Small Unmanned Aerial System Applications in the Building Enclosure Industry: Using Thermal Imaging to Assess Building Performance

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In the architecture, engineering, and construction (AEC) industry, several disciplines have seen how small unmanned aircraft systems (sUAS) or drones can make critical, and sometimes dangerous, tasks more efficient, precise, and accessible. For example, drones can be used to perform thermal imaging scans to detect air, moisture, and heat leakage from a building enclosure—the glass, concrete, insulation, and other materials separating the inside and outside environments. Leaky buildings can be costly and dangerous, leading to damaged finishes, increased energy costs, and mold growth within walls and roofs. Infrared thermography is a relatively cost-effective, easy-to-use, nondestructive tool for these types of conditions, but the results require expert interpretation. By using drone technology correctly, AEC professionals can get detailed results to make informed recommendations that address underlying building concerns.

In this article, we will explore how the AEC industry has implemented drone use to conduct thermal imaging scans of buildings, address some of the nuances of using drones around building enclosures, and discuss the differences of sUAS methods compared to handheld scanning techniques. We will review industry standards and guidelines and share common project challenges and opportunities through a series of case studies.

Today's building enclosure systems are more complex than ever before, and, according to a study performed by ASHRAE, more than 84% of all construction-related claims, defects, and warranty callbacks are related to building enclosure (69%) and mechanical system (15%) design and/or installation issues.[1] Water infiltration, moisture accumulation, air leakage, and thermal bridging are among the most common and costly failures encountered in building enclosure construction, which can lead to damaged interior finishes, increased energy consumption, and mold growth within the walls.

Infrared thermography, or thermal imaging, which is often used to detect and determine the extent of water leakage into roofs and air leakage through the building enclosure, can also be used to detect thermal bridging, missing wall insulation, insulated glass unit failures, and concrete delamination. Infrared thermography uses an

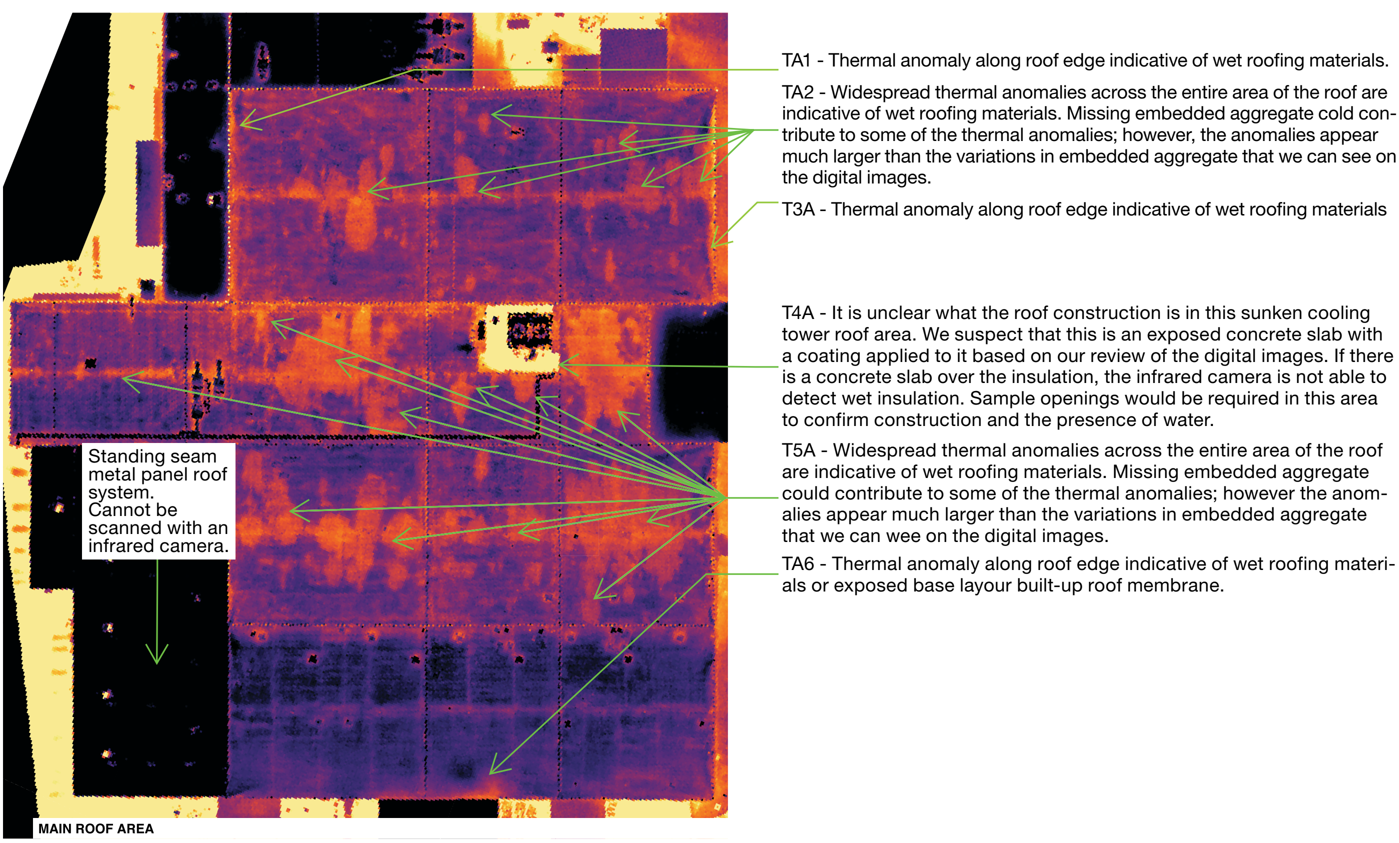

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Figure 1. *Infrared image of a roof composed of many images digitally stitched together.*

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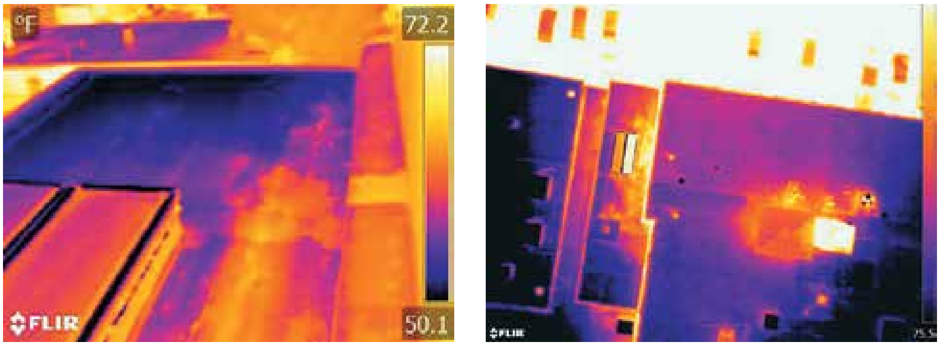

Figure 2. ***Infrared images from a handheld camera (left) and an sUAS-mounted camera (right).***

infrared camera to identify differential apparent surface temperatures that can result from wet roofing materials, air leakage, missing insulation, or delamination. The thermal images display apparent surface temperatures, which are calculated in the infrared camera based on the relationship between emitted radiation intensity and a material's emissivity; therefore, the camera does not directly measure the temperature or moisture content of building materials. The interpretation of thermal images involves identifying patterns to differentiate between possible building enclosure leaks and thermal anomalies caused by other sources (e.g., variations in membrane thickness, penetrations, variations in concealed construction).

Historically, the AEC industry has used thermal imaging as a tool to diagnose known building enclosure leakage issues in existing buildings. Building owners and developers have become more cognizant of building enclosure performance and the risks associated with building enclosure leakage, and the industry is experiencing an increased demand for thermal imaging as a preventive quality control field test during the construction of new buildings. Many new construction and large-scale renovation projects now require thermal imaging to be performed on the roofing and exterior wall assemblies prior to project closeout. The standard for building enclosure commissioning, ASTM E2813-18, *Standard Practice for Building Enclosure Commissioning*,[2] requires thermal imaging of the roofing assembly to achieve enhanced commissioning status and lists thermal imaging of the exterior wall assemblies as an optional test.

The AEC industry has used handheld infrared cameras to assess building enclosure performance for many years; however, developments in sUAS technology have made thermal imaging safer, more cost effective, and more accessible; have improved data clarity; and have expanded the range of thermal imaging applications in the AEC industry. Infrared scans that would have normally taken many hours to perform can now be performed in minutes while providing better quality, more comprehensive infrared images of the building enclosures (**Fig. 1**). Obstacles encountered when performing infrared scans using a handheld camera are minimized when using an sUAS; however, challenges and limitations still exist, and, as with any new technologies, sUAS use should be pursued with some level of caution. Successful sUAS implementation on projects requires training, experience, and certification in both sUAS piloting and infrared technology.

ASTM STANDARDS

The two most common ASTM standards for test procedures involving infrared technology that we use on new and existing buildings are ASTM C1153, *Standard Practice for Location of Wet Insulation in Roofing Systems Using Infrared Imaging*[3] and ASTM E1186, *Standard Practices for Air Leakage Site Detection in Building Envelopes and Air Barrier Systems*.[4] Brief summaries follow. Refer to Grey and Wartman[5] for additional discussion of the theory and challenges associated with these standards, as well as case studies.

ASTM C1153

ASTM C1153 outlines the necessary conditions and techniques employed to determine the location of wet insulation in roofing systems. This standard also addresses the criteria for infrared equipment, weather parameters, types of applicable roof construction, operating procedures, and invasive openings. It does not include determination of the cause of moisture or point of entry into the roofing system.

The scan relies primarily on solar exposure and the heat capacity differences between different building materials. During the day, roofing materials absorb heat, primarily due to solar exposure. At night, as solar exposure ceases and air temperatures drop, the roofing materials release the heat absorbed during the day. Water has a high heat storage capacity; therefore, materials that have absorbed moisture, such as insulation or cover boards that have been saturated by water infiltration, will cool at a slower rate than adjacent dry materials. As a result, the roof apparent surface temperatures above wet insulation will remain higher than surfaces above dry materials, until the roof surfaces reach equilibrium several hours after sunset. The concept behind infrared roof surveys is that visualizing these "warm areas," or thermal anomalies, on the roof will identify approximate locations of potentially wet roofing materials.

ASTM E1186

ASTM E1186 covers the procedure for qualitatively locating air leakage in building enclosure and air barrier systems. The standardized practice does not determine the quantitative rate of air leakage but provides seven different methods for detecting an air leakage site, one of which is through the use of infrared technology. Air-leakage locations are identified by performing an infrared scan from the interior or exterior in conjunction with either pressurizing or depressurizing the building.

To detect air leakage using infrared scanning equipment, ASTM recommends that the indoor-outdoor temperature difference be at least 5°C (9°F). Air is moved through the building enclosure by depressurizing or pressurizing the building interior. As the infiltrating air enters or exits the building, infrared images will detect local interior or exterior apparent surface temperature changes. The larger the difference between interior and exterior temperatures, the easier it is to detect the thermal anomalies on surfaces associated with air leakage. The thermal anomalies resulting from air leakage are different from those associated with varied levels of thermal conductance in the enclosure, allowing air leakage sites to be identified.

BENEFITS OF USING SUAS

As thermal imaging has gained traction, sUAS technology has improved and become more accessible. Many industries, including the AEC industry, are finding new applications for sUAS that provide cost and time savings while also providing higher quality end products. Using sUAS to perform infrared scans of building enclosures has diminished the severity of many of the challenges associated with using infrared thermography to assess building enclosure performance. In the following sections, we discuss several of the common challenges and how sUAS technology has improved the process and results.

Time and Cost Efficiencies

Infrared scans of roofing assemblies using handheld cameras are commonly performed from the roof level, often from a ladder, which is moved around the roof to allow capture of

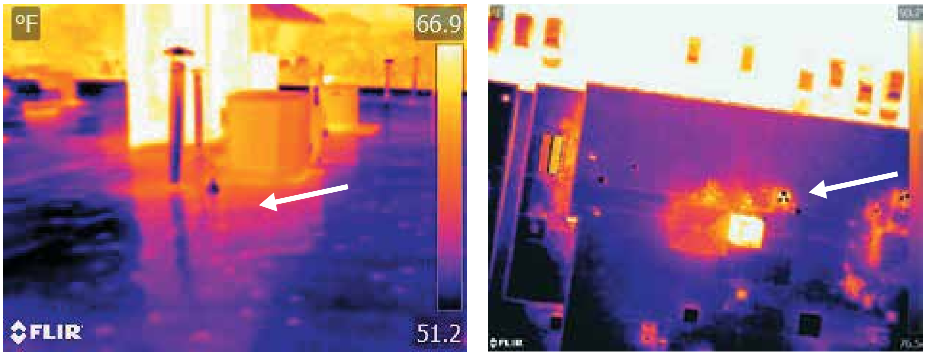

Figure 3. ***Infrared images of a roof taken by a handheld camera (left) and an sUAS-mounted camera (right). In the image from the handheld camera, the white arrow points to reflections cast onto roof; the white arrow in the sUAS camera image points to approximately same location but does not show reflections.***

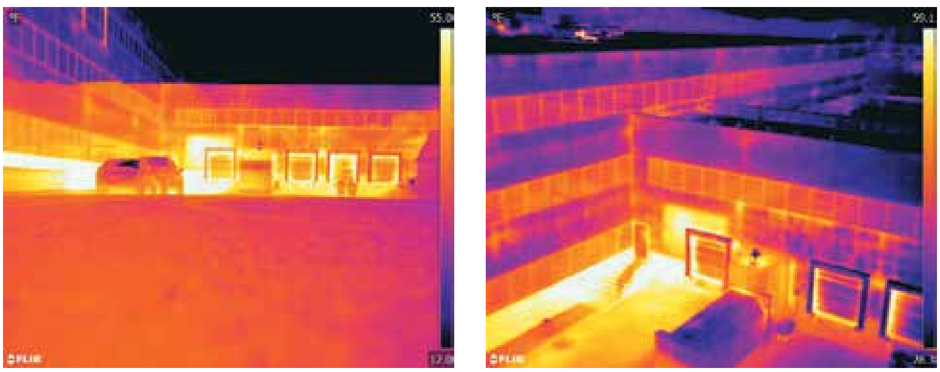

Figure 4. ***Infrared image from a handheld camera of an exterior wall showing reflections (left), and infrared image of the same wall, without reflections, from an sUAS camera (right).***

thermal images from various locations at slightly elevated vantage points. This process is time consuming and requires building access, and there are inherent safety concerns, as the scans are generally performed at night.

It can take several hours to perform an infrared scan of a roof using a handheld camera, whereas an sUAS-mounted camera can capture the same roof area in minutes due to the field of vision in the infrared camera, which is 15 degrees wide on a standard infrared camera. With this field of vision, the camera can capture approximately a 2.6 ft × 2.6 ft area of the roof surface at a distance of 10 ft (the approximate distance atop a ladder) when the camera is oriented directly perpendicular to the roof surface. However, the same camera can capture an approximately 26.7 ft × 26.7 ft area of the roof when mounted to an sUAS and flown 100 ft above the roof surface. **Figure 2** shows an infrared image of a thermal anomaly at a roof leak taken with a handheld camera from a ladder and an infrared image of the same location taken from an sUAS.

Similarly, using an sUAS to perform infrared scans of the exterior walls greatly decreases the amount of time necessary to perform the scan, as the sUAS can fly around the building capturing images at regular intervals without requiring the thermographer to walk the entire building perimeter and reposition for each photograph. These time savings in the field provide moderate cost savings to the owner compared to a traditional infrared scan, as additional office time is often required to process and review the hundreds of images captured during an infrared sUAS scan.

Environmental Parameters

The effectiveness of the scan depends on several environmental parameters that can cause significant changes in apparent surface temperatures, which can reduce the thermal pattern intensity. ASTM C1153 provides guidelines for these parameters, including minimum inside-to-outside temperature difference, minimum daytime-to-nighttime temperature swings, limitations of cloud cover, maximum wind speed, roof conditions, and precipitation limitations within 24 hours leading up to the scan. This list of guidelines can make scheduling infrared scans difficult, as these environmental conditions can be hard to predict accurately in advance.

The ASTM environmental guidelines must be followed more stringently when performing handheld infrared scans than when an sUAS is used. The infrared camera captures apparent surface temperature differences relative to extents of the camera's field of vision. When the infrared camera is mounted to an sUAS, the field of vision becomes much wider and the apparent surface temperatures are shown relative to adjacent materials over a larger area, which minimizes the effect of minor apparent surface temperature differences due to outside factors and reveals more widespread thermal anomalies associated with wet roofing materials or air leakage. This allows for the infrared scans to be performed during a wider range of conditions. In these scenarios, the ASTM environmental requirements are used as guidelines, with more emphasis on the thermographer's experience.

Reflections

Infrared images are most accurate when taken from a 90-degree angle looking directly perpendicular to the surface being scanned (reflective surfaces require a skew angle varying slightly from 90 degrees). Unfortunately, due to building geometry and limited access, achieving the ideal angle often is not possible, especially when using a handheld infrared camera. When images are taken from other vantage points, adjacent surfaces often cast reflections, or "thermal shadowing," onto the surface that is being scanned. These reflections can mask thermal anomalies associated with water or air leakage or result in false positives if the thermographer is not experienced with these types of scans. Scanning around reflections is common, and simply adjusting the camera angle can generally help determine whether the anomaly is a reflection or indicative of water or air leakage.

Compared with a handheld camera, an sUAS-mounted camera offers greater flexibility to take photographs from various distances and angles, thereby minimizing challenges associated with reflections. **Figure 3** shows an angled infrared image taken from a ladder on the roof with thermal shadowing from a headhouse on the roofing membrane, and an image of the same location taken from an sUAS at a 90-degree angle from the roof. The thermal shadowing does not appear in the image taken from the sUAS, and it is clear that there are no thermal anomalies potentially associated with wet roofing materials or air leakage at this location.

Similarly, **Fig. 4** compares an infrared image of an exterior wall taken with a handheld camera near grade and an infrared image of the same exterior wall taken with an sUAS-mounted camera. The first image shows reflections on the cladding from the adjacent wall, whereas the image taken from the sUAS minimizes the thermal shadowing on the cladding, even though the location has complicated building geometry.

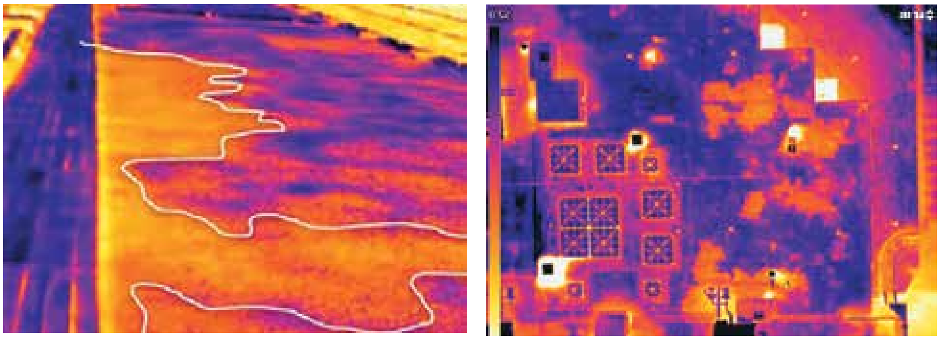

Figure 5. ***Infrared images of a ballasted roof from a handheld camera (left) and an sUAS-mounted camera (right).***

Aggregate Ballast Roof Systems

Infrared surveys are useful for locating wet insulation in most membrane roof systems containing rigid insulation boards located below the roofing membrane. It becomes difficult to locate wet insulation when there is aggregate ballast over the roof membrane, as the ballast stores heat and inhibits the thermal anomalies on the surface of the roof. It is difficult to produce useful thermal images of ballasted roofing assemblies using a handheld camera unless significant water infiltration into the roof assembly exists, because thermal images may display thermal anomalies due to variations in the aggregate ballast thickness or moisture content of the aggregate ballast instead of the apparent surface temperature of the roofing assembly below the aggregate ballast. The thermal patterns associated with aggregate ballast are often indistinguishable from "hot spots" associated with small, localized areas of wet insulation. Relatively new leaks are more difficult to discern from aggregate patterns than older leaks that have large, significantly wet areas.

Using an sUAS, each image typically shows a larger area than a handheld camera, which results in muting of the thermal anomalies associated with local variations in the ballast and reveals the more widespread thermal anomalies associated with wet roofing materials below. **Figure 5** shows thermal images of ballasted roofing assemblies taken with a handheld infrared camera and an sUAS-mounted infrared camera. The image from the handheld camera shows thermal anomalies associated with variations in the ballast, making the exact extent of the wet roofing materials difficult to determine. The infrared image from the sUAS was taken from approximately 150 ft above the roof surface, which muted the localized thermal anomalies associated with the ballast; thus, this image shows only the more widespread thermal anomalies associated with wet roofing materials.

The use of the sUAS allows the infrared scans to be performed on ballasted roofing assemblies where handheld infrared scans were previously not effective. It is important that building owners and clients be aware that even with the use of sUAS on aggregate ballasted roofs, only large, more significant issues will likely be visible, and that an infrared scan may not provide useful information, especially if there are areas of ponded water on top of the roof membrane. When surveying aggregate ballasted roofs, it is also critical that thermographers perform the scan under the best environmental conditions possible, be able to differentiate between aggregate thickness and thermal anomalies, and potentially be able to adjust their camera angles to help mute aggregate variations.

Quality of Data/Ease of Analysis

In our experience, the quality of the data and deliverables provided by an sUAS infrared scan is superior to the quality of those provided by handheld infrared scans. Capturing larger areas of the roof in individual or stitched images allows design professionals to see a holistic infrared view of the roof that can be easily analyzed to identify larger patterns, which are more difficult to discern when reviewing the many individual images typically provided using a handheld camera. This is due to the consistency of the images and the software available to aid in processing the data. Images taken with a handheld camera are disparate, as they are taken from different angles and sometimes different heights, depending on the available vantage points. Typically, the thermographer must review images from a handheld camera in real time and mentally process the data while on site performing the scan to determine if and where additional images are required at localized areas to identify larger thermal anomalies and patterns.

When using an sUAS, the thermographer typically has a mapped flight plan to ensure that the images are taken from the same height and angle from the roof. The mapped flight takes hundreds of images that overlap by 75% to 90%. Then the individual images can be stitched together in postprocessing to show the entire roof surface in one image. This allows the thermographer to review the building from a holistic view and identify leakage patterns and areas that require further review.

Based on our experience, we recommend that the thermographer provide a combination

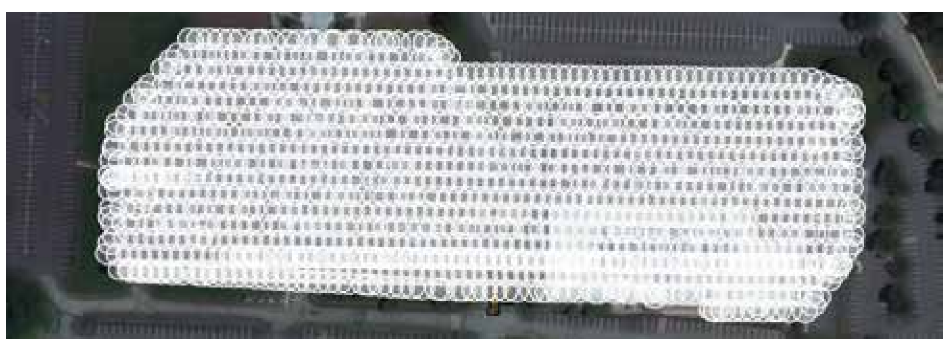

Figure 6. ***Image showing every photo taken during the mapping of a roof. Each white circle is one photo.***

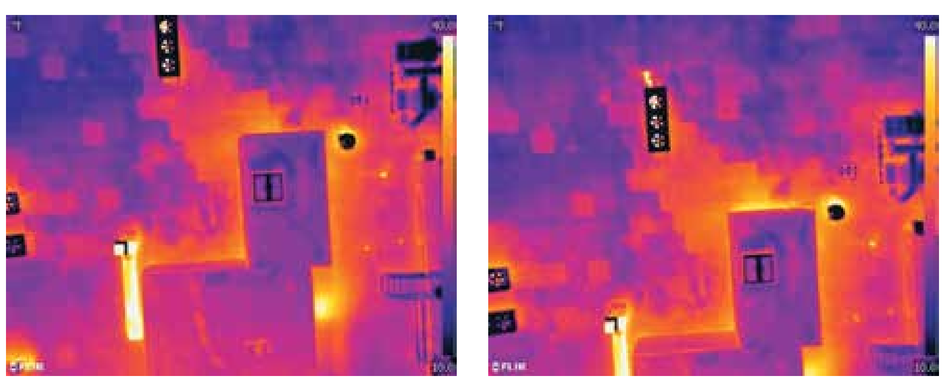

Figure 7. ***Sequence of infrared images in one area 50 ft above the same roof shown in Fig. 6, showing the extent of overlap required to create a stitched infrared image.***

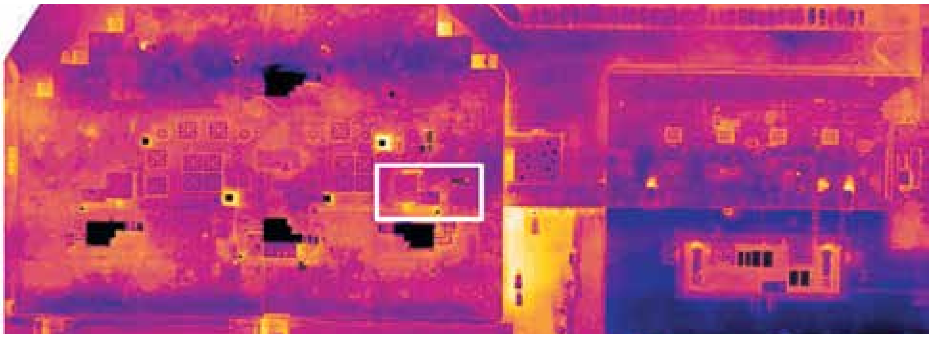

Figure 8. ***Fully stitched digital infrared image of the roof. The white box indicates the location where the three 50-ft images in Fig. 7 were taken.***

Figure 9. ***Fully stitched digital image of the roof.***

of stitched digital and infrared images with additional close-up images at problem locations, which allows the client or end user to compare the images and locate the observed thermal anomalies on the roof more easily. In addition, smaller thermal anomalies may appear more distinct in enlarged close-up images compared to the overall stitched roof images.

Figures 6 through 9 are representative of a typical deliverable from an infrared sUAS scan of a roof and include the mapping sequence. Figure 6 contains over 1000 close-up overlapped individual images (every white circle is an image). Figures 7, 8, and 9 show an individual image, a stitched infrared image, and a stitched digital image, respectively. These images collectively provide a visual representation of the extent of leakage within the roofing assembly. The stitched infrared image in Fig. 8 shows an existing roofing assembly with numerous large thermal anomalies (lighter yellow areas) associated with roof leakage. The image makes it clear that the water leakage is pervasive and that much of the leakage originates around mechanical units and other penetrations through the roof.

One challenge with stitching infrared images into one complete building image is that there is limited software available that can effectively stitch infrared images, which contain embedded complex data. Compared to a typical digital photo where each pixel contains colors, each pixel of an infrared image contains measurable temperature data. As the infrared scan is performed, the roof is cooling at a rapid rate and, depending on the size of the roof, the thermographer may capture infrared images across the roof with varying temperature ranges. When comparing individual images, this is not an issue because the thermographer is focused on identifying and analyzing patterns rather than the temperature data. However, temperature variations from progressive cooling can result in thermal contrasts in different areas of the roof in the final stitched images, which makes analyzing and identifying thermal anomalies more difficult. For example, the stitched infrared image in Fig. 8 shows thermal contrast in areas where thermal anomalies are not present.

CHALLENGES

Many of the obstacles encountered when performing infrared scans using a handheld camera are minimized when using an sUAS; however, challenges and limitations still exist, and successful implementation of sUAS systems on projects requires training, experience, and certification in both sUAS piloting and infrared technology. The following challenges and obstacles affect how and when sUAS can be used. In some cases, performing a handheld infrared scan cannot be avoided.

Initial Requirements

All commercial sUAS operations are regulated by the Federal Aviation Administration (FAA) and require a certified operator to perform the work. Prior to September 2016, commercial operations required a Section 333 exemption, which required that the operator hold a pilot's license. In September 2016, the FAA enacted Part 107 of the Federal Aviation Regulations for non-hobbyist sUAS operations. The required Part 107 certification is acquired by paying a fee of $150 and scoring a 70% or better on a 60-question multiple-choice test. Upon completion, the certificate holder is immediately authorized to perform commercial work in Class G airspace without additional permissions. Most infrared scans are performed at night and require a 107.29 Daylight Operation Waiver. This is obtained by submitting a request via the FAA's Drone Zone website (faadronezone.faa.gov) and providing a work plan with all relevant steps that the applicant will take to perform the work in a safe manner. Individuals with Part 107 certification must recertify every 24 months, a process that entails a multiple-choice test similar to that of the original certification. The Part 107 rules have simplified the path to licensure, which is why sUAS pilots are becoming more common in the AEC industry.

Building Location Challenges

The most important consideration when proposing an sUAS operation is the airspace restrictions at the project site. The FAA provides an ArcGIS UAS Map that outlines the most current airspace restrictions, including maximum allowable altitude above ground level. If a project is within proximity to an airport, some additional authorization may be required. Several airports participate in Low Altitude Authorization and Notification Capability (LAANC), which allows for instant authorization assuming that the flight will remain at or below the published altitude limit in the FAA's ArcGIS UAS Map and will be happening during daylight hours. If it is necessary to operate the sUAS at a higher altitude than the published limit, the operator will be required to submit a request through one of the LAANC providers, identifying the location of the operation and the reason for requesting to fly higher than the posted maximum. Depending on the region, the LAANC providers typically respond between two and seven days. Applicants who need to operate outside of daylight hours must have an approved 107.29 waiver and must submit an airspace authorization request through FAA's Drone Zone portal, attaching the approved waiver. Because the response time for these applications will vary, it is important to submit applications as promptly as possible to ensure approval before the operation date.

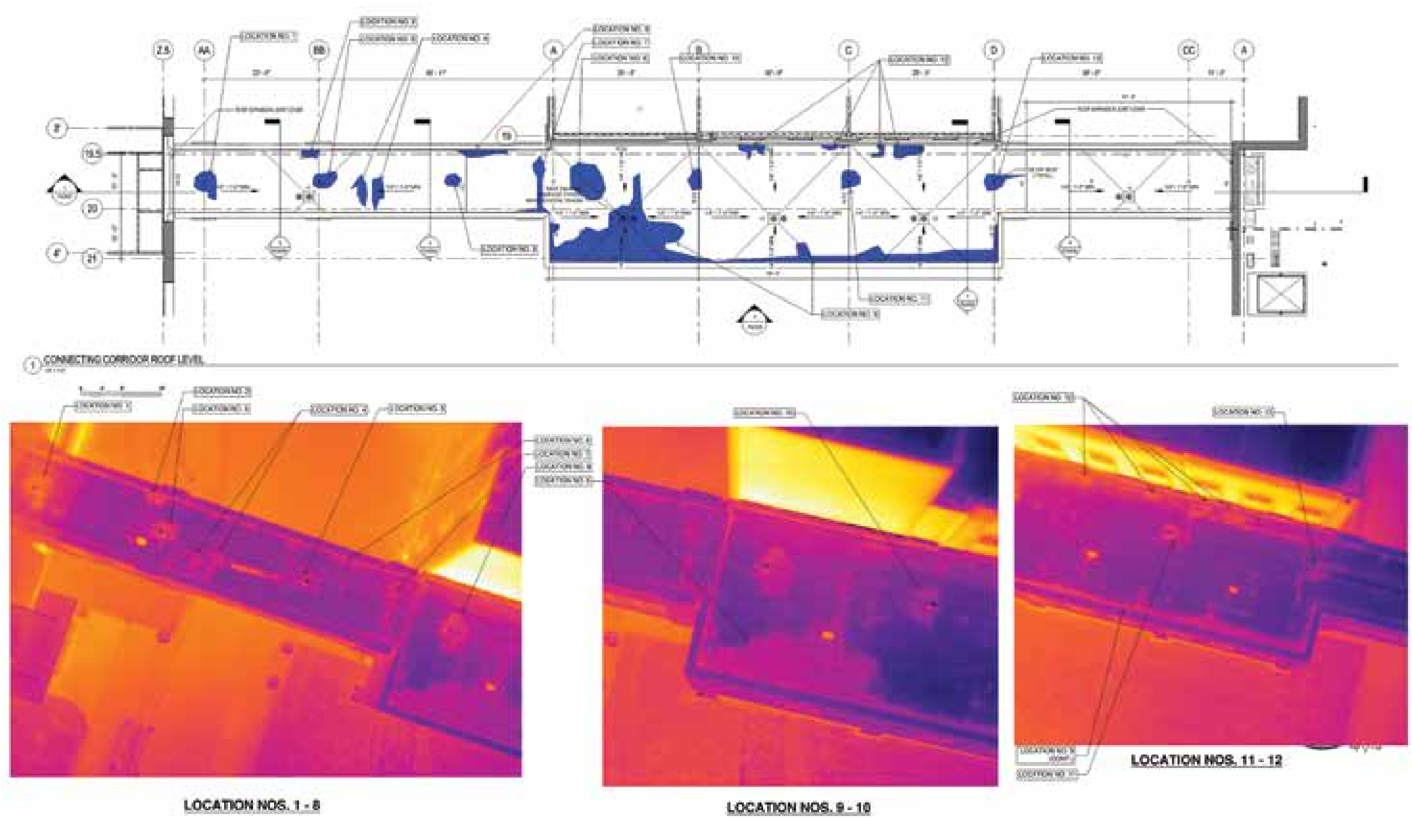

Figure 13. ***Marked-up roof plan with identified thermal anomalies (top), and three representative infrared images of thermal anomalies (bottom).***

return to the site, make openings at all identified thermal anomalies, remove all wet roofing materials, and repair the roofing assembly. If this had not been addressed, the moisture would have remained trapped in the roofing assembly and would have resulted in accelerated deterioration of the roofing materials and potential leakage into the building.

Existing Construction Investigation of Roof Water Leakage (ASTM C1153)

We were hired to design the roof replacement for a large apartment complex consisting of 46 high-rise buildings. Prior to our firm being engaged, a firm offering infrared thermography services performed infrared scans of all 46 buildings using a handheld camera and made recommendations to the owner to replace all 46 roofs due to apparent water within the roofing system. The firm's reports contained minimal infrared data, stated that the roofs were wet without indicating that any follow-up confirmation was performed via test cuts (as required by the ASTM standards), and did not provide sufficient information regarding potential sources of water infiltration or the extent to which the roof was considered wet. The owner chose to replace all 46 roofs based on these reports. The roof replacement was intended to be phased over several years, with an intention to start with the roofs in the worst condition and end with the roofs in best condition. However, we were not able to categorize the roofs according to severity using the reports prepared by others based on images from a handheld infrared camera; therefore, we recommended that the owner perform new infrared scans.

The complex is located in a highly populated city area with a "no sUAS" policy, is within the vicinity of a major airport, and is in an FAA no-fly zone. Initially, we assumed that flying an sUAS above the roofs would not be possible given the site's proximity to the airport; however, scanning all 46 roofs with a handheld camera would have required up to 15 nights (approximately three to four roofs per night) with weather conditions acceptable to scan aggregate-ballasted roofs. We contacted the local authorities and airports and determined that the runway that made this area an FAA no-fly zone was under construction and was thus not in use. This provided us a limited window of time to use an sUAS to scan the 46 buildings, which we completed in two nights.

The roof area on each building was relatively small; therefore, we opted to capture images from approximately 100 ft above the roof level to expedite the capturing and analysis process. This resulted in four to six infrared images per roof,

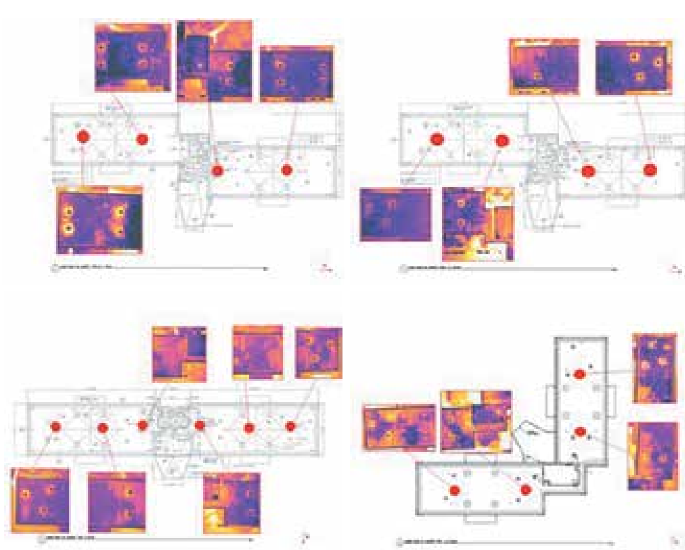

Figure 14. ***Representative infrared report images for 4 of 46 high-rise buildings investigated for roof water leakage.***

which could be processed quickly to provide a comprehensive understanding of the extent of the moisture within the roofing assemblies (**Fig. 14**). Our results were consistent with the handheld scans, which concluded that all the roofs contained wet insulation; however, by reviewing infrared data for the full roof area, we were able to more accurately quantify the area of wet roofing per roof (25%, 50%, 75%, etc.). Organizing the data in this way allowed us to rate the roofs based on the extent of apparent water leakage on an area basis and use that information to propose a phased approach for replacement.

The ability to rate enclosures or roofs based on condition is valuable for owners of multiple buildings, such as big-box retailers or universities. Since this project, we have used infrared to assess multibuilding campuses and inform capital planning efforts to help owners prioritize future expenditures for roof replacements and facade repairs.

CONCLUSION

Infrared thermography is a useful tool for cost-effective evaluations of various building enclosure systems. Owners can use infrared thermography as a quality control process on new buildings, to detect air or water leakage in building enclosures, to help diagnose known leakage issues, and to evaluate the efficacy of repairs, among many other applications. Depending on the application and scale, it may be prudent to consider using an sUAS, which eliminates many of the disadvantages associated with using a handheld infrared camera. Using an sUAS-mounted camera to take thermal images significantly reduces the time and cost of data capture, eliminates issues related to access and safety that are present when using a handheld camera at night, allows for scans to be performed during a wider range of environmental conditions, and improves the overall quality of images that are captured, resulting in a better end product for the client.

Though there are many advantages, the decision to employ an sUAS to perform an infrared scan must be carefully considered. It is critical to confirm that the sUAS operator is certified, trained, and educated on the applicable ASTM standards and understands the nuances associated with infrared thermography of building enclosures, and it is essential that the data can be collected in a way that it will provide the most useful deliverable for the specific project goals.

With any method of infrared thermography, proper verification is necessary for successful use. It is important for thermographers to understand the building enclosure components and environmental factors for scans to be successful and produce accurate information. Test cuts should always be performed to verify both the results of the scans and the construction of concealed conditions. Infrared thermography is a powerful tool to aid in the evaluation of building enclosure performance, but it must be accompanied by additional verification and engineering judgment.

REFERENCES

1. Grosskopf, K. R., P. Oppenheim, and T. Brennan, "Preventing Defect Claims in Hot, Humid Climates." *ASHRAE Journal* 50, no. 7 (July 2008): 40–52.
2. ASTM International. *Standard Practice for Building Enclosure Commissioning.* ASTM E2813-18, West Conshohocken, PA: ASTM International, 2018.
3. ASTM International. *Standard Practice for Location of Wet Insulation in Roofing Systems Using Infrared Imaging.* ASTM C1153-10(2015), West Conshohocken, PA: ASTM International, 2015.
4. ASTM International. *Standard Practices for Air Leakage Site Detection in Building Envelopes and Air Barrier Systems.* ASTM E1186-17, West Conshohocken, PA: ASTM International, 2017.
5. Grey, C. N., and E. C. Wartman, "Infrared Technology Applications in Building Envelopes: Applications, ASTM Standards, and Limitations." Paper presented at Infrared Training Center User Conference, Coventry, UK, September 28, 2017.

ABOUT THE AUTHORS

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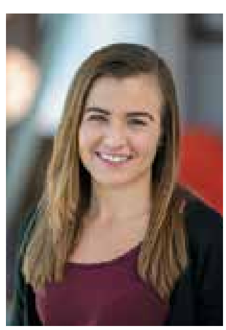

Kelsey A. Dunn, PE

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Sean D. Gordon

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