3D Drone-based Time-lapse Thermography: A Case Study of Roof Vulnerability Characterization using Photogrammetry and Performance Simulation Implications

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Abstract
Thermal building performance simulation is regularly informed by and contrasted with thermal images, mainly focusing on defect identification using perspectives from the infrared (IR) spectrum. However, standard IR readings are typically undergone in singular points in time, when in several cases, such as varying pressure differences or latent heat gain, anomalies can only be revealed at specific times of the day, possibly in different seasons of the year. We present in this paper a novel workflow for 3D envelope modeling using aerial time-lapse IR data collection by utilizing Unmanned Aerial Systems (UAS, a.k.a. drones). A comprehensive envelope thermal profile is developed for the roof of a case study building employing photogrammetry software Agisoft Photoscan, which generates temporal IR inspections of building skins using multiple 3D thermography CAD models. The ultimate goal is to develop a building inspection framework that utilizes UAS equipped with IR cameras to collect data time series, which in turn informs envelope modeling for accurate performance simulation.

Key Innovations
- Collecting 3D envelope data for enhanced building performance modelling and simulation.
- Developing a novel time lapse thermography inspection methodology that employs drones to inspect building envelopes at different times to characterize an envelope’s performance without being constricted spatially.
- Employing drone-collected and geolocated RGB and IR images to build 3D envelope CAD models using photogrammetry and introducing the concept of 4D thermography to identify envelope defects.

Practical Implications
The proposed method uses drone-based 3D temporal thermography investigations to demonstrate: 1) opaque roof diurnal resistivity variability investigations to characterize envelope vulnerability over time; 2) moisture content evaluation in roofs using solar loading to identify potential problematic envelope susceptibilities and; 3) anomaly detection (thermal bridges) beyond point-in-time instances for closer inspections at various heights using UAS to quantify probable energy losses. These issues are presently underrepresented in building simulation tools, if captured at all. To change this, we need to expand our knowledge about the occurrence, magnitude and frequency of these changes. The results also indicate that drone-based time-lapse thermography is capable as a technique to generate a comprehensive building envelope thermal profile for facilities management and retrofitting design purposes.

Introduction and Literature Review
It is generally accepted that there often is a significant discrepancy between the thermal building performance as predicted from the use of simulation tools, and the actual performance as reported from measurement and monitoring campaigns. This discrepancy is generally known as the “energy performance gap.” There is an increasing body of literature that addresses this performance gap (Turner and Frankel, 2008; Carbon Trust, 2011; Menezes et al; 2012; de Wilde, 2014; Jain, 2020). Amongst the causes for this energy performance gap are defects in the building envelope, caused by design errors, workmanship issues, facility management challenges, and wear and tear of building systems. Thermal imaging is a technology that has been employed in diagnostic applications in various scientific fields such as medicine (Ring and Ammer 2012), agriculture (Vadivambal, and Jayas 2011) and building science (Kylili et al. 2014). IR imaging relies on detecting black body radiation, which enables a diagnostic viewpoint on materials through analyses developed in thermodynamics. In built environment investigations, thermal imaging has been used for differing functions such as detection of thermal bridges, moisture characterization, and envelope defect diagnostics (Grinzato et al 1998). The terminology “thermodynamics” reveals how thermal processes are dynamic in nature; it is the observation of performance over time that can enable a more accurate building envelope thermal performance characterization. However, IR readings are typically single point-in-time and are constrained by human movements with a handheld camera. This almost steady-state observation is not sufficient for in-depth envelope performance inferences. Clearly, thermography may make significant contributions in assessing the state of the building envelope, and towards identifying the role that building defects may play in any existing energy performance gaps. This paper, therefore, investigates airborne time-lapse thermography using drones as a method of translating 3D envelope CAD models generated via RGB and IR photogrammetry into whole Building Energy
Modeling (BEM) software. The goal is to develop a novel 4D approach that incorporates defects detected at varying situations and instances of time into comprehensive thermal profiles for envelopes.

**Time-based Thermography**

Time-based thermal applications find their origin with the use of the “Pulse Thermography” technique, also referred to as “Active Thermography.” It is in contrast with “Passive Thermography,” which requires no artificial intervention to the surface prior to conducting the readings (Usamentiaga et al. 2014). Pulse thermography requires artificial radiation to be emitted towards a surface, and then recording the results using a thermal imager. At the material-scale, an early investigation developed a method that utilizes an oscilloscope camera to instantly capture a still image of a surface when the pulse is emitted. Three thermal properties were identified accordingly: thermal diffusivity, heat capacity, and thermal conductivity (Parker et al. 1961). “Transient Thermography” was later invented and described in a patent (Reynolds et al. 1983). Dynamic analyses were further developed to assess surfaces and composite materials using a video recorder with playback capability and a TV monitor to record, pause, and observe thermal events that have occurred (Milne and Reynolds 1985). This was further applied in work that defined how sequential thermal images can be used to identify defects through differences in thermal diffusivity across the sequence (Hobbs 1992). At the urban-scale, an airborne multispectral camera was used to capture images of an urban environment in a downward time series. The research focused on measuring the sensible heat flux across building façades, with the limitation of considering building façade as a uniform surface with a constant assumed an emissivity of “1” for all materials and surface (Iino and Hoyano 1996). Similar work attempted to estimate surface temperature in urban environments comparatively with data obtained by infrared thermometry taken from the ground and the air. However, building elements other than the vertical and horizontal facets were not considered (Voogt and Oke 1997).

The building-scale came into focus with the investigation of pulse-based thermography applications to identify various defects such as plaster/brick delamination, moisture damage, insulation deficiencies, and thermal bridges. The research indicated that because the patterns on surfaces recorded by the IR camera are subject to different climatic conditions, such patterns should be regarded as a function of spatial coordinates and time (Grinzato et al. 1998). Further work inspected a building façade at different times of the year to encapsulate sensible heat flux. The setup utilized a fixed IR camera that took different snapshots of a targeted building façade at different times of the day over different seasons. The objective of the research was to address the non-uniformity of the sensible heat flux across the façades in different conditions, which was achieved by creating “Multi-Temporal Thermographs,” which were described through the term “Time-sequential Thermography” (Hoyano et al. 1999).

With handheld IR cameras becoming more commercially available, the detection of building envelope defects through time-based applications reemerged. Multiple publications employing radiometric thermography to analyze pixel-level differences over time to identify micrometer level defects. Temporal resolution investigations were inspired by the field of nature photography, to describe photographing or filming a subject over extended periods to document their change or growth (Edis et al. 2015), (Fox et al. 2015). The term “Time Lapse thermography” can be concurrently seen to evolve with the development of thermal cameras that became cheaper, more readily available, and are able to record videos. The term has now seen wider use (Barra-Castanedo et al. 2017), (Simmons et al. 2018), (Al Gharawi et al. 2019) with variations such as “Time-series Thermography” (Cheng and Shen 2018). Through this review, we identify that while Active Thermography can be a useful method for research in controlled lab experiments, Passive Time Lapse Thermography is a viable candidate for in situ nondestructive evaluation of building envelopes. However, it was not employed to explore whole facades beyond handheld devices.

**Transient Envelope Performance Simulation**

As reviewed, there is a variable nature of envelope performance that is contingent upon time and climatic conditions. Since analysis in real time may not be feasible, BEM tools are typically employed to study this fluctuating nature in thermal conditions within an existing envelope. Different Building Performance Simulation (BPS) tools, however, approach this transience differently. EnergyPlus factors in time by conducting timesteps that can consider unsteady state heat transfer through the envelope (Crawley et al. 2001). Its main limitation is that it is strictly one dimensional. It considers the envelope surface as uniform geometry and does not localize areas where thermal anomalies can manifest. THERM can better localize thermal bridges through a two-dimensional finite-element heat transfer model in different building components (THERM 2019). THERM’s limitation is that its workflows do not encompass changes in thermal conductivity and moisture-based effects on envelope performance. WUFI, on the other hand, does account for both thermal and moisture-based effects in its calculations. It iterates on previously utilized Glaser Method that accounts for vapor diffusion in components by allowing the use of unsteady state transport in their calculations (Karagiozis et al. 2001). Though, like EnergyPlus, it does not localize issues to a particular area in the geometry. Other tools such as TRNSYS offer a component-based modeling approach that has the ability to determine the thermophysical properties of the simulated element over time, offering a transient thermal simulation of heat transfer through the building envelope (Beckman et al. 1999). But it also considers the envelope surface as uniform. It is worth noting that most whole building simulation tools, such as EnergyPlus and TRNSYS, use the one-dimensional modelling approach. Tools that capture 3D effects such as THERM and WUFI typically
limit themselves to details of the building only, such as corners and façade sections. Engineering tools such as COMSOL study heat and moisture variations over time, as well as moisture storage, latent heat effects, diffusion, and convective transport of moisture (Pryor 2009), but are not integrated within a larger whole BEM framework.

Thus, current BPS software limitations include being predominantly 1D or 2D simulations only. This entails excluding factors that can alter the envelope over time during time-based simulations, having present timesteps that cannot be altered with ease, as well as relying on initial assumed conditions for the entirety of the simulation without factoring in building envelope defects that manifest due to physical deterioration of envelope components over time. This limits the accuracy of material simulations over time. A 3D generated thermography model that can localize spatiotemporal envelope defects can transform modeling into 4D thermal simulations that factor localization and transience to inform both facilities management and retrofitting design.

Research Methods

This paper proposes the development of novel 3D thermography models constructed from time lapse IR image data collected using UAS to inform BPS envelope modeling inputs. A case study is presented for a courtyard building on the Georgia Institute of Technology campus (Figure 1), where the research team employed a DJI Matrice 200 UAS equipped with a Zenmuse X2 camera (640x512 resolution) to fly in two path types, perimeter polygon and in a strip, as showcased in Figure 2. The flights were conducted on Friday December 22nd 2020 and repeated in 2-hour intervals starting at 9 AM until 5 PM (5 flights). In this work, we are focusing on the roof as a building element that is typically assumed to perform uniformly and is neglected in as-built inspections due to the impossibility of perceiving the entire component without being significantly higher than it. The outcome of the strip flight generated stitched 3D photogrammetry of the roof at each flight timestep, and the outcome of the polygon path generated a full 3D model of the courtyard building. Both flight types were automated on the Litchi app, in a tablet device connected to the drone’s remote controller. They were conducted at 30-meter height from the ground and captured images every 0.5 meters on the planned path.

3D Photogrammetry

Photogrammetry is the science and technology of extracting information from 2D images and mapping them onto a 3D space (Dai and Lu 2010). With drone-captured images and their camera calibration parameters, 3D digital models or 2D orthophoto mosaics can be acquired through the processing of image sets, using triangulation and photogrammetric techniques. Diverse photogrammetry tools have been developed to effectively process UAS data to reconstruct 3D digital models or 2D orthophoto mosaics for building objects, including: 1) open software such as PMVS, MicMac, Meshroom, VisualSfM, SFMToolsKit, bundle adjustment, and python photogrammetry toolbox; 2) commercial software like Agisoft PhotoScan, Acute3D, Photosynth, Arc3D, Autodesk 123D Catch, Pix4D, and PhotoModeler; and 3) CV algorithms like Scale Invariant Feature Transform (SIFT) and Structure from Motion (SIM) (Nex and Remondino 2014); (Bemis et al 2014); (Eltner et al 2016); (Yahyanejad and Rinner 2015). For this paper we chose Agisoft Metashape (also known as Photoscan) as the processing software, since it has been shown to have better performance for building model reconstruction (Aicardi et al 2016).

Figure 1: Case study courtyard building (Architecture East) as captured from drone photography during roof inspection.

Figure 2: Strip (above) and Polygon (below) flight paths for photogrammetry data collection.

The drone-captured image sets for the building’s roof from strip paths and the building envelope from polygon paths were respectively processed using the Metas...
variable heat flow performance. A nomalies can be observed during certain conditions while not manifesting radiation at those spots. Heat signatures on the eastern side of the protrusion indicate a thermal bridge that is only observed when the roof has cooled down sufficiently. This observation when paired with the reassessment of timestep 1’s heat signature on the eastern side indicates a mixture of both longwave radiation from the eastern side of the protrusion and a thermal bridge. Much of the moisture damage has now disappeared and is barely visible under such conditions due to decreasing absorption of solar radiation at those spots.

Table 1: Photogrammetry computational results.

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<th>Timestep</th>
<th>Images Number</th>
<th>Point Number (Density)</th>
<th>Orthomosaic Resolution</th>
<th>Orthomosaic Pixel Unit Size</th>
<th>Processing time</th>
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<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
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<td>93</td>
<td>203</td>
<td>257</td>
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<td>2,650,538</td>
<td>2,700,298</td>
<td>3,021,024</td>
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<tr>
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<td>1586*1121</td>
<td>1504*855</td>
<td>1468*886</td>
<td>1426*846</td>
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<tr>
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<td>1.99 cm/pix</td>
<td>6.25 mm/pix</td>
<td>6.14 mm/pix</td>
<td>5.09 mm/pix</td>
</tr>
<tr>
<td>Timestep 5</td>
<td>5.09 mm/pix</td>
<td>6.25 mm/pix</td>
<td>6.14 mm/pix</td>
<td>5.09 mm/pix</td>
<td>11'41''</td>
</tr>
</tbody>
</table>

Results

The outcomes of the photogrammetry process are presented first from a computational processing perspective, followed by showcasing the output of time lapse thermography for the roof.

3D Photogrammetry Process

Table 1 summarizes the results of processing the time lapse roof scanning and building images, including the total number of images, the density of reconstructed point cloud, the resolution for the ortho-mosaic images, and the processing time using an Intel® Core™ i9-9900 CPU @ 3.10GHz processor. The reconstructed 3D point cloud density for the roof at different time lapses ranged from 2,650,538 to 3,004,163 points – the more image input, the higher the point density. The reconstructed 3D roofs were then projected to the ground as 2D ortho-mosaic images, with a resolution at approximately 1500x900. Within the ortho-mosaicked roof images, each pixel unit represented real-world sizes from 5.09 mm to 1.99 cm, which was of high density to reflect the as-built situation. The total processing time for roof image sets took between 5 minutes to 13 minutes, which is related to the number input images.

4D Thermography Outputs

Figure 3 demonstrates the 3D time lapse thermography presented through a series of 2D projections. For comparable observations, the 3D model is showcased as a roof layout to avoid distortions in perspective. The roof’s UAS IR imaging on a winter day indicates variable heat flow performance. Anomalies can be observed during certain conditions while not manifesting in others. Each time step is demonstrated separately:

- **Timestep 1 between 09-10 AM**: a more uniform thermal performance across the roof, with the exception of the envelope protrusion in the middle (Area 4) and the vents on the western side. A prominent water damage spot (Area 1) on the western side represents discoloration of the white roof membrane and was absorbing more heat radiation than its surrounding. The protrusion in the middle of the building is radiating heat mainly towards the eastern side, indicating that solar loading is occurring in the morning with sun rise from the east, and is quickly emitting longwave radiation back towards the colder roof surface whose white membrane would reject heat more efficiently than the bricks on the eastern side.

- **Timestep 2 between 11-12 PM**: noticeable water and moisture damage are now clearer across the roof (Example Areas 3), and the roof structure experiences clear thermal bridging (Example Areas 2), which were not appearing at timestep 1. At this time of the day, a higher temperature differential between uninsulated and insulated surfaces is experienced, in comparison to the previous timestep. Radiation from the southern side of the protrusion (Area 4) is now more evident and extends longer, as the sun’s location is more towards the solar loading.

- **Timestep 3 between 01-02 PM**: roof moisture damage is more evident as time progresses (Area 1), as the roof is receiving radiation at solar noon, the most direct angle at 12:49 PM. As the sun has moved to a more central position the radiation on the eastern side of the protrusion has significantly subsided, while it remains prominent on the southern side. With a higher sun angle, and more radiation absorbed by the roof, the structural system thermal bridging effect becomes more prominent in uninsulated structural members, as the differences grows (Areas 2).

- **Timestep 4 between 03-04 PM**: prominent thermal bridging is evident through the structure (Areas 2), and moisture damage signatures are now subsiding on the eastern side (Areas 3).

- **Timestep 5 between 05-06 PM**: thermal bridging effects are now less prominent across the structure. Heat signatures on the eastern side of the protrusion indicate a thermal bridge that is only observed when the roof has cooled down sufficiently. This observation when paired with the reassessment of timestep 1’s heat signature on the eastern side indicates a mixture of both longwave radiation from the eastern side of the protrusion and a thermal bridge. Much of the moisture damage has now disappeared and is barely visible under such conditions due to decreasing absorption of solar radiation at those spots.
Discussion

We discuss the outcome of this work through several avenues that start with modeling implications in the field of BPS, followed by nuanced discussions of the workflow’s mechanisms, limitations and possible directions for future work.

BPS Evolution: Envelope Modeling Impacts

The novelty of the digital modeling technique we are presenting through 4D thermal photogrammetry in this case study would unfortunately find little translation in current BPS tools to inform retrofitting design or building facilities management. As mentioned earlier in the introduction, the current state-of-the-art in BPS is either 1D or 2D with no localization effects or representation of defects that have temporal properties. The assumption is typically node-based heat flow calculations that lumps an entire surface’s performance. And even though drone-based audits have been recently used to calibrate BEM (Bayomi et al 2020), if the roof of this case study was to be modeled in whole BEM, it would be assumed as a single plane, with no localized thermal bridging, insulation deterioration or moisture damage. An expert’s effort would have incorporated multipliers or fudge factors in simulation templates that represent defects but would not fully capture the distinctions presented through time lapse thermography, such as spatiotemporal influences that may through transience dissipate or exacerbate.

The findings of this work, therefore, confirm the previously explained ‘Energy Performance gap.’ There is now a need to evolve our BPS tools through the employment of cyber-physical systems that captures our deteriorating realities (Rakha and Gorodetsky 2018). An envelope for a thermal zone that interfaces with the external environment should not be reduced to a singular representation of an ideal situation and should instead allow for spatiotemporal discretization. How the BPS community should model thermal bridging, infiltration / exfiltration, physical damage etc. is research that would be pursued in the next step in evolving this work. This should include a comprehensive investigation of all Non-Destructive Testing (NDT) techniques that can inform envelope energy modeling (El Masri and Rakha 2020), including employment of data geo-registration in models (Chen et al 2021); (Hou et al 2021), and full integration of 3D photogrammetry. Figure 4 shows an instance that demonstrates the previous results for the roof, but would also capture the vertical facades, and can comprehensively represent an audit for an entire building’s envelope.

Timesteps and Flight Automation

The two-hour timesteps designed for this experiment were specific to battery charging requirements of the employed drone, a limitation that continues to effect drone-based building audit missions (Rakha et al 2018). Further envelope performance discrepancies may be observed at smaller timesteps, like 30-minute increments, which was presented earlier in the literature (Fox et al 2015). As drone and battery technologies continue to advance, an
autonomous building inspection procedure using time lapse thermography with land-and-charge capabilities can make envelope audits more regular, more accurate, cheaper and safer, with little-to-no human interaction in data collection.

Identifiable Patterns Irrelevant to IR Time Lapse

The use of UAS in building performance inspection allows for typical thermography findings to be pursued, irrelevant of the proposed time lapse approach. For example, structural and insulation issues may be swiftly identified without the need to repeat the process over time. Other patterns may include challenging issues, such as interference from the context or neighbouring buildings, as well shadows from landscaping or other built environment elements. A trained thermographer should be able to recognize such patterns immediately. The challenge to discuss is how does the identification of such patterns effect BPS. Beyond the complexities of modeling building envelopes comprehensively, the inclusion of contextual influences is critical. Further research should address how recognized patterns, such as shadows, can affect whole BEM envelope models generated from this proposed framework.

Conclusion

We presented in this paper a novel workflow for 3D envelope modeling using aerial time-lapse IR data collection using UAS. A comprehensive roof thermal profile was developed for a case study building employing photogrammetry software Agisoft Photoscan, which generated temporal IR inspections of a building’s roof using multiple 3D thermography CAD models. The goal was to develop a building inspection framework that utilizes drones equipped with IR cameras to collect data time series, which in turn informs envelope performance modeling to accurately depict thermal resistance as well as anomalies for more accurate BPS. The paper concludes that on-site building envelope inspections are significantly enhanced by a time-based passive thermography audit approach that has spatial liberty due to the use of UAS and discussed the potential for integrating this technology effectively in BEM to inform both facilities management and retrofitting design. Future work should explore full envelope 4D CAD modeling and the use of other NDT techniques in concert with thermography. Advances in this field are expected to leap the process of building envelope energy audits forward to become ubiquitous and informative to decision makers aiming to retrofit and manage our existing built environments to become significantly more highly performing.

Acknowledgement

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References


Figure 4: 3D thermography CAD model, produced in Agisoft Photoscan from the polygon path. Data was collected on Jan 29th, 2021 at 2 PM and the model was processed from 300 images in 17 minutes.


