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Aerial Thermography as a Tool to Inform Building Envelope Simulation Models

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ABSTRACT

The building sector consumes more than 33% of global energy use and around 50% of electricity consumption, and is responsible for one third of global carbon emissions [1]. Envelope and windows alone impact over 50% of energy loads in buildings [2]. Thus, understanding building envelopes' thermal performance is critical to the application of energy efficiency retrofits. Through detecting main envelope thermal deficiencies and areas of deterioration, suitable energy management measures can be effectively determined. While simulation models are considered as reliable tools to understand building energy performance, they rely significantly on assumptions related to envelope performance [3,4]. The main contribution of this paper stems from the proposed analysis framework, which integrates Unmanned Aerial Vehicles (UAVs) equipped with thermal cameras in estimating thermal transmittance properties of existing building envelope, specifically opaque walls, and using these data to calibrate energy simulation models for better predictions. Results revealed a significant increase in the accuracy of heating energy use prediction during winter months. With the proposed workflow, simulation errors were reduced from over 20% to less than 1%.

Author Keywords

Aerial Thermal Mapping; Energy Simulation; Drones; Thermal Transmittance; Energy Efficiency.

ACM Classification Keywords

Building Energy Simulation; Experimentation; Performance.

1 INTRODUCTION

Building envelopes play a major role in energy consumption, as they account for 25% of total energy use [5]. Yet, envelope improvements can impact around 57% of commercial buildings' energy use and 42% of residential energy use [1]. Thermal transmittance of buildings' envelopes (also known as U-value) is considered one of the key properties that directly affect a buildings' energy use [6,7]. On the other hand, an envelope's thermal transmittance is not consistent, as its thermal properties change significantly over time with respect to surrounding environmental conditions, building maintenance and level of deterioration in materials' conditions. It was previously estimated that designed U-values are reduced over time by around 50% or more post occupancy [8]. As a result, this can potentially affect modeling and predicting of energy use for post occupancy conditions.

Infrared thermography (IR) has recently gained significant interest as a reliable tool to analyze building envelopes' existing thermal properties qualitatively. This in addition to the ability of identifying insulation damages. Envelope thermal inspection using hand held IR camera is one common way to identify potential heat losses and areas of deterioration [9,10]. However, this process can be time-intensive in situations where the building skin has a relatively large surface area. This paper examines and validates the applicability of utilizing UAVs equipped with IR camera to estimate building envelope's thermal transmittance. The main objective of this work is to demonstrate how this method can be used to simulate and predict heating energy use more accurately. To verify the applicability of this approach, the paper analyzes two different scenarios: energy use prediction depending solely on designed U-values, and after estimating U-values from the envelope's thermal mapping. The two scenarios are compared against metered energy use to estimate how this method can be deployed to inform building energy simulation models.

2 METHODS

There has been a growing interest in the use of drones in surveillance, and most recently building inspection [11]. their efficiency lies in the ability to collect high-resolution data that is time efficient with minimum human labor [12]. Using aerial thermography provides a comprehensive overview of envelope heat flow as temperature data are collected over the same timeframe, which as a result has a bigger advantage over the point-based data method. The proposed framework of estimating u-values using aerial

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thermography is developed through four main steps, as illustrated in figure 1 below. In the proposed framework, we first utilized UAVs equipped with IR camera in the data collection process. Collecting such data will aid in revealing issues such as insulation deficiency, heat losses as well as overall performance of existing conditions. In the following step we applied thermal imaging analysis to investigate envelope's thermal performance through surface temperature examination. Using temperature differences between indoor and outdoor, we numerically estimate the envelope thermal transmittance [9]. Finally, we integrated calculated U-Value into an energy simulation model to estimate heating energy use for the winter months.

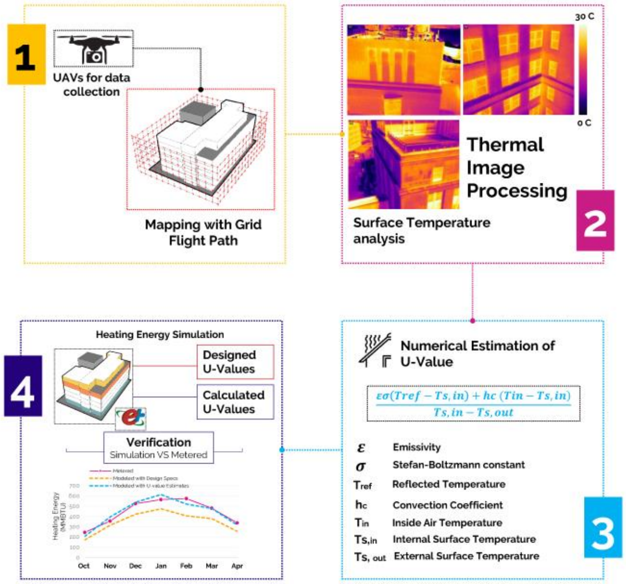

Figure 1. Analysis framework and methods used.

3 EXPERIMENTAL STUDY

An academic building on the MIT campus in Cambridge, MA, is tested for the proposed analysis framework. The selected building's envelope was recently renovated to incorporate materials with lower thermal transmittance to improve energy efficiency (Figure 2). In this study, we used An Inspire 1 drone by DJI, equipped with a FLIR Zenmuse XT thermal for data collection.

Figure 2. Envelope condition prior to retrofitting

The accuracy of data collected from the thermal flight is strongly dependent on two main factors: flight procedures (flying method) and outdoor climate conditions. According to Snell & Spring [13], for more accurate measurements, there should be a minimum temperature differences of 10 °C between the indoors and outdoors. Thus, we conducted the flight during the early morning of March 31st, 2018 with an outdoor temperature average of 8 °C. There are numerous flight methods while using UAVs in thermography analysis. From reviewed literature [11], we used the strip method for data collection. This method is based on flying the UAV in vertical and horizontal strips perpendicularly facing each façade as illustrated in Figure 3 below. We calculated the flying distance from the façade based on the camera's angel to ensure 90% overlap for each image captured.

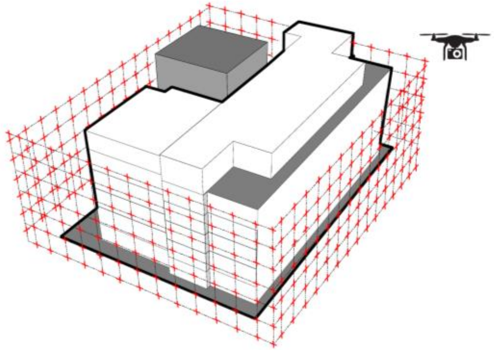

Figure 3. Flying method used for data collection (grid pattern with 90% overlap).

Next, over 500 images were captured and analyzed for each façade using FLIR analysis tool, as shown in Figure 4. From this analysis we identified surface temperature variation in each façade to identify areas of thermal deficiencies and heat losses. The subsequence stage of the analysis is based on measuring heat flow as well as indoor and outdoor air temperature differences. In heat flow calculation, we included thermal conduction, convection and radiation driven by temperature differences between the indoors and outdoors. The average indoor temperature used in the calculation represented typical set points for different spaces (classrooms, conference rooms and offices). Surface temperature indoors was measured using a hand-held thermal camera for each façade instantaneously with the outdoor measurements captured by the UAV's IR camera.

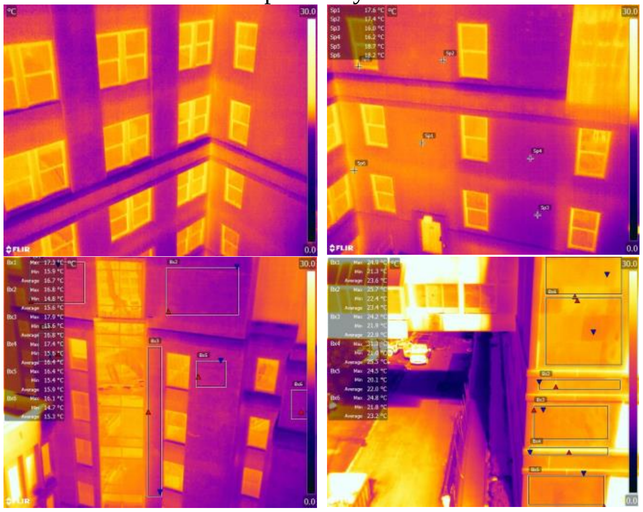

Figure 4. Sample of thermal imaging analysis

In order to calculate U-values, we used the convection coefficient (hc) derived from Tanner et al. [14] standardized value of = 8.7 W/m^{2}K. The overall heat transfer coefficient is calculated using equation (1) as follows:

$$\frac{\varepsilon\sigma(T_{ref} - T_{s,in}) + h_c\,(T_{in} - T_{s,in})}{T_{s,in} - T_{s,out}} \qquad (1)$$

Where:

ε is the emissivity on the spectrum ranging between 0.1 and 1.0, σ is Stefan-Boltzmann constant that equals to 5.67e-8 W·m^{-2}·K^{-4}, h_c is the convection coefficient, T_{ref} is the reflected temperature, $T_{s,in}$ is internal surface temperature, Tin is the indoor ambient air temperature and $T_{s,out}$ represents external surface temperature.

Although wind speed has an effect on convection coefficient estimations, we estimated thermal transmittance numerically depending solely on temperature variation between the indoors and outdoors.

Thermal transmittance of each façade is calculated separately by averaging 500 temperature readings in each façade to calculate the overall U-value of the façade. We calculated areas that are classified as thermal bridges with respect to their average area to the total façade's area using equation (2):

$$U_{avg} = U_1 * \frac{A_1}{A_1 + A_2} + U_2 * \frac{A_2}{A_1 + A_2} \qquad (2)$$

Where:

U_1: U-value calculated for thermal bridge area
U_2: U-value calculated for total façade area
A_1: Area of the thermal bridge
A_2: Non-thermal bridge area.

To examine the applicability of thermography analysis, we developed an energy simulation model in EnergyPlus and incorporated calculated U-values to model heating energy use for two cases. First, an energy model that involves envelope parameters based on retrofitting specifications. A second case that uses U-values calculated from the thermal mapping. Then we compared the two cases against metered energy use data to examine the reliability of the proposed analysis framework.

4 SIMULATION VERIFICATION

A previously developed detailed whole building energy model for the studied building was utilized for this analysis. The model, graphically represented in Figure 5, was generated at the time of building renovation. All envelope thermal performance parameters, internal load densities, operating schedules, lighting power and mechanical system inputs in the energy model were based on the design drawings and specifications.

Figure 5. Graphic rendering of the previously developed energy model (left) and building photograph post renovation (right)

Using the methodology discussed above, the U-Values of exterior walls of the building were numerically estimated based on the data collected by a thermal flight. Table 1 compares these properties with the as-designed values based on design specifications that were previously assumed as inputs in the energy model.

Exterior Wall U-Value (Btu/hr-ft^2-°F)			
Orientation	Designed Opaque	Calculated Opaque	Designed Fenestration
SE, SW	0.053	0.282	0.361
W		0.203	
N, NE		0.142	
E		0.192	

Table 1. As-designed and estimated wall U-Values

Figure 6 compares the simulated winter heating energy use from the previous model with the updated model results after incorporating calculated estimates. These results are juxtaposed against the actual metered heating energy post-renovation and show that the model error reduced from over 20% with previous assumptions (yellow and black lines) to less than 1% with current estimates (green and black lines).

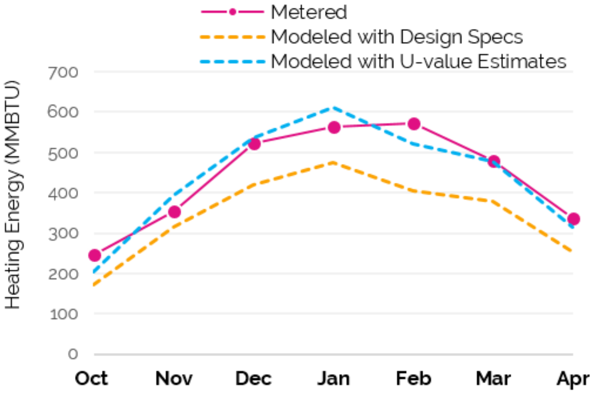

Figure 6. Comparison of metered and modeled heating energy use

5 DISUCSSION AND CONCLUSION

This paper aspires to initiate a framework by which building retrofitting design is informed through a substantial alteration in the methods and modes of performance evaluation. The innovation aims to be on multiple fronts: the use of UAVs makes evaluators experience substantially more limited physical barriers. This is especially evident when accessing multiple buildings and not relying on singleframe images for inspection; developing 3D models that designers are able to interact and engage with in terms of developing solutions for building vulnerabilities, and finally targeting compromised areas and designing retrofits to address directed, and efficient building skin issues. The presented workflow has demonstrated significantly reduced errors, and further work should demonstrate its applicability (and limitations) in other climates and more sophisticated built environment situations.

Typical energy audits face multiple challenges that the proposed workflow can address, including i) inaccessibility to areas such as roofs, ii) significant time-consuming inspection activities, with possibility of human error, and iii) unsafe and life-threatening settings for detailed inspection. These difficulties in the auditing process create challenges for supporting whole Building Energy Modeling (BEM) practices, and do not inform retrofitting design decisions accurately when accounting for construction defects or degradation. In addition, current retrofit BEM tools face multiple barriers, including time consumption and labor intensity due to manual modeling and calibration processes. Therefore, there is a need to provide institutions, developers and owners with the means to examine buildings safely, accurately and rapidly to build reliable simulation models that inform precise and directed retrofitting design to achieve target savings from existing building envelope improvements.

Future work should further validate the use of UAVs to examine buildings to build reliable models that inform directed retrofitting design. This validation process should include advanced statistical methods to verify the reliability of the models, including measuring errors accurately (using Root Mean Square Error (RMSE) or other robust methods). The process should also expand to measure heat transfer anomalies in other building components other than walls, such as windows and roofs. Finally, the presented process should be incorporated in BEM frameworks to build simulation models that better represent the existing built environment, rather than estimate performance. The process should prove most-useful in the context of multiple buildings. The workflow can then be used as tool to identify the most effective retrofitting solutions at the neighborhood scale, in a fraction of the time that would have been used to assess multiple buildings using traditional means of building performance inspection.

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