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ESTABLISHING A DECISION-MAKING SUPPORT FRAMEWORK FOR OPTIMIZING UNMANNED AERIAL SYSTEMS (UAS) FLIGHT PLANNING TO MONITOR HERITAGE BUILDING DEFECTS

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Abstract: Due to the excellence in mobility and automation, Unmanned Aerial Systems (UAS, a.k.a. drones) have been widely implemented in detecting building anomalies and assessing construction conditions. Additionally, the AECO industry is expanding significant interest in the preservation of as-built heritage using Building Information Modeling (BIM), generally described as Heritage or Historic BIM (HBIM), which focuses on long-term documentation and real-time monitoring of historical buildings. This research proposes a vision for integrating UAS and HBIM for continuous building-defect monitoring by establishing a decision-making support framework for autonomous drone inspection. Three essential aspects concerning defect monitoring will be presented: a summary of the taxonomy of historical building defects (BDs) for identifying appropriate detecting occasions, the potential to increase the efficiency and adaptability of drone utilization by specifying drone types based on defects and taking dynamic environmental conditions into consideration to predict and prevent latent damages. By reviewing current literature about BDs and drone flight planning, a framework contributing to the automation of drone inspection for precaution and protection of built heritage will be proposed, serving as a contribution to the body of knowledge. As for the contribution to the industry, this research provides a futuristic vision for automatic control of managing real-time BDs and enhances the automated command of UAS and the promotion of digital twin construction for historic buildings through continuous data acquisition and registration.

Keywords: Unmanned Aerial Systems / Drone; HBIM; Building defects; Inspection

1 INTRODUCTION

Traditionally, numerous approaches are applied to assess building components in elevated areas, such as staging, rafts, ladders, scaffoldings, and ropes. Due to the increasingly high risk and expense of the traditional method, Unmanned Aerial Systems (UAS, a.k.a. drones), a non-destructive testing (NDT) tool with affordable costs (typically less than $1,500 per device) and good mobility, is considered as a promising alternative for executing building inspections adequately (Masri and Rakha. 2020). Equipped with remote sensing gears, UAS display a strength in inspecting existing building stocks since data collected by drones can be documented and analyzed to monitor building performance (Rakha and Gorodetsky. 2018). Based on the research by Ioniță and Ţurcanu-Caruțiu (2021) and Germanese, et al. (2019). UAS has been proven to become the most suitable platform in terms of minimizing operational costs, improving data quality, and enabling flexibility of mission planning. While confronting complicated metropolitan surroundings and intricate building interiors, it’s challenging to reach and deliver satisfactory results simply with terrestrial scanning technologies. Consequently, drones are appropriate for handling close-range photogrammetry (CRP) tasks due to their size, kinematic stability, great mobility, and flying capabilities (Ioniță and Ţurcanu-Caruțiu. 2021). In most cases, a single NDT method is insufficient to provide defect information of the entire building required for further diagnosis. Hence, a combination of different types of gears is expected (DIAS, et al. 2017). Equipped with diverse sensing gears, including high-resolution cameras, infrared thermography cameras, LiDAR instruments, ultrasonic, multispectral cameras, and GPS systems (Adamopoulos and Rinaudo. 2020), the cutting-edge UAS, which are capable of conducting comprehensive building condition assessments, can be considered as the ideal solution to the problem stated above.

In order to maximize the preservation of the architectural, historical, cultural, social, political, and material value of historic buildings, careful conservation strategies with minimum intervention drawn from in-depth research are required to maintain the original dignity (Zhang and Dong. 2021). Differing from modern buildings with the emphasis of detecting and fixing building anomalies timely, heritage buildings highlight the detecting and long-term monitoring of BDs. Understanding the current building's performance and documenting existing BDs in a timeline has become essential to prevent deterioration and anticipate latent threats. Deterioration is blamed for compromising building safety and serviceability. Furthermore, since traditional inspection procedures are time-consuming and labor-intensive in terms of information collection and registration, they are incapable of satisfying the increasing demand for heritage building inspection, resulting in backlogs of inspection and unpunctual building health information acquisition. Therefore, Building Information Modeling (BIM), which creates a 3D intelligent model, can support timely interaction among stakeholders, which is a suitable information management system for managing BDs. Recently, BIM practices designed specifically for historic buildings are generally described as Heritage BIM or HBIM. As it's known to all, existing BIM systems begin from the design phase with standardized object families for new buildings, usually starting from scratch (Liu and Willkens. 2021). However, as differences in terms of approach and goal of HBIM are demonstrated, new educational lessons and training for users and operators targeting overcoming fundamental obstacles stemming from the distinctions between BIM and HBIM are needed. Besides, current gaps through literature review concerning drone utilization and the taxonomy of BDs are found. Conducting a comprehensive literature review of contemporary applications of UAS specific to building inspection and BDs detection is in demand. By examining and evaluating the strengths and limitations of each drone type, a decision-making support framework would be drawn in order to determine the best detecting occasions, enhancing the efficiency and adaptability of drone utilization.

2 RESEARCH METHODOLOGY

The research methodology adopted in this article is the systematic literature review. In order to examine existing research on UAS application, identify limitations in detecting BDs, summarize adaptabilities of each drone type, as well as investigate diverse influencing environmental conditions concerning drone inspection, a total of 36 articles are under review. The whole process is divided into three stages: database selection, keywords selection, and final literature selection. The review survey is conducted using numerous online scholarly sources. Keywords "drone", "building defect", "building anomaly", "HBIM", "heritage building", "building monitoring", "drone flight planning," etc., are applied to filter potentially appropriate articles. In the end, the articles that demonstrate the methodologies, the applicable gears, and the best time occasions for BDs detection are presented in this paper.

3 LITERATURE REVIEW RESULTS

3.1 Summarization of Building Defects for Heritage Buildings

The first goal of the literature review is to identify the taxonomy used for categorizing BDs. BDs could be understood from two different perspectives. From a cause-oriented viewpoint, finding the responsible factor that causes heritage building anomaly is essential but requires in-depth analysis and expert judgment. For example, penetrating dampness might be ascribed to humidity within cavity walls and further to building design flaws. As for the criteria on the basis of defect causes, based on a 9-month survey on 74 buildings by Chong and Low (2006) in their paper, three major design-related defect causes are concluded as weather issues, occupants' impact, as well as load and moisture influence. Finding the responsible cause requires comprehensive building information, which usually cannot be determined without significant investigation. On the other hand, from a consequence-oriented perspective, a building's negative manifestation can be directly detected and described. Compared to the perspective of cause-oriented categorization, consequence-oriented categorization is targeting at categorizing BDs based on the impacts on the building components. According to the research by Bagdiya and Wadalkar (2015), general BDs for all types of buildings could be categorized as structural defects and non-structural defects, based on the elements or components where BDs exist.

This paper emphasizes the use of UAS to detect and collect building defect data from a consequence-oriented perspective, which is the first step in collecting building health information. Through literature review and consideration of the BIM platform, two main types under this criterion are summarized as global building defects and local building defects. Within the global BDs domain, tilt, moving, missing, and deformation are considered the four key types which represent angular, locational, and shaped defects of the whole building component or multiple components. In contrast, local BDs represent abnormalities specifically attached to and within the boundaries of a certain part of the building component, including cracking, spalling, exposed bricks, moving (partial dislocation), thermal leak, moisture risk, penetrating dampness, corrosion, missing, fungus, and efflorescence. The summary of heritage building defects is shown in the table below (Table 1). With the support of analysis software, data captured by drones can be used as direct proof of BDs. Besides, the applicable gears required for collecting the defect data and the appropriate methodologies are also listed.

Table 1: Summary of heritage building defects

BD Category	Defect Type	Gear	Methodology	Source
Global BDs	Tilt	OC & LS	Compare point cloud with well-defined parametric objects	(Reinoso-Gordo, et al. 2018)
	Moving (Dislocation)	OC & LS	Compare survey data with historical data	(Reinoso-Gordo, et al. 2018, Brechin, et al. 2015)
	Missing	OC	2D images are processed by the Regions–Conventional Neural Networks algorithm	(Hatır, et al. 2021)
	Deformation	OC & LS	Compare point cloud with well-defined parametric objects	(Reinoso-Gordo, et al. 2018)
Local BDs	Crack (Cavity)	OC	Deep learning and computer version to detect 2D images and 3D point clouds	(Pathak, et al. 2021)
		OC	AI-based detection system / Regions–Conventional Neural Networks algorithm analyzes 2D images	(Mansuri and Patel. 2021) (Hatır, et al. 2021)
		OC	Photogrammetry technique processes 2D images to assist 3D modeling, then Pushover analysis in Finite Element environment	(Cascardi, et al. 2021)
		OC	Image processing and marker-based technique to track cracks evolution	(Germanese, et al. 2019)
		TC	Applying infrared thermography passive and active methods to capture 2D images	(DIAS, et al. 2017)
		OC	Directly using 2D images	(DIAS, et al. 2017)
		UT	Ultrasound waves detect directly	(DIAS, et al. 2017)

Void (Internal Crack)	UT	Ultrasound waves can detect unseen and internal voids directly	(DIAS, et al. 2017)
Spalling (Detachment)	OC	Deep learning and computer version to detect 2D images and 3D point clouds	(Pathak, et al. 2021)
	OC	AI-based web detection system on 2D images	(Mansuri and Patel. 2021)
Moving (Partial Dislocation)	OC & LS	With measuring tapes to ensure precise measurement of vertical, horizontal, and diagonal directions' moving	(Ferrero, et al. 2021)
Thermal Leak	TC	2D infrared images construct a 3D thermography point cloud model to analyze	(Rakha, et al. 2022)
Moisture Risk	OC	2D images construct a 3D point cloud model to analyze	(De Oliveira, et al. 2021)
	TC	Applying infrared thermography passive and active methods to capture 2D images	(DIAS, et al. 2017)
Penetrating Dampness	LS	Point cloud model with the on-site survey to analyze	(Calì, et al. 2021)
Corrosion	OC & LS	2D images and point clouds to FEM analysis	(del Rio, et al. 2020)
Missing	OC	2D images are processed by the Convolutional Neural Network-based algorithm to analyze	(Zou, et al. 2019)
Fungus (Mold)	OC	Directly using 2D images	(DIAS, et al. 2017)
	OC	2D images are processed by the Regions–Conventional Neural Networks algorithm	(Hatır, et al. 2021)
Efflorescence	OC	2D images are processed by the Regions–Conventional Neural Networks algorithm	(Hatır, et al. 2021)

*Optical Camera (OC); Laser Scanner (LS); Thermographic Camera (TC); Ultrasonic Testing (UT)

3.2 Categorization of Functionalities for Drones

Evolved throughout the past decade, UAS has shifted from fulfilling military missions only to both military technology as well as public consumer services, in which sensing built environment serves a significant role, according to the summarization from Rakha and Gorodetsky (2018). Drones have been classified by several studies and organizations based on their weight, operating altitude, wingspan mode, and other criteria (Nooralishahi, et al. 2021). For instance, the U.S. Department of Defense has summarized UAS into five main groups based on size, maximum gross, takeoff weight, normal operating altitude, and airspeed. Because of the advantages that UAS offers, fields for inspection and monitoring have been expanded into power infrastructure, building and urban planning, archaeological and cultural sites, agriculture, mining, oil and gas, construction, telecommunication towers, etc. (Nooralishahi, et al. 2021). Additionally, as Saeed, et al. (2022) asserted in their research, based on the applications of drones in the construction area, there are a total of six primary purposes that require assistance, including surveillance or monitoring of the environment, data collection, distributed processing, object detection and tracking, emergency services, and path planning and navigation. Among these applications, surveillance and monitoring of latent building defects, cracking detection, and emergency services concerning latent building defects could be applicable in assisting HBIM establishment and maintenance.

Aiming at detecting BDs, this research proposes a categorization of UAS based on the different gears it carries, because different gears with unique devices match different BDs detection. In general, four types are concluded: high-resolution optical drones, infrared or thermographic drones, LiDAR or laser scanning drones, and ultrasound testing drones. As for the first type, it could be applicable to almost every superficial BDs detecting situation due to the excellent quality of the images if the required illumination level is reached. Consequently, although the position and perspective of the cameras are adjusted autonomously in order to capture a clear view of the defects, the flexibility and availability are limited and weather-dependent (Drone. 2017). Besides, capturing images from the ground or remotely with drones requires expertise and familiarity with the building itself. What's more, numerous environmental obstacles exist during the process of image capturing, such as cloud shadows, wind disturbance, etc. Then comes the thermographic camera on the drones, which collect thermal information of buildings. More specifically, it is the infrared radiation objects emit, known as the heat signature, that they capture. With radiometric capabilities, thermographic cameras are able to measure the exact temperature of any item in their field of view. These temperature-related data are essentially significant as they could help the inspection process since anomalies in the thermal aerial images could assist in determining the pinpoint and accurate location of heat escaping, which might be caused by cracking and corrosion of building components (Dinh, et al. 2017). Moreover, as one of the most enlightening and creative technologies, Light Detection and Ranging (LiDAR) has recently gained popularity in drone surveying and inspections. Compared with high-resolution optical cameras, the fusion of optical imagery and LiDAR photogrammetry has demonstrated significant advances, as proved by the research of Zhang and Lin (2017). For 3D laser scanning in the process of LiDAR image capturing, 3D point clouds are directly captured with the aid of inertial measurements and satellite positioning data. Afterward, by combining these points, which contain spatial and color details within specialized point cloud software, a more integrated and detailed point cloud model is built. Finally, unlike ordinary ultrasonic sensors, ultrasonic testing drones are installed with special ultrasonic equipment designed for inspection rather than obstacle avoidance. By analyzing the different spreading speeds of ultrasonic waves in different materials or mediums, the stiffness and compactness of the material could be evaluated. Generally, an ultrasonic device consists of two essential transducers: the emitter and the receiver of ultrasonic waves (DIAS, et al. 2017). By taking advantage of the mechanism of ultrasound, ultrasonic testing drones are able to diagnose internal areas of material. For example, by utilizing an ultrasonic testing drone, voids inside the material of building components (e.g., walls) could be detected without compromising the building structure, which is coherent with the fundamental creed of NDT.

3.3 Consideration of Dynamic Environmental Conditions

Through the routine inspection and monitoring work, two major obstacles are presented for building defects detecting drones: the interference to drone performance caused by wind and the interference to different BDs detection caused by local climate.

While considering the effects of wind on drone's routing, the selection of appropriate algorithms and the composition of collected data sets are the major issues that need to be discussed. According to the research by Ito, et al. (2022), the vehicle routing problems (VRPs) of defect monitoring drones could be concluded as: minimization of energy consumption, overall distance, and delivery time to the consideration of battery capacity and utilization of wind changes to detour from the original planned path to assist with the autonomy of energy consumption saving. Besides applying the Traveling Salesman Problems (TSP) algorithm, a real-time data set of wind information is also needed to optimize better drone routes. Based on Ito, et al. (2022), wind information would contain parameters including air temperature, wind speed, precipitation, and other atmospheric information, resulting in adverse impacts on drone performance.

The first factor of the local climate would be the moisture problems. Common as they are, moisture problems can only be detected as they are in advanced stages (Rocha, et al. 2018), especially in heritage buildings. Therefore, with the aid of thermographic cameras, humidity or moisture problems could be detected by capillarity within buildings. For monitoring occasions on rainy days, testing inspection should be carried out to verify the accuracy of both humidity effects and data transmission throughout the process (Rocha, et al. 2018). As for the appropriate inspection time, based on the results from Rocha, et al. (2018), they could be indicated by the thermal gradient between the affected and intact areas. However, the severity of humidity problems could not be determined and evaluated through a single inspection. As for the second factor, thermal leak, Entrop and Vasenev (2017) have done a literature study and a series of test flights to survey the PV panels and the thermal shell of a building, resulting in establishing a protocol concerning all the responsible entities during the inspection process, including weather conditions (outdoor temperature, wind speed and direction, and precipitation), the object of research (photovoltaic panel, air leakage, thermal bridge), and operation subsystem(controllers, pilot, video pilot). Also, they assert that the appropriate time for conducting surveys specific to the thermal bridge would be the period before sunset since thermal energy at that moment is sufficient to demonstrate the presence of a thermal leak. While González-Aguilera, et al. (2013) states that for other thermographic inspection, the time before sunrise or after sunset would be better to avoid the false-positive results caused by the direct reflection of sunlight. To be more specific, Rakha, et al. (2022), conducting a survey and simulation using a drone with time-lapse thermography, proved that the best survey strategy is through 2-hour intervals and five times a day, starting from 9 AM to 5 PM, including all the seasons in a year, assuring the completeness and effectiveness of each survey. Especially for cracking detection, Germanese, et al. (2019) proposes checking at least once per month for a whole year to fully acknowledge the evolution process of cracking. Finally, the last factor is the impact of natural disasters. Based on the assertions of Binda, et al. (2011), all emergency activities could be divided into two phases: the emergency phase and the post-emergency phase. The emergency phase consists of the survey and assessment of the damage using UAS and the implementation of temporary measures of safety issues. In contrast, the post-emergency phase focuses on constantly monitoring damage progress by repeating drone inspections.

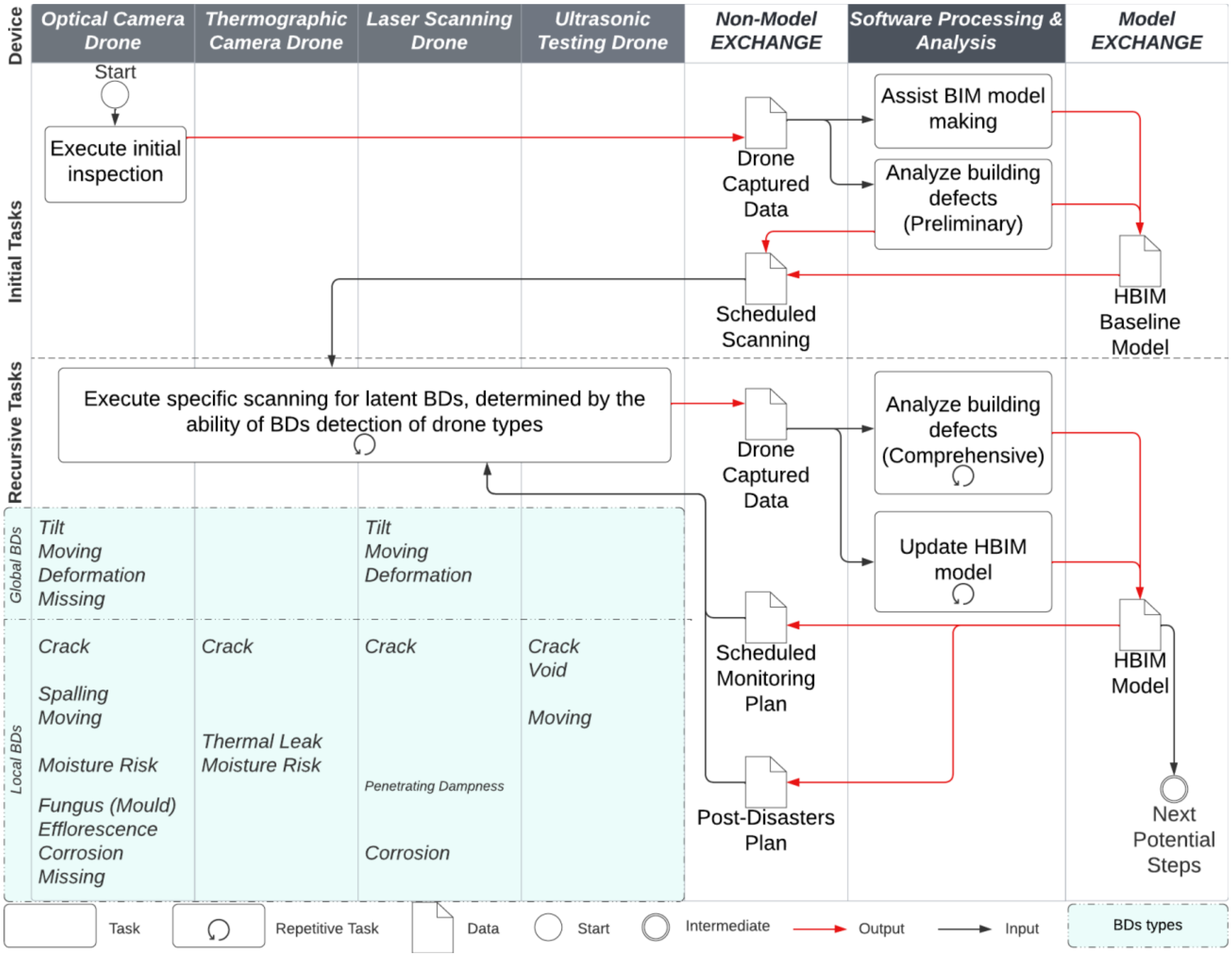

Figure 1: Process model of BDs monitoring based on drone types

4 PROCESS MODEL & SCHEMA DEVELOPMENT

4.1 Process Model of Selecting Occasions and Drone Type for Building Defects Monitoring

Based on the literature review results, this paper proposes a process model (Figure 1) that specifies drone type selection, streamlines process workflow, and identifies essential data exchanges. The process model starts with an optical camera drone for initial building inspection. Then drone-captured images and videos are handled by photogrammetry software to produce a 3D point cloud model containing the building's geometric information, which can assist the first version of the HBIM model construction. Conventionally, the drone path for generating point cloud is frequently referred to as the strip method that goes in vertical and horizontal strips route in a zig-zag pattern (Rakha and Gorodetsky. 2018). There is no absolute best solution for image overlapping rate and resolution requirements. Higher-resolution images with a higher overlapping rate can lead to a denser and more accurate point cloud model. However, it also increases drone budget, software processing time, and computer hardware demand. According to Rakha and Gorodetsky (2018), the building's image overlapping rate for photogrammetry processing ranges from 60% to 95%. The diverse project should take their budget and demand into this image resolution and overlapping decision. The point cloud model will assist in HBIM baseline model construction, and the drone-captured images will be analyzed as preliminary BDs detection. After the HBIM baseline model is made, the model can inform and generate a scheduled scanning plan according to the results of the preliminary BDs analysis. The above workflow can be understood as the initial tasks of routine building inspection. After the initial tasks, the workflow will enter recursive tasks that drone continuously capture data, and data is analyzed constantly to monitor building health. The recursive tasks aim at establishing a more comprehensive HBIM model with the utilization of optical camera, thermographic camera, laser scanning, and ultrasonic testing drones over time. The circular process updates the HBIM model and schedules monitoring and post-disaster plans. The algorithm to generate a scheduled monitoring plan should consider dynamic environmental conditions in BDs detection (Table 2) and allow for a flexible schedule based on local weather conditions to achieve the best performance of drone-captured data. As for post-disaster plans, drones can quickly execute damage assessments related to safety issues and keep tracking the potential damage progress.

Table 2: Temporal conditions for building defect detection

Situation	Suggested Time Occasion	Source
Moisture-Related BDs	During rainy days	(Rocha, et al. 2018)
Crack	At least once a month	(Germanese, et al. 2019)
Thermographic Camera Drone	Before sunrise or after sunset to avoid false positive	(Rakha, et al. 2022)
Optical Camera Drone	Slightly cloudy day to avoid strong sunlight reflection	(Rakha and Gorodetsky. 2018)

4.2 Schema Development for Building Defects

Images and other data captured by drones require further processing and analysis for maximum utility. Detection and analysis procedures could be repeated over time, detecting displacement and degradation over the building's lifecycle. The intent is to identify the rate of degradation or correlation between weather events or seasons and observed building defects. Once the structural part of the as-is heritage building model is imported, a pushover analysis could be adopted to evaluate the building's seismic capacity (Cascardi, et al. 2021). Also, Chen and Rakha (2021) demonstrate that a CV-based algorithm can process UAS-captured images to register and transform 2D pixels image of façade defects into a 3D point cloud model, where an as-built point cloud model with locationally recorded defects may aid the automation of scan-to-BIM process and support assessment in the digital environment. Collected data by drone could be utilized for Predictive Analysis (PA) to predict futuristic building failure under specific situations so that the system can take measures in advance to avoid unnecessary loss (Rao, et al. 2019).

A BIM platform that integrates building geometric and non-geometric information with the existing condition can be developed for long-term BDs monitoring but demands further study as existing schemas fail to link HBIM information with as-built conditions. Most research reviewed here manually inputs BDs information captured by drones (Bastem and Cekmis. 2021), directing that future research should adopt emerging technology such as Artificial Intelligence (AI) to match and integrate model and information automatically. As for data structuring issues, the Industry Foundation Classes (IFC) are currently utilized in the open BIM environment for new buildings. However, IFCs do not have the ability to represent condition assessments or building heritage data and lack a classification system for historical building components (Diara and Rinaudo. 2020). Ongoing work by this team proposes a data method to link building defects with building components to store heritage building anomalies, providing a data relationship for the IFC data schema (Figure 2). This paper proposes building defect as a new entity linked with IfcBuildingElement and can be hosted by any building component. By adding attributes to IfcBuildingDefect, the BIM environment should have the ability to store building defects type, description, location, last scan-capture date, next scan-schedule date, and linking images, which can inform the next UAS inspection planning. The Level of Detail (LoD) requirement for building defects modeling is under discussion. More accurate BDs modeling is generally more labor-intensive and time-consuming, so combining Artificial Intelligence (AI) and Machine Learning (ML) algorithms to achieve an automatic Scan-to-BIM process will be a future research direction.

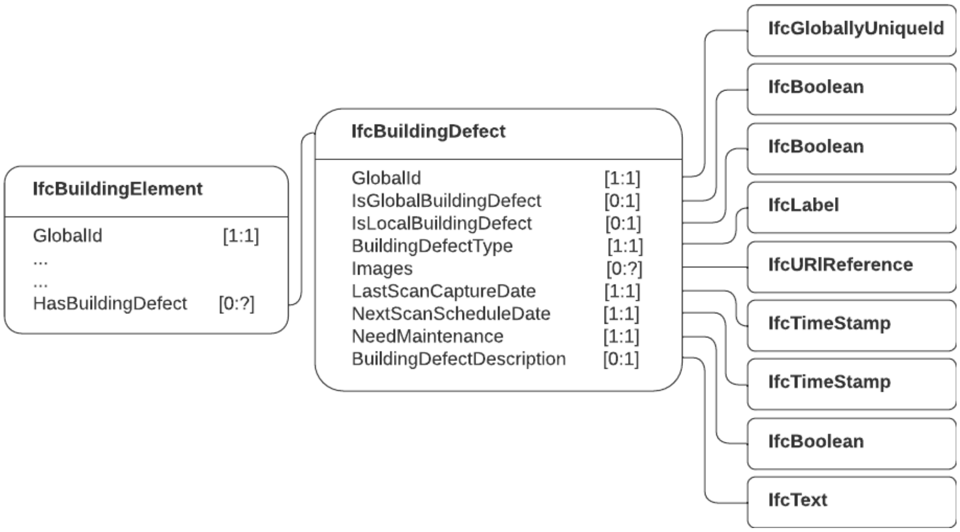

Figure 2: IFC data schema for building defect storage solution

5 CONCLUSION

By reviewing current works of literature about building defects and UAS utilization of building inspection, a decision-making framework of the process model that specifies drone types and key data exchanges for long-term building defects monitoring is established. The process model streamlines building defects capture workflow and enriches the research background about automation of drone inspection for precaution and protection of heritage buildings. Also, this research provides a futuristic vision for automatic control of managing real-time building defects by continually data acquisition by drone and registration in the BIM environment, which enhances the automated command process of UAS, promotes the digital twin's construction for historic buildings, and serves as the contribution to the industry. Future research should extend the IFC data schema in the BIM environment that is more capable of storing building defects information and drone path planning execution. The Level of Detail (LoD) in the digital modeling of building defects requires comprehensive analysis and discussion, while Artificial Intelligence would be an advanced approach to solve this problem. Developing advanced data visualization on building defects is required, which will assist in tracking and checking the severity of building anomalies for involved stakeholders.

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