Towards Automated Thermal Profiling of Buildings at Scale Using Unmanned Aerial Vehicles and 3D-Reconstruction

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Abstract
With increases in energy demand and problems due to climate change, governments are increasingly focused on building efficiency retrofits and renovations. To help inform these improvements, energy audits are often performed with thermal cameras that can detect poor insulation and air leakage; however, the data collection process is labor intensive and does not offer a comprehensive view of the buildings. We introduce our vision for a new, more scalable approach: automated 3D thermal profiling of buildings using unmanned aerial vehicles (UAV) and 3D-reconstruction. To demonstrate feasibility, we used 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.

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Introduction
The building sector accounts for 41% of primary energy consumption in the US, far more than any other sector, and contributes an increasing portion of total carbon dioxide emissions—40% in 2009 compared to 33% in 1980 [9]. One reason for these high emissions is building age. Residential buildings, for example, constitute 95% of all buildings in the US and are on average over 50 years old [11]. Most were constructed with energy inefficient designs and their materials suffer from degradation effects due to weather and wear, further impacting efficiency. To address these issues, renovations and retrofits of existing building stock has become a national priority. The US Department of Energy has set a goal of reducing housing energy use by up to 70% [6].

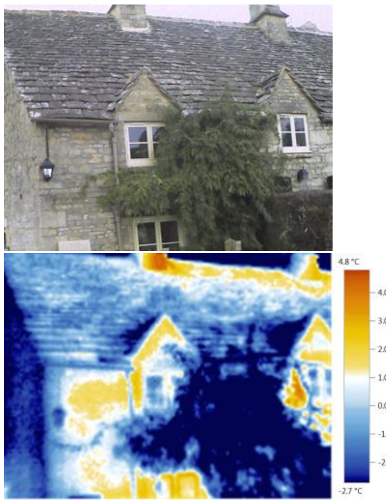

Figure 1: Energy auditors use thermal imagery cameras to find poor insulation and air leakage. The thermal image above taken in the winter shows heat leaking out of the rooftop and windows (from an energy assessment report [8]).

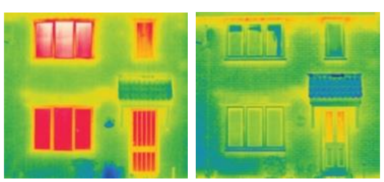

Figure 2: A building façade before a renovation (left) and after (right). The thermal imagery highlights significant improvements in heat loss through the installation of energy-efficient windows and doors (from [7]).

The key to these renovations is to identify *where* the inefficiencies and degradations exist so that improvements can be performed appropriately. One approach is to deploy sensors to monitor building health and operation (*e.g.,* [2, 5]). However, because these systems cannot detect structural or exterior problems such as heat loss from poor insulation, energy auditors often employ thermal cameras (*i.e.,* infrared thermography [1, 3]). Thermography can be used to detect: cracks, insulation problems, insufficient door/window seals, moisture build-up, and other issues with thermal signatures (Figure 1 and 2). Recently, new techniques have emerged that provide more comprehensive 3D views of the thermographic data by combining thermal imagery with LiDAR [11] or RGB imagery via *Structure-from-Motion* (SfM) [4]. For both 2D and 3D thermography, the problem is that collecting and analyzing this data is labor-intensive and highly dependent on the skills/expertise of the auditor.

In this paper, we introduce our vision for a new, more scalable approach: automated 3D thermal profiling of buildings using unmanned aerial vehicles (UAV) and 3D-reconstruction. Our overarching vision is to fundamentally transform the cost, scale, and data granularity with which thermography can be performed on buildings. While our work is still in the early stages, we envision a four-part system: **(i) for data collection:** a programmable aerial vehicle with GPS and inertial sensors along with LiDAR, an RGB camera, and a thermal camera on a controllable gimbal; **(ii) for control:** a custom user interface that allows an analyst to manage/control the vehicle, which would function autonomously once directed at a building or a set of buildings; **(iii) for processing:** a computer vision-based subsystem that performs the 3D-reconstruction and thermal overlay; **(iv) for analysis:** a fully interactive analysis and visualization system for understanding the collected data and advancing the analyst's understanding of a building's thermal profile.

In this poster paper, we focus primarily on aspects of data collection (i). To demonstrate the feasibility of our vision, we used an unmodified Parrot AR.Drone 2.0 and a FLIR thermal camera to collect RGB and thermal images of a University of Maryland building. We then use SfM of the RGB images to generate a 3D reconstruction and the thermal data as an overlay onto the 3D building (Figure 6). In the future, we plan on using a hexcopter, such as the DJI Flame Wheel, that has a controllable gimbal and can be configured with various sensor payloads.

Compared to the state-of-the-art [4, 11], our envisioned approach has the following advantages: first, because of the freedom of movement offered by a UAV, we can collect data on otherwise impossible or difficult areas (*e.g.,* rooftops, high floors). Second, and relatedly, we should be able to collect data at much higher granularity for each building area (*e.g.,* similar to Vidas and Moghadam's handheld 3D thermography system [10]). Third, by dramatically lowering the cost of data collection through automation, we should enable new types of analyses such as temporal comparisons based on time-of-day, day-of-week, and season as well as occupancy levels.

Preliminary System Design

The core components of the system consist of a UAV, a central image processing server, and a software interface tool for the analyst. The primary initial use case of the system is as follows:

Figure 3: Manually collected thermal data with the FLIR e4 thermal camera.

Figure 4: Example RGB image.

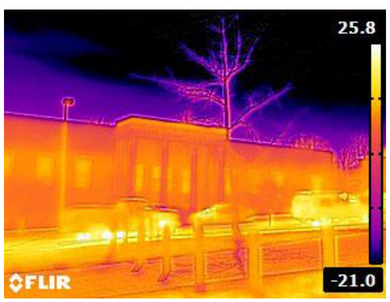

Figure 5: Thermal image of same building as above.

1. The analyst connects to the server, selects a target building, and describes a flight plan for the UAV.
2. The server converts the analyst's input into a plan for performing a thermal audit.
3. The UAV surveys sections of the target building.
4. On completion of each section, the UAV: returns to a docking station, transmits the data to the server, recharges, and awaits further instructions.
5. The server automatically processes the returned data which includes: image preprocessing, reconstruction using SfM, segmenting the target building, and generating the thermal overlay.
6. The server then analyzes the results and generates the next piece of the audit plan.
7. The raw data, reconstruction results, and associated metadata are then sent to the analyst.
8. The analyst reviews this information and provides feedback to the server for the next audit plan.
9. This procedure continues until the entire building is surveyed and there are no further instructions.
10. On completion, a full 3D model with a thermal overlay is generated; the analyst uses tools provided by the system to perform further analysis.

As UAV technology improves, the above steps can likely be simplified (*e.g.,* longer battery life would reduce necessary dockings, real-time processing would allow the UAV to dynamically sub-sample important areas).

Study Method

To demonstrate the feasibility of the system, we perform data collection with a UAV and process the data with automated scripts and an SfM reconstruction tool. We also use this tool to produce reconstructions from data collected using a handheld thermal camera and we overlay the results with thermal information.

UAV data collection. Using a Parrot AR.Drone 2.0, we extract frames from its video feed at a rate of one frame per second. We then down sample the frames to match the handheld data and the SfM tool is applied.

Handheld data collection. We performed thermal audits using a FLIR thermal camera (Figure 3). This camera simultaneously takes both conventional RGB (Figure 4) and thermal (Figure 5) photographs. We are able to perform SfM reconstruction when we produce a large enough data set with a high variance between images; however, the time to manually capture data sets with these qualities is prohibitive.

Structure-from-Motion (SfM). The data is pre-processed and the RGB images are run through VisualSFM [4] until a viable reconstruction is produced. We manually segment and cleanup the resulting model.

Thermal overlay. Using the output from SfM, our application collects the images associated with each 3D point and back projects them to the 2D coordinates in each image; a lookup in the corresponding thermal image is performed and an output file is produced containing the thermal data.

Results

Figure 6 demonstrates a reconstruction generated from UAV data collection. The reconstruction was made using a set of 1500 images, collected in 0.5 hours, and processed in 18.0 hours on an Intel iCore 2.7GHz with 16GB of RAM. The thermal overlay was generated from handheld data collection based on a set of 500 images, collected in 3.5 hours, and processed in 7.0 hours. Thermal overlay of this model took an additional 0.5 hours to generate. All times are approximate.

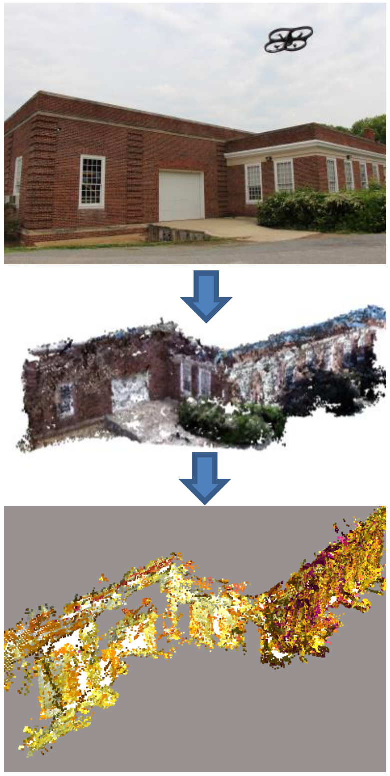

Figure 6: Example of partial 3D-reconstruction using UAV and data from our thermal camera.

Discussion and Conclusion

From our results, we find that using our UAV for data collection is more efficient with respect to time as we can extract frames from a video feed faster than we can manually capture data using our thermal camera. Additionally, the flight of the UAV provides more image variance and enables us to generate images sets with less effort. Data collection with our current UAV is limited by the camera being in a fixed position (*i.e.,* non-gimbaled) and we cannot accurately capture the full structure in flight (*e.g.,* roofs); though, the resulting reconstruction demonstrates the feasibility of using a UAV as we propose. We also conclude that applying a thermal overlay can be done with properly aligned camera systems. A limitation of our current work is that UAV used has a very short flight time and no ability to carry additional components. Upgrading our UAV will improve the data quality and results.

In conclusion, we believe that new techniques using UAV will provide a scalable approach to thermal profiling. Our formative work demonstrates that data collected from a UAV can produce a 3D-reconstruction of a building and that a thermal overlay can be applied. Future work includes further automation of the data collection and processing pipeline as well as integrating a UAV with a thermal camera, additional sensors, and command and control components. Finally, we are developing a visual analytics tool for the data.

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