Heat Mapping Drones: An Autonomous Computer Vision-based Procedure for Building Envelope Inspection using Unmanned Aerial Systems (UAS)

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Abstract

Comprehensive and accurate energy audits are essential to maximize energy savings and improvements in buildings realized from the design and implementation of deep retrofits for building envelopes. This paper presents a methodology for employing drones to conduct rapid building envelope performance diagnostics and perform aerial mapping of energy flows. The presented framework is tested on the Syracuse University campus to showcase: 1) visually identifying areas of thermal anomalies using an Unmanned Aerial System (UAS) equipped with thermal 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, respectively. A discussion of the findings suggests refining procedure accuracy, as a step towards automated envelope inspection.

Keywords

Building Envelope Inspection; Energy Audit; Thermal Imaging; Unmanned Aerial Systems (UAS); Computer Vision.

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 (U.S. DOE, 2015). Research conducted in Metropolitan Boston, MA, found that within 135 residential houses surveyed with infrared technology, heat transfer and air leaks through cracks were the reason behind about 40% of energy lost (Shao, 2011). 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 (U.S. DOE, 2015). HVAC and lighting loads in existing residential and commercial buildings consume 35% and 11% of total building energy, respectively, which totals more than 17 quads of residential and commercial building primary energy use (Ibid., 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 be implemented (U.S. DOE, 2012). To identify compromises in the building envelope, energy auditors traditionally use tools such as blower door tests to detect infiltration/exfiltration regions, as well as thermal bridges (Ibid., 2012). Unfortunately, predicted savings and delivered savings typically do not match (Shapiro, 2011). 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 (Ibid., 2011). A myriad of negative effects follows, including environmental impacts that were not accounted for, discrediting energy efficiency retrofits as well as loss of investment monies (Ibid, 2011). 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 opportunities (Ibid., 2011). In large commercial buildings, energy auditors typically emphasize exciting technical challenges that focus on Heating, Ventilation and Air Conditioning (HVAC) or integration of renewable energy in the form of solar panels, while ignoring less attractive building envelope issues such as window performance, thermal bridges, air sealing and insulation deterioration (Shapiro, 2009). This can also be coupled with situations that are considered uneasy, dangerous or inaccessible to the auditor, including high-rise or large-span structure envelope inspections, as well as building roofs (Ibid., 2009). In this paper, a methodology is presented to address these critical challenges by employing a UAS platform.

Tools such as infrared cameras and Unmanned Aerial Systems / Vehicles (UAS / UAV) enable professionals to analyze building envelopes efficiently and accurately while reducing operational costs and safety risks. Additionally, when paired with video recording, photography, or multi spectral imaging, drones can safely, economically, and efficiently carry out a building energy audit (Kylili, Fokaides, Christou, & Kalogirou, 2014). UAS provide building auditors with a unique aerial perspective. This viewpoint allows easy access to remote or inaccessible areas (which may include natural or human built obstructions) without compromising the safety of the auditor (Mavromatidis, L, Saleri, & Batsale, 2014). Another benefit of utilizing UAS for building audits is its nondestructive and non-contact nature (Grinzato, 2012); (Barreira & Freitas, 2007);

(Bonora, Tucci, & Vaccaro, 2005). This increases the accuracy of collected data and allows for audits and visual data gathering in historical or structurally damaged buildings (Harvey, Rowland, & Luketina, 2016); (Corsi, 2010); (Grinzato, 2012); (Clark, McCann, & Forde, 2003). To expand on limited research and practice, this paper employs a drone equipped with a thermal camera, to conduct rapid building envelope performance diagnostics and perform aerial assessment mapping of building energy flows.

Previous research work addressed the use of UAS and thermography in building inspection, diagnostics and energy audits. An earlier attempt by Dios and Ollero presented infrared based automated detection techniques for thermal heat losses in building windows using UAS. The research proposed a method to detect heat losses around windows and display them on a 3D model of the building. To capture data from facade and inspect its thermography, the procedure uses a UAV which carries a video camera and a thermal camera that operates at far-infrared band. A fixed 7° C threshold is used to segment heat loss areas, which are then further filtered. This approach of using a fixed pre-set threshold is prone to errors, and can become infeasible in most of the other seasons and weather conditions, and also for different building materials, and different causes of heat losses (Dios and Ollero, 2006). Zhang and Jung presented a method for thermal inspection of roofs using UAVs to facilitate both visual interpretation and autonomous detection. The investigation used Markov Random Fields (MRF) to segment the anomaly regions on the thermal image. Images are divided into superpixels, and MRF is applied onto superpixels instead of applying it onto image pixels (Zhang, Jung, Sohn, & Cohen, 2015). Guerriero and Daliento focused on solar panels, and proposed a computer vision method for the identification of the borders of photovoltaic cells using a thermal camera mounted on UAVs. The work avoided use of high pass filters, and instead identified the borders by extracting those points whose temperature is lower than the median value of the temperature distribution (Guerriero & Daliento, 2017). Pereira and Pereira proposed to use UAVs and visible range images for autonomous inspection of cracks on buildings. This approach does not use thermal images. It compares two different computer vision algorithms and evaluate their performances in many aspects including the runtime on different platforms, binary size, code complexity etc. (Pereira & Eduardo, 2015).

The use of impulse infrared thermography was introduced by Mavromatidis, et al. as a method to examine old civil infrastructure and residential buildings' energy consumption, ageing process and life cycle. The method suggests overcoming the limitations of examining passive thermal emission of surfaces by the use of a stable UAS to record transient temperature response during the analysis time duration (Mavromatidis, et al. 2014). Gonzalez-Aguilera, et al. justify collecting data only before sunrise and after sunset to reduce the likelihood of collecting false positives due to direct solar radiation (Gonzalez-Aguilera, et al. 2013). A technique of visual inspection of buildings was developed by Eschmann et al. The study used UAS to create an initial database for digital building monitoring. It was proved that the high-resolution camera attached to the micro aerial vehicles provided useful information for infrastructural inspection purposes, even under non-optimal flight conditions. However, improvements were recommended including a better stabilization of flight platform, anti-collision and navigation systems and route planning algorithms. Also, improvements for manual-based frameworks for image post-processing were recommended, as each flight produces significantly large amount of data (Eschmann, et al. 2012). A more comprehensive method to reduce manual workflows was introduced by Mauriello and Froehlich. 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 (Mauriello and Froehlich, 2014). The study continued and contributed to an initial human-centered investigation of thermographic automation. The research concluded that thermal tools should be designed for both expert users, such as auditors, and for client interaction. Automation challenges were 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, ranging from static imaging and impulse IR, to employment of UAS in primary audit activities, a comprehensive building envelope inspection procedure was not engaged. In this paper the research question is: can the use of drones as part of building envelope inspection processes accelerate energy audits and make it more accurate using computer vision? The paper aims 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) employing a CV analysis approach for the automation of envelope anomaly detection.

Research Method

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 analyze and segment thermal images, and autonomously detect thermal anomalies.

Energy Audit Flight Procedure

Preflight considerations: Energy leakage detection relies upon certain environmental conditions. Firstly, local climatic factors, such as rain, snow, and heavy wind are not typically appropriate weather conditions for drone flight. Secondly, 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° C, as well as a notable pressure difference should be observed between the interior and exterior of the building. Radio interference has the potential to affect the drone's flight capability, therefore, ensuring that there are no radio or Wi-Fi interferences in the air or on the ground level is important (FLIR, 2012). To address possible radio and Wi-Fi intrusion, it is recommended that residents and owners are asked to minimize or eliminate activities that can create such interference, as part of the expected audit notification process. Sunlight, shadows and self-shading also have the potential to affect thermal imaging, therefore, it is useful to take regular images in tandem with infrared (IR) images for future reference and identification and understanding of false positives, as well as completing flight audits of envelope components at close time intervals on the same day. Consequently, a pre-flight checklist can include the following:

- Measure outdoor environmental conditions, and determine if the climate is suitable for flight (temperature, humidity, wind speed, cloud coverage, etc.)
- Measure (or assume) indoor temperature, and calculate resulting temperature difference.
- Determine if the difference is within acceptable range (10° C or more).
- Determine building usage (building type, operating hours, etc.).
- Notify occupants, and minimize radio and Wi-Fi interference.
- Record window coverings and furniture re-configuration (if any) for audit purposes.

Flight path design: 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. This movement is repeated until the entire façade has been documented and the drone proceeds to the next façade in a similar manner. 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, repeating until the entire façade has been documented. 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). For more complex geometries, facades should be divided into geometric zones into which a typical flight pattern may be applied. Bays can be determined either by window placement, structural qualities of the façade, or predetermined regions of interest. It is important to consider the overlap in bays and ensure that the entire façade is covered and no regions are neglected. These flight patterns minimize the amount of time necessary to capture the entire facade.

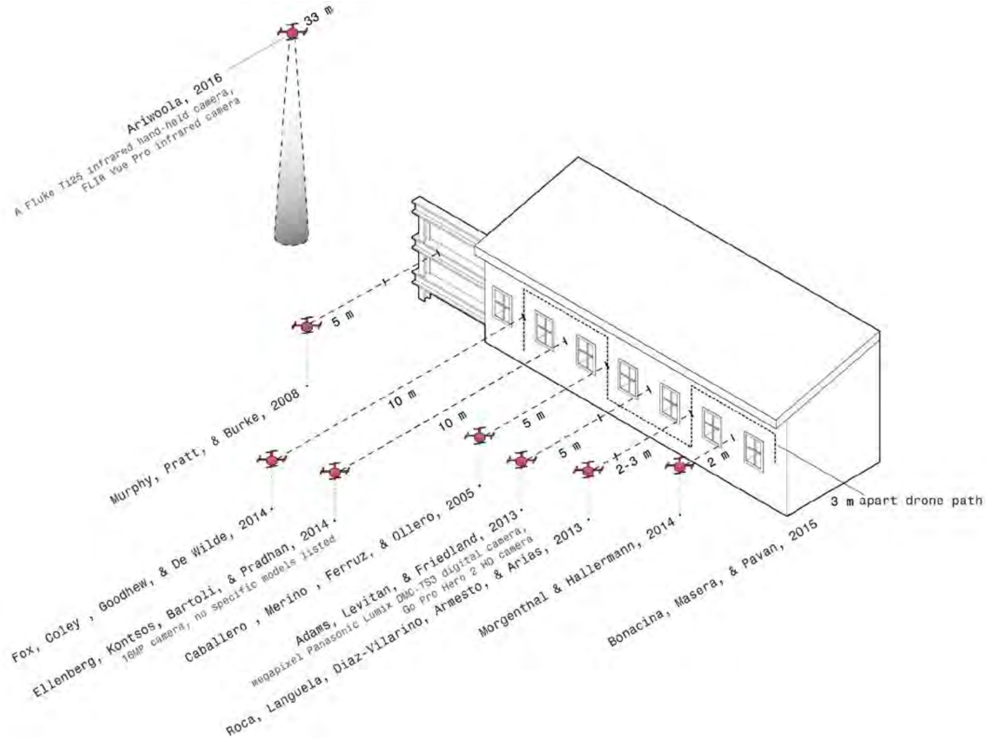


Figure 1 - Representation of flight path distances from reviewed literature.

In order to identify flight path parameters, the literature was reviewed for inspection distances for structural performance and building examination (Figure 1) and the investigation concluded that envelope inspection distances vary according to equipment and building conditions. A general distance of approximately 13m away from a building is proposed, at changing bay heights of 2-3m, with images gathered approximately every 2m along the flight path. The goal is to ensure approximately 70-80% overlap between photos captured for the purposes of using 3D photogrammetry to construct CAD models (Figure 2).

Figure 2 - In-flight imaging procedure for possible dual cameras, demonstrating target % overlap for auditing purposes.

Post-flight analysis: Gathered data should include preflight environmental conditions, preflight 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). Additional comparisons can be drawn between the building being audited and similar sized buildings in the area. It is also beneficial to support claims with energy use index (EUI) calculations of the building before audit and after thermal leaks are repaired (Hassouneh et al, 2015). This paper hypothesizes that the following building envelope issues can be identified in post-flight analysis using the designed procedure:

- Exfiltration / Infiltration

As exfiltration and infiltration occur most commonly around doors, windows, and other access points to the building, their presence will be most visible on the perimeters of such access points. Thermal images of leaking doors or windows will have patches of either cooler or warmer air clustered around the region, where the weather barrier is compromised. Common false positives occur on the glass of the window where the reflection of the drone or auditor affects the surface temperature (Hassouneh et al, 2015).

- Missing / Deteriorating Insulation

Missing insulation is identifiable in thermal images as patches of colder or warmer temperature in between the framing of the building or roof. False positives can occur when heavy furniture or drapes with insulating properties are not moved away from the wall before flight, and they may appear in thermal images as missing insulation. Other factors such as indoor climate control and shadows also have the potential to disrupt thermal patterns. Cross referencing regular images captured in tandem with the thermal images should distinguish false positives. (Lechner, 2014)

- Thermal Bridges

Thermal bridges can be classified as either geometric or material. Material thermal bridges occur when a building material with high thermal conductivity is improperly sealed or installed which created a ‘bridge’ for outdoor temperature to move indoors. In IR imaging these can be identified as clusters of cooler or warmer air around the perimeter of any building element which penetrates the building envelope. Geometric thermal bridges are an effect of the geometry of the building envelope (Lechner, 2014). Examples include wall corners, junctions between the roof or wall, and connections between walls and floors. In addition, protruding elements like balconies have the potential to create enough shading that the shaded area is consistently cooled. Geometric thermal bridges are identified similarly to exfiltration and infiltration; the main differentiating factor being the location (Danielski and Fröling, 2015). Construction drawings can be consulted preflight to determine if detailing led to thermal bridging even before an inspection starts, and the workflow can be further validated through this examination.

- Regions of Failure

After identifying thermal leaks, certain regions of interest may arise and necessitate further imaging. Smaller scale cracks and leaks may need to be documented with a handheld camera by the auditor on foot (Ibid., 2015), or a closer drone flight around the area of interest. Different distances generate different data; greater distances generate data of the whole form of the inspected building, while smaller distances generate greater detail; both are needed to generate a comprehensive model.

Computer Vision Algorithms

The developed 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 (Figure 3) 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 sharp temperature changes on the thermal image.

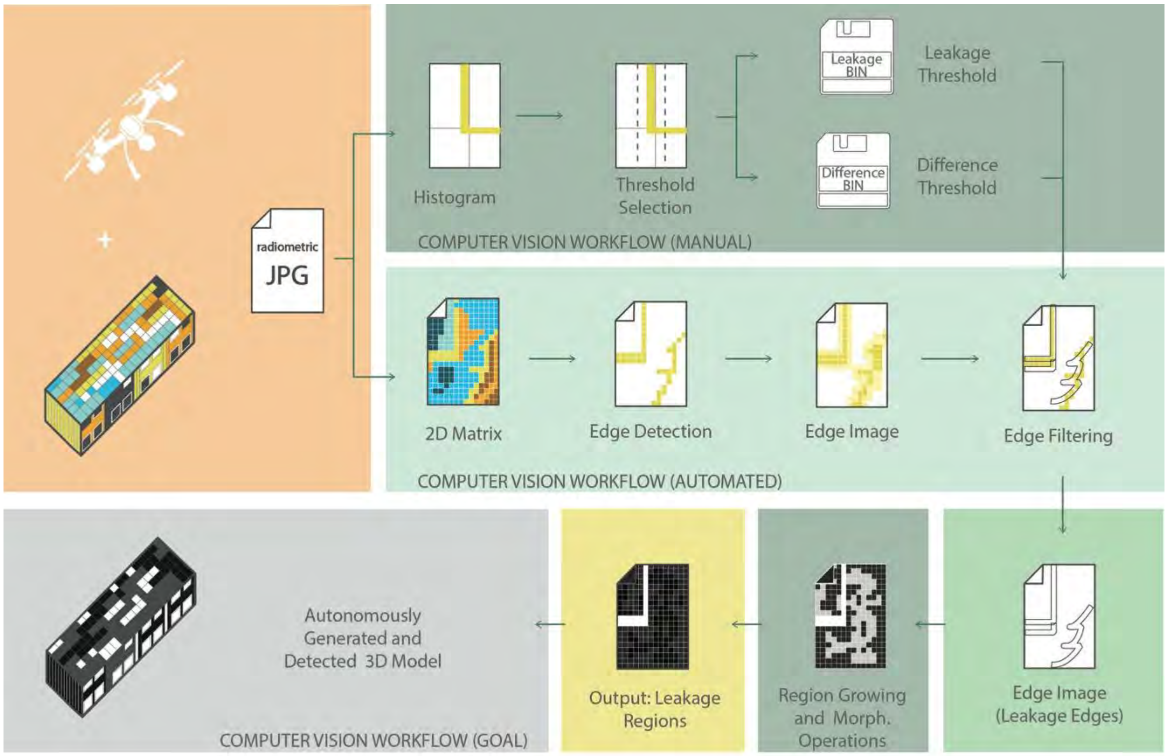


Figure 3 - Computer vision workflow, from image capturing and analysis to mapping of thermal anomalies.

In this framework, a thermal image is considered as a 2D matrix, whose cells (pixels) are temperature values. A naïve solution to segment out the heat leakage regions involves looking for "hot-enough" pixels (in winter, for outdoor images) and labeling them as leakage pixels. However, this approach can 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. 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 6b 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 6d, which do not correspond to thermal anomalies. In order to address this challenge, this framework eliminates these false detections and eventually segments out the leakage regions by not only detecting thermal edges, but also following along and monitoring each side of the edge to filter out false positives, and then applying region growing technique on the residual leakage regions.

Dynamic threshold detection

The first stage of the algorithm outputs two thresholds that are calculated per image based on the temperature distribution, seasonal conditions, and the location of inspection. Consequently, instead of defining a strict, preset threshold, the algorithm finds appropriate thresholds for each image before further processing. These two thresholds are referred to as "leakage threshold" and "difference threshold." The leakage threshold is used to determine whether a region should be considered as a leakage candidate, while the difference threshold is used to check if there is enough temperature change happening at a certain region. They are computed by employing a temperature histogram, whose size is dynamic based on the representativeness of its bins (Figure 4). The leakage bin is defined as the bin where actual heat leakage pixel values fall, and the opposite bin is defined as the bin at the opposite side of the leakage bin. In order to eliminate some of the false positives, a lower α limit is used on the representativeness of the opposite bin, since the expectation is for it to contain enough number of values. If the opposite bin contains less than α, the values that fall into it are removed and the histogram is recalculated until the opposite bin has strong representativeness. Next, an upper β limit is used on the leakage bin, which is not expected to dominate the temperature distribution since the total area of potential leakage regions is likely to occupy a smaller portion of the entire image. If the representativeness of the leakage bin is higher than β, the histogram's number of bins is incremented and recomputed until the limiting condition is met. The aforementioned α and β limits are variable percentage values that can vary from one experimental setup to the other.

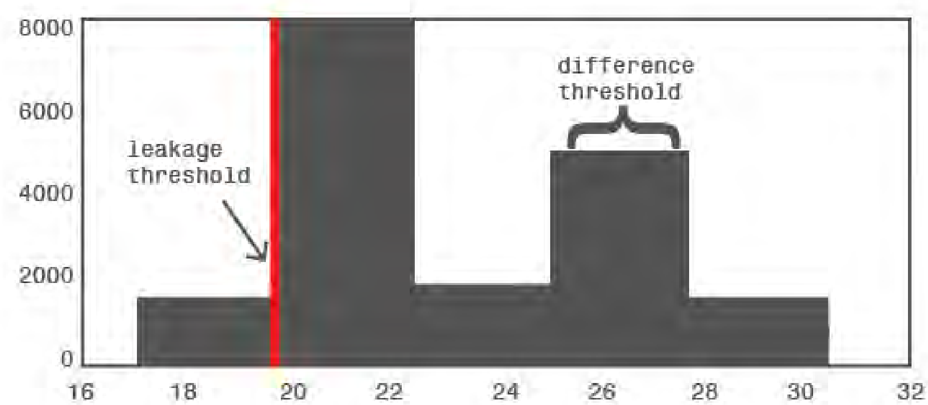


Figure 4 – An example 5-bin histogram of a thermal image taken during winter. The pixels which fall into the leftmost bin are likely to be from a leaking region.

Thermal edge filtering and segmentation

In the second stage of the algorithm, the thermal edges are found by using a Canny edge detector (Canny 1986). Then, by utilizing the two thresholds established in the earlier stage, some of the edges generated by the Canny edge detector are filtered out. The filtering operation is done by processing every pixel on each edge line along the edge direction as shown in Figure 5 and judging if they are pixels on the edge of a heat leakage or not. During this process, the algorithm compares the values in the neighborhood of the pixel that is currently being processed. The neighborhood is a set of values perpendicular to the edge direction. If the highest value in the neighborhood is less than the leakage threshold (that is, the corresponding point of the material is not hot enough), the current edge pixel is removed. If it is larger than the leakage threshold, then the algorithm checks whether the difference between the highest and lowest values is larger than the difference threshold. If the difference is not larger, the current edge pixel is removed. Otherwise, the algorithm keeps the edge pixel and moves on to the next one. Thermal leakage edges are found after processing every pixel on each edge and performing elimination.

Figure 5 illustrates the above-described process on a single thermal edge pixel. The red line is the edge segment being followed, and the black 7-cell strip is the neighborhood of the pixel that is currently being processed (with value 27.27°C in Figure 5). For this example, if the maximum value in the neighborhood (27.71°C) is larger than the leakage threshold found in the earlier stage, and the maximum temperature difference in the neighborhood (13.95°C) is greater than the difference threshold, the current pixel is kept as part of the leakage edge. Otherwise, if any of these two conditions are not met, the current edge pixel is removed.

Next, the actual leakage regions enclosed by these edges are segmented out. To group the actual leakage pixels and segment the heat leakage regions, region growing is first applied to min/max pixels saved during the edge following operation. In the region growing operation, for each thermal pixel that is considered as a leak in the edge filtering stage, a cluster of pixels is created whose values are at most with a temperature difference (θ) different than the leak pixel. Then, by merging these clusters, the actual leakage regions appear. However, the segmented leakage regions contain gaps inside them due to the irregularity of a surface's temperature distribution. In order to fill those gaps, morphological closing is applied as postprocessing. The residual binary image shows the leakage regions as seen in Figure 6e.

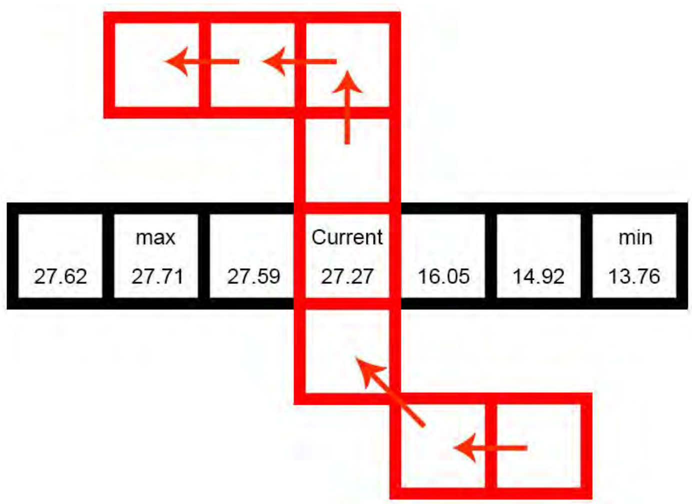
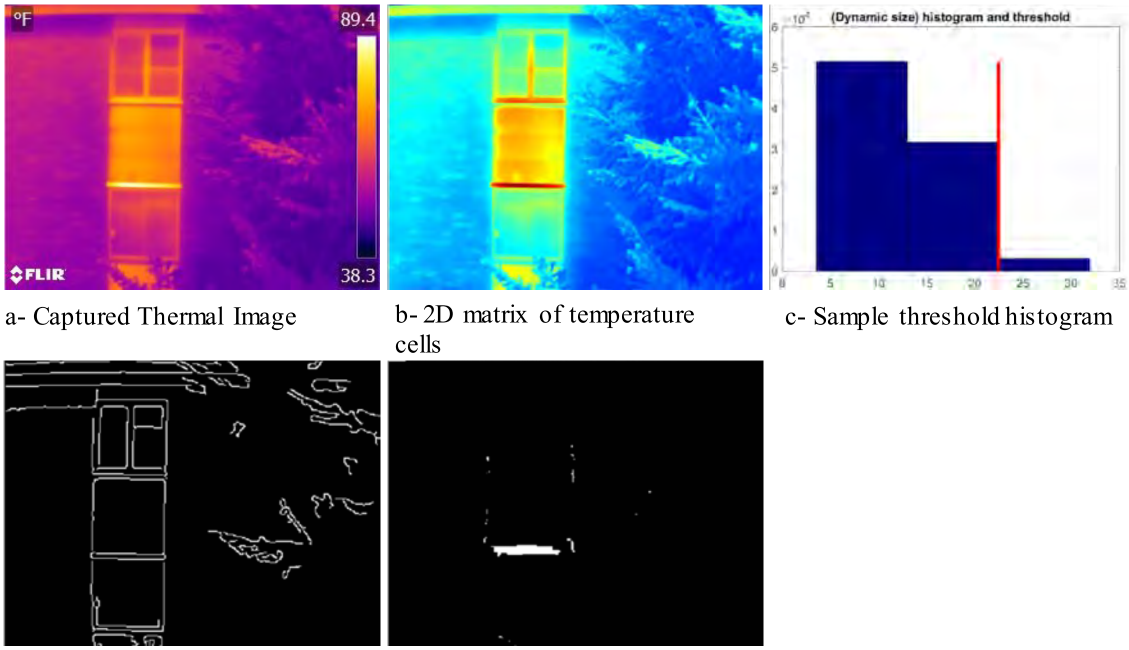


Figure 5 – Illustration of the Computer Vision edge following process.



a- Captured Thermal Image

b- 2D matrix of temperature cells

c- Sample threshold histogram

d- Edge detection

e- Leakage segmentation

Figure 6 - Edge processing and analysis of a sample thermal image.

Experiment Design

For this study, a proof-of-concept experiment was designed by the research team to inspect a cluster of dormitory buildings on the Syracuse University campus in Syracuse, New York. 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 Litchi app version 1.17.2, and Pix 4D 2.1.61 for roof images, and the images were processed and analyzed using the FLIR Tools program. Figure 7 illustrates the flight path and data-gathering processing for CV analysis. Note that, due to proximity to trees, all eastern facades of the buildings and limited portions of the northern and southern facades were not inspected. Figure 8 shows the drone in the inspection setup and a facade of an inspected building.

The data was collected externally during winter, so the algorithm was set to search for hotter anomalies in the experiment. In the first stage of the algorithm, α and β were set to empirically found values of 10% and 15%, respectively. Therefore, it was assumed that the total area of leakage regions would be less than 15% of the image, and to be representative enough, the number of samples in the opposite bin needed to be larger than 10% of the total. For the second stage of the algorithm, the Canny edge detector was used to generate the edge images of the thermal capture. The standard deviation (σ) of the blurring filter of the Canny edge detector was set to 1, and the other two parameters of the detector—low threshold and high threshold—were set to 0.08 and 0.2, respectively. Small values for thresholds were chosen to preserve as many edges as possible. Although this would possibly introduce many false edges, they would be eliminated in the subsequent stages. The only parameter used at the edge following the procedure was the neighborhood size. A total of 13 values were checked (6 on the right, 6 on the left, and the pixel itself) in the experiment. This value was set based on the image's resolution and the smoothness of the leakage regions' spread. In the region growing part of the postprocessing, the maximum allowable temperature difference (θ) to merge the neighboring pixels with the leakage region was set to 0.05°C. This criterion allowed the algorithm to include neighboring pixels with temperature values that vary within 0.1°C so that the results were reported as regions instead of thermal edge lines.

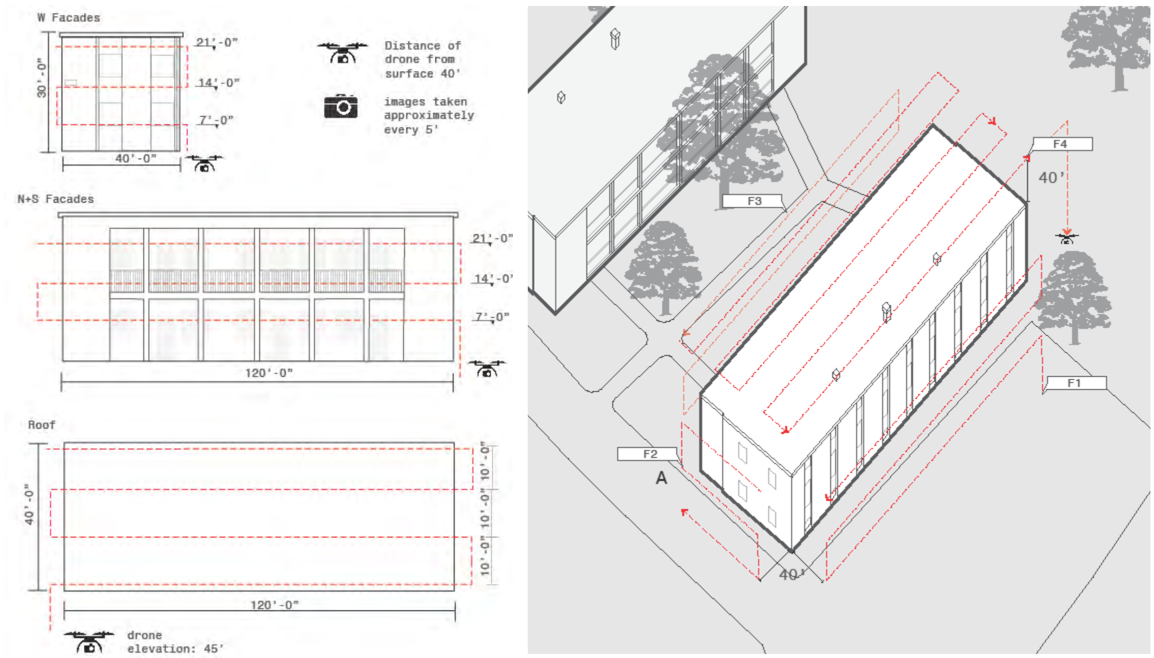


Figure 7 - The experiment's flight path and imaging procedure.

Results

The experiment outcomes follow the methodology and are divided into detailing the inspection outcomes and the image segmentation results.

Building Envelope Audit

The audit flight took place on two separate days, the first day inspected 3 buildings using 3 batteries taking infrared videos, and the second flight inspected two buildings taking still pictures. Each flight date was undertaken in 120 minutes, and 100 to 200 pictures were captured per building surface. 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 9 showcases 5 major categories of audit results that include:

- Rust – showcased through deterioration in the building façade. This is observed as a thermal anomaly in IR images, and is confirmed with RGB images or auditor observations.
- Water damage – infiltration and puddling of water on the roof at seams. This can be detected typically post rain events.
- Thermal bridges – due to faulty construction practice while installing roofs, or possible unfit detailing. The reason cannot be concluded, because construction drawings were not consulted. As an example, a number of roof nails were observed tearing through the envelope and creating thermal bridges.
- Penetration – malfunction of envelope integrity (in façades and roofs). Fixing of the roof using nails penetrated through the roof, and caused integrity damage beyond thermal bridges.
- Brickwork deterioration – at openings and penetrations in the façade. Although this is not a direct insulation observation, it is effecting heat retention through the façade.

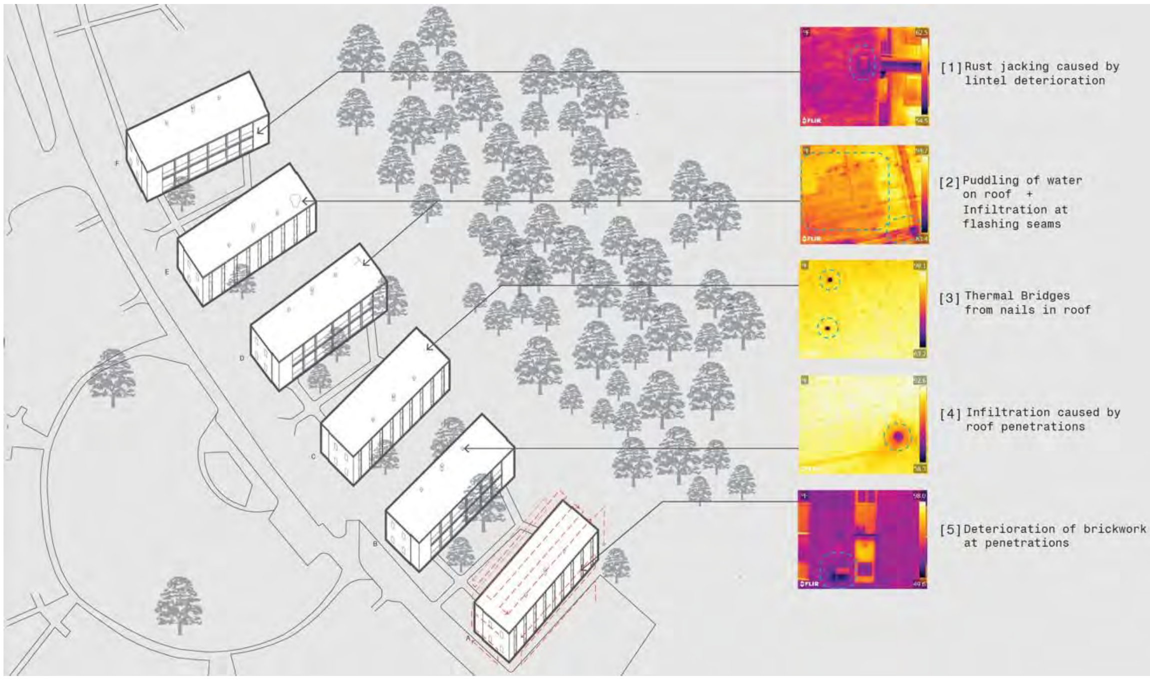


Figure 8 - Sample results from building envelope audit.

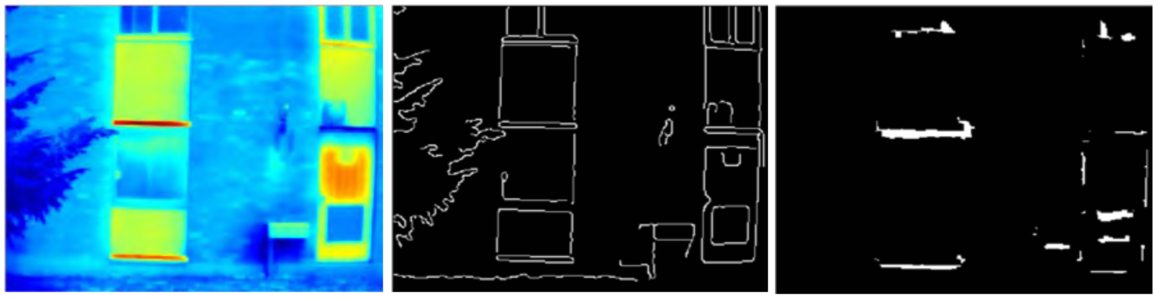
Thermal Anomaly Segmentation

The developed algorithm was tested on 149 collected thermal images. Building scientists within the research group identified a total of 1018 heat leakage regions in the images. The algorithm was applied, and it successfully detected 751 of identified anomaly regions, and missed 267 actual thermal leakage regions. The workflow also reported 237 regions that are considered false positives. The method was evaluated based on precision and recall measures, which are two well-known measures for evaluation of a model in machine learning. Precision is defined as the fraction of true positive samples over all positive samples, which also include false positives. Recall, similarly, defined as the fraction of true positive samples over the relevant examples, which also include the false negatives.

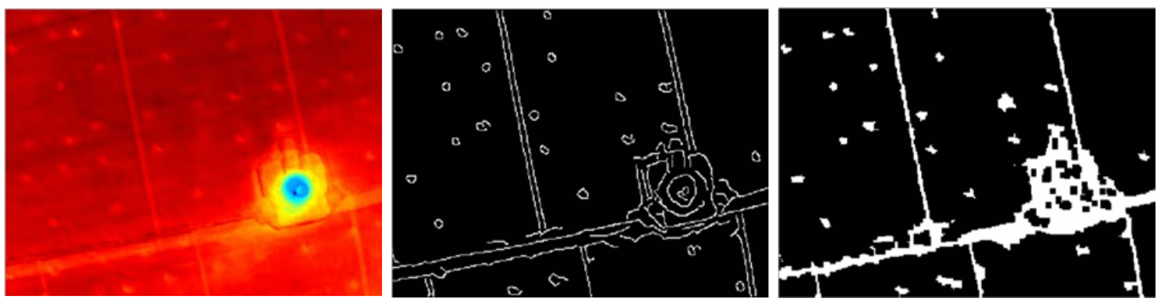
$$precision = \frac{Tp}{Tp + Fp}, \qquad recall = \frac{Tp}{Tp + Fn}$$

$$Tp: True\ positive, \qquad Fp: False\ positive, \qquad Fn: False\ negative\ (miss)$$

The model is expected to perform well on precision and recall measures for a detection task. A higher precision score means that most of the detections are actual leakages, while a higher recall score means that most of the actual leakages are detected. The importance of these measures can differ based on the needs of the application. In this scenario while some false positives can be tolerated, i.e., relatively lower precision, the recall rate was expected to be as high as possible, since the aim is to not miss any of the actual thermal leakages. The method resulted in precision and recall rates of 76% and 74%, respectively. In order to increase the recall rate, the techniques for elimination of false positives could be less restrictive, by tuning some parameters such as decreasing the threshold in Canny edge detection or modifying the representativeness factors in threshold selection stage. Although this will decrease the precision rate, the number of missed leakages will decrease too. In addition to low-level tuning of the algorithm, a comprehensive and systematic audit procedure will also increase the recall rate by inspecting a location from multiple viewpoints and capturing overlapping thermal pictures. Figure 9 and 10 highlight a series of sample heat leakage images and their corresponding detection results.



a) Successful infiltration detection.



b) Successful thermal bridge detection.

c) False positive detection of infiltration and missing envelope deterioration.

Figure 9 - Experimental results from different sides of the inspected buildings. In each triplet, the left images are the IR scenes, the middle are the edge detection, and the right are the segmented leakage regions.

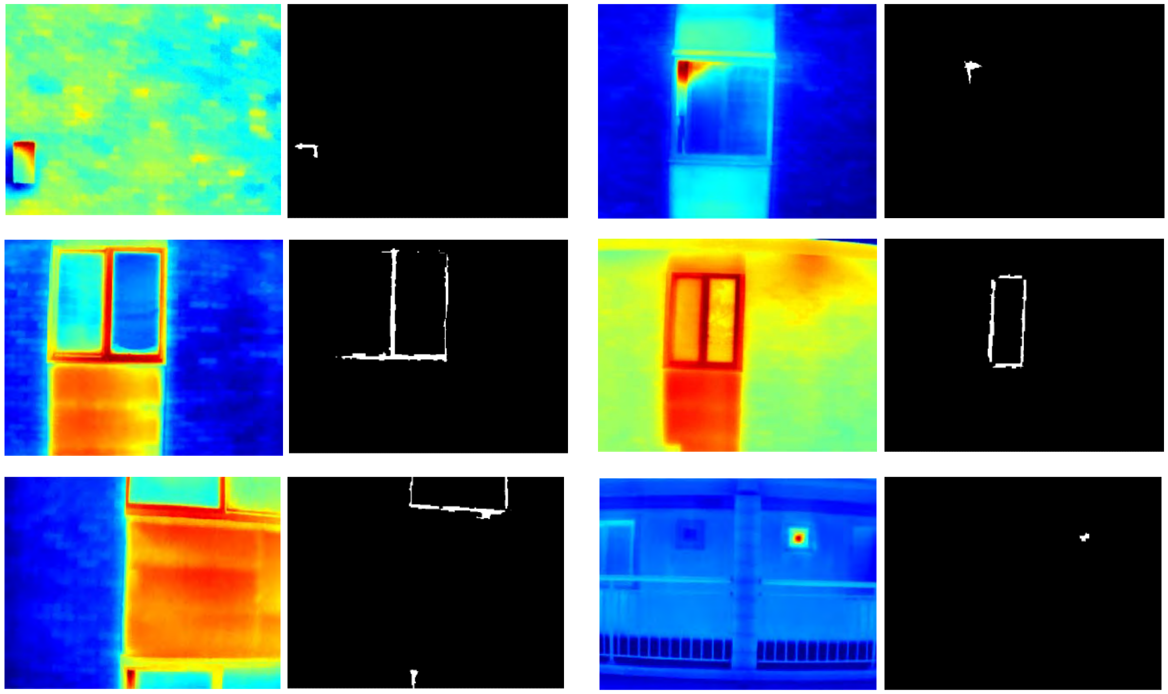


Figure 10 - Various successful detection of thermal leakage. In each pair, the left images are the IR scenes and the right are the segmented leakage regions.

Discussion

The findings are discussed by investigating the presented framework and computer vision algorithm in terms of novelty, potentials, limitations and suggested future research directions.

Research Novelty in Architectural Design

The aspiration for this work is to profoundly inform building retrofitting design by radically altering the methods and modes of performance evaluation. The use of drones creates the opportunity for evaluators to have limited physical barriers when accessing the built environment, and not to rely on single frame images for inspection. By developing three-dimensional models, designers are able to interact and engage in terms of developing solutions for building vulnerabilities. The evaluations of the built condition will allow designers to be strategic with the solutions used, targeting compromised building areas, and designing retrofitting to address directed, efficient and specific building envelope and skin issues.

The novelty of this process lies in the comprehensiveness and specificity of the prescribed methodology. The work has been designed based on a comprehensive review of comparable methods utilizing thermal imagery in the buildings sector, and the research was not limited to the combination of thermal imagery and drones nor the use of thermal imagery for the identification of poor thermal performance in the building envelope. Established methods of anomaly detection with building thermography were assessed, whixh 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 (Fox, et al, 2014). Some of these methods take their research a step further by proposing various combinations of either piloted or robotic vehicles for the thermal cameras such as vans (Hogner & Stilla, 2007) or specifically designed terrestrial robots (Borrmann et al, 2014). The research varied greatly when detailing (or not detailing) the number of images required and the post processing workflow. From this variety of research, the literature gap was identified, and a novel combination of flight path design, in-flight recommendations, and post processing workflow was developed based on the strengths and weaknesses of comparable methods. The presented method combines accessible tools, as the drones, thermal cameras, and software used are publicly available to consumers, with a technical understanding of building envelope performance and thermal imaging principles.

Framework Potentials

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. It is therefore recommended that future research should compare this workflow and a typical envelope audit to outline potentials and limitations with the proposed procedure. The presented method also addresses challenges faced by traditional methodologies in inspecting high-rise and large-span structures via inspections performed remotely through UAS technologies, and it is capable of carrying various sensors to conduct building diagnostics on-the-fly. Therefore, the use of multi-spectral sensors should be studied.

At this stage, the current approach cannot replace traditional audit processes entirely. The equipment used is able to detect a difference in temperature, and the process is not designed to rationalize the source of temperature differential, or consider how in certain instances there will be an anomaly for reasons other than leakage, such as material change, solar gains, or various components separate from the building. However, the use of drones can drastically enhance the whole building audit process, and become a part that completes envelope inspection in a faster and possibly expansive approach. Inspection of whole neighborhoods to identify potential targets for enhancement efficiently needs multiple scarce and valuable resources such as time, expertise, equipment, and more. This qualifies the value of the framework, and complements existing audit processes. The process still needs a critical human eye to be able to employ the vast amount of information generated, and make complex design decisions. Envelope inspection can be automated using drones and computers, but human oversite is needed, and designer reactions to detected anomalies is imperative.

<u>Limitations and Challenges</u>

Several challenges need to be addressed as technology evolves, and the framework is further developed.

- Angular Deflection – IR and RGB images maybe be compromised due to angular deflection, which is a challenge with respect to camera angle when the camera captures deflection of light particularly from shiny materials such as glass and metal. Although images are currently perpendicular to the façade, future work will focus on using complementary paths that better capture artifact depths. Presently, reflection affects temperature readings, and in many instances, would not be considered as reliable.

- Inspection Distance - The distance from the drone to inspected buildings is presented as a fixed value in this work, but in real applications it could be approximated, especially when changing infrared and RGB photographing methods. The use of wide lens cameras has a varying effect on the resulting images and models. Approximated distances were achieved through numerous trials, and they are a function of the size and geometry of buildings, as well as the Field of Vision (FOV), and are therefore subject to change if given different existing conditions.
- Calibration - IR sensor calibration before flights is critical, and when flying calibration may include editing out the emissivity of the sky. Some input values can be manipulated in post-flight evaluations, but settings should be consistent, in order for outputs to be comparable across models.
- Data Gaps - Obstructions on the façade can lead to gaps in the gathered data. These gaps make energy audits for those portions of the building incomplete. This is a weakness of the procedure and will need to be explored further in the future, but different flight paths can be considered to address the best possible evaluation given the existing condition of the building. It is recommended to investigate potential data gaps through close up investigations on foot, without the use of drones.
- Manual Setup - The manual procedure definition pre, during and post flight is critical, despite the current goals of full-automation. Site conditions, solar radiation, construction materials, validation of gathered data, etc. are all varying parameters for

each audit project. Manuel input allows an individual to adjust the experimental parameters to maximize effectiveness.

- Technology Limitations - the technology-based process to be addressed beyond the teams' area of focus include: A) Battery power limitations, with land-and-charge potential, which can be addressed with more efficient flight design and less stopping time. B) Obstacle interference with UAS and possible crashing, where pre-designing flights with minimum obstacles and tailoring paths around site conditions is a possible solution. C) Required input for drone navigation in unfamiliar or obstacle-heavy spaces, therefore visiting the site prior to flights allows for preliminary flight plans to address this limitation. D) challenging to reach building systems due to the size and navigation of the UAS, and as drone technologies develop smaller drones will enable us to inspect building systems in detail (Zhang, et al. 2017) E) Signal acquisition risks as well as signal interpretation challenges, which are not as evident in less dense urban areas. F) Variance between drone GPS and satellite acquired GPS, with accuracy being more evident with on-board drone GPS signaling.

<u>3D CAD Model Development</u>

Further development for the procedure is to combine GPS positioning and 3D photogrammetry to collect accurate as-built data that would be used to create detailed CAD models and thermal performance maps. Thermal imaging would then be used for structural inspection, as well as heat flow assessment for insulation examination. Aerial roof inspection will result in rapid understanding of installed building energy systems, as well as providing data to enable highly accurate evaluations of potential for photovoltaic installation and performance. As a demonstration of this discussion, further photos were taken beyond the experiment during the drone flight at various angels, and were employed using 3D photogrammetry software Pix4D to generate a 3D point cloud from the 2D images. The program extracts pixels from 2D images, and with multiple geo-located 2D image triangulates individual pixels from photos within a 3D point cloud model (Figure 11). The generate3d model can be exported to other 3D modeling software and design environments, such as Rhino3D (Figure 12). Such possible outputs from a building inspection using drones can be used as a communication tool with building professionals, as well as a new tool for visualizing thermal performance, and as an educational visual to demonstrate envelope properties.

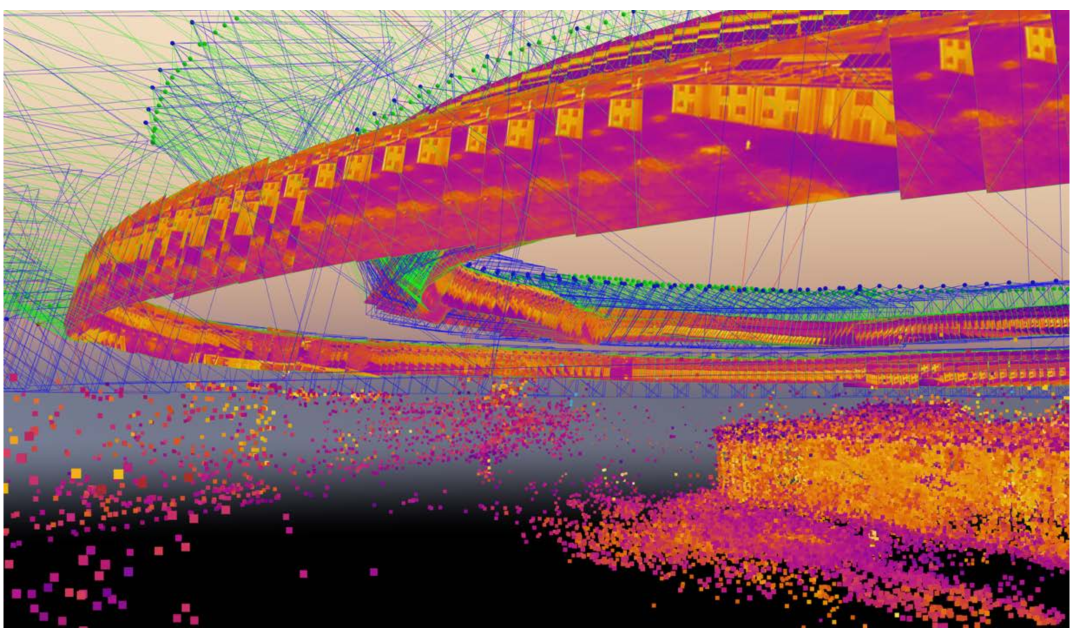


Figure 11 - Example model construction using 3D photogrammetry software Pix4D.

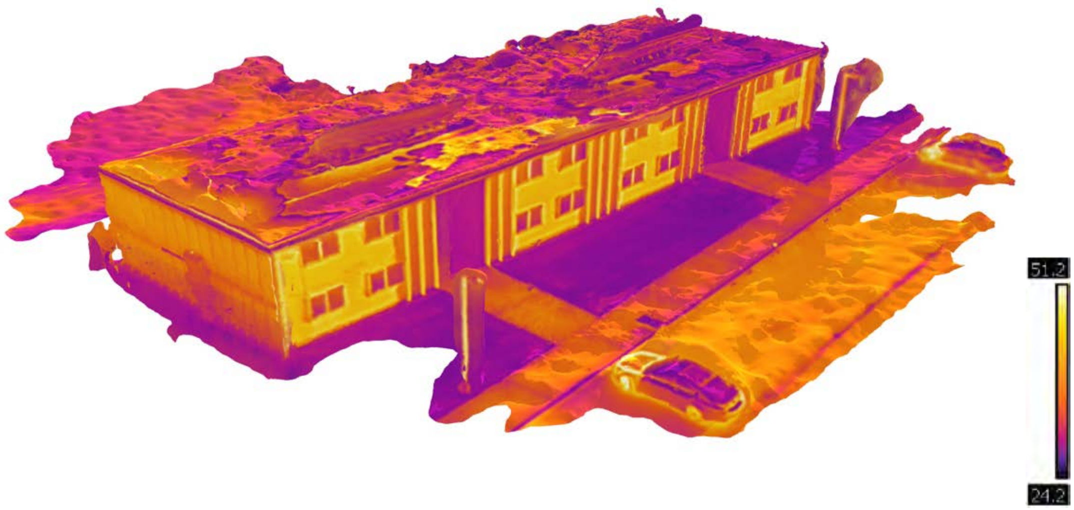


Figure 12 - Constructed 3D model using IR images in °C, demonstrated in the design environment of Rhino3D.

Envelope Inspection Automation

The developed computer vision algorithm's success rate is acceptable in terms of experimental performance. However, the algorithm should be further developed to limit false positive results. As future work, the algorithm is intended to run in real time on the UAS platform, while it is inspecting a building, to reveal thermal anomalies autonomously. Therefore, the primary contribution of this work is a novel computer-vision-based framework, which autonomously detects and segments thermal anomalies in building structures by using images obtained by a UAS equipped with a thermal imaging camera. Real time imaging can have further challenges, such as minimum control over false positives and minimum control of thresholds that produce positive results.

To the best of the authors' knowledge, this is the first autonomous heat leakage segmentation framework which can inspect thermal leaks independent of the inspected structure and the temperature distribution of the surrounding environment. Currently, the developed algorithm involves a few empirically determined numbers that are based on certain assumptions. These will be addressed in future work. It is also recommended to further validate the workflow through experimentation repeatability, where the results are tested by deploying two different paths, or using the same path multiple times, and validate the outcome through error graphing analysis.

4 Conclusion

The first UAS to fly was an explosive laden balloon sent to damage Venice in 1849 (McDaid, 2013). Since then, UAS have evolved in tandem as both cutting-edge military technology and commonplace consumer equipment (Corsi, 2010). This shift towards public use presents opportunity for cost efficient, expedient, and safer operational procedures that can be applied to a vast variety of disciplines (Ibid., 2010). 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 (U.S. DOE, 2015). In this paper, an inspection framework that employs a developed computer vision algorithm to autonomously detect thermal anomalies was presented. The procedure was detailed, potentials were investigated and limitations were stated. The aim of this work is to provide institutions, developers and owners with the means to examine buildings accurately and rapidly. 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. Future work should compare the workflow with traditional envelope inspection methods, develop the workflow to produce 3D CAD and thermal mapping digital models, as well as test the computer vision framework for on-the-fly capabilities.

5 Acknowledgements

This publication is based on work funded in part by Gryphon Sensors, Syracuse University's Office of Research (Grant #SP-29403-2), the Campus as a Lab for Sustainability program at Syracuse University, the National Science Foundation (NSF) under CAREER grant CNS-1206291, NSF Grant CNS-1302559 and NSF Grant 173978. The authors would like to thank Mr. Ian Joyce, the Center for Advanced Systems Engineering (CASE) and the Syracuse Center of Excellence at Syracuse University for drone flight, data gathering and faculty development support.

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