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Machine-Aided Rapid Visual Evaluation of Building Façades

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Abstract

After a disaster, engineers must evaluate the potential risk posed by damaged components on building façades (e.g. falling debris) before allowing re-occupancy. Currently, human engineers must physically visit each and every building to conduct manual inspection, which is extremely time-consuming and expensive. Harnessing the capacity to use vision sensors and associated sensing platforms (e.g. unmanned aerial vehicles (UAVs)) would improve the current visual inspection procedure in the case of real-world buildings. In this study, we develop a technique to perform rapid and accurate visual inspection of building façades using images collected by UAVs. An orthophoto corresponding to the building façade is automatically constructed from those images using the structure-from-motion algorithm, followed by image stitching and blending. This orthophoto provides an overview of the building façades, which is useful for shifting through the façades for the purpose of damage detection and documentation.

1. Introduction

During tornado or hurricane, non-structural components installed at the building façades are directly exposed to strong winds or airborne debris. Among them, glass panels are a typical component that is vulnerable to damage (1, 2). In high-rise buildings in urban areas, a complete inspection must be rapidly conducted to avoid collateral accidents because broken glass panels installed at higher position may fall to the street below and cause serious injury on pedestrians and/or damage to objects (e.g. road or vehicle).

Current building construction provisions require exterior non-structural components to be secured to avoid such accidents caused by the falling hazard (3) However, they are not designed to sustain severe wind loads or airborne debris strikes (4). Some examples of building damage due to past tornado events are shown in Fig. 1. In 2000, Bank One tower, severely damaged by a F3 (Fujita scale) tornado in Fort Worth, TX, lost around 3,000 glass panels (5, 6). In 2008, a EF2 (Enhanced Fujita scale) tornado strike in downtown Atlanta, GA damaged over 500 glass panels of the Westin building, resulting in $20 million of replacement cost for the glass panels (7).

Unfortunately, manual inspection is now the only way to evaluate the conditions of such structures (8). Human inspectors manually inspect defects in each glass panel installed at each floor of all buildings. There is no a standardized procedure to inspect the individual glass in each pane. They often fail to inspect the entire area of glass panels in the case when the top region of floor-to-ceiling glass panels is inaccessible or office furniture blocks its view. The inspectors should manually annotate and document the condition (e.g., broken, dislocation, and crack) of each glass panel on a drawing or sketch of the building façade. Imagine that many buildings require inspection after a disaster. The current process would be very inefficient and time-consuming.

(a) (b)

Figure 1. Damage on building façades: (a) Bank One building, after a tornado in 2000, Fort Worth, Texas, U.S. and (b) Westin Peachtree Plaza Hotel, after a tornado in 2008, Atlanta, Georgia, U. S.

To enable rapid visual evaluation, we can exploit aerial images collected using UAVs. A large volume of images is readily collected from the building exterior without much cost. These images view the building façade from various viewpoints. However, the main challenge is in dealing with the large number of such images which capture the entire building façade using UAVs. They should be captured at a close distance to the building façade to record sufficient details of each building component. Each image may include only a small portion of the building façade. Thus, it would not be possible to manually identify where each image views the building façade. Although GPS is recorded on each image, it does not provide enough accuracy regarding its camera pose and location (typical error range of 5~15 m) (9). Approximation of its relative location using the sequence of the images is the only available way to estimate the position of the images, which is inadequate to achieve efficient visual evaluation. Hence, we can benefit from an automated method that can estimate the pose of each image and arrange them with respect to the test building façade.

To tackle this challenge, we have developed a technique to support rapid visual inspection of glass panels on the building facade. An orthophoto of the building façade is automatically generated using the structure-from-motion (SfM) algorithm followed by image stitching and blending. The resulting orthophoto is a high-resolution image containing the entire building façade. The tool developed in this study has zooming and panning functions in such way that inspectors can easily view the details for any suspicious regions on the building façade. Moreover, this orthophoto is geometrically correlated to each of the images collected. Once an inspector chooses a point on the orthophoto, any images correlated to the point are displayed to the inspectors. Thus, inspectors can evaluate the condition of individual glass panels using images and easily make their documentation.

The remainder of this paper is organized as follows. Section 2 begins with the overview of the method, followed by providing the details of each technical step. In Section 3, the method is experimentally validated through a demonstration on a real building. Sections 4 and 5 include the discussion and conclusion respectively.

2. System Overview

The technique developed here is to support inspectors in performing a visual inspection of the building facades using images collected from UAVs. An overview of the technique is presented in Fig. 2. Step 1 is to collect a large volume of images from the buidling façades under various different viewpoints. Step 2 is to estimate a projection matrix for each image using SfM and detect the building plane to compute a planar homography for each image. Step. 3 is the construction of a high-resolution orthophoto of the building façade. More details of each step are illustrated in the following subsection.

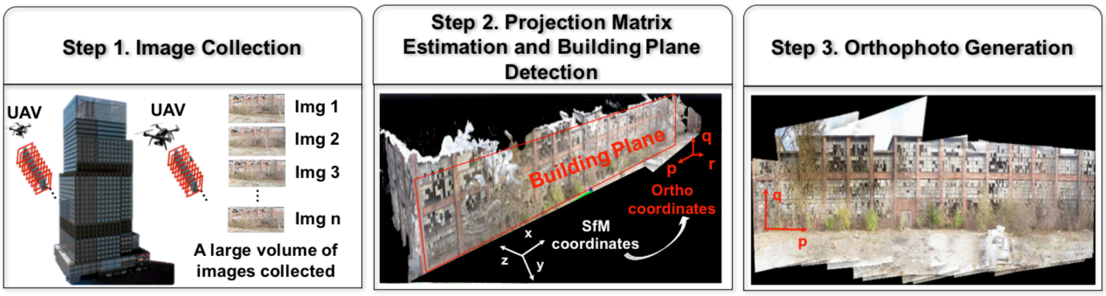


Figure 2. System overview

2.1 Image Collection

Collecting quality images is a crucial step for generating a high-quality orthophoto. In this technique, we do not manually choose favorable images but rather use all the raw-image set as an input data. In step 1, we suggest two guidelines to ensure successful generation of the orthophoto. First, a large number of images are collected while maintaining a close-distance between the UAV and building façade. The distance between the camera and the building façade is determined depending on the required resolution for damage inspection. Second, it is recommended to have at least 75% overlap between the sequence of the collected images (10). While covering the entire area of the target building façade, users should have an appropriate flight plan including frame rate, flight speed, and the distance between the camera and building façade. In general, a grid pattern with a regular spacing is recommended as the flight path, as is illustrated in Fig. 3.

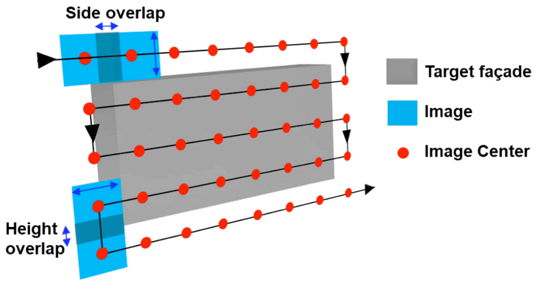
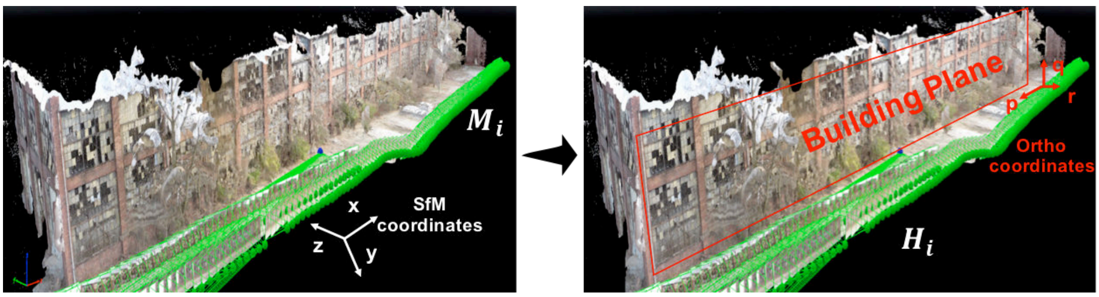


Figure 3. Recommended aerial image collection plan following regular squre grid pattern.

2.2 Projection Matrix Estimation and Building Plane Detection

In Step 2, the projection matrix for each image is estimated and the building plane is detected using the point cloud generated, as depicted in Fig. 4 (a) and (b) respectively. After applying feature detection and matching processes (e.g. SIFT or SURF) to the collected images, the projection matrix, denoted **M**, is determined using SfM. Sparse 3D point cloud is also produced from matched features, which are extracted from the target building. SfM enables this expensive computation, and automatically estimates **M**. Consider that each image, **i**, has an associated 2D coordinate system (the pixel coordinates). $\mathbf{M_i}$ stands for the geometric relationship between the point cloud and each of the images, which represents a transformation between the SfM coordinates and the pixel coordinate system; it enables connecting a 3D point in SfM coordinates system, *x-y-z* axes, to corresponding 2D points in the collected images. **M** for each image **i** is expressed in homogeneous coordinates: a 3×4 matrix (11, 12, 13, 14, 15). **M** includes both intrinsic parameters (focal length, principal points, and camera center) and extrinsic parameters (camera location in 3D and rotation angle) of the image. Note that neither prior knowledge of the scene nor camera parameters are required in this step.



(a) **(b)**

Figure 4. Projection matrix and planar homography estimation (a) projection matrix estimatimation in SfM coordinates; and (b) building plane detection in Ortho coordinates to estimate planar homography.

The produced point cloud forms a sparse shape of the targeted building façade, and we can detect a building plane among this point cloud. We applied the MLESAC (Maximum Likelihood Estimation SAmple and Consensus) estimator for detecting this plane. MLESAC follows the similar sampling strategy as the RANSAC (Random Sample Consensus) estimator, but place more weight on inlier samples for a better fitting (16). The detected building plane is defined in *Ortho* coordinate (expressed in *p-*

q-r axes) defined in this work. Finally, the pixel coordinates of the collected images and the *p-q* plane in *Ortho* coordinate system will be used for estimating homography, denoted $\mathbf{H_i}$, for each image.

2.3 Orthophoto Generation

An orthophoto is a planar image created by combining the collected images while also removing perspective distortion (17). It has a uniform scale in each direction that defines its plane, thus truly represents an accurate view of a large scale of building façades. Using computed **H**, each image can be projected to the building plane detected in to *p-q* plane. To obtain high-quality orthophto, we apply image blending algorithm that utilizes gain compensation and multiband blending (18). Also, the orthophoto is geometrically connected to the collected images by estimating **M**. The inspectors can choose a point on the orthophoto, then images correlated to the point are displayed to conduct further visual evaluation. Fig. 5 depicts image projection to the detected building plane and generated orthophoto with image blend.

(a) **(b)**

Figure 5. Orthophoto generation using planar homography H estimated for each image (a) image projection on the detected building plane and (b) generated orthophoto to display to inspectors.

3. Experimental Validation

3.1 Description of the Test Building

An abandoned building (hereafter, test building) is selected for validating the developed method, shown in Fig. 6. The façade of the test building is 137 m wide and 16m high. A large portion of the façade area consists of glass panels of which glass material has minimal reflection. There are many damage presented on the glasses, such as, cracks or broken in the glass panels, and even dislocations (completely missing glass panels).

Figure 6. Dimensions of the test building and façade region.

To compute the projection matrix of each image, an open source SfM software, VisualSfM is used here. VisualSfM provides a 3D visual interface to examine intermediate steps of the SfM, such as the feature matches and the camera poses. VisualSfM implements the SiftGPU Library and parallel processing with Graphical Processor Units (GPUs) (19, 20) for increasing computational speed. Once the projection matrices are computed, building plane detection and orthophoto generation procedures are deployed in MATLAB (21).

3.2 Image Collection from a Test Building

A low-cost UAV (3DR Solo Quadcopter) with a consumer grade compact camera (Canon PowerShot SX280 HS) is used for collecting images from a test building façade. The camera is lightweight (210 g) that can be carried by the UAV. We do not manually control the camera during the flight, and no zoom or flash functions are used. All images are taken during daytime and have a resolution of 4,000 × 2,664 pixels.

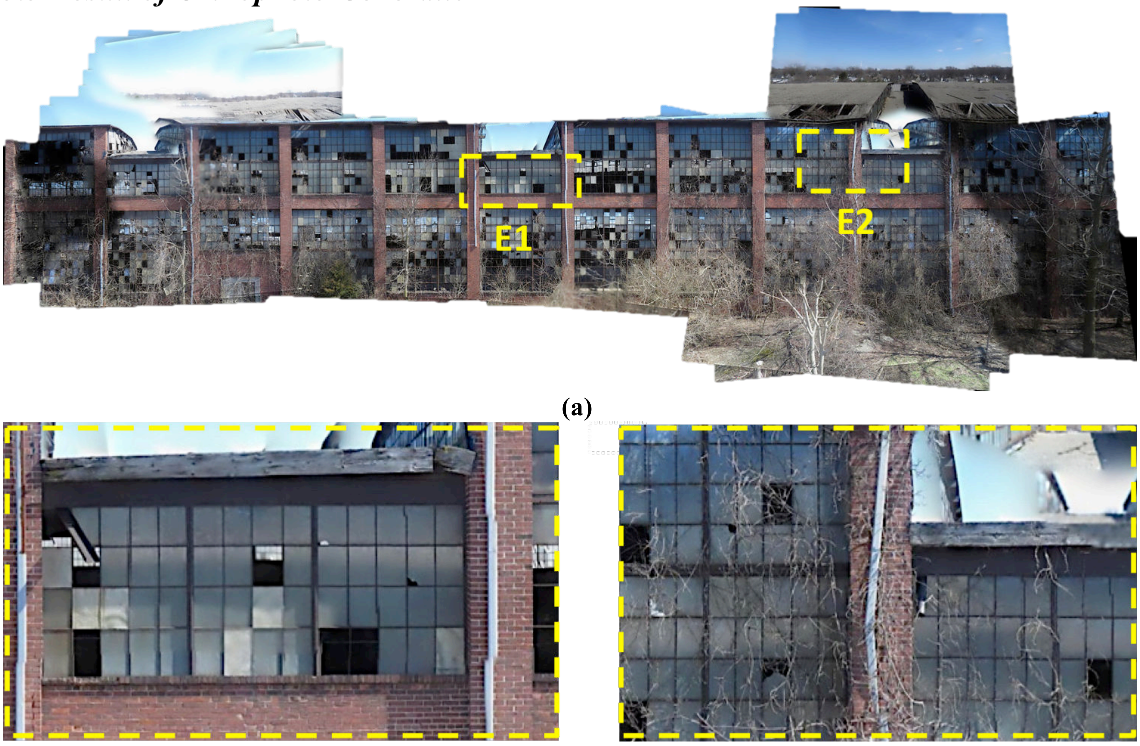
At least a 75% overlap between the collected image sequence is recommended for the successful SfM process (13). To satisfy this requirement, the camera is set to a burst mode and each image is captured every second (1 frame/sec) during the flight. In our experiment, further image collection guidelines using the UAV are followed:

- First, images are collected according to a regular grid pattern as introduced before in Fig. 3. The pilot holds the altitude and translates the UAV horizontally from the one to the other end. Then, the pilot lowers (or elevate) the altitude and repeat the prior process. In this way, the UAV flies in a sweeping pattern to gather the images over the entire façade.

- Second, the pilot maintains the UAV at a low and constant flight speed. The speed of UAV will be determined based on the distance between the UAV and test building as well as the level of details for target objects on the façade. In our experiment, the distance is set to be roughly 4 ~ 5 m for detailed inspection. The flight speed is set to be slow (around 0.5 m/s), allowing more than 75% overlap between images but also minimizing the risk of capturing blurry photos.
- Third, data collection is repeated four times by varying the camera angles in each time. We make four different angle variations; front, oblique-right, oblique-left, and downward. Here, the façade of the test building contains many glass panels. Those glass panels do not generate much visual features that are used for the SfM process. This causes a failure of estimating the projection matrices. Therefore, we collected oblique images. Oblique images include larger regions increasing overlap between the images, although those are not suitable for the actual visual inspection.

With these guidelines, a total of 1,520 aerial images were collected in the time span of around 20 min (5min / loop).

3.3 Result of Orthophoto Generation



(a)

(b)

Figure 7. Orthophoto generation: (a) E1 and E2 selections that inspectors select on the orthophoto and (b) the corresponding areas (enlarged)

By the 1,520 aerial images collected and obtaining the projection matrices, an orthophoto is successfully generated for the entire building façade. Fig. 7(a) shows the view of the orthophoto for the building façade for this study. It can be further enlarged to allow the user to inspect detailed condition of areas. As the orthophoto is stitched and blended from the raw images, the enlarged regions in the Fig 7. (b) show clear views that enable visual evaluation. Also, note that in this case, there may exist unavoidable occlusions due to the foreground objects in front of the building façade (trees, in this case). In this case, these unavoidable areas may be inspected using the linked raw images once user chooses a region for inspection.

4. Discussion

To implement this technique, some challenges need to be considered for a successful orthophoto generation. The main challenge of the technique is the orthophoto generation for a building façade not plain. This could be alleviated by defining multiple building planes for multiple orthophoto generations, but, the processing time would increase. There is also a need to deal with obstructions in the view, such as trees or vines.

5. Conclusion

For post-disaster response, buildings must be rapidly inspected to prevent the potential loss of life and damage to property. Here, we present and validate a vision-based approach for supporting rapid inspection of the building facades. The key contribution of the technique developed here is to construct the exterior building image for the visual inspection. A UAV is used to quickly collect a large volume of aerial images of the region to be inspected. This technique will streamline current manual visual inspection processes, thus to be used when the rapid evaluation in community is required after disaster strikes an urban town. Also, using this orthophoto would increase reliability of image-based visual evaluation and enable easy documentation for the reference. This orthophoto can assist users to conduct visual inspection. The feasibility of the technique is demonstrated using an abandoned building that has several damage on the facade.

Acknowledgements

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