OUTDOOR THERMAL ENVIRONMENT ASSESSMENT OF EXISTING RESIDENTIAL AREAS SUPPORTED BY UAV THERMAL INFRARED AND 3D RECONSTRUCTION TECHNOLOGY

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Abstract. The underlying surface temperature is an effective evaluation index to study the urban micro-scale thermal environment. For surface temperature acquisition, the thermal infrared camera mounted on an unmanned aerial vehicle (UAV) can reduce field work intensity, improve data collection efficiency, and ensure high accuracy at low cost. In order to convert the 2D thermal image into a more intuitive 3D thermal model, the UAV-based thermal infrared 3D reconstruction is adopted. The key element of thermal infrared 3D model reconstruction lies in the processing of thermal infrared images with low resolution and different temperature scales. In order to improve the quality of the final thermal 3D model, this paper proposes the reconstruction of the detailed 3D mesh using visible images (higher resolution), and map then mapping thermal textures onto the mesh using thermal images (low resolution). In addition, absolute temperature values are extracted from thermal images with different temperature ranges to ensure consistence between color and temperature values in the reconstructed thermal 3D model. The thermal 3D model generated for an existing residential area in Nanjing successfully displays the temperature distribution of the underlying surface and provides a valuable basis for outdoor thermal environment assessment.

Keywords. Thermal Image; UAV; 3D Reconstruction; Residential Outdoor Space; Underlying Surface Temperature; SDG 3; SDG 11.

1. Introduction

The development of urbanization brings large-scale construction which has significantly changed the urban pattern. Furthermore, the urban thermal environment has deteriorated, and this results in a reduction in the quality of the environment for urban residents. The comfort of the outdoor thermal environment has a direct bearing on the timing and frequency of outdoor activities. This is emphasized by the closed community management policy adopted in many locations after the outbreak of COVID-19. A healthy and comfortable outdoor thermal environment is necessary for residents to take part in outdoor activities.
It has been shown that the change in the underlying surface property caused by urban expansion has a significant impact on the urban thermal environment (Liu et al., 2021). The spatial distribution pattern and degree of coverage of urban vegetation confirm this (Huang et al., 2019). When examining current renovation of existing residential areas, an understanding of the impact of various underlying surface materials on the outdoor thermal environment can provide a scientific basis to determine the greening layout, tree species configuration and underlying material design for residential area renewal.

From the perspective of the residential thermal environment itself, various meteorological elements related to the site thermal environment are usually taken as evaluation indices. These include temperature, humidity, wind speed, solar radiation, etc. At present, these site thermal environment meteorological indicators are obtained from site meteorological measurements, software simulation and thermal infrared imaging technology. Although site meteorological measurements are very accurate, they require considerable manpower and expensive instrumentation for mobile observations in urban residential areas with strong internal environmental heterogeneity. Moreover, the observation point data cannot completely show the thermal environment in the space. Site models constructed using computer numerical simulation can have considerable differences from the actual site environment, as they do not consider the influence of regional microclimate on human thermal perception. These models do not provide sufficient guidance for precise design of small-scale outdoor environments. Thermal infrared technology converts the thermal infrared signals from ground objects into visually distinguishable images, and calculates temperature values to reflect the surface temperature distribution. At present, the surface temperature distribution map obtained by this technology is the most intuitive method commonly used in urban research to reflect the regional thermal environment (Wu et al., 2016; Zhao et al., 2020).

In recent years, lightweight thermal infrared products mounted on small UAV platforms have provided an efficient low-cost solution to obtain surface temperature (Tian et al., 2019; Rakha and Gorodetsky, 2018). Surface temperatures can be calculated from the color rendering of the thermal infrared images collected. However, the underlying surface temperature obtained in this way can only be displayed as a two-dimensional thermal infrared image. There is still a lack of effective methods for three-dimensional visualization analysis of the spatial distribution of surface temperature in the environment. In addition, due to the small viewing angle and the low resolution, the current two-dimensional thermal images do not meet the requirements for large-scale research areas.

To tackle this shortcoming, this study proposes a method to produce a 3D thermal infrared model by combining UAV thermal infrared images and 3D reconstruction technology. The proposed method converts the 2D thermal image into a more intuitive 3D thermal model. It can not only visualize the surface temperature distribution in space but also simply output temperature data at selected points for further analysis. This model can be used to evaluate the thermal environment in existing urban residential areas with complex spatial characteristics. This method is then adopted to build a 3D thermal model of an existing residential area in Nanjing. The results showed that the proposed method has good precision and efficiency. The heat gain difference
and internal mechanism of various surface underlying surfaces in existing residential areas revealed in the study can provide a scientific basis for outdoor environmental design in residential renewal.

2. Methodology

The methodology for the outdoor thermal environment assessment of existing residential areas using UAV thermal infrared data and 3D reconstruction technology consists of the following steps: data acquisition, 3D reconstruction and temperature analysis. These are shown in flowchart form in Figure 1.

2.1. DATA ACQUISITION

Data acquisition refers to the collection of visible and thermal infrared images of the study area using a camera on a UAV. In order to ensure the quality of data acquisition, it is necessary to plan the flight path of the UAV to ensure that the image data can be collected on this predetermined flight path whilst avoiding the risks and errors of manual data collection. The main parameters for route planning are the altitude, speed, camera angle and photo overlap rate, according to the scope and accuracy requirements of the research area. These parameters are used to generate the flight path for the UAV.

Before each take-off, it is necessary to input the real-time atmospheric temperature, humidity, emissivity and other parameters defining the prevailing weather conditions to improve the accuracy of temperature observation. Each data acquisition run is completed within a five-minute period to ensure that temperature data for different pictures in the run is unlikely to change much.

2.2. 3D RECONSTRUCTION

Similar to the three-dimensional reconstruction process for visible images, the recognition of feature points in thermal infrared images is the key to the success of three-dimensional reconstruction. Before starting the 3D reconstruction process, it is necessary to eliminate images that could influence feature point recognition due to color imbalance and blur.

The image resolution of a thermal infrared camera is usually much lower than that of an RGB camera, so the quality of the reconstructed 3D model is inferior to that of
the visible 3D model. In order to improve the quality of the final thermal 3D model, this study reconstructs a detailed 3D mesh using higher resolution visible images and then maps thermal textures onto this mesh. The specific process is defined as follows. The visible and thermal infrared images collected over one data acquisition period are imported into a 3D reconstruction software, Pix4Dmapper. Aerial triangulation is carried out by using the precise positional data from each visible and thermal infrared image, and the results of this aerial triangulation serve as a reference for the three-dimensional fusion of the two different image types. Feature point detection algorithms (SIFT, Scale-invariant Feature Transform) and feature point matching algorithms (SFM, Structure-from-Motion) are used to identify the same location points in each image and derive their 3D positions, so as to complete the sparse point cloud reconstruction. PMVS (Patch-Based Multi-View Stereo Software) technology is used to generate the dense point cloud. The Delaunay triangulation algorithm can then be used to construct an irregular triangulation network (TIN, Triangulated Irregular Network) from the dense point cloud. The thermal 3D model with thermal infrared texture is generated by mapping the thermal infrared image texture onto the TIN model.

2.3. VALIDATION AND ANALYSIS

It has been shown that the accuracy of temperature measurement by thermal infrared cameras is related to the shooting angle and the shooting distance. The thermal infrared camera mounted on a UAV experiences variable shooting angles and distances when acquiring thermal infrared images at high altitude due to variations in the flight altitude and pitching angle. In order to verify the accuracy of the temperature data obtained by the UAV thermal infrared camera, the surface temperature data for different positions at different camera heights and angles is obtained by means of control variables. Regression analysis is conducted. In order to verify that the same underlying surface does not show excessive temperature change within five minutes, the temperature data is analyzed to compare the readings before and after the five-minute period.

In order to obtain more accurate surface temperatures for different underlying surfaces, multiple sample points are selected for temperature measurement at different positions for each underlying surface in the study area. This eliminates potential errors that could be caused by single samples.

3. Case Study

3.1. STUDY AREA

A residential area in the Xuanwu District of Nanjing (Latitude 32.1 N, Longitude 118.8 E) is selected as the study area (Figure 2a).

Built in the 1990s, the residential area epitomized many old residential areas in Nanjing that are facing renovation and upgrading. Against the current background of urban renewal, research and analysis of the thermal environment characteristics of this area can be significant when formulating a renewal and transformation strategy for this and other residential areas of the same area. The size of the study area is approximately 165 m by 140m, with a homogenous base environment, including green space, water, buildings, hard pavement and other underlying surface types (Figure 2b).
3.2. DESCRIPTION OF DEVICE CONFIGURATIONS

The DJI Mavic 2 Enterprise Advanced (M2EA) is used for the acquisition of visible image and thermal infrared image data. The M2EA is equipped with advanced dual-light cameras, including a 640×512 resolution thermal infrared camera and a 48-megapixel visible camera using a 1/2 inch CMOS sensor (Table 1). The onboard RTK module enables the M2EA to accurately locate, ensuring that visible and thermal images acquired simultaneously have similar external orientation parameters.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Thermal</th>
<th>Visible</th>
<th>Photo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length</td>
<td>38mm</td>
<td>24mm</td>
<td></td>
</tr>
<tr>
<td>Image size</td>
<td>640×512</td>
<td>8000×6000</td>
<td></td>
</tr>
<tr>
<td>Image format</td>
<td>DJI R-JPEG</td>
<td>JPEG</td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>-40-150°C</td>
<td>——</td>
<td></td>
</tr>
</tbody>
</table>

3.3. ROUTE PLANNING AND DATA ACQUISITION

Before formal data acquisition, the UAV is tested, and the relevant shooting parameters are set. The meteorological parameters required for thermal infrared camera correction are obtained from the values taken at the handheld weather station at the operation point. The emissivity is uniformly set to 0.95, and the color bar is set to iron red.

Route planning is done using the specific software DJI poilt V2.3 configured for the M2EA. The route coverage area is defined to as the study area. In the relevant interface, the route type is created as oblique photography, and the relevant route parameters set at the same time. Existing studies have found that the effect of 3D reconstruction is optimum when the route height is twice the height of the photographed object (Han et al., 2019). In this exercise, the route height is set at 60 meters. The flight overlap rate and the side overlap rate are both set to 70%, and the camera angle for oblique flight is -60° (Figure 3). After the first route setting, it was verified that there were no overlaps between the planned route and high buildings in
the surroundings, so as to avoid risk of collision during the process of data acquisition.

In order to effectively observe temperature change in the underlying surface for the existing residential area, data acquisition was carried out on November 14, 2021. The M2EA took off every hour between 8:00 and 17:00 throughout the day to complete the mission and obtain the corresponding visible and thermal infrared images. Since the focus was on the surface temperature of the underlying material and to ensure that the flight time did not exceed five minutes, the planned route consisted of only a single orthographic route. For verification of the 3D reconstruction, all planning routes were carried out at 12:00. About 150 visible and thermal infrared images were obtained for each mission at each time point (Figure 4). An additional 370 photos were obtained for the planning route mission at 12:00.

3.4. DATA PREPROCESSING AND 3D IMAGING

The data acquisition steps obtained several original thermal infrared images with location information and temperature information. The temperature data in these JPG files can only be used in the DJI Thermal Analysis Tool V2 for simple temperature measurement, and cannot be recognized by other software. In order to utilize the temperature data in the reconstruction process, it is necessary to convert the original picture file into an R-jpg file that can be recognized by FLIR or pix4d mapper to extract the data. The ThermoConverter software is used for conversion, and batch processing made this a quick process.

![Figure 5. Thermal 3D model (a, b) and thermal ortho map (c) of study area](image)
The processed data is imported into the pix4D Mapper software one by one for each time period, and the single reconstruction process is rapidly completed. Thermal infrared texture mapping on the visible 3D model is realized by combining the initial processing results from the two reconstruction projects (visible image and thermal infrared image project). After merging the projects, in the advanced settings for the processing options, the point cloud group is selected as the visible image, and the mesh texture is checked as the thermal infrared image. The reconstructed thermal 3D model is shown in Figure 5(a, b).

The reconstructed ortho map can display the temperature information through the relevant settings, by generating the index map through the index calculator (Figure 5c). The temperature data can be obtained by clicking the mouse, and the numerical information (exponential value) is shown at the lower right of the software interface.

4. Results and Discussion

4.1. THE ACCURACY OF 2D THERMAL IMAGES

Existing studies have discussed the relationship between flight altitude and thermal infrared temperature measurement accuracy (Tian et al., 2019). In this case study, the temperature measurement data of the same underlying surface at two flight altitudes of 10m and 60m are obtained at the same time for analysis. The results show little difference in the surface temperature measurements taken at different flight altitudes, and the error is within the allowable range after calibration of the thermal infrared camera.

![Figure 6. Linear regression plot of temperature before and after the time interval(a), Linear regression plot of temperature at two different shooting angles(b)](image)

The temperature data at different locations before and after five-minute intervals are obtained by thermal infrared temperature measurement, and regression analysis is carried out (Figure 6a). The analysis shows that the surface temperature changes little during this time interval. Therefore, it is feasible to select images within five-minute intervals for 3D reconstruction when extracting surface temperatures for different
underlying surfaces.

Since 3D reconstruction requires the fusion of thermal infrared images from different shooting angles, it is necessary to verify the correlation between temperature values at different shooting angles. The results show that the temperature values at two different shooting angles (60° and 90°) have a high degree of fit, with a Pearson correlation coefficient of 99.6%, which is significant at the 0.01 level (Figure 6b). This analysis shows that it is feasible to select thermal infrared images from different shooting angles for 3D reconstruction.

4.2. THE EFFICIENCY OF THE THERMAL INFRARED 3D MODEL

In a similar manner to three-dimensional reconstruction of visible images, the efficiency of thermal 3D model reconstruction is closely related to altitude and image overlap. With the same image overlap, the lower the UAV altitude, the higher the corresponding ground resolution. This results in better resolution of the reconstructed model, but also a correspondingly longer software processing time. In addition, it becomes necessary to increase the flight time to obtain sufficient images to meet the set overlap rate, and this has a negative effect on the time-sensitive thermal infrared temperature measurement.

With the 70% overlap rate adopted in this case study, the ground resolution of the thermal infrared image is 7.79 cm / 3.07 in. The time-related statistics for the whole stage are shown in the Table 2. It can be seen that all external and internal steps can be completed in a relatively short time to obtain a thermal 3D model for the study area. When compared with traditional field weather measurement, this approach using UAV thermal infrared technology is more efficient and obtains temperature data over a large area in a short time.

<table>
<thead>
<tr>
<th>Steps</th>
<th>Time consuming</th>
</tr>
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<tbody>
<tr>
<td>External</td>
<td></td>
</tr>
<tr>
<td>Route planning</td>
<td>2min</td>
</tr>
<tr>
<td>Data acquisition</td>
<td>5min+4*6min</td>
</tr>
<tr>
<td>Image convert</td>
<td>10min</td>
</tr>
<tr>
<td>Initial Processing</td>
<td>6min (Thermal)+38min (Visible)</td>
</tr>
<tr>
<td>Internal</td>
<td></td>
</tr>
<tr>
<td>Point Cloud Densification</td>
<td>50min56s</td>
</tr>
<tr>
<td>3D Textured Mesh Generation</td>
<td>12min21s</td>
</tr>
<tr>
<td>Index map generation</td>
<td>1min19s</td>
</tr>
<tr>
<td>Total</td>
<td>150min</td>
</tr>
</tbody>
</table>

4.3. THE INFLUENCE FACTORS OF UNDERLYING SURFACE TEMPERATURE

In this study, measurements are taken for different underlying surface types in the region. These consist of four kinds of artificial underlying surface, namely concrete, asphalt, square brick (brick1) and floor brick (brick2), and three kinds of natural
underlying surfaces, water, grass and shrubs. The daytime variation characteristics of
the surface temperatures for the different types of underlying surfaces are analyzed, as
shown in Figure 7.

During the observation period, the daytime variation curve for the seven underlying
surfaces showed a single trend, rising from 08:00, reaching a peak around 14:00, and
then decreasing. The rate of increase and decrease of the artificial underlying surfaces
is significantly higher than that of the natural surfaces. The daily maximum temperature
of the constructed surfaces is generally about 15°C above that of the natural underlying
surfaces.

Among the three kinds of natural underlying surfaces, the temperature changes in
grassland were the most drastic. The temperature variations for the water and shrubs
are low, showing good temperature stability. Water has a high specific heat capacity
and strong heat absorption capacity, and solar radiation does not have much effect on
the water surface temperature. In addition, water evaporation keeps the temperature
stable. The important factors affecting vegetation surface temperature are solar
radiation and vegetation transpiration. However, the grass in the study area is short and
not shaded, and transpiration of vegetation was not obvious when receiving solar
radiation, so the cooling effect was not as effective as that of shrubs.

Figure 7. The daytime variation in temperature for different types of underlying surface

Amongst the four kinds of artificial underlying surfaces, the temperature changes
in a day differ due to the different absorption and radiation characteristics of the
materials. Concrete has the highest heat absorption and the most drastic temperature
change, followed by the asphalt pavements. This shows that concrete and asphalt have
the greatest impact on the thermal environment in residential areas.

5. Conclusions
This paper introduces the use of UAV-mounted thermal infrared cameras and 3D
reconstruction technology to analyze and evaluate the mechanisms by which
underlying surface materials influence the outdoor thermal environment. The major
findings follow.

The mapping texture of thermal infrared images onto a visible 3D model can produce a high quality thermal 3D model. The extraction and application of absolute temperature values in thermal images of different temperature ranges can ensure the consistency of color and temperature values in reconstructed thermal 3D models. Verification and data analysis indicate that this thermal 3D model has high accuracy and efficiency. In addition, the model can effectively display the surface temperature distribution at any point in the research area.

In the case study, the underlying surface temperature of a typical residential area in Nanjing is investigated in detail. The statistical analysis of temperature is used to determine the heat gain in different underlying surfaces during daytime. Solar radiation has a significant effect on the heat gain of the underlying surfaces, and the shielding of buildings or tall trees can obviously reduce the heat gain. The temperature of the natural underlying surfaces is clearly lower than that of the constructed surfaces. In the renovation design of outdoor spaces in existing residential areas, the outdoor thermal environment can be improved through the use of green layouts, tree species configurations and underlying surface material design.

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References


