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Campus as a Lab for Computer Vision-based Heat Mapping Drones: A Case Study for Multiple Building Envelope Inspection using Unmanned Aerial Systems (UAS)

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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 design disciplines. In architecture praxis, UAS equipment with remote sensing gear presents 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. Comprehensive energy audits are essential to maximize energy savings in buildings realized from the design and implementation of deep retrofits for building envelopes, together with energy system repairs or changes. This paper presents a methodology for employing a UAS platform to conduct rapid building envelope performance diagnostics and perform aerial assessment mapping of building energy. The investigation reviews 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 a university campus site to showcase: 1) visually identifying areas of thermal anomalies using a UAS equipped with IR cameras; 2) detailed inspection applied to areas of high interest to quantify envelope heat-flow using computer vision techniques. The overall precision and recall rates of 76% and 74% were achieved in the experimental results, respectively. A discussion of the findings suggests refining procedure accuracy, as a step towards automated envelope inspection.

KEYWORDS
Unmanned Aerial System (UAS); building Inspection; retrofitting, energy audit; thermography

INTRODUCTION

The buildings sector accounts for about 76% of electricity use and 40% of all U.S. primary energy use and associated greenhouse gas (GHG) emissions. More than half of all U.S. commercial buildings in operation today were built before 1970 and this large existing building stock performs with general lower efficiency. HVAC and lighting loads in existing buildings consume 35% and 11% of total building energy, respectively, which totals more than 17 quads of residential and commercial building primary energy use (U.S. DOE, 2015). In order to achieve substantial energy savings in existing and deteriorating built environments, retrofitting strategies that respond to accurate and reliable energy audits should to be implemented. Unfortunately, predicted savings and delivered savings typically do not match. This can be attributed to imprecise energy audits, which may lead to lower than expected energy savings, no energy savings or in some cases occasional increase in energy use. A myriad of negative effects follow, including environmental impacts that were not accounted for, discrediting energy efficiency retrofits as well as loss of investment monies. This is typically a result of many challenges that energy auditors face, including insufficient building information that leads to misrepresentation in energy models, overestimated savings, ineffective selection of improvement strategies and incomprehensive improvement scope that result in missed improvement opportunities (Shapiro, 2011). In this paper, we present a methodology to address these critical challenges by employing a UAS platform. More specifically, we employ a drone equipped with a thermal camera, to conduct rapid building envelope performance diagnostics and perform aerial assessment mapping of building energy. The paper aims to identify standard procedures for operating a UAS for energy audit missions, and to automate the envelope assessment method using computer vision algorithms.

Previous research work addressed the use of UAS and thermography in building inspection, diagnostics and energy audits. An earlier attempt by Martinez-De Dios and Ollero presented infrared-based automated detection techniques for thermal heat losses in building windows using UAS (Martinez-De Dios and Ollero, 2006). The use of impulse infrared thermography was introduced by Mavromatidis et al (2014) as a method to examine old civil infrastructure and residential buildings' energy consumption, ageing process and life cycle. A more comprehensive method to reduce manual workflows was introduced by Mauriello and Froehlich (2014). It utilized an unmodified Parrot AR. Drone 2.0 and a FLIR thermal camera to collect RGB and thermal images of a building and generate 3D reconstructions. Automation challenges were further presented, which included data quality, data overload, technical feasibility, privacy and problems of overreliance on automated scans (Mauriello et al, 2015). While UAS platforms were used in various building inspection activities, a comprehensive building envelope inspection procedure was not engaged. We aim to address this gap in the literature by presenting a twofold approach to the inspection of building envelopes: 1) using a geometric data-gathering process, tested in the field, and 2) a computer vision analysis approach for the automation of envelope anomaly detections.

METHODS

The research framework is divided into two methods. First, the design of flight paths and implementation of data collection using photogrammetry and thermal imaging. Second, the use of computer-vision workflows to analyse and segment thermal images, and autonomously detect thermal anomalies.

Energy Audit Flight Procedure

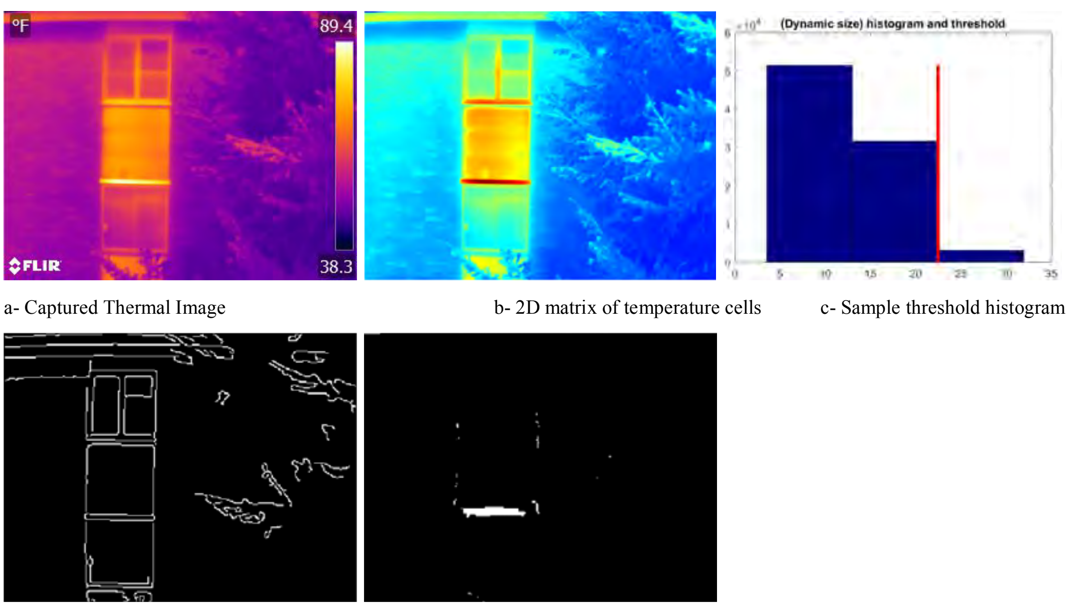
Preflight considerations: Energy leakage detection relies upon certain environmental conditions. Local climatic factors, such as rain, snow, and heavy wind are not typically appropriate weather conditions for drone flight. Certain environmental factors that can affect external surface temperatures of buildings such as indoor and outdoor temperature, humidity, wind speed, cloud coverage, solar radiation, and precipitation are considered. A temperature difference of about 10° Celsius, as well as a notable pressure difference should be observed between the interior and exterior of the building. (FLIR, 2012).

Flight path design: There are two common flight paths that can be adopted for the majority of typical buildings. For flat facades which are mostly vertical, the flight path should begin on a predetermined corner and follow vertical bays upward, move across to the next bay and downward. For flat facades that are mostly horizontal, the path should begin at a predetermined corner and continue to the right before moving up a bay and continuing in a linear manner to the left. After capturing façades, the drone should move on to capture thermal images of the roof in a similar grid manner, starting from one corner and moving in either a horizontal or vertical pattern along a superimposed grid, until the entire roof has been captured (Eschmann et al, 2012). Based on empirical experimentation and a brief review of the literature, we propose a general distance of 20' away from a building, at changing bay heights of 7-10', with imaging gathered approximately every 5' along the flight path.

Post-flight analysis: Gathered data should include pre-flight environmental conditions, pre-flight interior conditions, IR images or videos, and corresponding non-thermal images or videos. The primary goal of drone-based energy audits is to visually identify thermal leaks and support these claims with temporal data extracted from the images (Lee and Ham, 2016). We hypothesize that the following building envelope issues can be identified in post-flight analysis using the designed procedure: 1) Exfiltration / infiltration, 2) Missing / deteriorating insulation, 3) Thermal bridges and 4) Regions of failure (cracks, etc.)

Computer Vision Algorithms

Our computer vision framework for heat leakage detection is composed of two stages: 1) A global lookup of a thermal image and 2) edge filtering and segmentation, where the actual leakage regions are identified. The detection framework assumes that a thermal anomaly is defined as regions where sudden or abnormal temperature changes happen in the thermal image. When an expert inspects a color-mapped thermal image which is taken outdoor during a cold winter season, she/he observes the leakage as a light (cold) region surrounded by darker (hotter) regions. Therefore, the main concept behind the detection algorithm is to find a sharp temperature change on the thermal image.



a- Captured Thermal Image b- 2D matrix of temperature cells c- Sample threshold histogram

d- Edge detection e- Leakage segmentation

Figure 1. Edge processing and analysis of a sample thermal image.

In this framework, a thermal image is considered as a 2D matrix, whose cells, i.e. pixels, are temperature values. A naïve solution to segment out the heat leakage regions would be seeking "hot-enough" pixels (in winter, for outdoor images) and label them as leakage pixels. However, this approach is expected to introduce multiple false positive results, since this kind of strong, pixel-wise separation simply detects hot regions without taking any distinctive characteristic of heat leakages into account. We observe that sharp temperature changes on a single-layer thermal image could be explained as nothing but thermal edges, which can possibly be the contours of leakage regions, and thermal anomalies are regions which have thermal edges. Consequently, by detecting those edges, anomaly regions would be segmented out. However, this argument is also not always true, since not all the edges found on thermal images are edges of leakage regions. For instance, red regions in Figure 1-b represent window leakage, and an edge detector would separate those regions. Yet, there are other visible edges, which will be detected on the same image such as trees as seen in Figure 1-c. Therefore, in our framework we eliminate those false detections, and eventually segment out the leakage regions by detecting edges, following them, and applying region growing.

Experiment Design

For this study, a proof-of-concept experiment was designed by the research team to inspect a cluster of dormitory buildings at a university campus in the United States. The team used 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 Pix4D app, and the images were processed and analysed using the FLIR Tools program. Figure 2 illustrates the flight path and data gathering processing for computer-vision analysis.

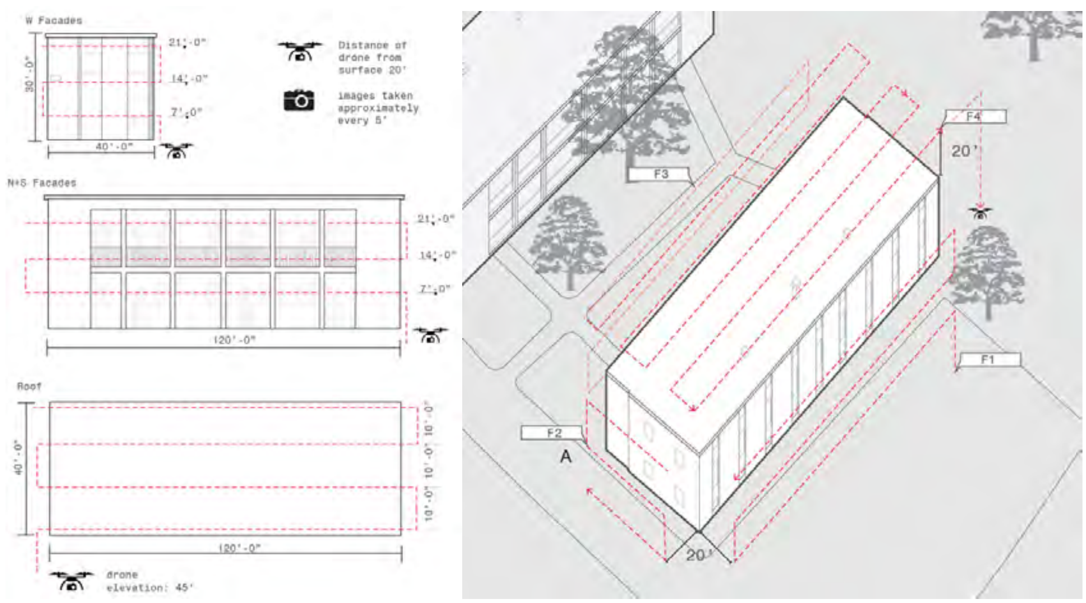


Figure 2. The experiment flight path and imaging procedure.

RESULTS

Building Envelope Audit

The audit flight took place on two separate days, the first day inspected 3 buildings using 3 batteries taking infrared video, and the second flight inspected two buildings taking still pictures, Building D was not fully inspected due to the proximity of trees on the southern façade as well. Each flight date was undertaken in 90 minutes. Figure 3 showcases 5 major categories of audit results that include: Rust – showcased through deterioration in the building façade. Water damage – infiltration and puddling of water on the roof at seams. Thermal bridges – due to faulty construction practice while installing roofs. Penetration – malfunction of envelope integrity (in façades and roofs). Brickwork deterioration – at openings and penetrations in the façade.

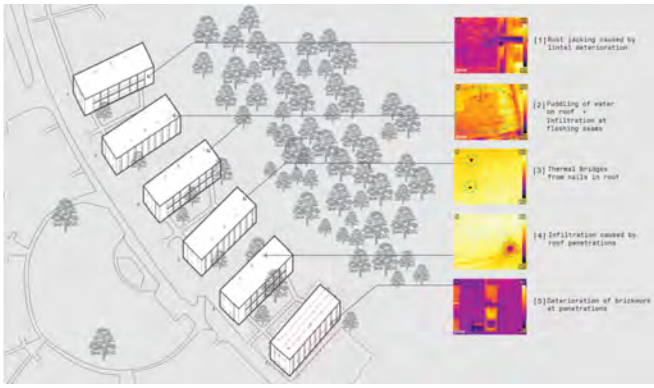
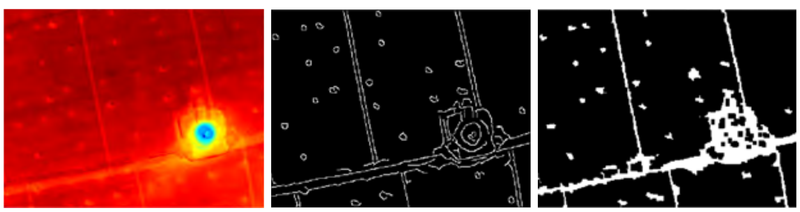


Figure 3. Sample results from building envelope audit.

Thermal Anomaly Segmentation

We tested the developed algorithm on 149 thermal images that contain a total of 1018 heat leakage regions. From these leakage regions, the algorithm successfully detects 751 of them, and missed 267 actual thermal anomaly regions. The workflow also reported 237 regions that are considered false positives. This resulted in precision and recall rates of 76% and 74%, respectively. These rates will increase as the algorithm is further developed to match expert identification of anomalies. Figure 4 highlights a series of sample heat leakage images and their corresponding detection results.

a) Successful infiltration detection.



b) Successful thermal bridge detection.

Figure 4. Experimental results from various sides of the inspected buildings. In each triplet, the left are IR scenes, middle are edge detection, and right are the segmented leakage regions.

DISCUSSION

The framework is presented as a workflow for building envelope diagnostic missions that would be administered by auditors to fly the UAS, which allows the use of thermal imaging for structural inspection, heat losses, infiltration, insulation conditions, glazing performance, as well as giving access to challenging to reach situations such as the roof. The proposed solution is being tested as a proof of concept that will significantly reduce the number of hours spent to produce high-quality, large-scale audits. Currently, an auditor may choose a repetitive pattern in a building envelope and assume that the performance is the same for all similar parts of the skin. The developed approach allows for comprehensive and accurate assessment with no such assumptions.

CONCLUSION

In regard to architectural practice, UAS equipped with thermal cameras present a unique opportunity for building inspection and more specifically, building energy auditing. The use of UAS in conjunction with building inspection and energy audits is ideal for a market saturated with degrading and energy inefficient infrastructure. In this paper, we presented an inspection framework that employs a developed computer vision algorithm to autonomously detect thermal anomalies. The ultimate goal is to enable assessments of entire campuses, neighborhoods and cities and map their energy performance accurately for identification of potential energy savings through retrofitting strategies.

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