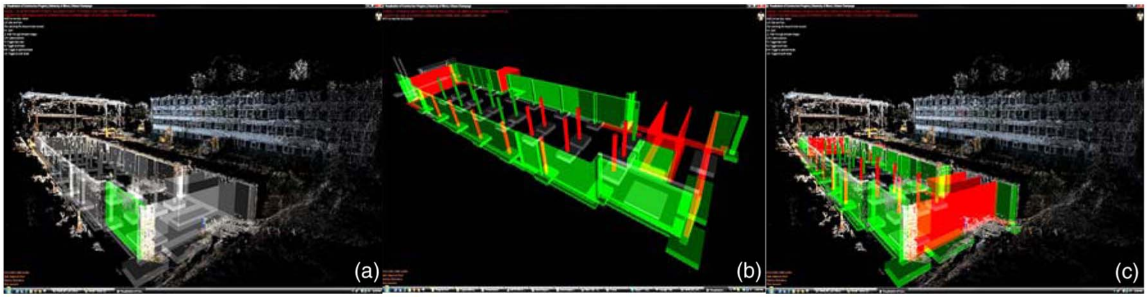

Fig. 14. The result of automated progress monitoring visualized with the D^{4}AR model (reprinted with permission from Golparvar-Fard et al. 2010): (a) a single element's progress status; (b) all elements color-coded; (c) all elements color-coded

walk of the basement area. Fig. 13(b) represents one of these site photos that is rendered over the camera frustum, visualizing the construction site through joint 3D point cloud and image representation. In this case, the camera is tilted by the user. In Fig. 13(c), the BIM is superimposed with the point cloud model. The resulting D^{4}AR model visualizes BIM, the as-built point cloud model, and the semi-transparent photo together.

Advances in Automated Visualization of Progress Deviations at Schedule-Activity Level

In a recent work, Golparvar-Fard et al. (2010) created and developed a new approach that builds upon these D^{4}AR models, automatically measures physical progress, and visualizes deviations between actual and expected progress by using a simple traffic light metaphor. In this case, behind and ahead-of-schedule elements are automatically color-coded with red and green. The automated progress monitoring module has been validated for automated detection of progress on structural elements and in an ongoing research; its application for different interior spaces and building systems are under investigation. The observed and perceived benefits of this approach are to minimize current challenges with extensive site data collections, nondetailed analyses of progress, and nonintuitive representations of performance discrepancies. Fig. 14 shows the color-coded elements of the D^{4}AR model that were represented in Fig. 13. In this figure, Fig. 13(a) shows the status of progress for a single element, and the color-coding in Figs. 13(b) and 13(c) represent the status of progress deviations for all elements. For those elements that have minimal visibility, the status of progress is not detected, and consequently those elements are not color-coded (remaining gray).

Conclusion

In construction, both activity and operations level planning, monitoring, and control can benefit substantially from dynamic 3D visualization. Research efforts in project level visualization (4D CAD) are rooted in scheduling interests and focus on communicating what components are built where and when. Operations-level visualization research efforts, on the other hand, are rooted in operations modeling interests. The work focuses on designing methods to visualize the operations and processes that are performed in building, in addition to evolving construction products. In addition to communicating what is built where and when, the effort is concerned with visualizing who builds it and how, by depicting the interaction between the various involved machines, resources, and materials. By utilizing an example of a multistory structural steel erection operation for comparison, this paper demonstrated that 4D CAD and simulation-driven dynamic 3D operations visualization differ in concept, content, and form. 4D CAD visualizations depict the discrete evolution of the construction product and are achieved by linking together project planning tools (i.e., CPM schedules) and CAD models of static facility components. Dynamic operations visualizations, on the other hand, depict not only the continuously evolving facility, but also the interactions of the various resources (machines, materials, and temporary structures) that are involved in building the facility. Enabling visualizations of the latter type is achieved by synthesizing operations planning tools (i.e., simulation models) and CAD models of both static and dynamic entities. Recent advances in these exciting areas of research were also highlighted, along with a description of some specific applications in field construction.

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