Review of Unmanned Aerial System (UAS) applications in the built environment: Towards automated building inspection procedures using drones

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Review

Review of Unmanned Aerial System (UAS) applications in the built environment: Towards automated building inspection procedures using drones

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ABSTRACT

Unmanned Aerial Systems (UAS – a.k.a. drones) have evolved over the past decade as both advanced military technology and off-the-shelf consumer devices. There is a gradual shift towards public use of drones, which presents opportunities for effective remote procedures that can disrupt a variety of built environment disciplines. UAS equipment with remote sensing gear present an opportunity for analysis and inspection of existing building stocks, where architects, engineers, building energy auditors as well as owners can document building performance, visualize heat transfer using infrared imaging and create digital models using 3D photogrammetry. This paper presents a comprehensive review of various literature that addresses this topic, followed by the identification of a standard procedures for operating a UAS for energy audit missions. The presented framework is then tested on the Syracuse University campus site based on the literature review to showcase: 1) pre-flight inspection procedure parameters and methodologies; 2) during-flight visually identified areas of thermal anomalies using a UAS equipped with Infrared (IR) cameras and; 3) 3D CAD modeling developed through data gathered using UAS. A discussion of the findings suggests refining procedure accuracy through further empirical experimentation, as well as study replication, as a step towards standardizing the automation of building envelope inspection.

1. Introduction

Humans live in aging built environments. Maintaining the energy efficiency of such infrastructure and building stock is integral in moving towards an environmentally sensitive and sustainable future in the age of climate change. 40% of U.S. homes were built before 1970 [1] and the buildings sector accounts for 40% of CO_2 emissions in the United States [2]. Therefore, to address the inefficiency of older infrastructure, building energy retrofitting practices typically identify, diagnose, and design solutions that address issues of building usage, systems and envelope [3]. In Metropolitan Boston, MA, for example, heat loss through window surfaces, cracks, chimneys, and soffits were each present in more than 70% of 135 houses surveyed with infrared technology. Heat transfer and air leaks through cracks and ducts were identified as the reason behind about 40% of energy lost in a residential building [4].

To identify problematic issues specific to the building envelope, energy auditors typically use tools such as blower door tests to detect infiltration/exfiltration regions, as well as thermal bridges [3]. Technologically advanced tools such as infrared cameras and Unmanned Aerial Systems/Vehicles (UAS/UAV) enable professionals to analyze such issues rapidly and accurately while reducing operational costs and minimizing safety risks, and when paired with video recording, photography, or multi spectral imaging, drones can safely, economically, and efficiently carry out a broad variety of surveying services [5]. UAS provide experts across industries with a unique aerial perspective. This viewpoint allows easy access to remote or inaccessible areas without compromising the safety of the pilot [6], and this combination of technology has and will continue to permeate a wide range of varying fields as its applications, innovations, and capabilities are discovered and improved upon [7].

The primary barrier to energy efficient retrofitting is the uncertainty over return on investment, an uncertainty that can be addressed when focusing on the building envelope with relatively quick and cheap visualization of thermal anomalies [8,88]. Thermal patterns gathered with infrared cameras attached to drones can be converted into automatically generated 3D CAD models using 3D photogrammetry software. These models, as well as the imagery gathered, are visual tools that aid the professional assessment of energy production and conservation in buildings, as well as communication between parties

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involved [9]. Although the use of drones and thermal cameras for surveying is an innovation that has benefited a variety of unrelated industries [5], a gap currently exists in the literature relevant to the built environment. In the few investigations that have combined UAS-based surveying with infrared imagery and 3D modeling to audit energy use in buildings, the procedure and methodology used is typically not described in a scientific approach that can be standardized. This paper's goal is it to report on a comprehensive review of contemporary developments in UAS technologies specific to such building performance inspection applications, and presents a novel proof-of-concept study for thermography-based building auditing using UAS. The manuscript, therefore, addresses this aim through the following objectives: 1) developing a timeline for military-specific and commercial applications of drones, 2) reviewing literature focusing on site investigations, 3) examining building analysis techniques using UAS and 4) investigating drone flight planning procedures for building performance inspection. The results specifically focus on applications of thermography and 3D CAD model generation, and a case study is presented for the methods on the Syracuse University campus in the United States. The paper concludes with a discussion that contextualizes past investigation directions, current research challenges, and a framework for future developments.

2. Historical background

2.1. Military origins and commercial developments

The genesis of drones dates back to Italy in 1849 during the first Italian war of Independence when the Austrian Empire devised a system of unmanned hot air balloons that dropped bombs on Venice. Later, during the American Civil war and the Spanish American war, hot air balloons and kites were used to gather and telegraph reconnaissance [10]. Military needs were the predominant driving force behind developing UAS technology until the 21st century. The only commercial developments were iterations in radio-controlled toy technology [7]. Military practices, on the other hand, were quickly developing largely due to innovations in manned aviation technology and practices.

As a response to the growing tensions between the U.S. and the Soviet Union during the Cold War, the U.S. Government began a highly-classified UAS research program which ran under the code name ‘Red Wagon’. During the same year, the Defense Advanced Research Projects Agency (DARPA) launched the first global satellite navigation system in the air which would later become the basis of all GPS technology developments [17].

In 2006, Frank Wang with the help of his friends, colleagues, and teachers, established DJI Technology from his dorm room in the Hong Kong University of Science and Technology. Since its inception, DJI has steadily grown in influence around the world and is currently regarded as a leading commercial drone company [19]. DJI's initiation marks the start of the personal and commercial drone trend as it is the first company to produce drones that are easily accessible to the public. In 2012, US Congress passed the Federal Aviation Administration (FAA) Modernization Act to require the FAA to integrate small drones into airspace by 2015. The FAA missed this deadline which was expected especially after Congress released a public statement acknowledging the unlikeliness of the FAA's success in organizing this transition [20]. Soon after, online retailer Amazon announced plans to deliver products with a drone taskforce [21]. At this point in history, the term “drone” had become a common household topic as the public gradually warmed to this pacified product of military progress.

Fig. 1 summarizes the previously detailed timeline. We confirm the observation that as experts in various fields come together to develop this emerging practice, differing processes and methodologies emerge [5]. No one field or industry has discussed a comprehensive review of drone surveying techniques. In addition, since each industry has specific needs or goals when using this combination of technology, established procedures are rarely applied outside of their original field. This literature review seeks to gather, compare, contrast, and assess current and emerging practices.

2.2. Thermography

People have been locating general anomalies by assessing temperature variance even before the ubiquitous use of electricity. Ancient Egyptians documented a practice wherein they would move their hands across the surface of a human body to scan and monitor changes in temperature [93]. Historians have also wondered what would have been the fate of the Titanic if the engineers had installed Bellingham's thermopile and mirror system to detect icebergs by means of temperature variance aboard the ship [7]. Infrared energy is absorbed and emitted by almost all materials and has a direct influence on the temperature of an object [60], and the efficacy of infrared technology has been steadily growing since World War II [7]. Aside from military applications, infrared technology has been adapted as a useful diagnostic tool as well as a cost reducing monitoring system [61]. The main benefit of infrared visualization is the stark contrast and almost immediate awareness of conditions that deviate from the norm [59,60]. The most common indicator of depredation in any physical phenomenon is temperature change, and thermal imaging tools can detect that through depiction of radiance, temporal, and surface properties simultaneously [7]. As technology advances, the resolutions of new sensors improve in tandem [62,63], and as IR sensors became significantly smaller in size and lighter in weight, they were further integrated with drones for surveying purposes, including building surveys.

UAS based surveying enables expedited auditing at minimal human effort and cost and is not limited by accessibility aside from drone obstacles which, naturally, are not encountered as often as human accessibility obstacles [71]. The scales, accuracies, and scopes of building energy audits are increased when the exterior façade is feasibly accessible with thermal cameras. Building audits conducted with thermal imaging can be executed using two varying methodologies: 1) Active Thermography, which begins with an external stimulus such as a rise in heat in order to observe hidden defects made clear by a contrast between typical and extreme temperatures, and 2) Passive Thermography, which observes thermal patterns in a built environments normal state with no man-made stimuli. To use Active Thermography to its fullest potential, it was recommended that auditors have preexisting knowledge of possible defects and focus on relatively smaller areas. Therefore, passive building thermography is more often utilized for audits of entire buildings with little to no pre-existing knowledge of defects [66].

3. Research methodology

The review initiated with a literature survey via multiple online scholarly sources. The reviewed works comprise 92 sources, the majority of which were written by authors associated with higher education institutions. Literature was gathered via a keyword-based search. The sources were selected based on their ability to detail the applications and current abilities of UAS and thermal infrared technology in improving existing building audit practices. This necessitated scholarly sources that detail the design of flight paths in relation to buildings, large expanses of landscape, and/or geoclusters. Additionally, sources that detail methods of photogrammetry, infrared based thermal pattern identification, and 3D model generation from point clouds illustrate rapidly expanding capabilities for infrared based surveying.

As the review specifically focuses on stages of an energy audit using UAS equipped with thermal cameras, an experimental setup is proposed as part of the work in each of the reviewed topics. For pre, during, and post flight analyses, investigation methods are developed, calibrated, and tested on the campus of Syracuse University as part of the findings for the literature review.

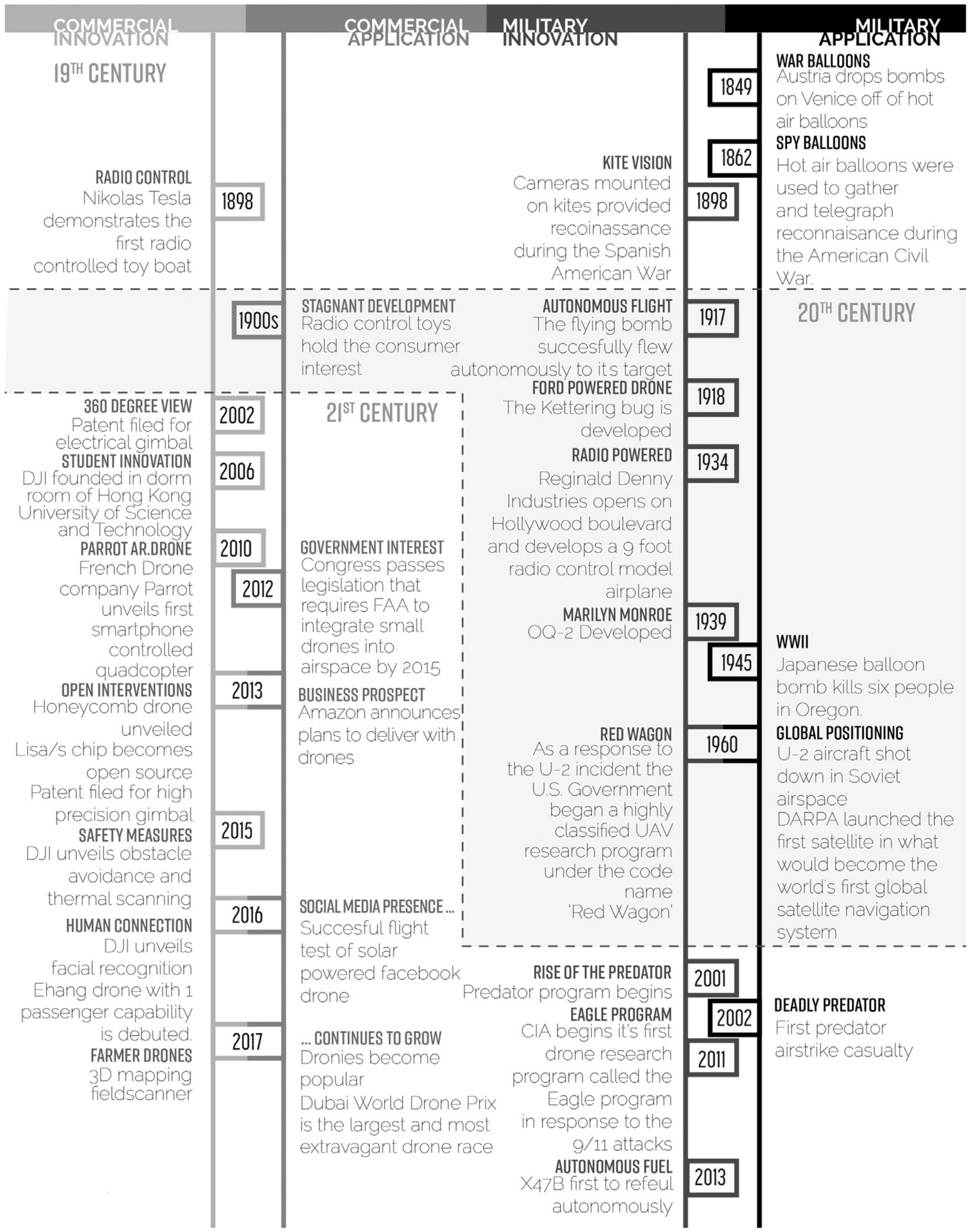

Fig. 1. A historical timeline of UAS technology developments in the 19th, 20th and 21st century. [11–16,18,22–25,85,86]

4. Research findings

The search for sources began as a broad investigation to understand the varied uses of thermography, benefits of UAS, and general procedures for applications of both technologies. 29% of the sources were mostly concerned with the process and reasoning behind building audits. 15% looked at current UAS trends. 13% presented historical background and development of UAS technology. 10% focused on 3D and Building Information Modeling (BIM), 9% investigated applications towards engineering, and 4% explored historical preservation. 4% detailed photogrammetry methods and 3% looked at applications towards agriculture. The remaining 9% or less, investigated multiple disciplines including volcanology, cartography, computer science, construction, hydrology, and sociology (Fig. 2).

Based on the compiled sources, Fig. 3 illustrates a decision tree which categorizes the current workflow of documented UAS based infrared surveying practices. The workflow is divided into three main categories; site acquisition, flight path planning, and post-analysis. This paper links building thermography methods with UAS by dissecting the process of the audit itself. The methodology is split into three steps; pre-flight drone path planning, in-flight infrared thermography, and post-flight image processing, segmentation, and automatic 3D model generation. The main issues observed throughout the literature are drone distances from surfaces and flight paths, use of thermography to diagnose issues, photogrammetry, and generation of 3D models in order to better inform both the development of a comprehensive methodology as well as to create a review of current practices in UAS based infrared building energy audits.

4.1. Drone flight – path

One of the unavoidable questions encountered while designing a UAS-based process is the flight path or pattern. Planning a drone flight necessitates an awareness of multiple factors such as distance from target, altitude, speed, overlap, and pattern [26]. The accuracy of the drone flight as well as avoidance of obstacles is heavily reliant on the

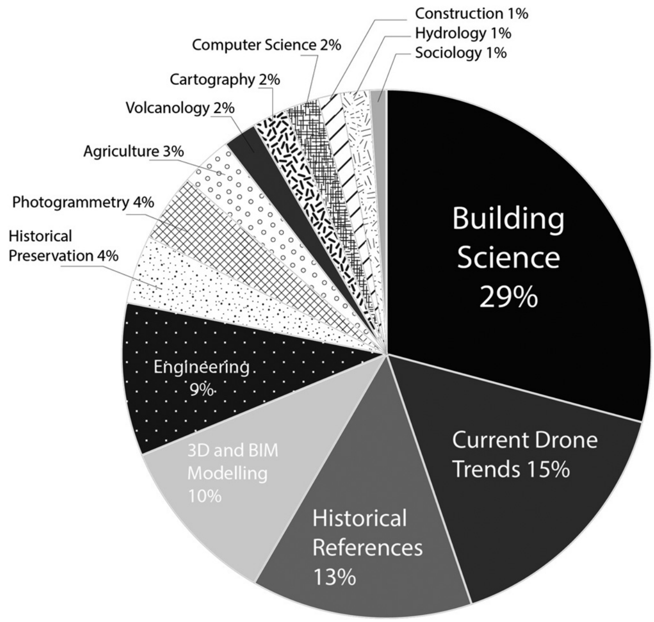

Fig. 2. Investigated literature by discipline for 92 publications.

accuracy of the Global Positioning System (GPS) and Inertial Navigation System (INS) [27]. Tahar has tested the accuracy of GPS onboard in combination with specific image registration algorithms versus ground control points informed by Google Earth Pro. The results found that the root mean square error was less for flights that utilized the onboard GPS than flights that used ground control points although the difference is equivalent to about ± 2 m [28]. Volkmann & Barnes also specify using Google Earth to inform their flight plan, although they point out that it is only an acceptable tool for onsite reconnaissance and preflight surveying because the imagery is often not current enough and does not depict drone specific obstacles [29]. Other common drone flight obstacles include battery life, a limited resource, and legal regulations of air space [29]. Fig. 4 combines recommended distances provided by multiple sources across varying fields. While each has its benefits, the optimal distance relies heavily on industry specific needs. Throughout the literature, it became clear that although each industry has found a method that works for them, none have identified an ideal distance for building energy audits.

Not all sources include the reasoning behind their flight plans, and although recently released software innovations have established relative industry standards, the wide range of recommended flight paths necessitates further conclusive research. Investigated literature clarifies that UAS based auditing requires an established flight plan that either targets regions of interest or audits the building and its surfaces in their entirety. Before addressing the building in question, it is necessary to note the surrounding natural environment and ensure that landscaping elements will not interfere with drone flight and that no relevant façade details are obscured. Often more than one audit is necessary to accurately capture the entirety of a building and often flight planners must determine the next-best-view (NBV) based on preliminary scans or surveys [31]. Blaer & Allen developed a voxel-based occupancy procedure for detecting areas of the building that were inadequately captured [32]. Corsi recommends auditing large surfaces to ensure accurate mean value and detection of local anomalies [7]. Son et al. propose determining regions of interest pre-flight based on construction drawings and knowledge of thermal patterns. This method minimizes the flight time by targeting predetermined areas, but might allow room for human error and missed thermal leaks [33]. Martinez-de Dios et al. detail a flight plan wherein the inspection of a building is divided into three tasks: stabilization, detection, and tracking. In this plan, the UAS hovers at predetermined inspection points and captures a series of images. Commonly available flight planning software has popularized the term 'waypoints' to refer to virtual reference points based on GPS coordinates that enable the UAS to autonomously fly and perform actions (record, photograph, hover, etc.) at each location. Collecting an abundance of images is useful in filtering out false positives and the distortions between consecutive images shows the translations and rotations of the drone [34,35]. For example, Haala et al. mainly use a system of waypoints which can be loaded before or during the flight [36]. Siebert & Teizer used an Extensible Markup Language (XML) based file structure with a wireless data upload link from a ground control station to input waypoints and create a flight path with the aid of external software [90].

Multiple researchers approach the issue of flight planning mathematically, by taking into consideration the limitations of camera technology and battery life to create formulas that inform drone distance from the target, speed of flight, and path geometry [37,38]. Emelianov et al. use mathematical principles to optimize the flight path of the UAS and scientific process to test the feasibility of auditing a geo cluster of 300 buildings with the use of a quadrotor. Their findings prove that with produced algorithms the quadrotor could scan the facades of 300 buildings in approximately 6 h given an unlimited battery life, although this hypothesis has only been tested at significantly smaller scales [39]. Laguela et al. developed algorithms to correct radial distortion and skewed scale. They achieved mixed results as neither method is optimal

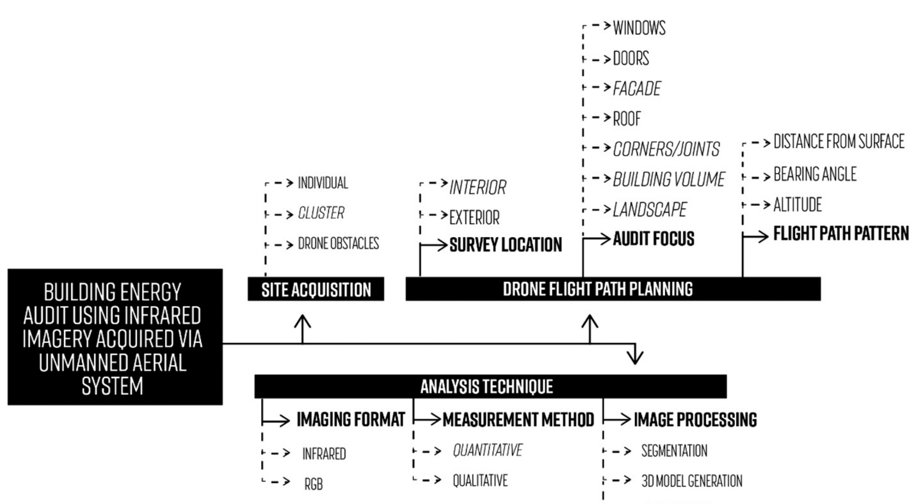

Fig. 3. Categorical decision tree for the workflow of UAS literature investigations.

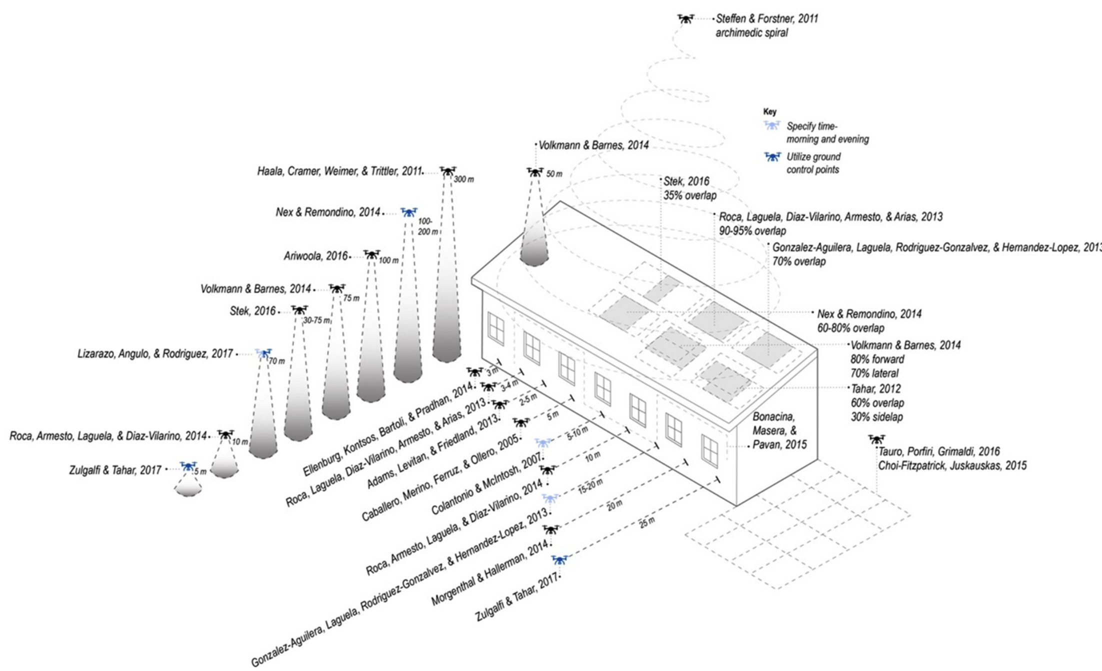

Fig. 4. Drone inspection distances as reported in the literature survey of façade and building inspection, energy performance inspection and Building Information Modeling (BIM) and mapping.

in every axis, and both methods result in one axis being skewed or inaccurate [40].

Although mathematical principles aid in the correction and optimization of UAS based auditing, various researchers choose to approach the question of flight path with a more geometric approach. The most common solution has been to fly the drone in either vertical or horizontal strips in a zig-zag pattern across the area of interest. This method is frequently referred to as the strip method [27,40,41,43,45]. Eschmann & Wundsam elaborate further on the strip method by testing the differences between utilizing vertical strips or horizontal strips. Their study finds that vertical strips result in unfavorable movement of the lens which decreases the clarity and quality of data gathered. Horizontal strips are proven to be ideal especially when paired with a low flight speed [43]. In addition to being a proponent of the strip method, Steffen & Forstner present research which advocates for the use of archimedic spirals to optimize flight plans [27]. Multiple researchers plan their flights according to a grid overlaid on the predetermined site boundaries, so that the drone flies to gather data of each grid unit [44,46].

The strip method frequently involves specified overlaps to ensure not only a robust and thorough collection of data, but also to ensure an easy transition into photogrammetry, 3D model generation, and/or analysis. To survey archaeological ruins, Stek recommends a > 35% overlap [47]. However, there is a great range found that includes 60% [28], > 70% [48]. 60–80% [49], 70% lateral and 80% forward [29] and 90–95% [50] For surveys of large or urban areas, a height of 100–200 m allows for high (unspecified) overlap and high-resolution data capturing [49]. Haala et al. further tested their methodology by surveying an agricultural site at 300 m above ground in an overlapping strip pattern with 90% forward overlap and 70% side overlap [36].

It is also critical to consider the altitude at which the UAS flies, as well as the distance it maintains from the target surface. Some researchers choose set distances such as 75 m above ground and 50 m above the tops of buildings [29], or a flight altitude of 50 m [45]. To survey archaeological ruins, Stek selected an altitude of 30–75 m above ground level to cover the full site [47]. Other distances vary dramatically, including a distance of 20 m away from target surface and an altitude maintained by the barometric height control [51]. Three to four meters away from the target surface as prescribed by a Kinect range sensor [50], two to five meters while assessing damage in post-disaster areas [52], five meters away [53] and less than 1 m while looking for small scale cracks in concrete and masonry [54]. Others might simply choose a set altitude of 70 m and do not describe deviating from that set distance [41], or a distance of 25 m from the building and five meters in the air [55]. A full account of all distances is represented in Fig. 4. Special topic research, such as the detection of sinkholes by means of UAS based thermal camera, was simulated with manmade sinkholes of varying depths and test flights at 50 m above ground. The UAS was successful in capturing thermal photos which identified the sinkholes of all depths [56].

The timing of the flight is important to note as well. Although the combination of image-based modeling and UAS based image reduces occlusion by shadow, daylight and solar radiation still affect the emissivity of materials which can create false positives or result in exaggerated readings [90]. Gonzalez-Aguilera et al. (2013) detail a unique process for acquiring thermal imagery where they choose to only take images before sunrise and after sunset to avoid false positives due to direct radiation [48]. Colantonio & McIntosh explain that exterior inspections are best conducted at night to minimize solar heat gain effects on the building envelope cladding. Inspections that focus on mechanical or electrical systems, on the other hand, should be conducted during the daytime while under maximum load [57]. Lizarazo et al. conducted test flights between 9:00 am and 11:00 am in order to ensure a similar solar illumination throughout the data collected [41]. With the wide range of UAS applications possible, optimal flight planning varies depending on the goal of the flight. Flights geared towards data and image collection for the purposes of photogrammetry or 3D model generation often necessitate extra steps and considerations as opposed to flights meant for the sole purpose of auditing or visualizing energy flows. For the purpose of aiding existing photogrammetry or 3D model generation software, some sources detail the use of Ground Control Points (GCPs). They describe marked physical locations around or on the surveyed area (such as colored markers in agricultural surveys or targets taped on the surface of the roof for a roof audit) that act as physical manifestations of the virtual tie-in points. Although their flight was limited to one façade and one pass around the building, Zulgalfi and Tahar are one such team that used ground control points with the intention of aiding the photogrammetry software in identifying tie-in points [55]. Other researchers specify ground control points so as to easily place the location of the photo while auditing volcanoes [30,42], or use ground control points to achieve spatial accuracy in their flight path (although current software capabilities address limitations in these methods) [41,49]. Feifei et al. use a UAS with four attached cameras to ensure high precision aerial triangulation for accurate results. The four combined wide-angle cameras increase the base-height ratio as well as expand the angle of view in lateral and longitudinal directions. This system requires less ground control points than typically recommended [58].

4.2. Drone flight – thermography

Building thermography for the purpose of anomaly detection can be carried out in a range of methods that include but are not limited to: aerial surveys, automated fly-past surveys, street pass-by surveys, perimeter walk around surveys, walk through surveys, repeat surveys, and time-lapse surveys [66]. Innovative approaches have been detailed for many of these methods and include use of various combinations of vehicles (whether unpiloted or robotic) paired with cameras of various capabilities, including research on building energy audits conducted by a terrestrial robot laden with infrared, photo and Light Detection and Ranging (LiDAR) technology [31]. Research teams proposed various methods, an example of which is by Hoegner & Stilla's use of vans as surveying vehicles with infrared imaging equipment to document and analyze thermal patterns in urban environments [67]. Lerma et al. use a combination of four different cameras to record data on World Heritage Monuments including a reflector-less total station, a terrestrial laser range scanning sensor, a digital photo camera, and a thermal camera [68]. Lopez-Fernandez et al. have utilized a UAS with infrared camera to analyze solar radiation on roofs in order to determine the optimal placement of solar panels [69]. The use of UAS for identifying ideal locations for solar and PV panels has been previously explored by comparing the use of UAS and photogrammetry techniques versus LiDAR imaging [8]. Utne, Brurok, & Rodseth used thermal imaging and non-intrusive condition monitoring to maintain safe conditions of static process equipment without necessitating human entry to machinery vessels. This improves operational and occupational safety, as well as reducing operational costs and reducing the need for maintenance [70].

Thermal cameras capture the infrared energy emitted by the surface layer which is heavily influenced by the emissivity of the material as well as environmental conditions, building orientation, and camera settings [64,66,72]. This poses interpretation challenges to auditors who are unfamiliar with the basics of thermal emissivity and according to Fox et al. and Gonclaves et al., pose that this is typically the most challenging aspect of working with thermal imaging. Proper camera settings are also integral to the success of the operation, and informed decisions must be made as to the appropriate thermal and spatial resolution as well as the temperature range [73]. Barreira & Freitas conducted sensitivity studies to gauge how thermal cameras capture data with varying emissivity conditions. The tests conclude that cameras set to the improper emissivity will capture unreliable data [64].

The nondestructive and non-contact nature of infrared thermography is especially of use to projects that deal with historical buildings or works of art [62,64,65], or to areas that have experienced catastrophic disasters [42]. Grinzato details an instance where a historic fresco, which seemingly survived an earthquake, was discovered to be full of cracks and weak points when captured with infrared cameras. This same approach can easily be adapted for the assessment of structural integrity in the built environment [62].

The use of infrared thermography in buildings is especially useful for visualizing the thermal patterns within the building envelope as well as the movement through and across various building materials [62]. The non-contact nature of infrared visualization is less likely to be inaccurate than any contact measurement method readily available due to the fact that it does not affect thermal equilibrium. By using airborne infrared cameras, auditors are able to capture a large surface with minimal effort. This is thought to be the only way to achieve a correct mean value and measure local anomalies [7]. To ensure accurate results, Borrmann et al. recommend a temperature difference of about 10 degrees Kelvin between the interior of the building and the exterior ambient air temperature. The ideal conditions for infrared auditing require stable weather conditions over a long period of time [83]. In addition, extensive exposure to solar radiation is not ideal as it may oversaturate and obscure smaller instances of leaks. For this reason, ideal weather conditions are partly cloudy morning hours during the winter months [31]. To insure an easy transition to the next step, photogrammetry and 3D model generation, Ham & Golparvar-Fard reinforce the necessity for captured thermal imager to be ordered, calibrated, and geo-tagged [74].

4.3. Drone flight - post processing (3D photogrammetry and CAD modeling)

Post processing is as integral to the operation as the drone flight itself to create a comprehensive and complete image of the audit results [75]. In regards to this practice, current building energy modeling and simulation tools face multiple barriers. Aside from accuracy issues, they are time consuming and labor intensive due to the manual modeling and calibration processes. Additionally, simulation software cannot determine construction defects or degradation [74]. Post processing begins with the awareness of five different conditions; altitude, quality, timing, spectrum, and overlap [76]. Photogrammetry techniques can either utilize direct geo-referencing, ground control points, manual tie-in points, or a combination thereof [63]. Geo-referencing is most easily achieved with time-stamped GPS data recorded during flight [91]. It is typical to use photogrammetry techniques to create a large and complete image of a singular façade [75]. Specifically, in regards to building energy inspection, the most common methodology for post processing uses threshold techniques and software to segment or enhance image saturation to further emphasize the region of interest [5,35]. Eschmann & Wundsam developed a technique centered around the removal and immediate reapplication of a Gaussian blur to gathered RGB images to highlight and emphasize cracks in the building envelope [43]. Yahyanejad & Rinner designed a robust registration methodology of visual and thermal images that begins with extraction of features in the individual images followed by matching corresponding feature points and identifying inliers between them. They use computer software and mathematical algorithms to compute the transformations for aligning individual images [76]. Kung et al. begin their photogrammetry process with aerial triangulation algorithms based on binary local key points whose output is a geo-referenced orthomosaic. This method does not necessitate ground control points and mainly depends on the on-board GPS and geotags provided by the UAS. They found that eliminating the measurements of the ground control points results in lower accuracy yet for difficult terrains this sacrifice is often needed [75].

3D modeling techniques can be organized into two sets of goals; groups of buildings (geoclusters), or singular buildings [58]. Although extensive research has been conducted, Borrmann et al. bring attention to the fact that, to the best of their knowledge at the time of publication, no truly autonomous system for 3D model generation of building geometry using thermal imaging has been recorded in a scholarly article [31]. LiDAR is argued to be superior for this task [39,77]. Most literature focusing on photogrammetry experimented with point clouds and have yielded commendable results though none with as much fine detail as with LiDAR technology. Lizarazo et al. use RGB photos to create 3D geometry first because the spatial resolution tends to be more optimized than the infrared photos. In addition, they developed algorithms and applied Wallis filters to successfully improve the accuracy of the final product [41]. Multiple researchers tested a methodology where RGB photos were used to create an initial 3D model where the infrared images would later be overlaid as they found that 3D model generation software tends to be more successful with RGB photos [55,69]. Volkmann & Barnes utilized a technique known as "multi-view stereopsis" that uses specific software to align the photos and create a sparse point cloud. The point cloud is then subject to linear transformation parameters and error analysis, which optimizes the sparse point cloud to create a dense point cloud, which is translated into the final model [29]. And finally, Hackel et al. developed a systematic process for detecting contours in large-scale outdoor point clouds. It is divided into a two-step process, first a contour score for each individual point is extracted using a binary classifier, then next step automatically selects the optimal set of contours from the candidates. According to the authors, this method out-performs the canny-style edge detection technique. The innovation in this method is detecting contours before surface reconstruction so that they drive the segmentation and fill in patches in the generated surface [78].

5. Case study

Reviewed literature varies and sometimes overlaps in recommended inspection methodologies. A case study was therefore developed as an application that combines and tests reviewed literature outcomes. The case study is investigated through the paper's objectives, by detailing pre-flight path design, during-flight data gathering and post-flight analysis. The inspected building was chosen as a generic residential structure on the Syracuse University campus. All flight parameters were varied, including flight path design, image capturing density, overlap and distances from buildings and external environmental conditions for surveys. The aim was to develop empirical setups for building inspection using UAS equipped with thermal cameras.

5.1. Pre-flight path design

Field tests were conducted with a DJI Inspire 1 drone, paired with a FLIR Zenmuse XT thermal camera. The accompanying DJI app was used during flight to monitor the thermal data. The flight path was predetermined and automated using the Litchi and DroneDeploy app for roof images. The images were processed and analyzed using the FLIR Tools program. We empirically found that using both the strip pattern and the archimedic spiral, as detailed earlier, have proven to be effective methods. The strip pattern with at least a 70% overlap is suitable for gathering data to audit or visualize energy use in buildings. An elliptical flight path with as much as 95% overlap is appropriate for photogrammetry and 3D model generation. A distance of 12 m away from the target surface with changing bay widths of 2–3 m is fitting for capturing images every one and a half meters along the path. For the generation of 3D models, flying multiple elliptical flights at varying altitudes can be ideal. The most effective altitudes have been found to be 18, 22, and 27 m, or twice the height of the building and twice the size of the building footprint. The flights should increase in altitude and size by roughly 1.25× per flight. The ellipses should overlap at least 70% and the frequency with which pictures are captured should result in a 90–95% overlap in captured data. Although this seems redundant, current 3D model generation software, like Pix4D, works best with a repetitive surplus of images. Fig. 5 represents the empirical parameters of flight path planning.

5.2. During-flight data gathering

For thermography purposes using UAS, our experimentation confirms that better conditions for thermal imaging are cloudy morning or evening hours with stable temperatures and no precipitation. At the time of writing this paper, a difference between indoor and outdoor temperature of at least 10 degrees Kelvin is recommended when a FLIR camera is being used [84]. This may not be necessarily the case for more sensitive state-of-the-art IR cameras, and also may not be feasible in regards to commercial year-round UAS applications. Appropriate emissivity values should be inputted to the thermal camera before flight, calibrated during flight when necessary, or modified post flight during analysis to ensure accurate readings. INS and GPS systems should be correctly calibrated to accurately geo-tag the images. Fig. 6 demonstrates examples of compromises of an example building envelope, identified with thermal imaging.

5.3. Results: post-flight 3D modeling

Photos taken during our test drone flight were used in the program Pix4D to generate a 3D point cloud from the 2D images. Multiple models may be recommended based on the number of photos taken. Based on empirical trials and observations, approximately 1000–1300 photos are recommended as a suitable number of photos for one simulation, due to current software limitations that may be resolved in the future. Multiple models may be merged upon completion, and this allows the operator to eliminate photos that may not calibrate properly. The program extracts pixels from 2D images by triangulation and locates individual pixels from photos within a 3D point cloud model. During this process, images of inferior quality and images that did not capture the subject will be rejected by the program. Upon generation of the model, we observed that the façade that produced the most detailed model is consistently located on the southern face of the inspected building. Using Pix4D modeler, the program runs a 15-point process that results in a report output noting the efficiency of the photos used in generating the model, image overlap, location, among other variables. This output notes weaknesses of the image retrieval process and should influence future flights. The model can be processed in other 3D modeling and CAD software such as Rhino3D. When opened in a .FBX file format, the 3D model will maintain render and texture capabilities. The model is compatible and is able to be used in rendering and 3D printing (Fig. 7).

The data collected in the inspection flight was used to compare three software platforms: Pix4D, DroneDeploy and Agisoft Photoscan. The comparison reveals that there are variations in terms of the processing workflow, model production time and the quality of the output. Table 1 details parameters pertaining to model production, where if a low quality and faster model is needed, Agisoft Photoscan may be useful, while Pix4D produced better quality model with the most quality control comparably, but it needs the most time as well. There is a reliance on cloud computing in DroneDeploy, with a limited number of images, which makes the production of 3D models limited when geometric accuracy is needed. However, at the time of writing this paper, DroneDeploy produced the highest quality model in terms of mesh smoothness and accuracy as compared to the thermal images used as inputs. Pix4D produced a more reliable model in terms of building angles, because it combined both RGB and IR images, yet, thermal anomalies detected through IR imaging, such as water puddling, were more evident on the roof of the DroneDeploy model. Fig. 8 showcases differences in the quality of the produced model for the case study.

6. Discussion

Drones have been adapted to improve upon traditionally manual and human reliant tasks across industries. To assess the current professional opinion towards drones, Mauriello et al. conducted a study wherein 10 professional building auditors were presented with scenarios where UASs and thermal imaging aided in the building inspection process. The test subjects were then asked to respond critically to the scenarios based on their experience working in the field of building audit. The results were positive, as all auditors tested agreed that UASs and thermal imaging provided benefits and improved workflow. Additionally, auditors believed thermal imaging would also prove to be a valuable tool in communicating with clients [9]. Opfer & Shields

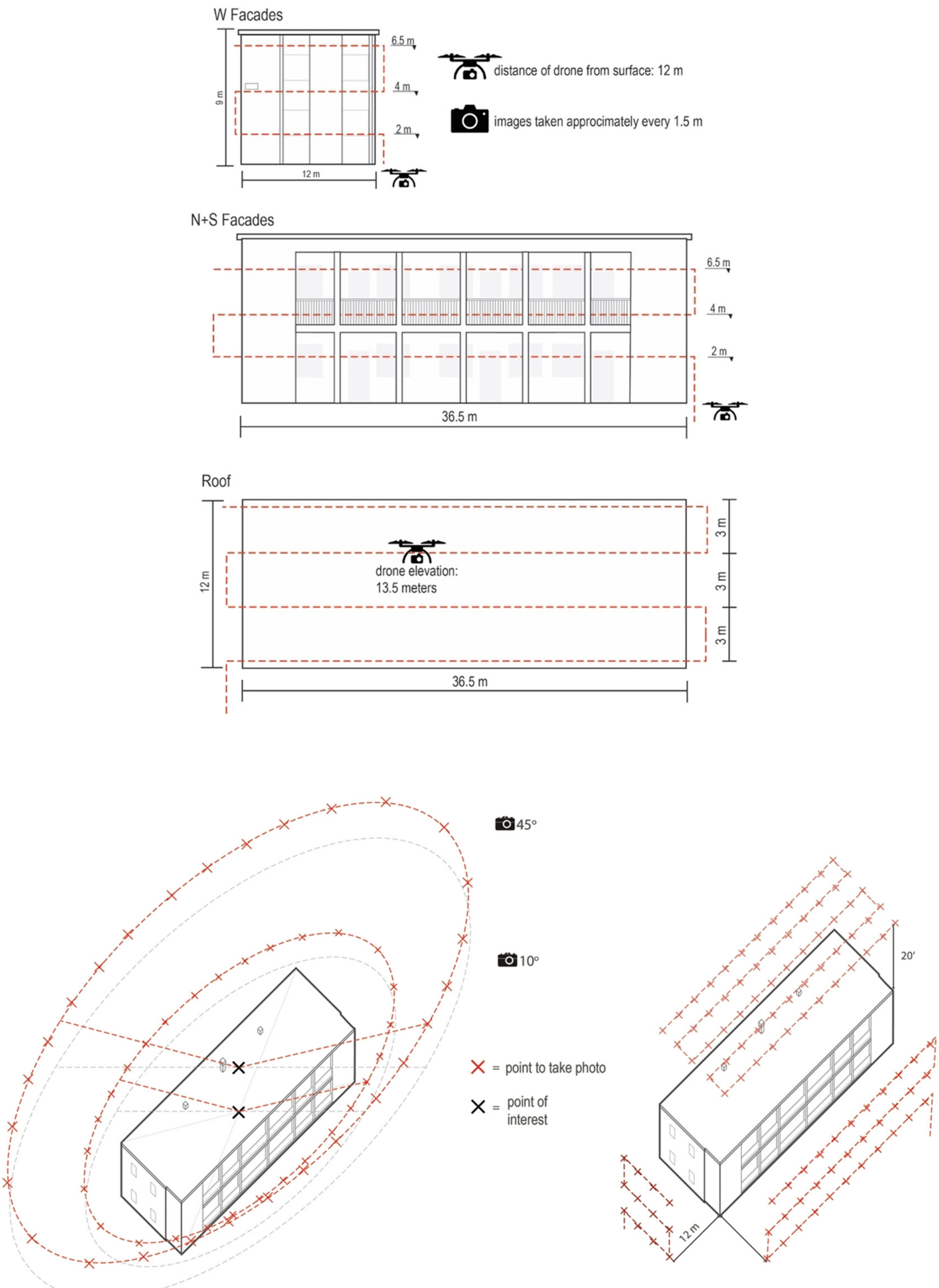

Fig. 5. Flight path parameters for building inspection.

conducted a similar study, where they informally surveyed 31 contractors who are already using UASs in their scope of work. Contractors surveyed explained that traditionally acquired aerial photography is expensive and typically not included in the project budget whereas UAS aerial photography is cheaper and more suited for job progress photography [79]. However, if IR imaging is to be used in such processes, developing thermography expertise is needed in order to correctly analyze and make meaningful interpretations from such images. This would include understanding environmental conditions of acquiring data, distinguishing critical differences in direct and indirect readings, as well as differences between qualitative and quantitative thermography [92].

The future of UAS-based applications for professional building surveying rests in experimentation-based research and subsequent standardization. While improving technology typically makes standardization and automation significantly more feasible, the limitations, considerations, and applications have the potential to change dramatically as well. In order to ensure accuracy and efficiency, more

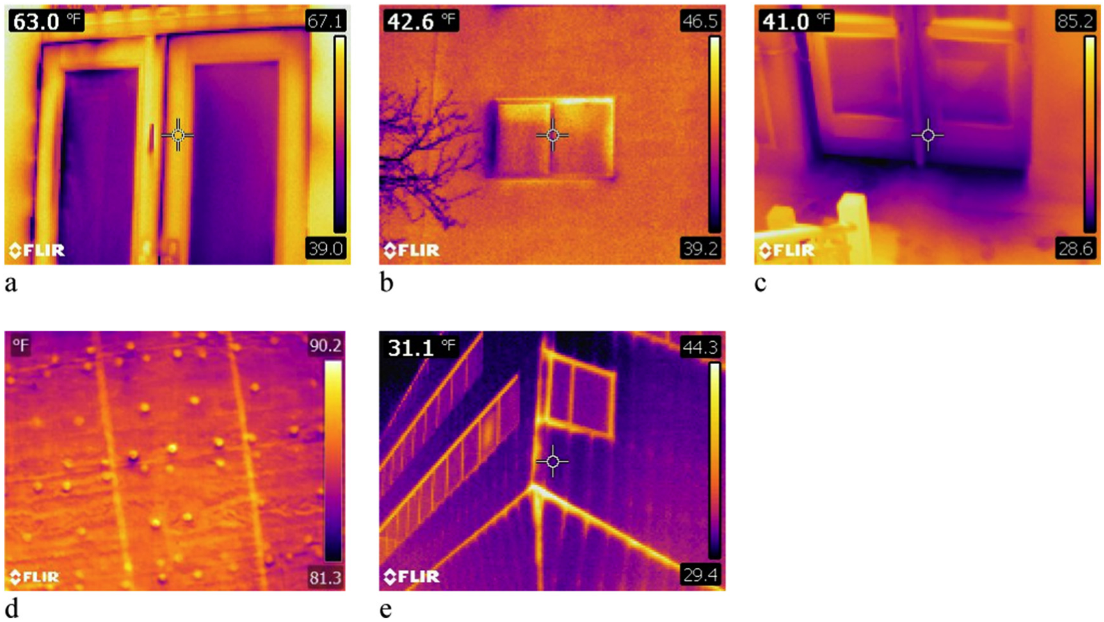

Fig. 6. Building envelope issues identified with a thermal camera.
a. Window pane and frame infiltration/exfiltration potential.
b. Window frame side failure, creating infiltration/exfiltration.
c. Door infiltration, with significant change in floor temperature.
d. Thermal bridging by nails that compromise the roof.
e. Thermal leakage as a result of envelope installation malfunction.

comprehensive methodology tests would be beneficial to not just the field of building surveying, but any field that utilizes UAS with thermal imaging capabilities. Standardized procedures or equations can be further developed for designing flight paths for optimal distances from the target surface, enhanced flight speed for clarity, and geometry that covers the entire target efficiently. Furthermore, post processing procedures would benefit from similar research in order to further uncover uses for thermal imaging in the inspection and design of buildings. As more technology and software is released, more of the post processing work will become automated, requiring less human input and participation and expectedly yielding more accurate results. More comparison between various methods is necessary to scientifically justify resulting standardizations. Flight procedures can then be designed for full automation, with minimum to no human interaction during building inspection activities. Global energy audit sectors could operate remotely, by sending UAS remotely for complete, on the fly, building energy inspection and modeling. This is estimated to cut audit time and increasing reporting accuracy, which would consequently result in reliable and unbiased recommendations for deep retrofit strategies. The challenges to be addressed in a fully automated UAS-based building inspection workflow include a) limitations in GPS positioning and relevant communication between drones and remote operating systems, b) battery power limitations, with land and-charge potential, c) obstacle interference with UAS and possible crashing, d) required input for drone navigation in unfamiliar or obstacle-heavy spaces, e) challenging to reach building components due to the size and navigation of the UAS, f) UAS operation vibrations interfering with data acquisition and g) signal acquisition risks as well as signal interpretation challenges.

Microsystem technologies used in both new markets and consolidated markets create a trend of technology transfer between commercial and military applications. Future trends for UAS and airborne building inspections rely on emerging technologies of sensor fabrication for mass production and the demand created by civil applications [7]. With the first emergence of UAS in the commercial market the technology and flight preparation tools were insufficient to conduct building energy audits, yet within the last few years of technological advances UAS have become better tools [91]. Incremental technological advances aimed at automation, cost reduction, weight reduction, payload increases, stability enhancement, and connectivity assurance cultivate an interest for UASs for professional building inspection use [5]. Emerging technology like micro drones expand accessibility and increase accuracy in an unexpected scale [87], while drones with increased payload capabilities and automated obstacle avoidance are being deployed for package delivery [21]. These innovations are aimed at increasing the independence, accuracy, and safety with which a UAS navigates a flight path which ultimately dictates the ease of use for the pilot as well as the quality of the end product of an airborne building inspection.

Greater GPS accuracy is still needed to expedite 3D model and flight path generation [27]. However, the miniaturization of technology necessary for UAS flight such as GPS as well as the emergence of affordable platforms is expected to vitalize the industry towards an improved methodology [29,63]. As multi-spectral imaging capabilities are also expanded upon, and quality of multi-spectral photography increases, smaller details will be captured and analyzed with greater accuracy. Within the scope of automated 3D model generation, the possibilities of generating 4-dimensional energy performance models which factor time into the 3D model are anticipated [74]. This volume of research into applications and further innovations has resulted in a strong community which is fully invested in the progression of a new field affectionately dubbed ‘droneography’ [29].

Innovations in the technology continue to grow as both consumer and military demand increases. Global expenditure on commercial UASs in 2014 totaled over $700 million with DJI accounting for the majority of sales. It is estimated that UAS sales will increase to $1 billion by 2018 [80]. This substantial increase links to how the technology will be growing in perception as well. Technoethics, an interdisciplinary approach to assessing technological impacts on societal morals and ethics, have the potential to be the driving force behind the integration of UAS into commercial and public airspace. To address public safety and privacy issues, Luppicini & So gather and review

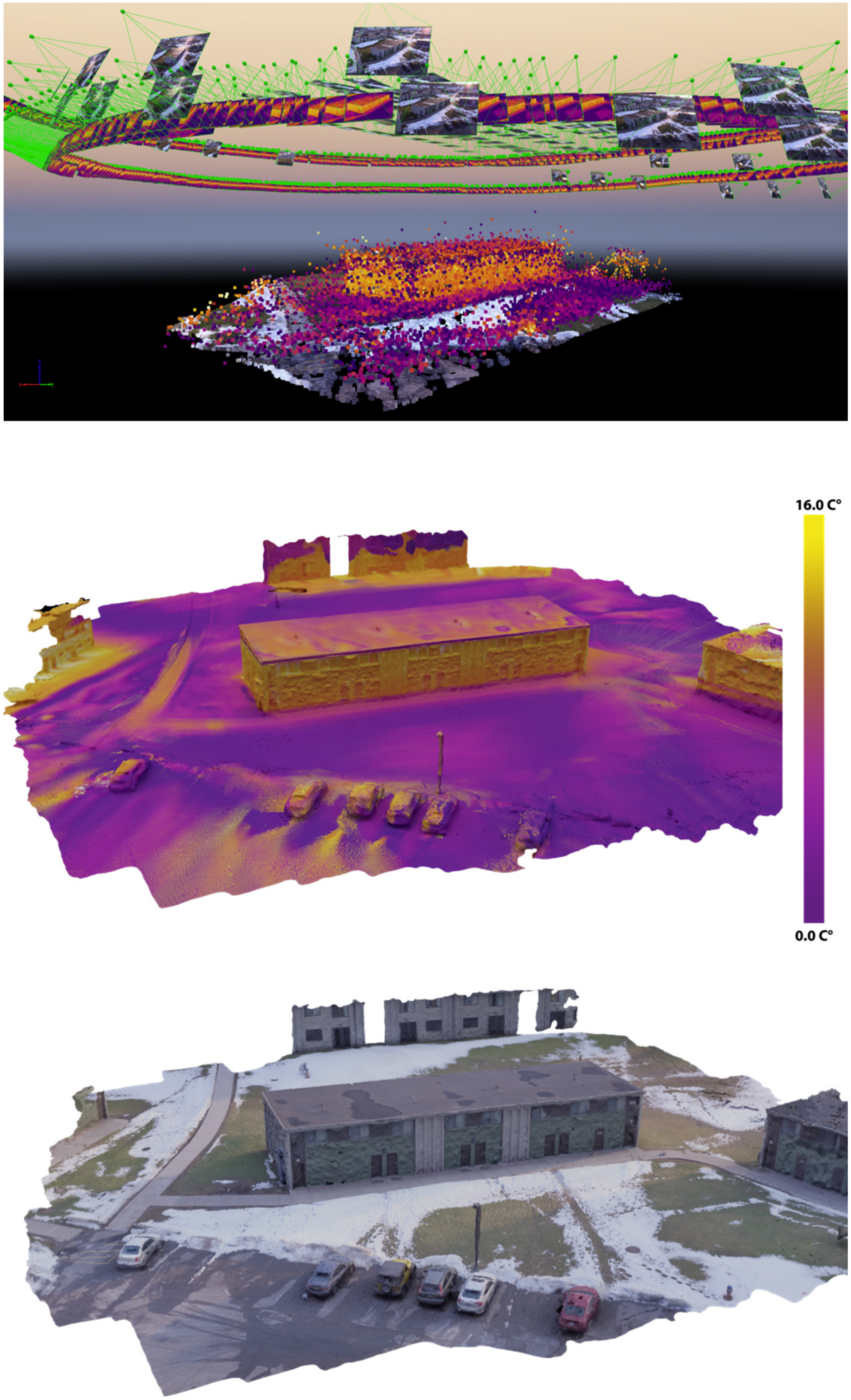

Fig. 7. Infrared and RGB models generated using 3D photogrammetry using Pix4D and Rhino3D CAD modeling software.

literature that outlines the main technoethical stigmas surrounding drone use which are safety, legality, privacy, air space use, informational integrity, and commercial concerns. The overarching issue is that the significance of drone use is greatly underrepresented in common media and therefore the general public maintains its general distrust towards UASs [81].

As the general public is more exposed to UAS technologies, and with the progression of time, more research will explore UAS used across industries and fields. More minute areas of life and work will become either automated or expedited with the presence of UAS, and the social stigma around unmanned flight may continue to develop alongside increased consumer awareness. The adaptation of this technology in standard building audit companies and organizations will necessitate a baseline understanding of thermography as well as a standardized procedure. Necessary UAS regulations are currently under development around the world so as to specify where, when, how and why drone technology can be used and allow for more legally sound exploration of potential uses [82].

Table 1
Comparison between 3D photogrammetry software (case study is between brackets).

	Agisoft Photoscan	Pix4D	DroneDeploy
Standalone computing	X	X	–
Cloud-based computing	–	X	X
Maximum number of images	Unlimited (1338 IR)	Unlimited (1338 IR/139 RGB)	500 images
Merging RGB and IR images	–	X	–
Model quality (w/o merging RBG and IR)	Low	Mid	High
Pixilation as compared to images	High	Mid	Low
Geometric output as compared to images	Low	High	Mid
Accuracy as compared to images	Low	Mid	High
Interactive assessment of model	Standalone (limited)	Cloud & standalone	Cloud-based
Time to process model	Low (4 Hrs)	High (18 Hrs)	Mid (8 Hrs)
Control of output model quality	Little to no control	High control	Some control

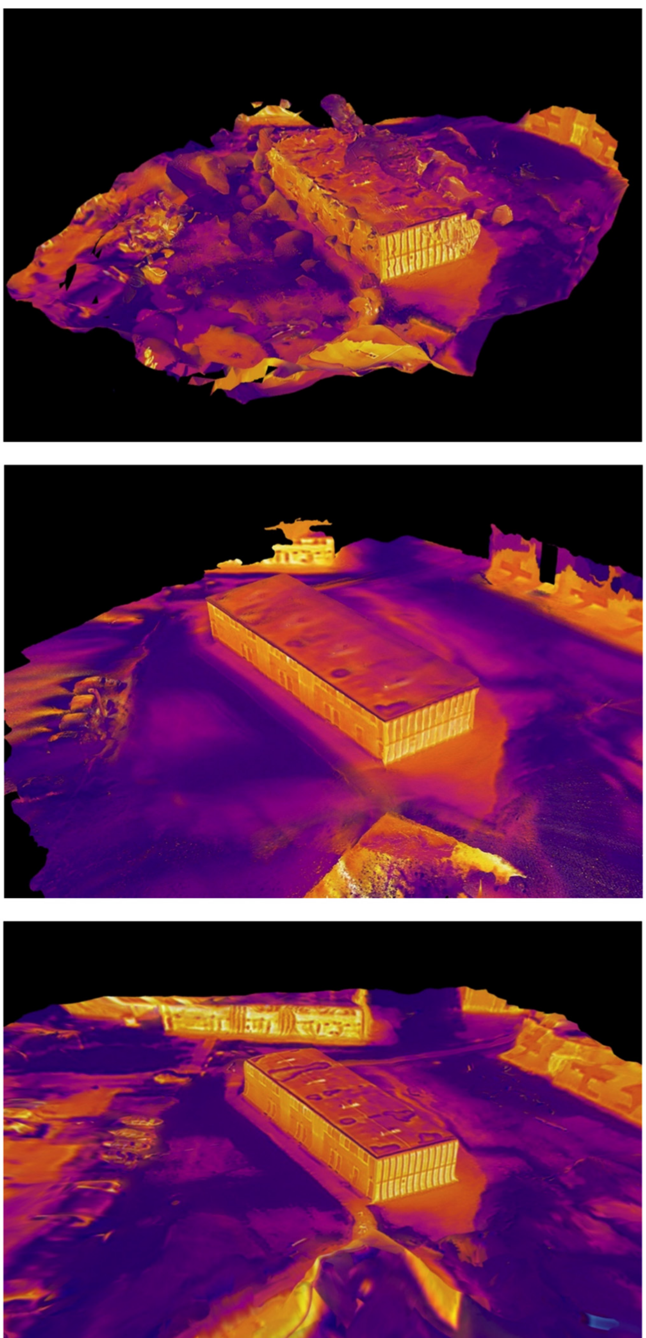

Fig. 8. Infrared model comparison between a) Agisoft Photoscan, b) Pix4D and c) DroneDeploy.

Limited opposition to this methodology should not be neglected. Vavilov claims that the use of mathematical equations and existing heat flow patterns is more accurate than IR imaging, although the investigation concludes that the difference is between 1 and 3 degrees Kelvin. The research argues that exterior surveying is insufficient for comprehensive analysis of building energy use and waste, interior inspections with handheld thermal cameras or traditional tests are described to be time proof and dependable [89]. Other researchers confirm this remark due to the fact that areas of thermal leaks are more clearly observed from the interior as opposed to the exterior [66].

7. Conclusion

This review detailed current procedures and methodologies of UAS-based thermal imaging practices. An experiment was conducted to empirically assess reviewed work, and a UAS-based building inspection method was presented, tested, and results were stated. Currently aging infrastructure and building stock necessitate energy retrofitting action and advancements in the methods with which thermal issues are identified will enable more action. In the age of climate change, the use of UASs and infrared imaging has proven to be a significant improvement on traditional auditing methods and techniques [7]. The increased accessibility, efficiency, and safety present a unique opportunity to expedite the improvement and retrofitting of aging and energy inefficient building stock and infrastructure. Existing software and mathematical concepts present a variety of options for post processing, analysis, and visual representation with reduced manual workflow, as a step closer towards fully automated building performance inspections using drones. Future research should build on the presented workflows to develop a standardized approach for building energy audits. This should include references to existing technological capabilities and further parameterization of the process to become more global through replicated experiments that validate the presented work.

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References

[1] U.S. Census Bureau, [Online]. Retrieved from: https://www.census.gov/programs-surveys/ahs/data/interactive/ahstablecreator.html#?s_areas=a00000&s_year=n2015&s_tableName=Table1&s_byGroup1=a4&s_byGroup2=a1&s_filterGroup1=

t1&s_filterGroup2=g1, (2015) , Accessed date: 6 February 2017.
[2] U.S. Energy Information Administration, How much energy is consumed in U.S. residential and commercial buildings? [Online]. Retrieved from: https://www.eia.gov/tools/faqs/faq.php?id=86&t=1, (2017) , Accessed date: 14 May 2017.
[3] U.S. Department of Energy, Thermographic inspections, [Online]. Retrieved from: https://energy.gov/energysaver/thermographic-inspections, (2012) , Accessed date: 18 May 2017.
[4] E.C. Shao, Detecting Sources of Heat Loss in Residential Buildings from Infrared Imaging, Doctoral Dissertation, Massachusetts Institute of Technology, Cambridge, MA, 2011http://hdl.handle.net/1721.1/68921 [Accessed 24 08 2017].
[5] A. Kylili, P.A. Fokaides, P. Christou, S.A. Kalogirou, Infrared thermography (IRT) applications for building diagnostics: a review, Applied Energy 134 (2014) 531–549, http://dx.doi.org/10.1016/j.apenergy.2014.08.005 [Accessed 22 05 2017].
[6] L.E. Mavromatidis, D.J. L, R. Saleri, J.C. Batsale, First experiments for the diagnosis and thermophysical sampling using impulse IR thermography from unmanned aerial vehicle (UAV), Quantitative InfraRed Thermography Conference, Bordeaux, 2014, http://dx.doi.org/10.21611/qirt.2014.213 [Accessed 04 06 2017].
[7] C. Corsi, History highlights and future trends of infrared sensors, J. Mod. Opt. 57 (18) (2010) 1663–1686, http://dx.doi.org/10.1080/09500341003693011 [Accessed 07 05 2017].
[8] S. Schuffert, T. Voegtle, N. Tate, A. Ramirez, Quality assessment of roof planes extracted from height data for solar energy systems by the EAGLE platform, Remote Sens. 7 (12) (2015) 17016–17034, http://dx.doi.org/10.3390/rs71215866 [Accessed 03 05 2017].
[9] M.L. Mauriello, L. Norooz, J.E. Froehlich, Understanding the role of thermography in energy auditing: current practices and the potential for automated solutions, Proceedings of the 33rd Annual Association for Computing Machinery Conference on Human Factors in Computing Systems, Seoul, 2015 [ISBN: 978-1-4503-3145-6. Accessed 18 05 2017].
[10] R. Naughton, Remote piloted aerial vehicles, [Online]. Retrieved from: http://www.ctie.monash.edu.au/hargrave/rpav_home.html/, (2003) , Accessed date: 24 August 2017.
[11] I. Shaw, History of U.S. drones, [Online]. Retrieved from: https://understandingempire.wordpress.com/2-0-a-brief-history-of-u-s-drones/, (2014) , Accessed date: 24 August 2017.
[12] A. Tarantola, This flying bomb failure was America's WWI cruise missile, [Online]. Retrieved from: http://gizmodo.com/this-flying-bomb-failure-was-americas-wwi-cruise-missi-1184824802, (04 09 2013) , Accessed date: 24 August 2017.
[13] J. Stamp, Unmanned drones have been around since world war I, [Online]. Retrieved from: http://www.smithsonianmag.com/arts-culture/unmanned-drones-have-been-around-since-world-war-i-16055939/#ZOkewSDbAgEoRHhA.99, (12 02 2013) , Accessed date: 24 August 2017.
[14] J.W. Saveriano, Superman, marilyn, robot planes, and UAVs, [Online]. Retrieved from: https://sandacom.wordpress.com/2010/03/26/superman-marilyn-and-robot-planes-uavs-part-2/, (26 03 2010) , Accessed date: 24 August 2017.
[15] J. Rizzo, Japan's secret WWII weapon: balloon bombs, [Online]. Retrieved from: http://news.nationalgeographic.com/news/2013/05/130527-map-video-balloon-bomb-wwii-japanese-air-current-jet-stream/, (27 05 2013) , Accessed date: 24 August 2017.
[16] A. Orlov, The U-2 program: a Russian officer remembers, [Online]. Retrieved from: https://www.cia.gov/library/center-for-the-study-of-intelligence/csi-publications/csi-studies/studies/winter98_99/art02.html, (2007) , Accessed date: 24 August 2017.
[17] E. Howell, What is DARPA? [Online]. Retrieved from: https://www.space.com/29273-what-is-darpa.html, (30 04 2015) , Accessed date: 24 August 2017.
[18] E. Helmore, US retires predator drones after 15 years that changed the ‘war on terror’, [Online]. Retrieved from: https://www.theguardian.com/world/2017/mar/13/predator-drone-retire-reaper-us-military-obama, (2017) , Accessed date: 24 August 2017.
[19] R. Mac, Bow to your billionaire drone overlord: Frank Wang's quest to put DJI robots into the sky, [Online]. Retrieved from: https://www.forbes.com/sites/ryanmac/2015/05/06/dji-drones-frank-wang-china-billionaire/, (06 05 2015) , Accessed date: 24 August 2017.
[20] C. Dillow, A brief history of drones, [Online]. Retrieved from: http://fortune.com/2014/10/09/a-brief-history-of-drones/, (09 10 2014) , Accessed date: 24 August 2017.
[21] G. Wallace, Amazon Says Drone Deliveries are the Future, [Online]. Retrieved from: http://money.cnn.com/2013/12/01/technology/amazon-drone-delivery/index.html, (02 12 2013) , Accessed date: 24 August 2017.
[22] D. Prindle, DJI's new obstacle avoidance tech aims to make drones crash proof, [Online]. Retrieved from: https://www.digitaltrends.com/cool-tech/dji-obstacle-avoidance-matrice-100-guidance/, (09 06 2015) , Accessed date: 24 August 2017.
[23] B. Popper, DJI's revolutionary phantom 4 drone can dodge obstacles and track humans, [Online]. Retrieved from: https://www.theverge.com/2016/3/1/11134130/dji-phantom-4-drone-autonomous-avoidance-tracking-price-video, (01 03 2016) , Accessed date: 24 August 2017.
[24] A. Dalton, Engadget, [Online]. Retrieved from: https://www.engadget.com/2016/07/21/facebooks-solar-powered-drone-makes-first-full-test-flight/, (21 07 2016) , Accessed date: 24 August 2017.
[25] E. Codel, Drones doing the darndest things, [Online]. Retrieved from: https://iq.intel.com/mind-blowing-drone-innovations/, (20 04 2016) , Accessed date: 24 August 2017.
[26] K. Kakaes, F. Greenwood, M. Lippincott, S. Dosemagen, P. Meier, S. Wich, Drones and aerial observation: new technologies for property rights, human rights, and global development, New America, https://www.newamerica.org/international-security/events/drones-and-aerial-observation/, (2015) , Accessed date: 7 September 2017.
[27] R. Steffen, W. Forstner, On visual real time mapping for unmanned aerial vehicles, Int. Arch. Photogramm. Remote. Sens. Spat. Inf. Sci. XXXVII (B3a) (2011) 57–62 [Accessed 12 08 2017].
[28] K.N. Tahar, Aerial terrain mapping using unmanned aerial vehicle approach, Int. Arch. Photogramm. Remote. Sens. Spat. Inf. Sci. XXXIX (B7) (2012) 493–498, http://dx.doi.org/10.5194/isprsarchives-XXXIX-B7-493-2012 [Accessed 18 07 2017].
[29] W. Volkmann, G. Barnes, Virtual surveying: mapping and modeling cadastral boundaries using Unmanned Aerial Systems (UAS), Proceedings of the Federation Internationale des Geometres (FIG) Congress: Engaging the Challenges—Enhancing the Relevance, Kuala Lumpur, 2014 http://www.fig.net/resources/proceedings/fig_proceedings/fig2014/ppt/TS09A/TS09A_barnes_volkmann_7300_ppt.pdf [Accessed 17 06 2017].
[30] A.P.M. Tarigan, D. Suwardhi, M.N. Fajri, F. Fahmi, Mapping a volcano hazard area of Mount Sinabung using drone: preliminary results, 1st Annual Applied Science and Engineering Conference, Pendidikan, 2017, http://dx.doi.org/10.1088/1757-899X/180/1/012277 [Accessed 18 06 2017].
[31] D. Borrmann, A. Nuchter, M. Dakulovic, I. Maurovic, I. Petrovic, D. Osmankovic, J. Velagic, A mobile robot based system for fully automated thermal 3D mapping, Adv. Eng. Inform. 28 (4) (2014) 425–440, http://dx.doi.org/10.1016/j.aei.2014.06.002 [Accessed 11 08 2017].
[32] P.S. Blaer, P.K. Allen, View planning and automated data acquisition for three-dimensional modeling of complex sites, J. Field Rob. 26 (11–12) (2009) 865–891, http://dx.doi.org/10.1002/rob.20318 [Accessed 18 05 2017].
[33] H. Son, S. Lee, C. Kim, Automated 3D model reconstruction to support energy-efficiency, Procedia Eng. 145 (2016) 571–578, http://dx.doi.org/10.1016/j.proeng.2016.04.046 [Accessed 20 08 2017].
[34] J.R. Martinez-de Dios, A. Ollero, Automatic detection of windows thermal heat losses in buildings using UAVs, World Automation Congress, Budapest, 2006, http://dx.doi.org/10.1109/WAC.2006.375998 [Accessed 20 08 2017].
[35] J.R. Martinez-de Dios, A. Ollero, J. Ferruz, Infrared inspection of buildings using autonomous helicopters, 4th International Federation of Automatic Control (IFAC) Symposium on Mechatronic Systems, Loughborough, 2006, http://dx.doi.org/10.3182/20060912-3-DE-2911.00105 [Accessed 20 08 2017].
[36] N. Haala, M. Cramer, F. Weimer, M. Trittler, Performance test on UAV-based photogrammetric data collection, International Society for Photogrammetry and Remote Sensing Zurich 2011 Workshop, Zurich, 2011, http://dx.doi.org/10.5194/isprsarchives-XXXVIII-1-C22-7-2011 [Accessed 24 08 2017].
[37] L. Lopez-Fernandez, S. Laguela, J. Fernandez, D. Gonzalez-Aguilera, Automatic evaluation of photovoltaic power stations from high-density RGB-T 3D point clouds, Remote Sens. 9 (6) (2017) 631, http://dx.doi.org/10.3390/rs9060631 [Accessed 26 07 2017].
[38] W.H. Maes, A. Huete, K. Steppe, Optimizing the processing of UAV-based thermal imagery, Remote Sens. 9 (5) (2017) 476–493, http://dx.doi.org/10.3390/rs9050476 [Accessed 28 06 2017].
[39] S. Emelianov, A. Bulgakow, D. Sayfeddine, Aerial laser inspection of buildings facades using quadrotor, Procedia Eng. 85 (2014) 140–146, http://dx.doi.org/10.1016/j.proeng.2014.10.538 Part of special issue: selected papers from *Creative Construction Conference*, Prague, 2014 [Accessed 23 08 2017].
[40] S. Laguela, L. Diaz-Vilarino, D. Roca, J. Armesto, Aerial oblique thermographic imagery for the generation of building 3D models to complement geographic information systems, 12th International Conference on Quantitative Infrared Thermography (QIRT), Bordeaux, 2015, http://dx.doi.org/10.21611/qirt.2014.041 [Accessed 04 08 2017].
[41] I. Lizarazo, V. Angulo, J. Rodriguez, Automatic mapping of land surface elevation changes from UAV- based imagery, Int. J. Remote Sens. 38 (8–10) (2017) 2603–2622, http://dx.doi.org/10.1080/01431161.2016.1278313 [Accessed 25 06 2017].
[42] M.C. Harvey, J.V. Rowland, K.M. Luketina, Drone with thermal infrared camera provides high resolution georeferenced imagery of the Waikite geothermal area, New Zealand, J. Volcanol. Geotherm. Res. 325 (2016) 61–69, http://dx.doi.org/10.1016/j.jvolgeores.2016.06.014 [Accessed 14 08 2017].
[43] C. Eschmann, T. Wundsam, Web-based georeferenced 3D inspection and monitoring of bridges with unmanned aircraft systems, J. Surv. Eng. 143 (3) (2017), http://dx.doi.org/10.1061/(ASCE)SU.1943-5428.0000221 pp. 04017003-1–04017003-10 [Accessed 02 06 2017].
[44] A. Choi-Fitzpatrick, T. Juskauskas, Up in the air: applying the Jacobs Crowd formula to drone imagery, Procedia Eng. 107 (2015) 273–281, http://dx.doi.org/10.1016/j.proeng.2015.06.082 [Accessed 20 08 2017].
[45] S. Laguela, L. Diaz-Vilarino, D. Roca, H. Lorenzo, Aerial thermography from low-cost UAV for the generation of thermographic digital terrain models, Opto-Electron. Rev. 23 (1) (2015) 76–82, http://dx.doi.org/10.1515/oere-2015-0006 [Accessed 20 06 2017].
[46] F. Tauro, M. Porfiri, S. Grimaldi, Surface flow measurements from drones, J. Hydrol. 540 (2016) 240–245, http://dx.doi.org/10.1016/j.jhydrol.2016.06.012 [Accessed 22 07 2017].
[47] T.D. Stek, Drones over Mediterranean landscapes. The potential of small UAV's (drones) for site detection and heritage management in archaeological survey projects: a case study from le Pianelle in the Tappino Valley, Molise (Italy), J. Cult. Herit. 22 (2016) 1066–1071, http://dx.doi.org/10.1016/j.culher.2016.06.006 [Accessed 18 07 2017].
[48] D. Gonzalez-Aguilera, S. Laguela, P. Rodriguez-Gonzalvez, D. Hernandez-Lopez, Image-based thermographic modeling for assessing energy efficiency of building facades, Energ. Buildings 65 (2013) 29–36, http://dx.doi.org/10.1016/j.enbuild.

2013.05.040 [Accessed 01 07 2017].

[49] F. Nex, F. Remondino, UAV for 3D mapping applications: a review, Appl. Geomatics 6 (1) (2014) 1–15, http://dx.doi.org/10.1007/s12518-013-0120-x [Accessed 06 06 2017].

[50] D. Roca, S. Laguela, L. Diaz-Vilarino, J. Armesto, P. Arias, Low-cost aerial unit for outdoor inspection of building facades, Autom. Constr. 36 (2013) 128–135, http://dx.doi.org/10.1016/j.autcon.2013.08.020 [Accessed 20 08 2017].

[51] G. Morgenthal, N. Hallermann, Quality assessment of unmanned aerial vehicle (UAV) based visual inspection of structures, Adv. Struct. Eng. 17 (3) (2014) 289–302 10.1260%2F1369-4332.17.3.289. [Accessed 10 06 2017].

[52] S.M. Adams, M.L. Levitan, C.J. Friedland, High resolution imagery collection utilizing unmanned aerial vehicles (UAVs) for post-disaster studies, Adv. Hurricane Eng. Learning from our Past (2013) 777–793, http://dx.doi.org/10.1061/9780784412626.067 [Accessed 12 08 2017].

[53] F. Caballero, L. Merino, J. Ferruz, A. Ollero, A visual odometer without 3D reconstruction for aerial vehicles. Applications to building inspection, International Conference on Robotics and Automation, Barcelona, 2005, http://dx.doi.org/10.1109/ROBOT.2005.1570841 [Accessed 09 08 2017].

[54] A. Ellenberg, A. Kontsos, I. Bartoli, A. Pradhan, Masonry crack detection application of an unmanned aerial vehicle, International Conference on Computing in Civil and Building Engineering, Orlando, 2014, http://dx.doi.org/10.1061/9780784413616.222 [Accessed 20 07 2017].

[55] M.N. Zulgafli, K.N. Tahar, Three dimensional curve hall reconstruction using semi-automatic UAV, Asian Res. Pub. Net. J. Eng. Appl. Sci. (ARPN-JEAS) 12 (10) (2017) 3228–3232 ISSN 1819-6608. [Accessed 03 06 2017].

[56] E.J. Lee, S.Y. Shin, B.C. Ko, C. Chang, Early sinkhole detection using a drone based thermal camera and image processing, Infrared Phys. Technol. 78 (2016) 223–232, http://dx.doi.org/10.1016/j.infrared.2016.08.009 [Accessed 13 07 2017].

[57] A. Colantonio, G. McIntosh, The differences between large buildings and residential infrared thermographic inspections is like night and day, 11th Canadian Conference on Building Science and Technology, Banff, 2007 http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.543.1644&rep=rep1&type=pdf [Accessed 25 06 2017].

[58] X. Feifei, L. Zongjian, G. Dezhu, L. Hua, Study on construction of 3D building based on UAV images, Remote. Sens. Spat. Inf. Sci. Volume XXXIX (B1) (2012) 469–473, http://dx.doi.org/10.5194/isprsarchives-XXXIX-B1-469-2012 [Accessed 30 07 2017].

[59] F. Lizak, M. Kolcun, Improving reliability and decreasing losses of electrical system with infrared thermography, Acta Electrotechnica et Informatica 8 (1) (2008) 60–63 ISSN 1335-8243. [Accessed 20 08 2017].

[60] M.R. Clark, D.M. McCann, M.C. Forde, Application of infrared thermography to the non-destructive testing of concrete and masonry bridges, NDT E Int. 36 (4) (2003) 265–275, http://dx.doi.org/10.1016/S0963-8695(02)00060-9 [Accessed 28 08 2017].

[61] R.J.P. Ferreira, A. Teixeira de Almeida, C.A.V. Cavalvante, A multi-criteria decision model to determine inspection intervals of condition monitoring based on delay time analysis, Reliab. Eng. Syst. Saf. 94 (5) (2008) 905–912, http://dx.doi.org/10.1016/j.ress.2008.10.001 [Accessed 02 06 2017].

[62] E. Grinzato, IR thermography applied to the cultural heritage conservation, 18th World Conference on Nondestructive Testing, Durban, 2012 http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.638.1122&rep=rep1&type=pdf [Accessed 27 08 2017].

[63] M. Hollaus, High resolution aerial images from UAV for forest applications, http://www.newfor.net/wp-content/uploads/2015/02/DL14-Newfor-SoA-UAV.pdf, (2014) , Accessed date: 29 June 2017.

[64] E. Barreira, V.P. Freitas, Evaluation of building materials using infrared thermography, Constr. Build. Mater. 21 (1) (2007) 218–224, http://dx.doi.org/10.1016/j.conbuildmat.2005.06.049 [Accessed 24 06 2017].

[65] V. Bonora, G. Tucci, V. Vaccaro, 3D data fusion and multi-resolution approach for a new survey aimes to a complete model of Rucellai's Chapel by Leon Battista Alberti in Florence, The International Committee for Architectural Photogrammetry (CIPA) 2005 XX International Symposium, Torino, 2005 OCLC: 420816504. [Accessed 12 08 2017].

[66] M. Fox, D. Coley, S. Goodhew, P. de Wilde, Thermography methodologies for detecting energy related building defects, Renew. Sust. Energ. Rev. 40 (2014) 296–310, http://dx.doi.org/10.1016/j.rser.2014.07.188 [Accessed 08 08 2017].

[67] L. Hoegner, U. Stilla, Texture extraction for building models from IR sequences of urban areas, Urban Remote Sensing Joint Event, Munich, 2007, http://dx.doi.org/10.1109/URS.2007.371812 [Accessed 20 08 2017].

[68] J.L. Lerma, M. Cabrelles, T.S. Akasheh, N.A. Haddad, Documentation of weathered architectural heritage with visible, near infrared, thermal and laser scanning data, Int. J. Heritage Digital Era 1 (2) (2012) 251–275 10.1260%2F2047-4970.1.2.251. [Accessed 30 07 2017].

[69] Lopez-Fernandez, Laguela, Picon, Gonzalez-Aguilera, Large scale automatic analysis and classification of roof surfaces for the installation of solar panels using a multi-sensor aerial platform, Remote Sens. 7 (9) (2015) 11226–11248, http://dx.doi.org/10.3390/rs70911226 [Accessed 30 07 2017].

[70] I.B. Utne, T. Brurok, H. Rodseth, A structured approach to improved condition monitoring, J. Loss Prev. Process Ind. 25 (3) (2011) 478–488, http://dx.doi.org/10.1016/j.jlp.2011.12.004 [Accessed 04 08 2017].

[71] L. Ma, M. Li, L. Tong, Y. Wang, L. Cheng, Using unmanned aerial vehicle for remote sensing application, 21st International Conference on Geoinformatics, Kaifeng, 2014, http://dx.doi.org/10.1109/Geoinformatics.2013.6626078 [Accessed 18 07 2017].

[72] N.P. Avdelidis, A. Moropoulou, Emissivity considerations in building thermography, Energ. Buildings 35 (7) (2003) 663–667, http://dx.doi.org/10.1016/S0378-7788(02)00210-4 [Accessed 29 07 2017].

[73] M.D. Gonçalves, P. Gendron, T. Colantonio, Commissioning of exterior building envelopes of large buildings for air leakage and resultant moisture accumulation using infrared thermography and other diagnostic tools, Thermal Performance of the Exterior Envelope of Whole Buildings X International Conference, Clearwater Beach, 2007 https://www.cebq.org/documents/RD-0123-AThermalSolutions2007-FINALPAPERMGr1_000.pdf [Accessed 07 07 2017].

[74] Y. Ham, M. Golparvar-Fard, An automated vision-based method for rapid 3D energy performance modeling of existing buildings using thermal and digital imagery, Adv. Eng. Inform. 27 (3) (2013) 395–409, http://dx.doi.org/10.1016/j.aei.2013.03.005 [Accessed 28 08 2017].

[75] O. Kung, C. Strecha, A. Beyeler, J.C. Zufferey, D. Floreano, P. Fua, F. Gervaix, The accuracy of automatic photogrammetry techniques on ultra-light UAV imagery, Unmanned Aerial Vehicle in Geomatics, Zurich, 2011, http://dx.doi.org/10.5194/isprsarchives-XXXVIII-1-C22-125-2011 [Accessed 04 07 2017].

[76] S. Yahyanejad, B. Rinner, A fast and mobile system for registration of low-altitude visual and thermal aerial images using multiple small-scale UAVs, ISPRS J. Photogramm. Remote Sens. 104 (2014) 189–202, http://dx.doi.org/10.1016/j.isprsjprs.2014.07.015 [Accessed 16 06 2017].

[77] D. Roca, J. Armesto, S. Laguela, L. Diaz-Vilarino, Lidar-equipped UAV for building information modelling, The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-5, International Society for Photogrammetry and Remote Sensing (ISPRS) Technical Commission V Symposium, 23–25 June 2014, Riva del Garda, Italy, 2014, , http://dx.doi.org/10.5194/isprsarchives-XL-5-523-2014 [Accessed 04 05 2017].

[78] T. Hackel, J.D. Wegner, K. Schindler, Contour detection in unstructured 3D point clouds, The Institute of Electrical and Electronics Engineers Conference on Computer Vision and Pattern Recognition, Las Vegas, 2016, http://dx.doi.org/10.1109/CVPR.2016.178 [Accessed 08 06 2017].

[79] Z. Qamar, Zero gravity, fully cute: New Japanese drone in space, [Online]. Retrieved from: http://www.cnn.com/2017/07/18/tech/cute-japanese-space-drone/index.html, (18 July 2017) , Accessed date: 8 February 2017.

[80] B. Rao, A.G. Gopi, R. Maione, The societal impact of commercial drones, Technol. Soc. 45 (2016) 83–90, http://dx.doi.org/10.1016/j.techsoc.2016.02.009 [Accessed 29 07 2017].

[81] R. Luppicini, A. So, A technoethical review of commercial drone use in the context of governance, ethics, and privacy, Technol. Soc. 46 (2016) 109–119, http://dx.doi.org/10.1016/j.techsoc.2016.03.003 [Accessed 30 07 2017].

[82] F. Remondino, L. Barazzetti, F. Nex, M. Scaioni, D. Sarazzi, UAV photogrammetry for mapping and 3D modeling- current status and future perspectives, International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XXXVIII-1/C22, 201, International Society for Photogrammetry and Remote Sensing (ISPRS) Zurich 2011 Workshop, Zurich, Switzerland, 14–16 September 2011, , http://dx.doi.org/10.5194/isprsarchives-XXXVIII-1-C22-25-2011 [Accessed 08 08 2017].

[83] N.D. Opfer, D.R. Shields, Unmanned aerial vehicle applications and issues for construction, 121st American Society of Engineering Education (ASEE) Annual Conference & Exposition, Indianapolis, 2014 https://peer.asee.org/23235 ISSN 2153-5965 [Accessed 05 06 2017].

[84] FLIR Systems, Thermal Imaging Guidebook for Building and Renewable Energy Applications, http://www.flirmedia.com/MMC/THG/Brochures/T820325/T820325_EN.pdf, (2013) [Accessed 04 06 2017].

[85] Lockheed Martin Aeronautics Company, Lockheed martin supports U.S. navy and Northrop Grumman in X-47B UCAS-D successful first flight, [Online]. Cision PR Newswire http://www.northropgrumman.com/Capabilities/X47BUCAS/Pages/default.aspx/a, (07 February 2011) , Accessed date: 30 July 2017.

[86] L. Mallonee, Move over, selfies. 'Dronies' are where it's at, [Online]. Retrieved from: https://www.wired.com/2015/09/move-selfies-dronies/, (2015) , Accessed date: 18 August 2017.

[87] K. Finley, World's smallest drone autopilot system goes open source, [Online]. Retrieved from: https://www.wired.com/2013/08/drone-autopilot/, (2013) , Accessed date: 8 January 2017.

[88] R. Ariwoola, Use of drone and infrared camera for a campus building envelope study, Electronic theses and Dissertations. East Tennessee University in Johnson City, Tennessee State. Paper 3018, 2016 http://dc.etsu.edu/etd/3018 [Accessed 30 07 2017].

[89] V.P. Vavilov, How accurate is the IR thermographic evaluation of heat losses from buildings? Quan. Infra. Thermo. J. 7 (2) (2010) 255–258, http://dx.doi.org/10.1080/17686733.2010.9737142 [Accessed 06 07 2017].

[90] Siebert, Sebastian, Jochen Teizer, Mobile 3D mapping for surveying earthwork projects using an Unmanned Aerial Vehicle (UAV) system, Autom. Constr. 41 (February 19, 2014) 1–14, http://dx.doi.org/10.1016/j.autcon.2014.01.004 [Accessed 14 08 2017].

[91] Pablo Rodriguez-Gonzalvez, Diego Gonzalez-Aguilera, Gemma Lopez-Jimenez, Inmaculada Picon-Cabrera, Image-based modeling of built environment from an Unmanned Aerial System, Aut. Con. 48 (2014) 44–52, http://dx.doi.org/10.1016/j.autcon.2014.08.010 [Accessed 17 07 2017].

[92] M. Vollmer, M.Ã. Klaus-Peter, Infrared Thermal Imaging: Fundamentals, Research and Applications, John Wiley & Sons, 2017 ISBN: 78-3-527-64155-0. [Accessed 05 06 2017].

[93] A. Bar-Sela, The history of temperature recording from antiquity to the present, in: M. Abernathy, S. Uematsu (Eds.), Medical thermology, American Academy of Thermology, Washington, D.C., 1986(ISBN:10: 0961490500).