Opportunities for Applying Camera-Equipped Drones towards Performance Inspections of Building Facades

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ABSTRACT

Over the past years, a growing trend of utilizing camera-equipped drones for periodical building facade inspection has emerged. Building façade anomalies, such as cracks and erosion, can be detected through analyzing drone-captured video, photographs, and infrared images. Such anomalies are known to have an impact on various building performance aspects, e.g., thermal, energy, moisture control issues. Current research efforts mainly focus on computational image processing methods to recognize certain types of facade anomalies. However, there is a lack of research on mapping detected anomalies into the building model and managing lifecycle inspection information. This paper aims to propose a systematic process for detecting and managing building façade anomalies based on drone-collected images. An overall data structure, data flow, and related processing techniques within this systematic process are defined. The proposed systematic process will support the facade anomaly detection and building maintenance decision-making.

INTRODUCTION

Over 15,000 buildings in the U.S. are required by local municipal laws to take periodic safety inspections of their facades. While these inspections primarily screen for unsafe conditions, conducting regular facade inspections can also benefit the measurement, prediction, improvement and management of the overall building façade performance (e.g., energy, thermal) (Gaspar Katia et al. 2016). The failure of building façade systems triggered from damage states such as water leaks or air infiltration may cause severe damage to properties, both economically and environmentally, and drastically reduce durability and useful life-time of buildings. As early-phase signs of building façade failures, the detection of building façade anomalies (BFAs) (e.g., cracks, stains, detachment, corrosion) can be valuable for the assessment of façade performance and decision-making of intervention strategies. Therefore, periodic inspections to detect and track such BFAs, and consequent remediation of issues or preventive maintenance strategies, can drastically reduce the occurrence of larger scale facade failures and long-term property damages.

Traditional diagnosis techniques for BFAs such as in situ visual conditions surveys, close-up measurements, laboratory test (Eschmann et al. 2012) are time and labor consuming and thus in most cases cost-inhibitive. Furthermore, such inspections may have safety issues, especially for high-rise buildings. Recently, the deployment of drone or Unmanned Aerial Vehicle (UAV) systems has emerged as a new trend supporting the examination of building facades. Equipped with a High-Definition camera, infrared camera, or a laser scanner (Mader et al. 2016; Weinmann et al. 2017), Unmanned Aerial System (UAS) can collect close-up facade images with diverse (RGB, temperature, geospatial) information. Through the post-processing and analysis of these multi-sensed images, certain types of BFAs can be detected with detailed attribute information. This presents new opportunities for measuring and improving a variety of building façade performance aspects that go beyond structural and safety issues.

Even though advanced methods have been developed for multi-sensed image collection and image data analytics, there is still a lack of knowledge and structure regarding the management of collected data, and its analyzed information and generated knowledge. More specifically, the often multi-sourced and multi-timed series of image data are not well-managed so that knowledge embedded in this large amount of data is not sufficiently utilized; the lack of management of analyzed results may cause difficulties in understanding the detected BFAs' influence on building performance. Therefore, this paper aims to propose a systematic process for the detection and management of building façade anomalies based on drone-collected images in support of measuring and improving a building's performance. This systematic process will solve the spatial modeling of drone-collected image data, the management of multi-sourced and time-series image data, the access to image data analytic tools, as well as the mapping of detected BFAs as a common knowledgebase.

BACKGROUND

Previous research has explored the application of UAS for the inspection of building facades systems, focusing on the application and workflow of drones, 3D building model reconstruction, and image data analytics for anomaly detection. For the application in building inspections, drone images can be used for 3D modeling, surveying, and damage assessment (Rakha and Gorodetsky 2018). The workflow of UAV photogrammetric includes mission planning, image acquisition, image stitching, and 3D modeling (Federman et al. 2017). For the reconstruction of 3D building models, studies have looked into computing methods for different types of sensed image data like point clouds (Tang et al. 2010), drone images (Irschara et al. 2010), and ground-based images (Oskouie et al. 2017). Others explored how to identify building facade elements like windows and doors (Hernández and Marcotegui 2009). For image data analytics, previous research mainly studied how to recognize and classify cracks (Bauer et al. 2016), or stains (Costa et al. 2014) through multi-spectral images collected by drones.

Although previous research has studied UAV applications, building modeling, and image-based anomaly detection, there is still a lack of research towards an integrated and systematic process of drone-based facade inspection. There is a gap between building modeling and image analysis for BFAs. Apart from research on building modeling methods, there is a need to design how to integrate and manage multi-sourced image data to support the efficiency and thoroughness of image analysis. There is also a need to manage analyzed information of BFAs to support the understanding of building façade performance. The following section proposes a systematic process for the detection of BFAs with drone-collected images.

SYSTEMATIC PROCESS OF BFA DETECTION WITH DRONE IMAGES

To improve the management of drone-based BFA detection for building performance assessment, a systematic process of BFA detection with drone images has to be defined. This process map (Figure 1) can be broken into mainly four systematic modules: the spatial modeling of drone-collected images, the management of multi-sourced and time-series image data, the access to image data analytical tools, and the mapping of detected BFAs.

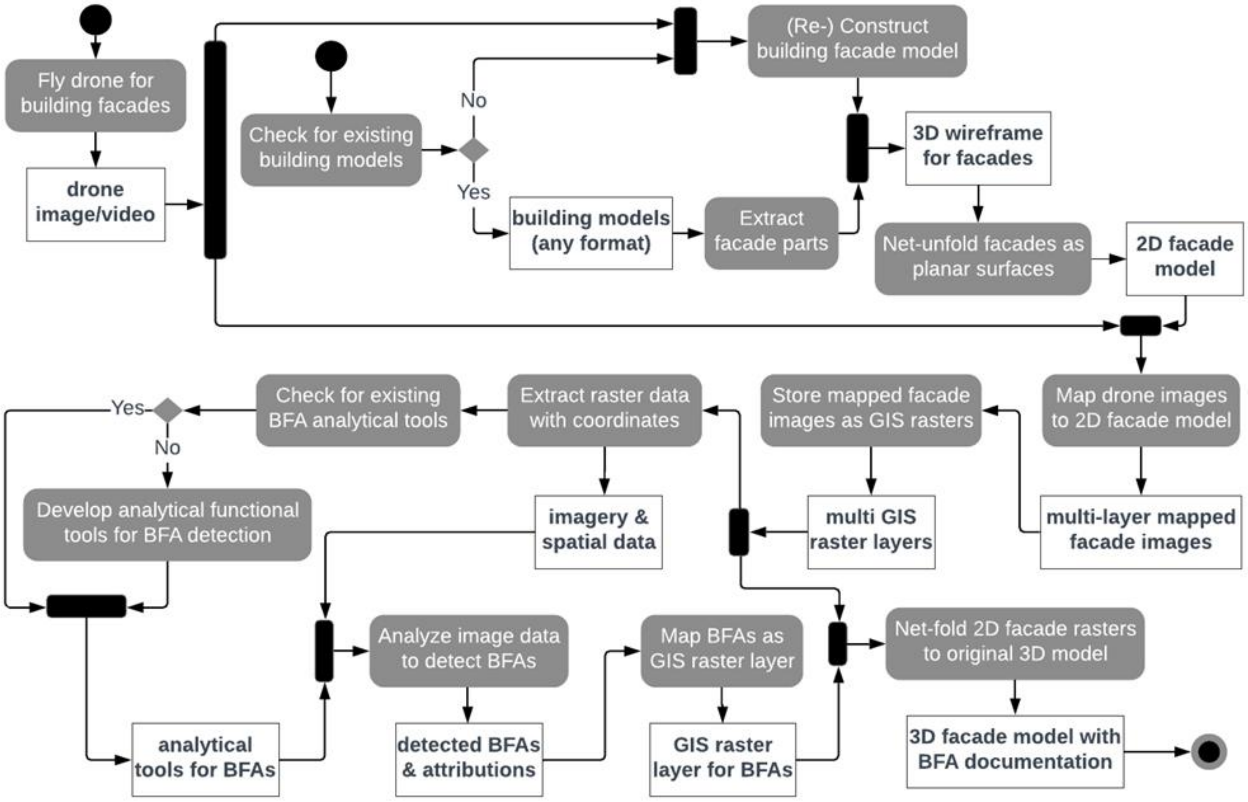

Figure 1. Systematic Process for Detecting and Managing BFAs

As shown in Figure 1, with multi-sensed close-up façade images collected from drones flying around a building, four modules of processing will be executed:

- Module 1 (spatial modeling): may contain the evaluation/extraction of existing models, construction of façade specific building models, and unfold methods of 3D building facades into planar surfaces for analysis and visualization.
- Module 2 (managing of multi-sourced images): mapping of drone images to existing building models, storing and extracting raster data of multi-sourced and time-series façade images.
- Module 3 (access to analytical tools): check for existing applicable image analytical tools and interfaces for BFA detection.
- Module 4 (mapping of detected BFAs): map detected façade anomalies to a planar façade storage space; assess, analyze, and visualize against different data layers, and fold results back to the original building model for additional/alternative visualization and inspection purposes.

Module 1: Spatial Modeling and Transformation

After exporting the prepared drone images, the first action is to evaluate the existence of any suitable building models. If such a model exists, export or reduction methods must be assessed to extract a reduced and simplified 3-D surface model for further processing and image mapping.

If there are no such building models, a 3-D façade surface model can be constructed by either manually sketching a 3-D wire model of high-level building contours, or by computationally processing collected 2D or 3D images such as laser-scanned point clouds, UAS-collected imagery data, and ground-based photos. For example, by computing co-planarity and other surface fitting algorithms for point clouds, model surfaces of building facades can be derived (Tang et al. 2010); drone-collected images could be processed by commercial 3D modeling software (e.g., Pix4D, PhotoScan, PhotoModeler) or open source 3D structural projection algorithms and software packages (e.g., SIFT matching, RANSAC, Structure from Motion) (Irschara et al. 2010). Moreover, façade architectural elements (e.g., windows, doors, columns) can be segmented to generate a mock-up model (Oskouie Pedram et al. 2017).

In the next step, we propose to transform the extracted, manually constructed, or computationally derived 3D building surface model with its basic spatial information into planar polygons that represent the different elevations and surfaces of the building enclosure in a single two-dimensional region, which allow for the utilization of many existing data evaluation and analysis methods found in GIS systems. The net-unfolding theory in computational geometry (O'Rourke 1998) provides a solution for the coordination transformation from a 3D object into a 2D plane. Through this process, 3D building facades with their architectural elements can be converted into 2D planes with unfolding transformation vectors and their geo-location information. This transformation will not only increase the efficiency of image mapping but also improve the storage and management of multi-sourced image data in the following steps. Figure 2 indicates the bottom-up procedure of how to get the 2D building façade model from existing resources or collected image data.

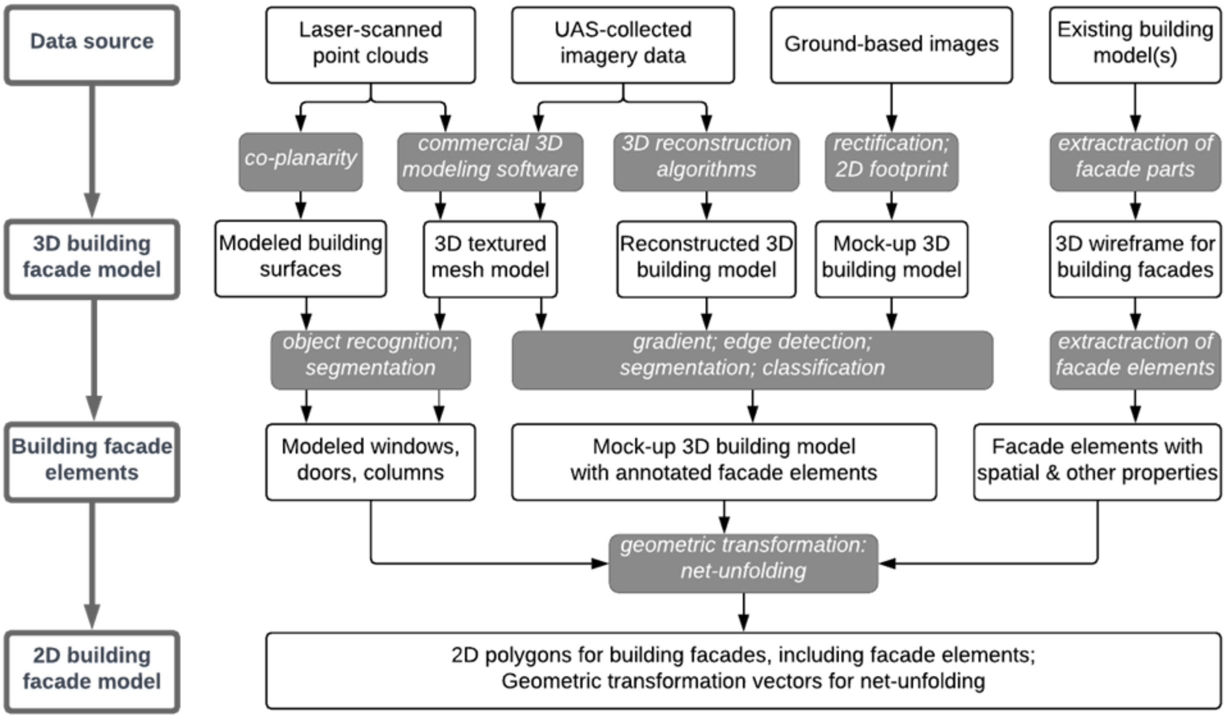

Figure 2. Bottom-up Procedure of Spatial Modeling of Building Façades

Module 2: Management of Multi-Sourced Images

To manage the various drone-collected close-up building façade images more effectively, they must be mapped into the unfolded building façade model and be assigned to their transformed coordinated position for each pixel. Through exploiting geometric and semantic cues from collected images, the labelling and annotation of image features (e.g., windows, doors, columns) can be acquired. These labelled and annotated image features can then be used for the alignment of scattered images onto each unfolded façade polygon. Existing multi-image matching techniques include semi-global matching algorithms, patch-based methods, optimal flow algorithms (Remondino et al. 2012). Furthermore, the locational data acquired from the UAS may also support this mapping procedure by narrowing the mapping zone depending on available GPS accuracy.

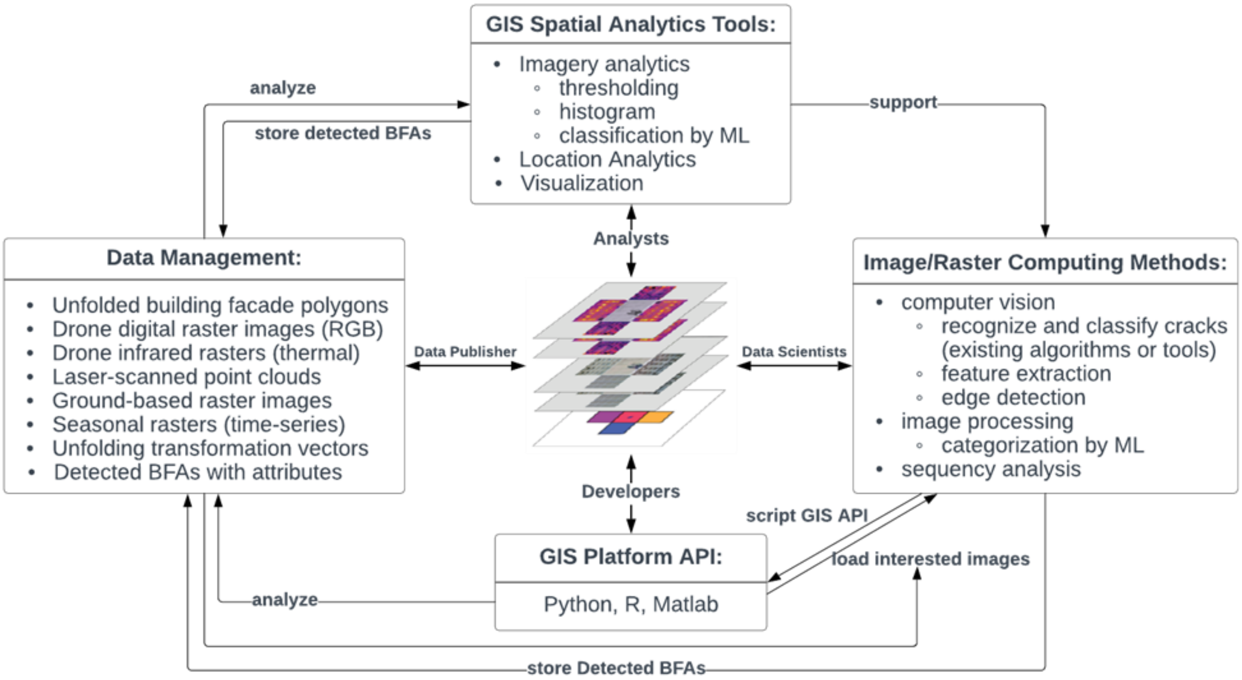

Figure 3. GIS Platform of Analytical Tools for BFA Detection

Once these multi-sourced images have been mapped into the GIS space, there are several types of building façade images that need to be managed. With the application of different cameras and lenses, different types of image data can be collected (e.g., RGB, infrared, wide-angle, or tele lenses). Additionally, periodical façade inspections, which are anticipated to become more affordable by deploying drones, could produce seasonal time-series façade images. Moreover, there may exist other image sources for the inspected façade objects like laser-scanned point clouds, drone-view and ground-based photos.

Geographic information systems (GIS) specialize in the storage, retrieval, manipulation, analysis, and display of geographically referenced data (Tong 2012). It enables rapid access to data and integrate various sets of information (Inkpen et al. 2008). GIS-based platforms can be extended to integrated building asset systems and support the life-cycle maintenance management (Kyle et al. 2008). After mapping the drone-collected images into the unfolded 2D façade model-space, they can be stored and registered as GIS raster layers. The retrieval of spatial and spectral data for the building façade images can then be used for the image analysis to detect BFAs in the following steps.

Module 3: Access to Analytical Tools

Different types of BFAs (e.g., cracks, corrosion, stains, deformations, detachments, dampness, etc.) can become object of interest for damage detection. For certain types of façade anomalies, especially cracks, previous research has developed detection methods, algorithms, and functional tools using image processing and computer vision techniques (Bauer et al. 2016; Mohan and Poobal 2017). For the detection of the other BFAs, analytical algorithms or tools can be developed for the recognition and categorization of these BFAs based on setting representative image features for anomaly patterns. Supporting techniques may include GIS imagery analytical tools, open source computer vision libraries, sequence analysis, etc.

Figure 3 shows how a GIS platform can be applied to support the access to analytical tools as well as the development of new interfaces for BFAs. GIS systems nowadays provide user friendly working environments including open source development opportunities such as tools using Python, R, and MATLAB. This allows the development of processing tools based on more complex and professional computing principles and algorithms. Through retrieving and loading the stored images within areas of interest to other computing platforms, anomaly patterns can be recognized and categorized with positional information. The developed processing tools also provide opportunities of directly interfacing with GIS analytics tools.

Module 4: Mapping of Detected BFAs

With the positional information of the detected BFAs, various anomaly areas can be labelled with attribute properties using geological symbology within a GIS. The storage of detected anomalies can also be used for time-series analysis and additional measurements and analytics to develop performance predictions. An advantage of the 2D GIS space is that all results can be converted into different topographies for visualizations, which in turn can display they entire building enclosure in a single view, an option that is not possible in 3D visualizations of buildings. However, for communicating assessment results back to clients it may be desirable to transform GIS results back to the original 3D building model. In summary, this mapping process benefit the analysis, detection, and tracking of maintenance issue related to BFAs and other risky areas. As an additional by-product of the GIS transformation, the mapped BFAs along with their detailed attributes could also support the optimization of drone usage (e.g., flight path, time, frequency) for periodical inspection of building facades.

CONCLUSION

This paper put forward a systematic process of BFA assessment, detection, and analysis processes through drone images. The presented process map addressed four distinctive problems that emerge within the practice of image capturing and evaluation of drone assisted façade inspections, which provides the flowchart of lifecycle building façade inspections with camera-equipped drones. Furthermore, the procedure of getting 2D building façade spatial models was defined to improve the efficiency of image mapping and building modeling. The mapped façade images stored in a GIS support the retrieval of spatial, spectral, and temporal data for image analysis and BFA detection. A GIS also provides a platform for developing and invoking image analytical tools for BFA detection. Ultimately, any detected and analyzed BFAs can be mapped back to the original 3D building model to support the understanding and maintenance of building façade risks. This systematic process brings benefits of increasing the efficiency of image analysis, improving the understanding of BFAs, making predictions of façade performance failure risks, and supporting the decision-making of lifecycle periodical building façade inspections and maintenance. Future research efforts will examine and develop interface solutions for each module and validate their effectiveness through case studies. It is our hope that the systematic analysis and management process presented in this paper will be utilized by other researchers and help streamline and integrate future developments.

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