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Sensitivity analysis of augmented reality-assisted building damage reconnaissance using virtual prototyping

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ABSTRACT

The timely and accurate assessment of the damage sustained by a building during catastrophic events, such as earthquakes or blasts, is critical in determining the building's structural safety and suitability for future occupancy. Among many indicators proposed for measuring structural integrity, especially inelastic deformations, Interstory Drift Ratio (IDR) remains the most trustworthy and robust metric at the story level. In order to calculate IDR, researchers have proposed several nondestructive measurement methods. Most of these methods rely on pre-installed target panels with known geometric shapes or with an emitting light source. Such target panels are difficult to install and maintain over the lifetime of a building. Thus, while such methods are nondestructive, they are not entirely non-contact. This paper proposes an Augmented Reality (AR)-assisted non-contact method for estimating IDR that does not require any pre-installed physical infrastructure on a building. The method identifies corner locations in a damaged building by detecting the intersections between horizontal building baselines and vertical building edges. The horizontal baselines are superimposed on the real structure using an AR algorithm, and the building edges are detected via a Line Segment Detection (LSD) approach. The proposed method is evaluated using a Virtual Prototyping (VP) environment that allows testing of the proposed method in a reconfigurable setting. A sensitivity analysis is also conducted to evaluate the effect of instrumentation errors on the method's practical use. The experimental results demonstrate the potential of the new method to facilitate rapid building damage reconnaissance, and highlight the instrument precision requirements necessary for practical field implementation.
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1. Introduction

Rapid and accurate evaluation approaches are essential for determining a building's structural integrity for future occupancy following a major seismic event. The elapsed time could translate into private financial loss or even a public welfare crisis. Current inspection practices usually conform to the ATC-20 post-earthquake safety evaluation field manual and its addendum, which provide procedures and guidelines for making on-site evaluations [1]. Responders such as ATC-20 trained inspectors, structural engineers and other specialists conduct visual inspections and designate affected buildings as green (apparently safe), yellow (limited entry), or red (unsafe) for immediate occupancy [2]. The assessment procedure can vary from minutes to days depending on the purpose of evaluation [3]. However it has been pointed out by researchers [4,5] that this approach is subjective and thus may sometimes suffer from misinterpretation, especially given that building inspectors do not have enough opportunities to conduct building safety assessments and verify their judgments, as earthquakes are infrequent.

Despite the de-facto national standard of the ATC-20 convention, researchers have been proposing quantitative measurement for more effective and reliable assessment of structural hazards. Most of these approaches, especially non-contact, build on the premise that significantly local structural damage manifests itself as translational displacement between consecutive floors, which is called interstory drift [6]. Interstory drift ratio, which is interstory drift divided by the height of the story, is a critical structural performance indicator that correlates the exterior deformation with the internal structural damage. The larger the ratio is, the higher the likelihood of damage. For example, a peak interstory drift ratio larger than 0.025 signals the possibility of serious threat to human safety, and values larger than 0.06 translate to severe damage [7].

This research proposes a new approach for estimating IDR using an Augmented Reality (AR) -assisted non-contact method. AR superimposes computer-generated graphics on top of a real scene, and provides contextual information for decision-making purposes. AR has been shown to have several potential applications in the civil infrastructure domain such as inspection, supervision, and strategizing [8]. AR-assisted building damage detection is a specific type of inspection.

2. Review of previous work

So far the most commonly accepted approach for obtaining IDR is via contact methods, specifically the double integration of acceleration.

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This method is most commonly used because of its robustness and widespread availability in the world's seismically active regions. However, Skolnik and Wallace [9] identified the vulnerability of double integration to nonlinear response. It has been suspected that sparse instrumentation or subjective choices of signal processing filters lead to these problems.

Another school of obtaining IDR is non-contact methods. Wahbeh and Caffrey [10] demonstrated a vision-based approach: tracking an LED reference system with a high fidelity camera. Ji [11] instead applied feature markers as reference points for vision reconstruction. Similar target tracking vision-based approaches have also been studied in [12] and [13]. However, all of them require the pre-installation of a target panel or emitting light source, and such infrastructure is not widely available and is subject to damage during long-term maintenance, since it is located on the exterior of the structure. Fukuda [14] tried to eliminate the use of target panels by using an object recognition algorithm, for instance orientation code matching. They performed comparison experiments by tracking a target panel and existing features on bridges, such as bolts, and achieved satisfactory agreement between the two test sets. However it is not clear whether this approach works in the scenario of monitoring a building's structure, as building surfaces are usually featureless.

Researchers also utilized terrestrial laser scanning technology in non-contact methods for continuous or periodic structural monitoring [15,16]. In spite of the high accuracy of such systems, the equipment volume and the large collected dataset put these methods at a disadvantage for rapid evaluation scenarios.

Kamat and El-Tawil [5] first proposed the approach of projecting the previously stored building baseline on the real structure, and using a quantitative method to count the pixel offset between the augmented baseline and the building edge. In spite of the stability of this approach, which has been tested in UM's Structural Engineering Laboratory with large-scale shear walls, it required a carefully aligned perpendicular line of sight from the camera to the wall for pixel counting. Such orthogonal alignment becomes unrealistic for high-rise buildings, since it demands that both camera and the wall be at the same height.

Dai et al. [17] removed the premise of orthogonality using a photogrammetry-assisted quantification method, which established a projection relation between 2D photo images and the 3D object space. They validated this approach with experiments that were conducted with a two-story reconfigurable aluminum building frame whose edge could be shifted by displacing the connecting bolts. The experimental results were in favor of the adoption of consumer-grade digital cameras and photogrammetry-assisted concepts. However the issue of automatic edge detection and the feasibility of deploying such a method at large scales, for example with high-rise buildings, have not been addressed.

This paper specifically addresses the above limitations and proposes a new algorithm called line segment detector for automating edge extraction, as well as a new computational framework automating the damage detection procedure. To verify the approach's effectiveness, a synthetic Virtual Prototyping (VP) environment has been designed to profile the detection algorithm's sensitivity to errors inherent in the used tracking devices.

3. Overview of proposed reconnaissance methodology

Fig. 1 exhibits the schematic overview of measuring earthquake-induced damage being manifested as detectable building facade drift. The previously stored building information is retrieved and superimposed as a baseline wireframe image on the real building structure after damage. Then the sustained damage can be evaluated by comparing the key differences between the augmented baseline and the actual drifting building edge. Fig. 1 also demonstrates a hardware prototype called ARMOR (acronym for Augmented Reality Mobile OpeRating platform) [35] where the developed application can be potentially deployed. The inspector wears a GPS antenna and a RTK (acronym for Real Time Kinematic) radio that communicates with the RTK base station. Together they can track the inspector's position up to centimeter-level accuracy. As discussed in Section 5.2, position and orientation tracking accuracy have great influence on the effectiveness of the estimation algorithm. Meanwhile, the estimation procedure and the final results can be shown in the HMD (acronym for Head Mounted Display) in front of the inspector.

The evaluation procedure is further illustrated in Fig. 2. The first step is for the camera to take pictures of the building. The orientation and location information about the camera needs to be recorded for 3D to 2D projection, as well as for 2D to 3D triangulation. The second step is to extract edges in the captured photo frames. A line segment detector extracts the vertical building edge, and an estimation method is used to represent the horizontal edge with the baseline. The last step involves the triangulation of the 3D coordinate at the key location from multiple corresponding 2D intersections between the vertical and horizontal edges. IDR is subsequently computed by comparing the key difference between two consecutive building floors divided by the story height. The accuracy of IDR calculation thus depends on the accuracy of internal and external camera parameters, the accurate detection of the vertical edge, and the estimation of the horizontal edge.

Besides being a quantitative means of providing reliable damage estimation results, the vertical baseline of the building structure is also a qualitative alternative for visual inspection of local damage. By observing the graphical discrepancy between the vertical baseline and the real building edge, the on-site reconnaissance team can approximately but quickly assess how severe the local damage is in the neighborhood of the visual field. In other words, the larger the graphical discrepancy is, the more severe the damage is. Fig. 3(a) and (b) focuses on different key locations of the building but are views taken from the same angle (i.e., direction). The right-bottom window on each image is a zoom-in view of the key location. The two vertical lines in the zoom-in window represent the detected edge and the vertical baseline respectively. The fact that the gap between the detected edge and the vertical baseline on Fig. 3(a) is smaller than that on Fig. 3(b), indicates that the key location on Fig. 3(b) suffers more local damage than that on Fig. 3(a).

4. Technical approach

The objective of this research was to design, demonstrate, and evaluate a new AR-assisted non-contact method for rapidly estimating the IDR in buildings that manifest residual drift from seismic damage. In particular, the research objectives included the verification of the developed algorithms, and the evaluation of the sensitivity of computed drift to measurement errors inherent in the used tracking devices. Access to a damaged high-rise building is rare. Moreover, such a test bed offers no possibility of inducing specific amounts of drift in the building stories for calibration or evaluation purposes.

In addition, an experimental plan conducted to understand the designed algorithm's sensitivity to ambient conditions and instrument uncertainty requires a controlled test bed environment. In order to demonstrate and evaluate the developed computational framework, this research designed a synthetic 3D environment based on Virtual Prototyping (VP) principles for verifying the developed algorithms, and for conducting the sensitivity analysis. A Virtual Prototype, or digital mock-up, can be defined as a computer simulation of a physical counterpart that can be observed, analyzed, and tested from life-cycle perspectives, such as design and service, as if it were a real physical model. The creation and evaluation of such a Virtual Prototype is known as Virtual Prototyping (VP) [18]. By using a digital model instead of a physical prototype, VP can alleviate several shortcomings in the design and evaluation process.

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