Enhancement of Building Façade Inspection Through AI and UAV Technology

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Abstract
Building façade defects can lead to safety risks due to falling elements, accelerated building deterioration due to water entry, and inefficient operation (e.g., heat loss). Manual inspection is challenging and costly, risking inspectors' safety when working at height. Using unmanned aerial vehicles (UAVs) with advanced imaging and artificial intelligence (AI) offers a promising solution. This study aims to map its requirements and proposes implementation processes, focusing on a case study in Singapore. The scope of the study is to find a façade inspection protocol that is safer for the inspector, non-disruptive for tenants, time and cost-efficient for the owner, and objective for the industry. The study's unique contribution is to provide valuable insights into inspection processes to commercialize AI for critical applications such as façade inspection.

Keywords: Safety, façade, inspection, AI, UAVs, energy efficiency, sustainability

1 Introduction

Deficiencies of high-rise building façades can generate public safety hazards as erosion and faulty craftsmanship may cause façade elements to fall. Moreover, façade deficiencies have an economic impact that can result in inefficient space heating, contributing to high energy consumption and associated greenhouse gas emissions. Manual inspection of such infrastructure is challenging due to accessibility constraints dictated by structural characteristics and the reliability of assessments. Consequently, manual inspection consumes significant time and financial resources while endangering the safety of façade inspectors working at height. Utilizing unmanned aerial vehicles (UAVs) to capture visual and thermal images presents a promising solution enabled by advancements in drone technology and AI data processing capabilities. However, there is a notable research gap within the existing literature regarding demonstrating a commercially viable real-time application of AI-based façade inspection. While extensive studies have been conducted on refining AI technology to capture real-time, high-resolution images with improved detection rates and precise data, a crucial gap remains in providing a practical, applicable case study to demonstrate the value of these advancements and their relevance to practitioners and industry stakeholders. This study aims to map requirements, describe implementation processes and outcomes, and develop conceptual abstractions to generalize insights. For this purpose, a case study was conducted in Singapore following the Periodic Façade Inspection (PFI) regime of the Building and Construction Authority (BCA) to propose a solution facilitating the adoption of AI and UAVs for building inspection. The study provides valuable insights into inspection processes to commercialize AI for critical applications such as façade inspection.

2 Research Methodology

The methodology of this study was designed using two approaches, a systematic literature review and a case study, to fulfill the research objective of generating generalizable insights into inspection processes to commercialize AI for critical applications such as façade inspection.

2.1 Systematic Literature Review

A systematic literature review was conducted utilizing the Web of Science and Scopus databases, employing a set of key terms including 'Façade,' 'Inspection,' 'Safety,' 'Drone,' 'AI,' 'Artificial Intelligence,' 'UAV,' and 'Unmanned Aerial Vehicles' in various combinations, searched across all fields. In the Web of Science, 45 relevant publications were identified, spanning from 1999 to 2023, while in Scopus, 54 relevant publications were found, covering the years 1981 to 2023. Non-English publications were excluded from consideration. After a meticulous examination, 19 publications in journal articles, congress, and conference proceedings pertinent to the topic were identified and reviewed. However, due to accessibility constraints, some publications could not be accessed even after full-text requests were made, resulting in a final count of 11 publications in the analysis. Within these 11 publications, all were trying to enhance the quality of work during a façade inspection in terms of safety, time, cost, and risk reduction.

A substantial body of research has been dedicated to façade inspections over the past two and a half decades. In addition, stringent legislation exists in Canada, Hong Kong, select states in the USA, and Singapore. A recent study (Chew 2023) underscores a significant public safety concern about falling objects from high-rise residential structures in Singapore. It presents a structured façade inspection regime and an evaluation framework to discern the severity of potential hazards associated with falling objects from high-rise buildings. A study of (Shi & Ergan 2020) offers comprehensive insights into prevailing methodologies within façade inspection projects in the USA, namely in New York City, while also pinpointing challenges inherent in these methodologies. Additionally, the study seeks to elucidate how technological advancements can effectively mitigate these challenges. Moreover, climate change has a potential impact on building façade defects (Chew et al. 2023). With climate change, façade defects such as corrosion, adhesive failure, and biological growth will cause the façade to deteriorate faster. Therefore, façade inspection regimes must be updated periodically to cope with changing conditions.

In the pursuit of digitizing façade inspections, a considerable volume of research has been devoted to technological advancements for data collection and processing. Recent advancements range from 3D point cloud data collection, AI-based image enhancements, and classification techniques to the assessment of flight risks using UAVs, as well as the automatic assessment of various types of façade anomalies. Motion blur from UAVs vibrations commonly degrades image quality, impacting data acquisition. Addressing such challenges improves image clarity, facilitating more accurate detection of concrete cracks on building façades. Visual inspection confirms the effectiveness of the proposed model by (Liu et al. 2020) in reducing blur, resulting in more explicit crack images. Moreover, (Emelianov et al. 2014) researched to enhance image quality by attaining heightened stability in UAVs during structural inspection endeavors. The efficacy of deep learning techniques in detecting defects is impeded by the scarcity of annotated data necessary for achieving high accuracy. (Katsigiannis et al. 2023) proposes a pioneering deep learning methodology for crack detection on brickwork masonry façades, employing transfer learning to surmount the limited annotated data availability challenge. Examining glass façades and concrete structures for damage, such as cracks, is imperative for ensuring the safety and maintenance of buildings. In this context, (Mohammad et al. 2020) study on a comprehensive automated vision-based inspection system to detect and recognize anomalies in such infrastructure. The utilization of these research areas further extends to assessing damage incurred by buildings due to seismic activity.

However, UAVs flying near buildings present safety risks due to their proximity. Ensuring UAV flight safety typically relies on a single, static risk assessment before each flight, followed by strict adherence to UAV regulations during flight. A study of (Yong et al. 2022) addresses improving drone safety by digitizing and automating real-time risk assessment, thereby enhancing safety measures for drone operations. (Guo et al. 2020) formulates an automated classification technique for façade defects, addressing the challenge of imbalanced data sizes among different defect classes within plastered and painted façades. Such aspects are paramount not only for safeguarding human life and minimizing financial repercussions but also for expediting the rehabilitation process and fortifying structural resilience (Mondal et al. 2020).

2.2 Case Study

Singapore introduced the periodic façade inspection (PFI) regime on 01 January 2020. Buildings that are more than 13 meters high and over 20 years old must be inspected minimally at a 7-year interval. The building façade inspection procedure entails a thorough visual examination of the entire envelope, encompassing 100% coverage. Subsequently, a targeted 10% physical hands-on inspection is conducted on selected façade sections to supplement the visual assessment.

Inspection subject

A case study is based on a report generated by TÜV SÜD Asia Pacific Pte. Ltd. for a TÜV SÜD building in Singapore. The site consists of one building used for commercial purposes and as office space. The report presents the results and findings from the inspection. Furthermore, it includes recommendations on how defects must be monitored or fixed. Before the inspection, some documents, such as sections, elevations, and floor plans, were made available by the Client. Façade maintenance information is not available since the structure was recently constructed. The objective of the façade inspection is as follows: (1) Determine the original façade system and assessment process. (2) Examine the condition of the building façade to identify defects, including those with potential safety concerns through visual assessment. Photographic records of the defects and observations are recorded. (3) Provide recommendations for rectifying identified defects and other related issues affecting the façade integrity.

The building construction type is a reinforced concrete structure and cladding system. The cladding system is aluminum cladding and a semi-unitized curtain wall. The construction of the one block structure was completed in 2021, as depicted in Figure 1.

Figure 1. The building structure.

TÜV SÜD Asia Pacific conducted a desktop study of the drawings provided by the Client to better understand the façade system installed. Relevant drawings were collated and reviewed before the inspection works. Initial visits and information from the Client on some areas with potential defects were also considered. All sides of the building were inspected for a complete coverage of the building façade. The building was inspected with reference to the available site layout plan provided by the owner, as depicted in Figure 2.

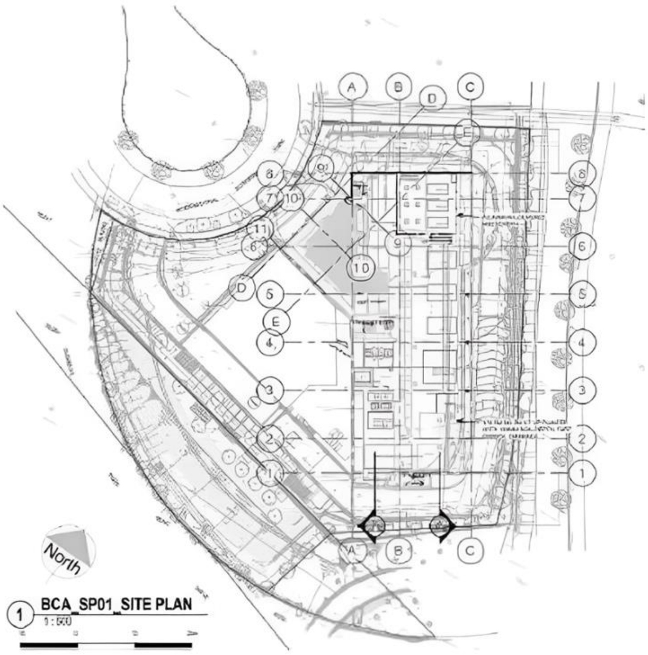


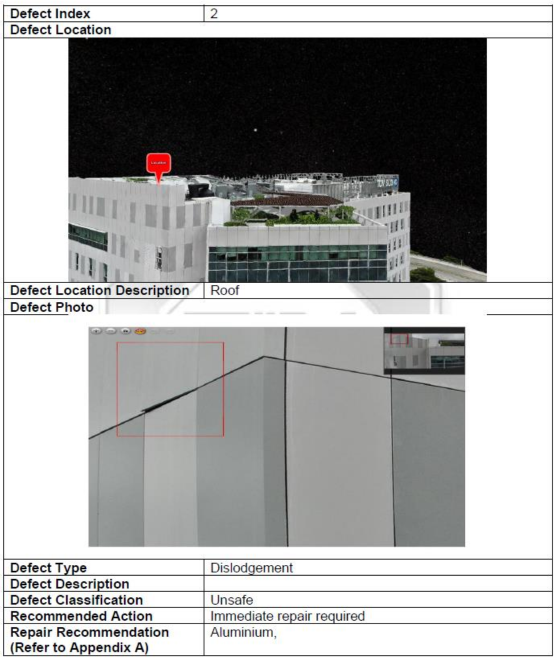
Figure 2. Façade reference layout plan.

The façade of the inspected building is brand new since the structure was recently constructed. All areas of the façade were inspected for deterioration, including but not limited to façade elements, windows, fixtures, etc. The building was inspected externally by visual inspection. Two methods were used to inspect to the highest standard. These are (a) Inspection using drones (visual images): A drone is flying 5-10 meters from the building. The drone carries a visual camera to take photos of the façade elements. The photos captured have a resolution of 0.5mm/pixel. Thermal images are collected alongside the visual images. The photos are used to capture any observed defects or abnormalities. (b) Inspection using a handheld camera with a high-powered camera to capture any observed defects or abnormalities: For areas that are impossible for the drone to approach, e.g., the areas blocked by trees, the observation of façade elements is done from ground level or at height from other neighboring buildings providing an alternative view of façade elements that are unreachable by drone.

In the report, defects of visual inspection by drone are listed as a summary finding list of six items. The list shows the defects' location, type, severity, classification, and repair recommendation, depicted in Figure 3. Also, a detailed description of each defect is listed in a table format showing the defect location on the generated 3D reality model created by image mapping and a 3D modeling tool, and a close-range photograph of the specific defect along with the details. Unsafe and safe defect types are depicted in Figures 4 and 5, respectively.

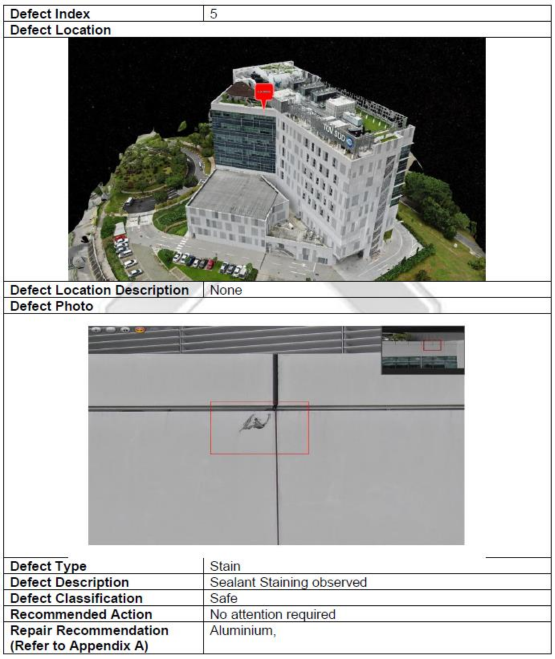
#	Location	Type	Classification	Repair Recommendation
2	Roof	Dislodgement	Unsafe	Immediate repair required
3	Level 1	Mould/Biological Growth	Safe	Repair required
4	None	Stain	Safe	No attention required
5	None	Stain	Safe	No attention required
6	East Elevation	Dilapidated Repair Works/Poor Workmanship	Safe	No attention required
7	testing	Stain	Safe	No attention required

Figure 3. Summary of defect list.



Defect Index	2
Defect Location	
Defect Location Description	Roof
Defect Photo	
Defect Type	Dislodgement
Defect Description	
Defect Classification	Unsafe
Recommended Action	Immediate repair required
Repair Recommendation (Refer to Appendix A)	Aluminium,

Figure 4. Defect No.1 detail depiction (unsafe).



Defect Index	5
Defect Location	
Defect Location Description	None
Defect Photo	
Defect Type	Stain
Defect Description	Sealant Staining observed
Defect Classification	Safe
Recommended Action	No attention required
Repair Recommendation (Refer to Appendix A)	Aluminium,

Figure 5. Defect No.2 detail depiction (safe).

In this case, a total of six defects were found. One was labeled as unsafe and immediate repair required, one was safe, and repair needed, and four defects were considered safe, with no attention required. This defect was found to be a potential risk of falling, which may endanger the public's safety. Apart from this one finding, the façade was in excellent condition overall. The report concluded that the façade contains a minimal number of defects that will render it at risk of producing falling objects. Remedial work is required to restore the structural integrity of the façade to full confidence in safety.

3 System architecture of the Smart Façade Inspection (SFI) service

Various possible defects can reliably be detected with 95% accuracy using automated visual inspection technology. These defects include cracks, corrosion, fallen façade elements, peeling and flaking, and plaster slab dislodgement. Other possible defects are also possible to detect but with less accuracy, such as delamination, concrete spalling, decolorization, and efflorescence. Expert review is required to verify automated findings. TÜV SÜD's Smart Façade Inspection (SFI) service has 3 components. Utilizing an advanced piloting system, the drone guarantees operational safety while conducting high-quality visual inspections. Structured data is securely managed through TÜV SÜD's inspection platform, employing automated masking techniques to safeguard private information and protect the client's privacy. Cutting-edge Artificial Intelligence (AI) processing large quantities of data supports professional engineers in generating inspection reports that adhere to the highest industry benchmarks. The software constructs 3D models of building façades, enhancing comprehension of structural elements, and seamlessly identifying detected defects within the structure. The TÜV SÜD SFI platform application grants-controlled access to comprehensive data, report findings, and 3D models. Repairs and follow-ups can be seamlessly managed through the platform to improve efficiency and save costs. An established protocol for the systematic capture, storage, analysis, and exchange of data is imperative, and this system seamlessly encompasses all these functionalities.

The core of the SFI are 2 AI systems as depicted in Figure 6. The first algorithm is to preserve privacy; data is encrypted on the drone while collecting so that not even the pilots can access the raw data. Upon onboarding the data onto the platform, privacy-related information will automatically be masked. The second algorithm provides the defect annotation from the generated taxonomy data.

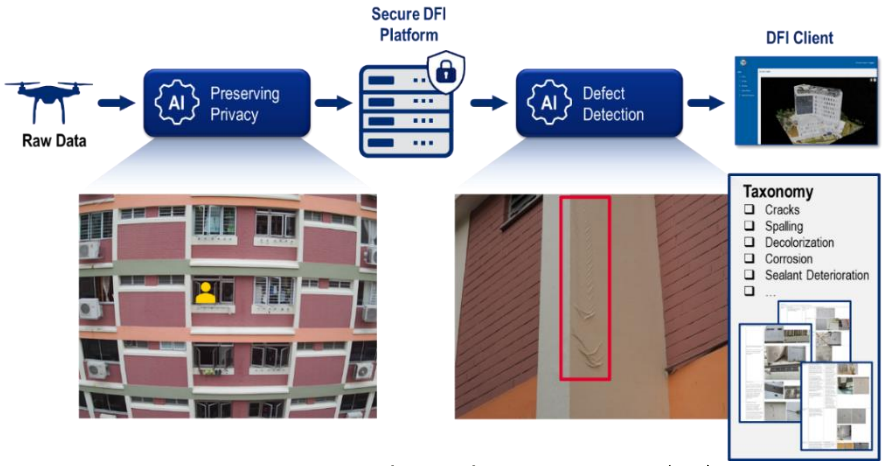


Figure 6. AI engines of drone façade inspection (DFI).

A fully synchronized triple camera system is used to provide different perspectives for defect analysis to control adverse effects such as lighting and motion blur. Furthermore, not all defects are visible in RGB images. Thermal images provide additional information on the nature of façade defects. The solution was found by deploying a zoom RGB camera with a 0.5mm/pixel resolution for visual defect detection, a wide RGB camera of 80° FOV for analyzing the building structure, and a radiometric thermal camera for hidden defect detection.

The Smart Façade Inspection execution process consists of an on-site inspection and off-site analysis (Figure 7). During the on-site inspection, the drone team arrives at the inspection site and confirms the documentation and risk assessment. It then sets up the equipment and secures take-off and landing zones. After confirming the flight plan and calibrating an auto-navigation system, it executes the inspection flight. Data is encrypted and securely transferred to the SFI platform. During the off-site analysis, captured data is converted into a 3D reality model and processed through AI algorithms. Inspection results and a 3D model are then available on the secure TÜV SÜD Smart Façade Inspection (SFI) data platform.

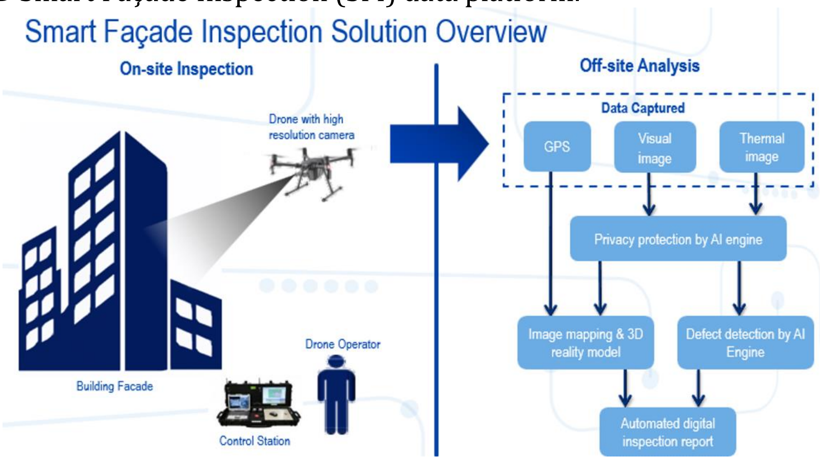


Figure 7. Smart Façade Inspection execution.

Solution Implementation

SFI was developed to make the whole process automated, safe, and more time-efficient for managing facades. Components are introduced below that comprise the overall solution.

3.1 Use of Industrial Drones

A mixture of large and small drones is used to capture images of the façade exterior at various angles for varying degrees of elevation and environmental obstruction. For example, the DJI M300 is a large drone used for immense payloads and optimum façade capturing. At the same time, the DJI Mavic 2 Pro is a small and tethered drone that is used for façade exteriors with constrained flight paths, while being constantly powered in flight. Each drone, along with its inbuilt sensors, can provide in-flight data such as elevation and GPS coordinates to better verify and validate the captured photos. Using all these captured data, the accuracy of the captured images and their respective metadata is preserved, thus providing a more accurate representation later in the generated 3D models.

3.2 3D Model Generation

Once all images have been through the various image analytics, images are put through ContextCapture software to piece together and generate a 3D model. The generated model, therefore, becomes a digital twin of the building under inspection, allowing users to navigate and visually see the exact condition of the building and its facades during the point at which the images were captured. This enables users to identify the defects that require immediate attention and, likewise, other defects that can be considered low severity and need not be attended to immediately (Figures 4 and 5).

3.3 Privacy Preservation

Before any captured image and video information can be processed further, one must ensure that any sensitive and human-identifying information gets obfuscated. For this purpose, humans and vehicles in captured images and videos are blurred using EgoBlur, a software library developed by the Meta Research Group. It utilizes a FasterRCNN-based object detector, which identifies human faces and vehicle license plates and blurs them, generating a privacy-preserved output of the processed images and videos.

3.4 Defect Detection

Once the captured images and videos have been processed by the privacy preservation module(s), another round of object detection was performed to identify the various defects that may be found on the façade exterior of buildings. To do this, TÜV SÜD curated their custom training, validation, and testing data and annotations tailored to known defects such as chipping, cracks, delamination, efflorescence, corrosion, blistering, etc. The use of Instance Segmentation Models based on the YOLO (You-Only-Look-Once) architecture is employed to pick up these defects in images and videos. Defects are being highlighted after AI processing for further validation with field experts to ensure that the detected defects align with human judgment before they are presented in the inspection reports.

3.5 Communication Protocols

All captured images and videos from the drone cameras are processed within internal company premises and stored on local NAS servers. Raw images and videos are promptly deleted after they have gone through the privacy preservation process, and each set of project images is retained exclusively for use in their respective projects.

4 Conclusion

This study summarized selected studies, a regulatory framework, and a case study that implemented related processes for semi-automated building inspection. The aim is to document a solution that enables the integration of AI and UAVs into building inspection procedures. The ultimate goal is to support the development of conceptual frameworks that can offer insights applicable beyond this specific case study. This study's contribution and original value are demonstrated by a commercially viable real-time application of AI-based façade inspection by a performed case study. However, the existing system predominantly addressing reinforced concrete façades. The system could be advanced to encompass all types of façades, including metal panel cladding, curtain walls (both stick and unitized systems), and others. The categorization of defect types and conditions must be expanded and harmonized to accommodate various types of façades. Future studies could focus on making the process quicker and, more suitable for on-board real-time computation and sharp images with higher detection rates. In the meantime, the data should be accurate and complete.

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