

HYBRID 4-DIMENSIONAL AUGMENTED REALITY

A High-precision Approach to Mobile Augmented Reality

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Keywords: Augmented Reality, Mobile Computing, Computer Vision, Structure from Motion.

Abstract: A construction project requires a large amount of cyber-information, such as 3D models. Unfortunately, this information is typically difficult for construction field personnel to access and use on-site, due to the highly mobile nature of the job, as well as a hazardous work environment. Field personnel rely on carrying around large stacks of construction drawings, diagrams, and specifications, or traveling to a trailer to look up information electronically. This paper presents HD⁴AR, a mobile augmented reality system for construction projects that provides high-precision visualization of semantically-rich 3D cyber-information over real-world imagery. The paper examines the challenges related to augmenting reality on a construction site, describes how HD⁴AR overcomes these challenges, and empirically evaluates the capabilities of HD⁴AR.

1 INTRODUCTION

Emerging Trends & Challenges: In 2010, the US spent 816 billion dollars on construction projects (AGC, 2011). It is estimated that a 0.1% improvement in efficiency of project delivery could save roughly \$200 million. Even though there are significant potential cost savings, the construction industry still faces major challenges in tracking and monitoring operations to promptly *identify, process, and communicate* discrepancies between actual and expected performances. The National Academy of Engineering has identified “enhanced visualizations, through advances in virtual and augmented reality” as a key challenge for 21st century engineering (NAE, 2011).

To successfully control execution of a project, the actual (physical) status of the infrastructure under construction needs to be constantly monitored and compared with the project’s cyber-information model, known as a *Building Information Model* (BIM) (Eastman et al., 2008). The BIM is a 3D CAD model that is annotated with cyber-information that provides semantics for the CAD elements, such as structural geometries and, their spatial and material properties, and can be augmented with cost and schedule information.

Despite the importance of cyber-physical information association on a construction site,

current monitoring practices include manual and time-consuming data collection (*e.g.*, walking around a construction site and writing down information on paper), non-systematic analysis (*e.g.*, rough comparisons of the notes to the 2D construction plans), and visually/spatially complex reporting (Golparvar-Fard et al., 2009); (Navon and Sacks, 2007) (*e.g.*, estimating how real-world 3D physical structures correspond to 2D building plans or virtual 3D models).

Open Problem: A key issue with these manual processes is that practitioners cannot access and interact with cyber-information through the physical structures that they are building. For example, there is no way for a field engineer to see a 3D plan for a wall overlaid directly on top of the physical element. Instead, field engineers must either carry bulky stacks of drawing and documents, or make trips back and forth to construction trailers and offices to look up plans for building elements and compare them to what was seen on the construction site. Because there is no easy way to visualize and query the BIM through the actual physical construction elements, it is difficult for field personnel to quickly detect discrepancies between the physical construction elements and the cyber building plans. Without quick identification of discrepancies, managers cannot easily adjust the construction plan to minimize the impact of problems.

While smartphones provide the platform and tools for AR (Wagner, 2009), existing mobile AR approaches are not well suited for a construction environments due to their lack of accuracy in spatially locating the user and rendering cyber-information over the correct physical elements. On a construction site, discrepancies between physical elements and the BIM must be detected to within a few centimetres or less. AR approaches, based on GPS and compass sensors (Gotow et al., 2010), can have multiple meters of inaccuracy, making them unreliable for construction scenarios.

Solution Approach → Hybrid 4-Dimensional Augmented Reality: This paper presents an augmented reality approach, called *Hybrid 4-Dimensional Augmented Reality* (HD⁴AR) that allows construction field personnel to use mobile devices, such as a smart phone or tablet, to take pictures that include a specific construction element, see BIM elements visually overlaid on top of the real-world imagery, touch or click on a BIM element in the image, and be presented with a detailed list of cyber-information, such as *plan* information (e.g., budget, specifications, architectural/structural details) or *actual* information (e.g., cost, safety provisions, physical progress) related to the physical element. Screenshots from the Android HD⁴AR client are shown in Figure 1.

This paper provides the following contributions to the study of high-precision augmented reality systems:

1. The paper shows how computer vision algorithms can eliminate the need for external sensors to provide reliable location tracking information for providing context awareness.
2. The paper demonstrates how imagery of physical elements can be used to access cyber-information.
3. The paper describes an AR technique with high-precision that does not rely upon marking physical construction elements with fiducial tags or external equipment to provide high-precision localization.

The remainder of this paper is organized as follows: Section 2 presents a motivating example that we use to illustrate the challenges of associating cyber-physical information on a construction site; Section 3 discusses HD⁴AR and its approach to high-precision cyber-physical information association; and Section 4 presents concluding remarks.

2 MOTIVATING EXAMPLE

As a motivating example, we use a scenario where a

field engineer is concerned about the construction progress and quality of a concrete foundation wall. With current approaches, the field engineer would return to a construction trailer or office and open 2D construction drawings (at best a 3D BIM), project specifications, and the schedule to find out when the construction of this element is expected to be finished and what is the required quality of the outcome. Once the drawings and/or 3D building model is opened, the field engineer must navigate the model to determine which, of possibly hundreds or thousands of walls, is the foundation wall of concern. Moreover, once the information is obtained, the field engineer may need to return to the construction site to compare the information that was retrieved to the actual construction status of the real foundation wall. Because there is no way to directly query the cyber information for the wall, the field engineer may not notice a discrepancy and will not be able to decide on a corrective action to minimize the impact of the discrepancy.

Instead, it would be beneficial if the field engineer can use the foundation wall as the basis for the query. A picture provides all that is needed to localize the user with respect to their environment, and thus reduce the information available down to what is relevant to the current scene. Given the close proximity of construction elements, the location and orientation of the picture needs to be accurately estimated to return the related information to the field engineer. This process should not affect the construction's workflow by requiring *tagging* of elements, which considering the number of elements (~1000-30,000 elements), makes tagging time consuming and often impractical.

3 HYBRID 4-DIMENSIONAL AUGMENTED REALITY

Using computer vision, researchers have shown that a set of overlapping images can be used to extract the 3D geometry of a stationary object, such as a building under construction (Golparvar-Fard et al., 2011); (Cheng and Chen, 2002); (Golparvar-Fard et al., 2009). As shown in Figure 1 the 3D geometry extracted using computer vision can then be overlaid and aligned with manually created BIM models of the construction project to create a fused cyber-physical model. Numerous research approaches have looked at the applications of these techniques (Golparvar-Fard et al., 2011); (Kiziltas et al., 2008).

After the cyber (e.g., BIM elements) and physical (e.g., extracted 3D geometry) models are aligned, they can be compared to determine how the actual state of the physical object compares to the representative cyber-model. Researchers have shown that the fused cyber-physical model is accurate to within millimeters (Golparvar-Fard et al., 2011) and can be used to predict with high accuracy the actual construction progress versus the planned cyber-model, even when visual obstructions are present (Golparvar-Fard et al., 2010). Moreover, as shown in Figure 1, *the fused cyber-physical model can be used to precisely predict where cyber-information, such as BIM elements, should appear in the original photographs and where physical objects actually appear in the cyber 3D space.* This ability to track where BIM elements (i.e., cyber-identities) should appear in photographs serves as the foundation of HD⁴AR.

3.1 HD⁴AR Usage Overview

HD⁴AR extends and integrates our previous research efforts in GPS-based AR, mobile device software optimization, and fused cyber-physical model construction to create a novel hybrid approach that is focused on fusing new photographs with existing cyber-physical models. HD⁴AR provides **augmented photographs**, rather than real-time augmented camera imagery. As shown in Figure 1, using our approach, a field engineer is able to take a photo of a physical object and the mobile device works with a backend server to produce an updated photo augmented with the cyber-information associated with the physical objects in view. The entire end-to-end process after the photograph is taken requires roughly a minute. The augmented photographs, with cyber-physical information associations, are **accurate to within a few millimeters** (e.g., 1-5mm) due to the empirically demonstrated high precision that computer vision algorithms provide (Golparvar-Fard et al., 2011). Moreover, after a field engineer has taken a photograph, he or she is able to **select physical objects in view as the context** and the system uses the fused cyber-physical model to identify the cyber-identity of those objects.

3.2 HD⁴AR Bootstrapping Process

In order to augment a given photograph with cyber-information, the HD⁴AR system requires that construction workers field personnel first take overlapping photos of the construction site. These

photos are used to extract an initial 3D point cloud of the site in a process known as Structure from Motion (SfM). SfM produces a point cloud of the natural visual features of the image set, estimating the 3D position of the features through image feature matching and an optimization process called bundle adjustment. This 3D point cloud is then aligned with the BIM in order to provide a correspondence between physical world positions and positions in the BIM.

The HD⁴AR system uses the Bundler package implementation of Structure From Motion (Snavely et al., 2006) to create the point cloud by the following process:

1. **Extract Visual Features:** A feature-detection algorithm is run on each image to create a key file of feature descriptors to be used as the basis for matching images to one another. Bundler by default uses the SIFT (Scale Invariant Feature Transform) algorithm (Lowe, 2004).
2. **Match Visual Features:** The set of visual features for each image are iteratively compared against each other, developing matching “tracks”. These tracks consist of specific feature points of multiple images, which are believed to represent the same physical feature point.
3. **Estimation of Camera Parameters:** Beginning with the two images containing the largest number of matches (or by manually selecting two initial images for bundling), the camera parameters are estimated for each image, and the 3D positions of their feature points are estimated. Then, each additional image attempts to register with the 3D cloud, using EXIF data to initialize focal length, and adding in the tracks of matched points within their view to expand the point cloud, and provide further basis for other images. This registration fails in the event that the estimated 3D layout of its matched points does not mesh with the set positions of the previous images.

4. **Bundle Adjustment:** In addition, while the images are being bundled, the bundle is run through a sparse bundle adjustment to minimize the error in the predicted 2D positions of the feature points in the photographs given their assigned 3D positions and where the feature points actually appear in the image.

3.3 Photograph Augmentation Process

Figure 1 shows screenshots from the HD⁴AR client running on an Android device with Android version 2.3.4. Once the point cloud is generated, the system is prepared to augment photos sent from the HD⁴AR



Figure 1: Screenshots of the android HD⁴AR client overlaying bim information related to a window.

client running on a user's mobile device. From a high-level perspective, this process operates as follows: Step 1, the field engineer, upon finding a section of the worksite he/she wishes to query, takes a picture of the area using a mobile device. Step 2, the device uploads the captured image to the HD⁴AR server. Step 3, the server runs a reduced form of the structure from motion algorithm to localize the image with the base point cloud. Step 4, using the localized image as input, the server determines what BIM objects are within the image's field of view, and where they appear. Step 5, the objects are sent back to the user device with positional information. Step 6, the user device renders the captured image, overlaid with the returned objects.

Step 1. Localization of Physical Elements in Cyber Model. As shown in Figure 1, a physical construction object (1) can be located in the 3D geometry model (2) (actual physical model), extracted with computer vision algorithms, and then mapped to 3D BIM elements in the (3) cyber model (e.g., BIM). This determination of the cyber-identity relies on mapping between the coordinate spaces of the models. If a physical object is at the same coordinates in the extracted 3D point cloud as a specific cyber-identity in the BIM, then it is associated with that cyber-identity. The (4) cyber-identifier, in turn, is associated with a BIM element and cyber-information items that contain data about the concrete foundation wall corner, such as concrete specs or expected quality of the finished surface, are associated with the cyber-identity.

Step 2. Reduced Single-image SfM. The user's photograph must be localized with respect to the 3D point cloud, using a reduced sequence of SfM algorithm steps used to create the point cloud itself. An initial estimate of the focal length of the camera used to take the image is extracted from the image's EXIF tags, or cross-referenced from a list of camera types. Next, feature point extraction is done to create a key file for the image that lists all of the image's feature points. The key file and the focal length are then used to mesh the image into the point cloud. The image's feature points are matched against the

feature points of other images in the set. If matching succeeds, the pose of the camera that took the image is known, resulting in rotation and translation values for the camera that took the newly added image, and adjustment performed on the new point cloud bundle to refine its accuracy.

Step 3. Building the Transformation Matrix. When an image is added to an existing point cloud bundle, the bundle adjustment will optimize with respect to the relative locations of all images in the bundle, including the newly added image, resulting in a new coordinate system. To determine visible cyber-elements, the 3D positions must be transformed into this new coordinate space. This is done using a transformation matrix built using four tracked points from both the original and transformed bundles, used to solve $Ax=B$, where Matrix A is a 12×12 matrix formed from using the positions of four points:

Table 1: Matrix A, formed with the original point coordinates.

Point1	Z	Z
Z	Point1	Z
Z	Z	Point1
Point2	Z	Z
...
Z	Z	Point4

where $PointN = [x_n, y_n, z_n, 1]$, $Z = [0, 0, 0, 0]$

B is a 1×12 matrix composed of the x, y, and z positions of the translated points from the new bundle. Solving for x produces a 1×12 matrix, which produces the transformation matrix T when parsed as:

Table 2: The Transformation Matrix.

X[0]	X[1]	X[2]	X[3]
X[4]	X[5]	X[6]	X[7]
X[8]	X[9]	X[10]	X[11]
0	0	0	1

Step 4. Transformation of the BIM Overlay Positions to New Coordinate Space. The 3D

coordinate of each BIM overlay position is matrix-multiplied to produce the BIM overlay's relative position in the new coordinate system, i.e.:

$$P' = T * \begin{bmatrix} P \\ 1 \end{bmatrix} \quad (1)$$

Step 5. Mobile Augmented Photo Viewer and Touchscreen Interface. Having determined the localized position of the camera in 3D space and transformed all relevant BIM overlay points into the new coordinate space, the next step is to determine which of the BIM's cyber-information items are visible in the user's image by projecting their 3D coordinates into the 2D space of the image. This 3D to 2D project is done by following this sequence of steps:

1. Item position in camera coordinates, where \mathbf{R} is the rotation matrix of the camera, \mathbf{t} is the translation matrix, and \mathbf{X} is the 3D coordinate of the point.

$$\mathbf{P} = \mathbf{R} * \mathbf{X} + \mathbf{t} \quad (2)$$

2. Flatten to Z-axis.

$$\mathbf{p} = -\mathbf{P} / \mathbf{P}.z \quad (3)$$

3. Resolve to 2D position, where f is the estimated focal length, \mathbf{p}' is the point in pixel coordinates:

$$\mathbf{p}' = f * r(\mathbf{p}) * \mathbf{p} \quad (4)$$

$$r(\mathbf{p}) = 1.0 + k1 * ||\mathbf{p}||^2 + k2 * ||\mathbf{p}||^4 \quad (5)$$

where $k1, k2$ are the estimated distortion parameters. Equations (2), (3), (4), and (5) used from Bundler's User Manual.

Cyber-information items with 2D positions within the bounds of the photograph are sent back to the mobile device along both their calculated 2D locations in the photograph and any textual data associated with the item.

Figure 1 shows screenshots from the Android HD⁴AR client overlaying BIM information related to a window on a photograph. In the screenshots, the 3D BIM information is precisely aligned with the real-world imagery despite changes in the position and orientation of the user's device. As shown in the third screenshot, clicking on elements can show additional cyber-information, such as this Android Toast notification, or open more detailed list views.

4 CONCLUDING REMARKS

The construction industry stands to gain much through the integration of cyber-information into regular operation. The HD⁴AR system was designed

with the intent of bringing augmented reality to construction technology, to better facilitate the use of cyber-information around worksites. It takes vital project information, (such as object placement, building materials, project scheduling, work delegation, etc.) which traditionally has been difficult to access on a jobsite (yet remains very important to project specification and completion), and makes it mobile, accessible, and possible to visualize over real-world imagery.

From our work developing mobile AR for construction sites, we learned the following important lessons:

1. Localization of Users Can be Accomplished Using Only 2D Images as Input. HD⁴AR demonstrates that it is possible to develop augmented reality systems without the need for external modifications; signal tracking; or GPS/wireless tracking modules, avoiding the pitfalls inherent to such techniques on construction sites. Using only captured images, SfM techniques can be used to build a base geometric model, which then can be used as a point of reference for other pictures to estimate relative location.

2. Information Retrieval Using HD⁴AR Can be Done in Less Time than Traditional Means. With current manual construction processes, construction field personnel must walk from an area of the construction site to the construction trailer, lookup up BIM information in a laptop computer, and estimate its correspondence to the real-world state of the construction site. While there has not been research done specifically into how long it takes an on-site engineer to retrieve information, it can be mathematically shown that (in most cases), HD⁴AR takes less time than manually retrieving the data. Our results showed that HD⁴AR takes around 100 seconds to process and localize an image using the largest base of images. Considering average human walking speed to be around 1 m/s, this means the average human will cover around 100m in 100s. So, in the event that the command trailer lies farther than 100m away, the engineer has already spent more time walking to the trailer than it takes for augmentation. Moreover, this estimate does not even consider the time it takes to manually narrow down the results and find the relevant information on a laptop, which, depending on how complex a project is, could take considerable time.

3. More Can be Done to Improve the Robustness of the Localization Algorithm. While our results do show that the HD⁴AR system can be used for localization, proving the concept of using natural

features as a basis for augmentation, only 20-25% of pictures, on average, can be localized. Improving the likelihood of an image being matched to its surroundings will increase system usability and performance.

4. There is a Need to Develop a Simple Means of Automatically Aligning the Geometric and Cyber-Models to Facilitate Augmentation. A key aspect of the HD⁴AR system is being able to augment an image with associated cyber information housed in a cyber-physical model. In order for this to work, the geometric and cyber-models must be aligned so that a user localized to the geometric model will simultaneously be localized with respect to the cyber model. Our current approach requires manual alignment of these models, which is not difficult, but not automated.

Our current version of HD⁴AR provides construction AR with millimetre precision and augmentation of photographs in ~1 minute. In future work, we are planning to field test HD⁴AR on several construction sites and improve both its speed and robustness.

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