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Comparison of building thermography approaches using terrestrial and aerial thermographic images

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Abstract. Thermography is commonly used for auditing buildings. Classical manual terrestrial thermography records images of individual buildings at a short distance. When auditing a large number of buildings (e.g. whole city districts) this approach reaches its limits. Using drones with thermographic cameras allows images to be recorded automatically from different angles, with faster speed and without violating property rights. However, an airborne camera has a significantly greater distance and more varied angles to a building compared to terrestrial thermography. To investigate the influence of these factors for building auditing, we perform a study evaluating seven different drone settings of varying flight speed, angle, and altitude. A comparison is drawn to manually recorded terrestrial thermographic images. While we find that a flight speed between 1m/s and 3m/s does not influence the thermographic quality, high flight altitudes and steep viewing angles lead to a significant reduction of visible details, contrast, and to falsified temperatures. A flight altitude of 12m over buildings is found to be the most suitable for the qualitative and quantitative analysis of rooftops and a qualitative analysis of façades. A flight altitude of 42m over buildings can only be used for qualitative audits with little detail.

Keywords: Building audits, aerial thermography, drones, urban areas

1. Introduction

The New Urban Agenda declared by the United Nations in 2016 emphasizes the key role of cities in promoting sustainable development and climate protection throughout the building sector [1]. Districts, such as communities or neighborhoods, are easier to coordinate than entire cities when planning energy retrofitting strategies of multiple buildings at once [2]. Numerous international approaches deal with retrofitting buildings on district scale, like Community Energy Strategic Planning (USA) [3], Community Energy Planning (Canada) [4], Positive Energy Districts (Europe) [5] and “energetische Quartierskonzepte” (Germany) [6]. These approaches are planned and coordinated by municipalities in cooperation with institutions like local energy agencies or urban research institutions.

In order to develop a targeted retrofit plan for a whole district, the first step is to document and analyze the thermal quality of existing buildings. A well-established, non-invasive tool for such an audit is thermography, which can be used to monitor and analyze the condition of building envelopes by means of infrared images [7]. Thermographic imaging is capable of identifying thermal weaknesses related to heat-, water-, and airflows through the building envelope. Lucchi [8] summarized the



different applications of thermography in building auditing, which include the thermal characterization of walls, glazing, and windows; thermal bridging and the detection of areas with excessive heat loss; the inspection of thermal insulation and air leakages; detecting moisture and water; measuring U-values; and determining the percentage of the areas with thermal anomalies [8].

Classical thermography studies use hand-held cameras on eye-level to obtain thermographic images of high quality [8]. However, stationary terrestrial thermography reaches its limits in the analysis of entire city districts due to the time-consuming nature of the method where large numbers of buildings of various heights are concerned [9]. Additionally, not all components of a building façade (such as the roof or upper floors) can be captured properly from the ground [10].

Using unmanned aerial vehicles (UAVs), colloq. drones, equipped with thermographic cameras can help implement large scale building audits [11]. The image acquisition process can be automated, allowing for faster completion at lower costs [12]. It becomes possible to obtain images at different angles (not just eye-level) and of high buildings that remain inaccessible via terrestrial thermography. Moreover, the thusly acquired images can easily be used to generate 3D models to provide a good overview of a whole district [13].

Nevertheless, only few scientific publications thus far discuss the use of airborne thermography for building audits. Entrop and Vasenev [14] provide initial research on the basics and possible flight patterns to reduce both time and cost of such a process. They consider a flight distance of between 5m and 10m to a building and use a flight speed of 1m/s after finding image quality to be insufficient when recorded at 1.5m/s. Although they give instructions on how best to perform building audits via UAV-based thermography, they do not specify the means by which thermal image quality is assessed [14]. Rakha and Gorodetsky [15] analyze suitable drone flight settings to create thermographic 3D models of individual buildings. They investigate different settings such as flight path, image overlap, and distance between infrared camera and building. The optimal flight route is found to be a strip pattern at a distance of 12m. Suitable altitudes above ground are chosen as 18m, 22m, and 27m – or twice the building height – to achieve a high enough overlap for 3D model generation. The authors conclude that thermographic drone imagery offers many new possibilities in automating building audits owing to its reduced effort and simplified post-processing [15]. Daffara et al. [16] also investigate suitable flight settings for the development of thermographic 3D building models. For this, they examine a distance of 10m to the building, a maximum height of 8m above the ground, and a high image overlap. They highlight the benefit of drone thermography for building energy audits, particularly of otherwise inaccessible building parts like rooftops [16]. Most recently, Hou et al. [13] explore an approach for thermographic 3D model development of entire city districts using UAVs. Different flight patterns such as vertical grid, horizontal grid, and mesh grid, as well as 90° (nadir) and 45° viewing angles in combination with a high image overlap are analyzed. The authors find that nadir flight captures more details on the roof, while a viewing angle of 45° is more suitable for detecting façade features [13].

In summary, there are no studies known to the authors that document quality criteria for thermographic images acquired via UAV. We therefore present a structured approach to evaluate different flight settings of a UAV-based thermal imager and compare the resulting images to those recorded via terrestrial infrared camera. We derive general statements about the quality, benefits, and deficits of the individual flight settings for building audits.

2. Methods and Materials

2.1. Image Dataset

The dataset used to evaluate the quality of airborne thermography consists of 140 aerial images of two German multi-family buildings. Seven different flight settings were implemented, resulting in ten images per building and setting. An additional set of 249 thermographic images depicting the same buildings were recorded from the ground perspective with a standard handheld camera.

Both buildings are located in the Sophienstrasse 195-197 and 201-203 in the medium sized city Karlsruhe (Germany), have a height of 18m, and belong to the building stock of the municipal housing association Volkswohnung GmbH. Both buildings were constructed in 1957, have 30 and 20 apartments respectively and are fully rented out.

Aerial images were acquired using a “DJI Matrice 600” drone equipped with the “Zenmuse XT2”, a combination of FLIR’s “Duo Pro R” thermal and RGB camera and DJI’s gimbal [17]. The terrestrial images were recorded with a “FLIR T200” hand-held camera [18]. While the latter generates standard JPEG images, the UAV camera saves thermal data in FLIR’s proprietary image format RJPEG.

The thermographic image acquisition took place on January 16th, 2022, from 7pm to 1am. Atmospheric temperatures lay between +2° and +3°C with wind speeds of 2 to 11km/h [19]. It was cloudy throughout the recording timeframe with a slight drizzle between 9.50pm and 10.20pm. The day before exhibited similar weather without any precipitation [20]. The meteorological conditions present during our study therefore align with the best practice rules for thermography according to Fouad and Richter [21]: a sufficiently high temperature difference of at least 15K between in- and outdoors was present, assuming the room temperature of these heated residential buildings was given as the standard +18°C. The recommended maximum outdoor temperature of +5°C was not surpassed and the temperature remained stable for at least 24 hours before image acquisition, ranging from –2°C at its lowest to +3°C at its highest [20]. To avoid the effects of solar radiation, image recording was performed after sunset on a cloudy day. The wind speed ranged from 1m/s to 6.7m/s, thus preventing a considerable change of the heat transfer coefficient. Additionally, no moisture was discernible on either rooftops or building façades, ensuring no falsified temperature recordings ensued. Some best practice conditions mentioned by Fouad and Richter [21], such as a maximum distance of 20m between camera and building and a fixed camera position, are inherently problematic to fulfil in UAV-based applications. These two aspects require a structured analysis as is performed in this study to investigate the effects of both speed and distance on this form of thermography.

The seven different flight settings of the drone (summarized in Table 1) vary according to viewing angle, distance between camera and building, respective distance to the ground, and flight speed. During the first three flights, the viewing angle of the thermographic camera was set to 90° (nadir) to properly record the building rooftops. The other four flights were acquired at an oblique angle of 45° to record the façade. The flight heights were set at 30m (in flights 3, 5 and 7) and 60m (in flights 1, 2, 4, and 6), which correspond to a distance of 12m and 42m respectively between camera and building. Lower flight heights couldn’t be realized on account of nearby obstacles, most commonly trees. In practice, a larger distance to the ground is advantageous in terms of flight duration, as an area can be covered in a shorter period of time using a wider mesh pattern. The speed was set to 1m/s (in flights 1, 3, 6 and 7) and 3m/s (in flights 2, 4, and 5) and was based on experiences from other studies [14]. The camera emissivity was set to 0.95 during all flights, as suggested by Fouad and Richter [21].

Table 1. Experimental parameters used during UAV-based thermal image acquisition (seven different flight settings)

	Viewing angle [°]	Altitude above ground [m]	Altitude above building [m]	Flight speed [m/s]
Flight 1	90	60	42	1
Flight 2	90	60	42	3
Flight 3	90	30	12	1
Flight 4	45	60	42	3
Flight 5	45	30	12	3
Flight 6	45	60	42	1
Flight 7	45	30	12	1

Thermal image acquisition via hand-held terrestrial camera was performed at a distance of 8 m to the building. The entire façade was imaged in small segments. Larger distances were not possible owing, again, to the presence of obstacles. As before, the emissivity of the camera was set to 0.95 [21].

To allow a better comparison of all captured thermographic images, we adapted their thermal coloring to an uniform temperature range of -8°C to $+8^{\circ}\text{C}$ using FLIR's Thermal Studio Suite software [22]. Figure 1 and 2 show examples of thermal images depicting the same building area, acquired via drone and hand-held camera respectively. Flights 1, 2 and 3 show the roof from nadir position, flights 4, 5 and 6 display the same façade, while flight 7 depicts the roof.

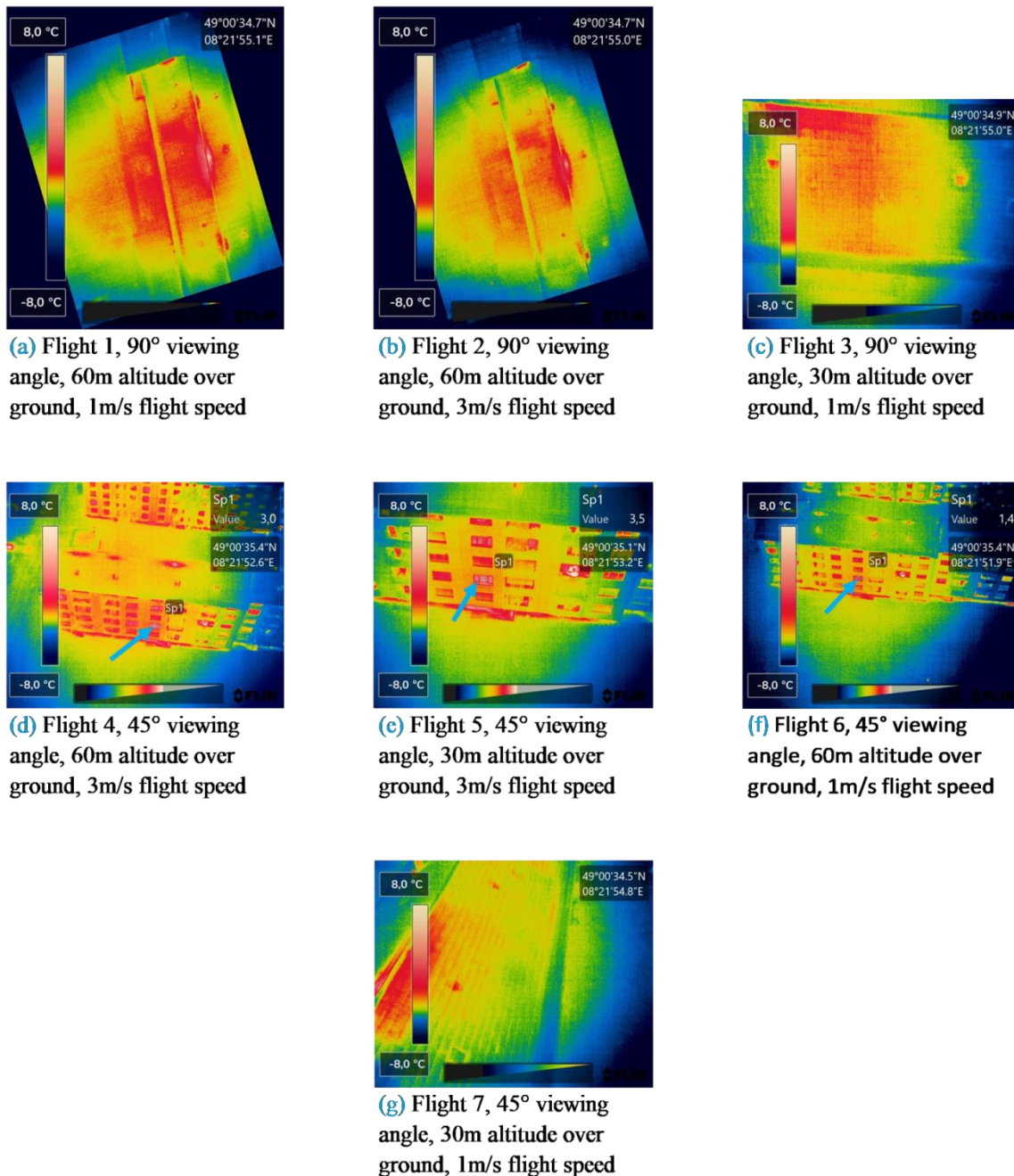


Figure 1. Aerial thermographic images of the building façade in Sophienstrasse 201-203 collected with a drone. The blue arrows in tiles (d, e, f) point to the same window as shown in Figure 2.

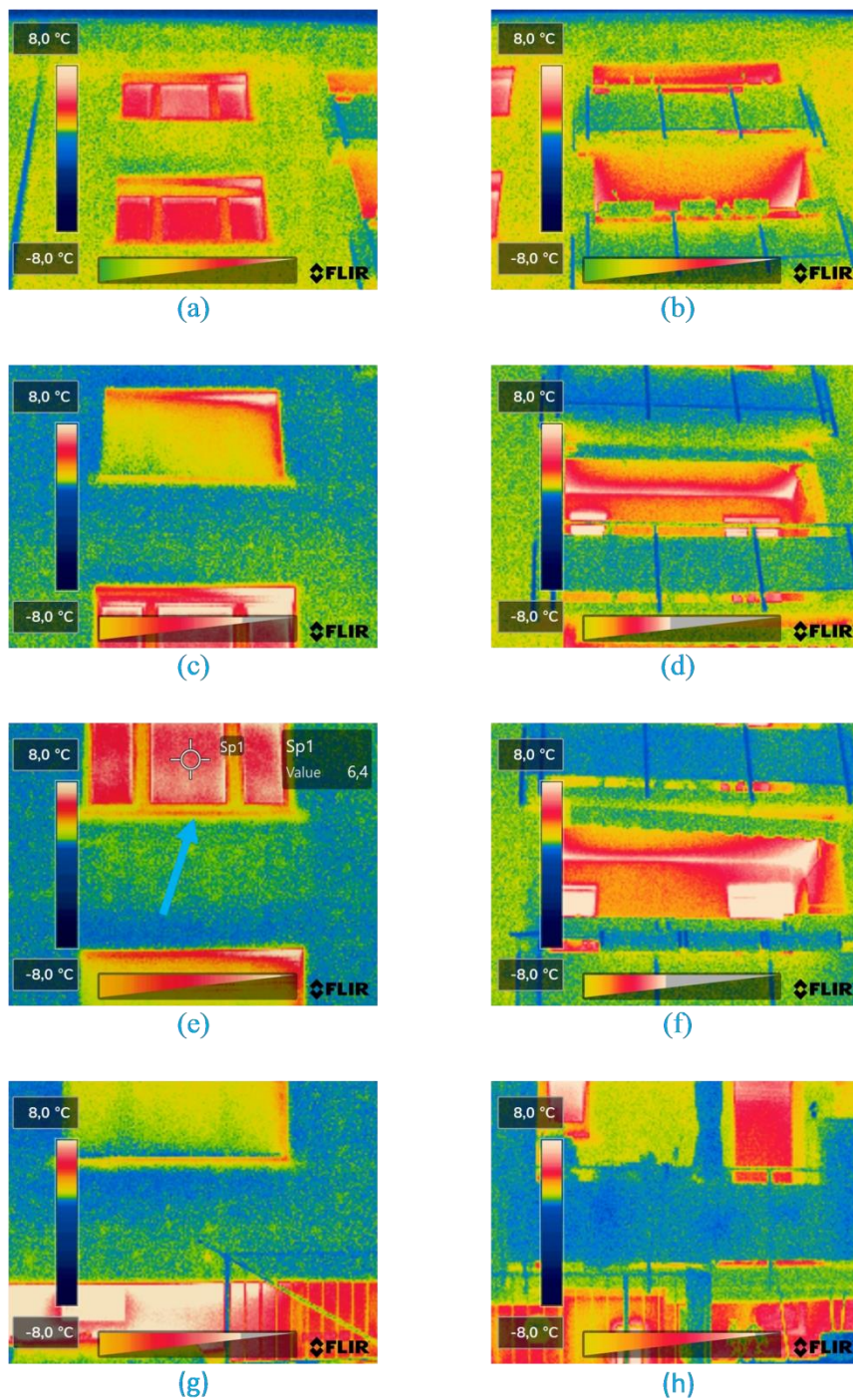


Figure 2. Terrestrial thermographic images recorded via hand-held camera showing the building façade in small segments at a distance of 8m. The blue arrow in the tile (e) shows the same window as the arrows in Figure 1.

2.2. Image Evaluation Criteria

We defined quality criteria to compare aerial and terrestrial thermographic images depending on motion, distance between camera and building, and the UAVs recording perspective:

- *Motion blur*: Motion blur occurs in image recording when the camera is moved during the capturing process. It leads to stripe-like, blurred areas in the images, which complicate the detection of thermal anomalies [23].
- *Contrast*: Contrast indicates differences in brightness and color within an image. The smaller an object appears on an image, the less contrast the image has, and the more difficult the detection of the object – as well as, in this instance, thermal anomalies upon it – becomes [24].
- *Visibility of image details*: The visibility of details can be influenced by the distance between the camera and a building as well as motion effects.³
- *Perspective*: The image perspective indicates which building parts can be recorded by a camera. It depends on the objects in the camera's field of view (e.g. trees), recording distance, and recording angle. The angle influences the visibility of certain thermal anomalies (e.g. those below eaves) and the reflection of infrared radiation (e.g. from windows).

Besides factors indicating the quality of the images, we defined a quantitative comparative criterium to identify thermal differences between terrestrial and aerial acquisition methods:

- *Comparative temperature difference*: The comparative temperature difference between the drone thermogram and terrestrial thermogram is defined as $\Delta T_{ij,kl} = T_{i,k} - T_{j,l}$, where $T_{i,k}$ is the temperature of the central point of a thermal anomaly on a thermographic image. Said image is recorded at a distance i of 8m (terrestrial), 12m, or 42m to the building, and viewing angle k defined as either t (terrestrial), o (oblique/45°), or n (nadir/90°). The temperature of the same point on another thermal image $T_{j,l}$ is defined by the distance j of 8m (terrestrial), 12m, or 42m to the building, and the viewing angle l – again either t (terrestrial), o (oblique/45°), or n (nadir/90°). Every such temperature value is determined using FLIR Thermal Studio's [22] Spot-function and denoted „Sp“ within the image. Since atmospheric air particles absorb infrared radiation, the temperature difference arises as a result of varying distances between building and camera. Greater distances can therefore distort image measurements. According to Fouad and Richter [21], the temperature deviation attributed to these factors is only negligible at distances of up to 20m. Another cause for thermal differences is the viewing angle; a steeper angle induces a change in emissivity. For angles greater than 60°, the emissivity becomes noticeably smaller and the temperature difference larger [21]. Quantifying the comparative temperature difference is important to deduce information on the usability of thermographic drone images for applications like the calculation of U-values (Section 1).

2.3. Image evaluation procedure

To evaluate the quality of the thermographic drone images, we manually checked all quality criteria according to Section 2.2. on the images of our dataset. For this, three exemplary building parts were selected, which are typically analyzed in thermographic building applications. We picked a window (indicated by the arrows in Figure 1 and Figure 2), a thermal anomaly located on the middle of the roof of Sophienstrasse 201-203, and a thermal bridge on the roof at the point where the building Sophienstrasse 201-203 connects to its neighbor. All three points are shown on exemplary thermal images in Figure 3. In total, we analyzed 21 aerial images and 24 terrestrial images in detail.

³ Besides physical influences, the visibility of details also depends on the resolution of an image. The UAV-based thermographic camera model is state-of-the-art and has an even better resolution than the hand-held one. The drone camera thus does not lead to a worse visibility of details than the hand-held camera (details on the camera models are given in Section 2.1.).

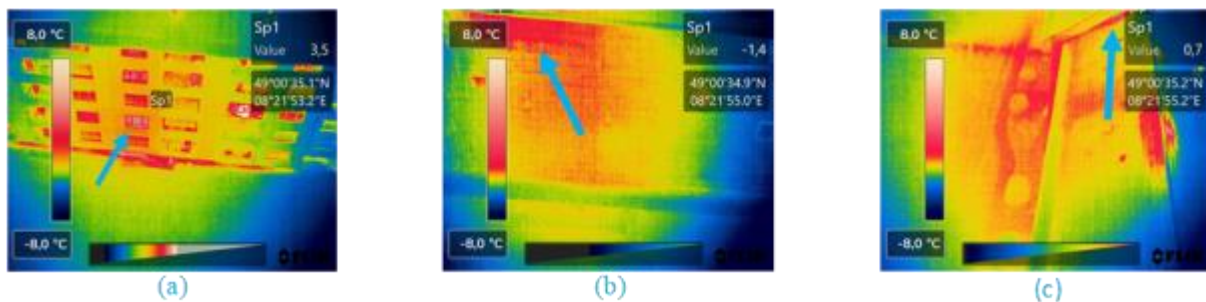


Figure 3. Three analyzed locations in Sophienstrasse 201-203 marked with blue arrows; (a) a window on the backside of the building; (b) a thermal anomaly on the roof near the ridge; (c) a thermal bridge below the eaves.

3. Results

For the analyzed dataset described in Section 2.1, we found the following results when considering the quality criteria defined in Section 2.2:

- *Motion blur*: In our dataset, none of the thermographic images show signs of blurriness in spite of the different flight speeds. We can therefore conclude that a flight speed between 1 and 3m/s allows for UAV-based thermal images without motion blur. For a greater efficiency during data collection, we recommend a speed of 3m/s instead of slower flight speeds.
- *Contrast*: The thermal color contrast in the images collected during flights 1 and 2 is weak and boundaries of the thermal anomalies can not be identified clearly. A reason for this could be the nadir viewing angle in combination with the large distance of at least 42m between camera and thermal anomaly. This value clearly exceeds the previously mentioned 20m limit above which a change in emissivity occurs. While inadequate contrast is given in all images recorded using those settings, the other flights display sufficient contrast.
- *Visibility of image details*: With increasing distance it becomes impossible to recognize certain details that are relevant for the interpretation of thermographic images. While thermal details like air leakages through window panes are clearly visible on terrestrial images, these details are not discernible at an altitude of more than 30m above ground. On images recorded with a flight height of 60m, it is not even possible to spot details like closed roller shutters (Figure 1 (d) and (f)). Other thermal anomalies solely visible on our terrestrial images include thermal bridges on the composite zone between window frames and panes as well as those on window sills. Thermal bridges on window frames themselves, however, can also be found in UAV-based images recorded at 30m (although they are indiscernible in those acquired at 60m).
- *Perspective*: All aerial thermographic images properly record building rooftops regardless of viewing angle. Flight 5 (minimal flight height, 45° angle) provides the best thermographic image of the rooftop, giving an optimal view of the full thermal bridge below the eaves. While the terrestrial perspective does not cover rooftops at all, it excels when used in window and building façade inspections. Window examinations can also be performed on images acquired at a 45° viewing angle, while the nadir perspective is not suitable for any façade analysis. As the results of both aerial flight modes do not differ in quality where roof inspections are concerned, the 45° viewing angle clearly is the more versatile option. It must be noted, however, that some examinations – for instance of balcony slabs and the underside of eaves – can only be performed on images recorded by hand-held camera.
- *Comparative temperature difference*: Regarding the analyzed window, a temperature difference $\Delta T_{60,8,0,t}$ of up to -5°C between the aerial (flight 6, $T_{60,o} = +1.4^{\circ}\text{C}$) and terrestrial ($T_{8,t} = +6.4^{\circ}\text{C}$) thermal images can be measured. A second comparison for the same window between an aerial image recorded at 30m altitude (flight 5, $T_{30,o} = +3.5^{\circ}\text{C}$) and the terrestrial one ($T_{8,t} = +6.4^{\circ}\text{C}$)

shows a temperature difference $\Delta T_{30,8,o,t}$ of up to -2.9°C . Where the rooftop anomaly near the ridge is concerned, a temperature difference $\Delta T_{60,30,n,o}$ of up to -1.7°C is measured between aerial images from flights 2 ($T_{60,n} = -1.1^{\circ}\text{C}$) and 7 ($T_{30,o} = +0.6^{\circ}\text{C}$). The thermal bridge on the roof displays a temperature difference $\Delta T_{60,30,o,o}$ of up to -3.4°C between aerial images from flights 6 ($T_{60,o} = -1.8^{\circ}\text{C}$) and 5 ($T_{30,o} = +1.6^{\circ}\text{C}$). All these examples show that larger distances lead to higher comparative temperature differences. This means that images recorded at 30m above ground (12m above the building) are preferable to those acquired at higher flight heights for rooftop and façade analyses via aerial thermography. For quantitative UAS-based thermographic applications, we see that a distance of 60m above ground (42 m above the building) leads to significant temperature falsification.

4. Discussion

Our study shows the influence of motion, distance, and recording angle of automated UAV-based thermal image acquisition on the quality of thermographic images. While the flight speed did not seem to have an influence on the image quality in our study, the distance and recording angle between the camera and building of interest can have a distinctly negative effect.

Our observations show thermal image quality to remain unchanged at low flight speeds of between 1 and 3m/s. We therefore suggest examining greater flight speeds to further increase the efficiency of the automated image acquisition process. While this contradicts Entrop and Vasenev's [14] experience of a 1.5m/s speed limit, recent advances in UAV technology may explain the new findings.

Varying distances and angles between thermal camera and investigated building surface can lead to a falsification of recorded temperature data, a lower contrast, and a decrease in visibility of image details, caused by a weakening of the returning infrared radiation or emissivity level. In our case study, we can clearly confirm the negative effect of increasing distances on these factors as described by Fouad and Richter [21]. Considering the pros and cons of different distances (30m and 60m above the ground) and flight angles (nadir and 45° angle), we can come to the following conclusion: The nadir perspective is suitable for analyzing rooftops, but provides no quality advantage compared to a flight angle of 45° , which additionally allows some façade analysis. Automated drone thermography is very suitable for the analysis of rooftops when choosing a medium flight distance such as 30m above ground (12m distance to the building). This setting (45° , 30m above ground) allows thermal patterns such as large thermal anomalies to be recognized. However, a quantitative temperature study and a detailed façade analysis is not possible owing to the comparatively large distance and steep angle of camera to building front. Images recorded at a 60m flight height (42m distance to the building) cannot be recommended for quantitative studies, although large thermal bridges and leakages are still discernible. This setting can still be advantageous if time constraints permit only a rough analysis of a district or building stock to identify larger areas of heat loss. Further statements on the thermal quality of specific buildings and areas then require more detailed analyses.

Despite the discussed revelations, our study suffers from some limitations. We only analyzed drone images of two buildings with merely seven different flight settings, all of which were recorded on the same day under similar weather conditions. On top of this, the quantitative analysis of the comparative temperature difference is only limited to three different points. Further comprehensive qualitative analyses are planned in follow-up work with more thermal images of buildings and additional evaluation criteria. We also intend to study different flight distances, higher flight speeds, and areas of different building types. Moreover, we want to structurally analyze the effort involved in UAV-based approaches compared to ground surveys by taking time and cost efficiency into account. Concerning our drone image data, it should be noted that all images include vignetting. The vignetting effect is a shadowing toward the edge of an image which falsely signals a higher intensity in the image's central region [25]. This is caused primarily by the camera itself. A technical optimization is planned to exclude this effect in future UAV-based images, for example by using a back-up aperture and thin rings as well as adapters to accommodate larger filters.

5. Conclusions

In this study, we compared the quality of automatically acquired UAV-based thermal images to classical terrestrial thermography via hand-held camera for building audits. For this, we collected a drone image dataset recorded using seven different flight settings of varying recording angle, flight speed, and distance above ground, as well as stationary terrestrial images with constant recording distance and angle. We investigated five quality criteria for thermographic images that we applied to three typical examples displaying thermal anomalies common to buildings.

We found that the studied flight speeds do not have a negative impact on the quality of thermography. On the other hand, large distances and steep angles to the building façade reduce the quality of thermographic images considerably. Automatic UAV-based thermography at a medium distance to buildings is especially suitable for the quantitative and qualitative analysis of rooftops. In this context, we see no advantage of the nadir perspective compared to a 45° angle. Analyses of images recorded at a very large distance are only suitable for efficient data collection and the qualitative recognition of patterns like large thermal bridges and air leakages. They do not allow for more detailed analyses nor give reliable quantitative information. Our results can be used for the structured planning of thermographic drone flights of large building stocks and will be improved upon by the authors in following studies.

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