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Rapid Post-Disaster Reconnaissance for Building Damage Using Augmented Situational Visualization and Simulation Technology

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Abstract: This paper discusses the feasibility of using augmented situational visualization, commonly referred to as augmented reality (AR), to evaluate damage sustained by buildings in the aftermath of natural and human-perpetrated disasters. This CMMI funded project is evaluating the hypothesis that previously stored building information can be superimposed onto a real structure in AR, and that structural damage can be evaluated by measuring and interpreting key differences between a baseline image and the real view of the facility. Two experiments were performed in conjunction with structural tests that were being conducted to investigate the seismic performance of concrete walls. The obtained results highlight the potential of using AR for rapid damage detection and indicate that the accuracy of structural displacements measured using AR is a direct function of the accuracy with which augmented images can be registered with the real world.

1. Introduction: Augmented Reality (AR) is the superimposition of computer-generated graphics over the user's view of the real world. By presenting contextual information to the user, the real world is enhanced or augmented beyond the user's normal experience. The addition of information spatially located relative to the user can assist in the performance of several scientific and engineering tasks. For this reason, researchers have explored the use of AR for several Architecture, Engineering, and Construction (AEC) applications.

For instance, Webster et al. [1996] presented a system that shows locations of columns behind finished walls, and re-bars inside columns. Roberts et al. [2002] used AR to overlay locations of subsurface electrical, telephone, gas, and water lines onto real-world views. Both applications demonstrated AR's potential in helping maintenance workers avoid buried utilities and structural elements when they make changes to buildings and subsurface infrastructure. Webster et al. [1996] also presented an AR system that guides workers through the assembly of an architectural space frame. Hammad et al. [2004] augmented contextual information and maintenance data on real views of bridges to help bridge inspectors conduct inspections more effectively. Thomas et al. [1998] and Klinker et al. [2001] explored AR to visualize architectural designs outdoors. Dunston et al. [2002] have also demonstrated the use of AR in collaborative design.

This paper presents the results of research being conducted at the University of Michigan to design and implement a new, AR based, rapid post-disaster building damage reconnaissance technology. The article reports the results of experiments that were conducted to evaluate the hypothesis that previously stored building information can be superimposed onto a real structure in AR, and that structural damage can be detected by measuring and interpreting key differences between a baseline image and the real view of the facility. In addition to the experimental results, the article describes the details of the computation method designed to calculate global building damage measures using AR.

2. Overview of Proposed Methodology: Fig. 1 presents a schematic overview of the proposed method. The underlying idea is that on-site reconnaissance inspectors can retrieve previously stored information about a building, superimpose that information onto the real structure in an AR setting, and evaluate damage simply by comparing the two views.

Sustained building damage can be evaluated by measuring differences between the augmented baseline image and the real view, and computing damage indices that correlate the differences to the building's structural integrity and safety. In order to achieve these objectives, on-site users of the system can use equipment that consists of an AR see-through display attached to a lightweight computing platform such as a laptop that is sufficiently powerful to perform basic image processing and display.

3. Technical Approach: The proposed technique is based on the premise that significant local structural damage manifests itself through proportional, permanent global changes that are detectable at the exterior of a building. The Interstory Drift Ratio (IDR) is a global measure that can be computed from external building dimensions and conveniently used to quantify damage. The residual IDR is a measure of how far each building floor has moved permanently relative to the one beneath divided by the story height.

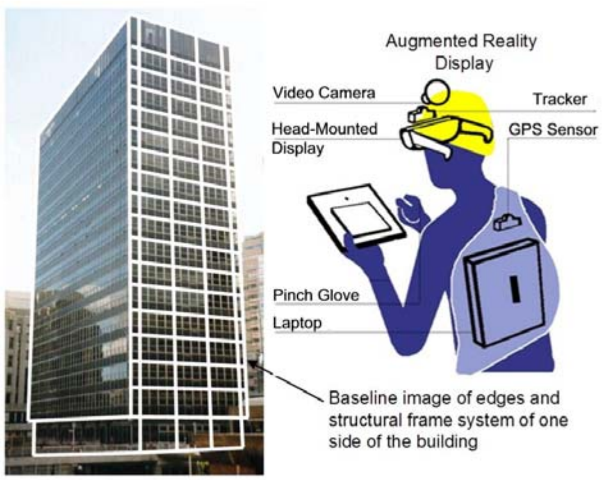

Figure 1: Overview of Proposed Damage Reconnaissance Methodology

Performance-based seismic design specifications that are based on IDR, such as FEMA [2000a], suggest that there is consensus within the earthquake engineering community that the index is a reasonable measure of damage. Due to its comprehensive nature and the fact that it can be reliably correlated to other damage indices, including local damage indices (e.g. as in FEMA 2000b), the IDR has been chosen as the representative building damage measure in this research.

The residual IDR at each floor of a building can be measured using a computation scheme based on AR by comparing a baseline image to the actual shape of a structure after a seismic event. By comparing computed IDRs to predetermined thresholds, a quick but thorough assessment of the level of structural and non-structural damage incurred can be made. Two particularly important thresholds are relevant in this context: immediate occupancy and collapse prevention limits. Both are well documented for various types of construction in existing specifications such as [FEMA 1997], and [FEMA 2000a, c].

In order to validate the practicability of this approach and to evaluate the extent to which interstory drift can be accurately measured using AR, two experiments were conducted in the University of Michigan Structural Engineering Laboratory (UM-SEL). The experiments were performed concurrently with tests that were being conducted to evaluate the seismic performance of fiber-reinforced concrete structural walls.

4. Description of Experimental Setup: The UM-SEL is equipped for structural testing of large-scale structural elements and subassemblies under monotonic and quasi-static cyclic loading. The principal element of the laboratory is a strong wall and floor system which forms a continuous L-shaped corner. The strong floor is a 1524-mm deep heavily reinforced concrete mat. The walls are 6096-mm high and 610-mm thick, backed by 2438-mm deep buttresses on 2438-mm centers. Both the walls and the buttresses are post-tensioned to the strong floor. The structural floor has tie-down locations (anchorages) positioned at 1219-mm centers in two perpendicular directions. Identical anchorages are provided in the two structural walls, with extra anchorages added at the centerline of the buttresses.

The experimental setup is graphically represented in Figs. 2. The specimens that were tested in the experiments were slender fiber-reinforced structural concrete walls measuring 3353-mm in height and 102-mm in thickness. The walls were connected to a base girder having a 610 x 610-mm cross-section. The base girder was tied down to a set of floor anchorages at a distance of 1219-mm away from the wall.

The wall specimens had a top beam with a 406 x 406-mm cross-section that was connected to a 445-kN actuator attached to the perpendicular side of the strong wall. The actuator was used to load the specimens in a cyclic manner (i.e. by pushing and pulling on the specimen) to simulate earthquake loading. The experiments were displacement controlled, i.e. the actuators applied a predetermined displacement regime to the specimen. The amplitude of the imposed displacement cycles gradually increased throughout the test to represent increasing seismic demand.

Prior to starting the structural testing in each experiment, a wireframe CAD image of the wall was registered against and augmented over the real specimen (Fig 3). Registration in AR terminology means that the real and virtual coordinate axes are made to coincide in 3D augmented space. After each stage of structural testing was completed and the specimen had incurred the imposed structural deformations, the horizontal discrepancy between augmented CAD image and wall specimen was measured at a key location along the wall's height.

Since the augmented CAD image coincides with the wall's original location, the measured discrepancy in displacement represents the horizontal drift sustained by the wall at the observed location.

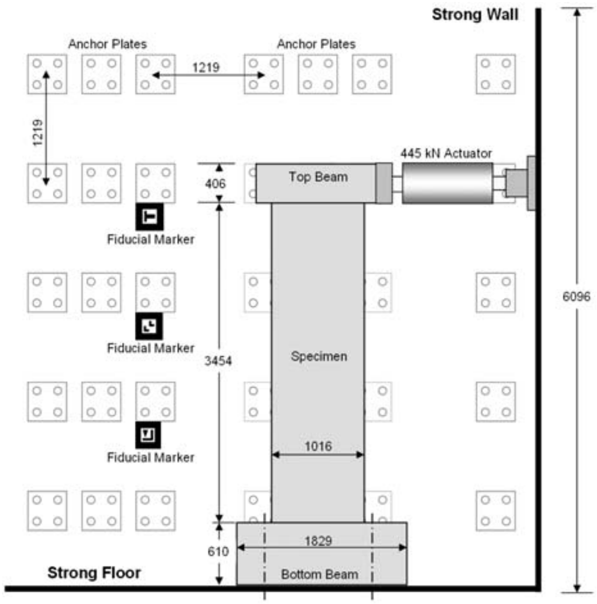

Figure 2: Experimental Setup in the UM-SEL (all dimensions in mm)

5. Selection of Registration Technique: In AR applications where a virtual image is superimposed onto a user's view of the real environment, it is necessary that the computer generated imagery coincide with the real-world within an acceptable level of accuracy [Holloway 1997]. In this study, high registration accuracy is necessary because sustained drifts could be as small as a few millimeters. If 50-mm of sustained drift is to be accurately measured in AR, then the registration accuracy of the augmented images must be significantly better than 50-mm.

In AR, registration is achieved and maintained by monitoring (tracking) the movements of the user's viewpoint and using that information to ensure that virtual images continually coincide with their real world counterparts [Barfield and Caudell 2001]. This is achieved by monitoring trackers (or sensors) placed in the environment or mounted on the user's body as navigation and tasks are performed in augmented space.

Traditional tethered tracking systems employ magnetic [Raab et al. 1979], ultrasonic [Intersense 2004], or optical [Welch et al. 2001] technologies. Although very accurate, these trackers rely on installation of large devices or dense arrays of beacons and sensors mounted in a finite enclosed area. Tracking systems can also be based on computer vision to track the motion of a camera mounted on the user. Examples include the placement and tracking of fiducial markers in the real environment [Kourogi and Sakaue 2001].

Marker based vision tracking schemes require initial placement of fiducial markers at strategic locations in the environment. Fiducial markers (or tracking markers) are unique patterns that can be recognized using machine vision [Kato et al. 2000]. The recognized patterns allow virtual imagery to be interactively superimposed over a live video feed of the real world thus facilitating the development of AR applications.

Another class of tracking systems is based on using local positioning and orientation sensors combined with dead reckoning and/or regular sensor updates [Reitmayr and Schmalstieg 2003]. Examples include the use of GPS sensors to track the user's position during navigation, and orientation trackers to monitor the head orientation or the direction of gaze [Piekarski and Thomas 2003].

In this research, traditional tethered tracking systems are ruled out because the AR system intended to detect building damage must essentially operate in an outdoor environment and not in a finite enclosed area. In vision based tracking, although the placement of fiducial markers at known locations in a chaotic post-disaster environment is challenging, the use of the tracking technology itself is conceivable in outdoor AR applications. User positioning and orientation with infrastructure-less technologies is well suited for outdoor AR because it does not rely on any pre-installed infrastructure (e.g. markers, sensors), and all equipment can be mounted on the AR user creating a self-contained tracking system.

Given this understanding, vision based and other infrastructure-less positioning/orientation techniques are being investigated in this project. In the first conducted experiment, registration was achieved by placing fiducial markers at known locations on the laboratory strong wall as portrayed in Fig. 3. In the second case, the user's video camera was mounted at a known location in the laboratory throughout the duration of the experiment.

Experiment I – Vision Based Tracking

The following steps summarize the marker-based AR process [Kato et al. 2000]:

- A camera captures video of the real world and sends it to the computer.
- The computer searches through each video frame for any recognized markers.
- If a marker is found, the position of the camera relative to the marker is calculated.
- Once the position of the camera is known, any computer graphics model (e.g. CAD image) can be drawn (i.e. augmented) relative to the marker position.
- The augmented graphics are drawn on top of the video of the real world and so always appear relative to a base marker.

- The final output which consists of graphics overlaid on the real world can be viewed and analyzed on the user's display.

Thus, if the position of a recognized marker is known in the real world, a CAD image can be placed at any desired location in augmented space. All that is needed is the real-world location of the marker itself and the desired placement position relative to the marker. This result was used to place a CAD image of the concrete wall at the corresponding location of the real, undamaged specimen.

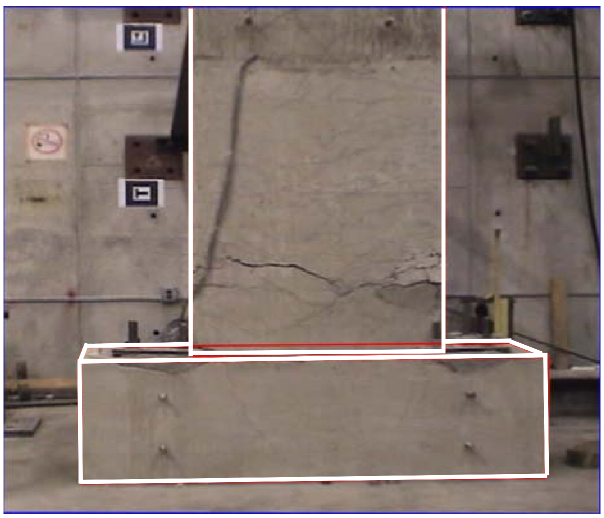

Figure 3: Schematic Overview of AR Setup in the UM Structural Engineering Laboratory

After the test of the wall was complete, the specimen had sustained significant damage and permanent lateral displacements. The horizontal discrepancy between the image and the deformed wall could then be observed and measured. This is graphically depicted in Figs. 3 and 4. In Fig. 3, the CAD image superimposed on the real specimen is only a schematic included for clarity in this discussion. The fiducial markers could not be recognized accurately for registration from a distant camera position that captured the entire width of the wall.

When the camera was moved closer to focus on a particular marker and the edge of the wall (Fig. 4), the marker could be optically recognized and thus provided a reference frame in augmented space to register the overlaid graphics against. However, the amount of jitter that was observed in optical marker recognition was significantly high even when the video camera was installed on a stationary tripod. The jitter in marker recognition translated into corresponding unsteadiness of the augmented CAD image, thus precluding any accurate measurements of lateral separation between the image and the specimen while the camera was rolling. This phenomenon prevented accurate observations and measurements of the horizontal discrepancy while the test was in progress.

In order to workaround this issue, six sets of 24 consecutive frames at random time points during the recorded video were captured. Only video recorded at the end of the test was considered. The drift observed in each image of such a set was computed and the average value was recorded as the representative displacement of the set. For each image, the displacement was computed by calculating the number of image pixels between known locations in the frame and then extrapolating the scale to the number of observed pixels between the edge of the damaged wall and the wireframe CAD image. Since jitter is inherently random and the augmenting of CAD images happens in real time during video playback or live camera feeding, it was impossible to observe the same horizontal drifts in subsequent tests even if the same video frame set was reused.

The best observation of average drift between the CAD image and the wall at the zenith yielded a measurement of 51-mm. The computed average top drift of 51-mm corresponded to an actual displacement of 44-mm that was measured in the tested wall specimen using traditional techniques. In the best observed set, the AR method therefore over-predicted the permanent drift by 16%. In the worst observed set, the average drift was computed to be 36-mm but in the opposite direction (i.e. left) of the true drift. Since the true displacement was 44-mm to the right, a computed drift of 36-mm in the opposite direction amounts to a prediction error of 181% [(44+36)/44]. A snapshot of an observed discrepancy between the augmented image and the damaged concrete wall has been zoomed for clarity in Fig. 4.

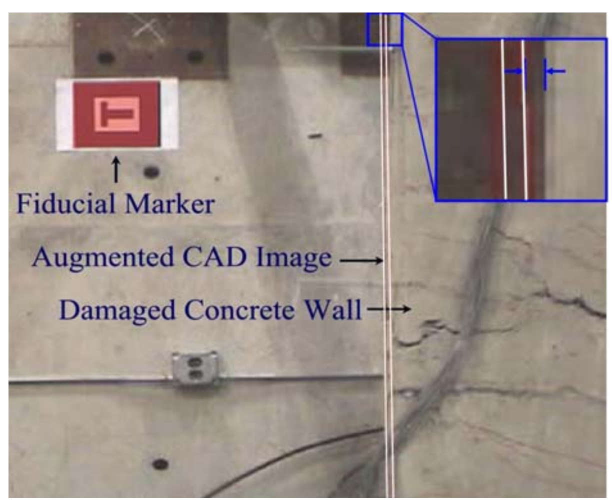

Figure 4: Observed Displacement (zoomed for clarity) Between Registered Augmented CAD Image and Real Damaged Concrete Wall Specimen

Experiment II – User Position and Orientation Tracking with Fixed Camera

The following steps outline the user position/orientation tracking-based AR process in this experiment:

- A camera captures video of the real world and sends it to the computer.
- The camera position and orientation in the local 3D augmented space are known.
- Once the position and orientation of the camera are known, any computer graphics model (e.g. CAD image) can be drawn (i.e. augmented) relative to the center of the camera's lens (which corresponds to the user's viewpoint).
- The augmented graphics are drawn on top of the video of the real world and so always appear relative to the user's viewpoint.
- The final output which consists of graphics overlaid on the real world can be viewed and analyzed on the user's display.

Thus, if the position and orientation of the camera is known in the real world, a CAD image can be placed at any desired location in augmented space [Behzadan and Kamat 2005]. All that is needed is the real-world location of the augmented CAD object itself. This result was used to place a CAD image of the concrete wall at the corresponding location of the real specimen. The subsequent steps of the experiment were generally similar to that of the first. There was, however, one notable difference.

The position and orientation of the camera was constant at each step throughout the duration of the experiment. Since the augmented images were placed in the scene relative to the center of the camera's lens, there was no jitter or any other source of unsteadiness in the overlaid graphics. This allowed accurate measurements of horizontal drift to be made at all intermediate stages of structural testing. Observations were made at the beginning and end of ten actuator loading strokes (i.e. after five loading cycles). The best observation (i.e. least % error) of drift between the CAD image and the wall yielded a measurement of 210-mm. This corresponded to an actual displacement of 214-mm.

In this observation, the AR method thus under-predicted the drift by 2.1%. In the worst observation (i.e. highest % error), the drift was computed to be 83-mm in AR corresponding to an actual displacement of 89-mm. This observation amounted to an under-prediction error of 7.2%. It is interesting to note that in all observations, the AR method under-predicted the actual sustained displacements. In addition, it was also observed that the % error generally decreased as the amplitude of the wall displacements increased.

6. Conclusions: The presented research evaluates the hypothesis that previously stored building information can be superimposed onto a real structure in AR, and that structural damage can be evaluated by measuring and interpreting key differences between a baseline image and the real facility. The computation of global building damage measures such as the IDR can provide a quick and accurate assessment of the extent of structural damage that a building has sustained in a disaster.

The presented AR based method can overlay facades of possibly damaged and displaced buildings with pre-existing images of the undamaged structures. The IDRs for the buildings' stories can then be computed by comparing the displacements at key locations with their original positions in the augmented images. By comparing computed IDRs to predetermined thresholds, a quick but thorough assessment of the level of structural and non-structural damage incurred in a disaster can be made. The experiments described in this paper validate the premise that the proposed AR based method is conceptually feasible for observation and measurement of horizontal drift in damaged buildings if acceptable registration accuracy for the overlaid graphics can be achieved.

It was found that fiducial marker based registration is inappropriate for this application because of consistent jitter during image recognition and the resulting unsteadiness of the augmented graphics. The observed jitter can be attributed to calibration and computer vision errors that are inherent in marker based AR [Barfield and Caudell 2001]. In addition, the dependence of marker based registration on ideal lighting conditions and the necessity to place markers in a chaotic, post-disaster environment make the practicality of this technique somewhat questionable for AR based damage detection.

Registration achieved by fixed user positioning and orientation was found to be conceptually best suited for this application. The second experiment demonstrated that if the user's video camera can be secured after accurate positioning and orientation, the achieved registration is precise and steady, allowing measurements of horizontal structural drift to be correctly made. The writers' ongoing work is attempting to achieve accurate outdoor user positioning and orientation using a high accuracy GPS sensor or surveying based approach.

Successful field implementation of the proposed technique promises significant advancement over current labor intensive, time consuming and error prone damage reconnaissance practices. Due to its low cost, simplicity, and achievable accuracy, the approach can have distinct advantages over remote sensing and sensor-based damage detection techniques. Unlike remote-sensing that can only detect partial or complete collapse, the proposed technique has the ability to quantify damage irrespective of the state of a building's facade. The relatively low cost associated with such a process is also in contrast to sensor network based systems that can be expensive to install and maintain.

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