COMBINATION OF THERMAL INFRARED IMAGES AND LASERSCANNING DATA FOR 3D THERMAL POINT CLOUD GENERATION ON BUILDINGS AND TREES

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ABSTRACT:

The thermal infrared study of urban environments is of growing interest. It allows to observe the variations of surface temperatures on objects over time and therefore the microclimate at the scale of a street. To facilitate the analysis of thermal interactions between urban elements, it is necessary to provide a 3D visualization of the thermography of a street. For this purpose, 3D thermal models combining geometric and thermal infrared (TIR) measurements are required. The chosen format for 3D thermal models is a point cloud with a temperature attribute. In our approach, two types of urban components are considered: buildings and trees. The geometric data of each component are acquired with a static laser scanner and the surface temperature is acquired with a thermal handheld camera. For the building, the approach consists in georeferencing TIR images and colorize the point cloud by projection. For trees, the approach consists of the colorization of each laser scan prior to the registration. The spherical panoramic images acquired with the Terrestrial Laser Scanning (TLS) are used as references to automatically georeferenced the TIR and thus to save time. The 3D thermal models obtained highlight the impact of sunlight on buildings and trees. At building scale, this thermal representation also helps to emphasize thermal bridges, as well as the shadow generated by surrounding trees. At tree scale, this representation is useful for monitoring the temporal and spatial variability of trunk's and leave's temperatures. Obviously, the thermal models underline the impact of trees on the urban environment.

1. INTRODUCTION

The thermal study of buildings and trees is essential in urban climatology. It allows a better understanding of the microclimate of a street, a district, or a city if large scale data are available. Trees, thanks to their evapotranspiration and their shadows, cool the air and improve the comfort of the residents. Thus, they are particularly beneficial during heat waves. These different phenomena as well as the thermal interactions between the different urban elements can be observed by measuring surface temperatures with thermal cameras.

The aim of this study is to produce a 3D thermal model of a site which will allow in the long term to validate 3D thermal predictions produced with microclimate simulation models. The 3D visualization of the thermography of a street facilitates the understanding of thermal interactions between urban objects and the local climate. However, the combination of 3D geometry of urban scenes with thermal infrared measurements taken from thermal cameras is not trivial.

The study area is located in Strasbourg (France) and covers three streets with three different tree species. Many sensors have been installed on several trees and around them in the streets to analyse the behaviour of plants in their urban environment but also their robustness regarding heat waves. In addition, periodical acquisitions with a static laser scanner (3D geometry in form of point clouds) and with a thermal camera (2D thermal images) are performed in the streets. Static laser scanners are widely used to acquire 3D geometric information in a fast and accurate way. These devices are usually equipped with a camera that produces panoramic images of the scene to colorize point clouds of each scan.

At this stage, only building facades and trees are considered. For both, a methodology for the combination of 3D geometry and thermal images is proposed. Building facades are flat and unlikely to change over time. Trees are more complex from geometrical and temporal point of view. The ramification of the branches and the foliage make the geometry of a tree complex, and it might change from one season to another. Thus, the general approach must be adapted to every object under study.

This paper is composed of four main parts. First, the related works about 3D geometry and thermal information combination are summarized. Then, the sensors for the acquisition of geometric and thermal data are presented. Subsequently, the developed methodologies for buildings and trees are explained. Finally, results of first experiments are presented and discussed.

2. RELATED WORK

The combination of geometric and thermal data is a current topic not only in climatology, but more generally in the field of multi-sensors data processing. Since the thermal information is generally captured as images, the developed methods are often based on photogrammetry, with the additional use of RGB photographs. After a calibration step, it is possible to deduce the exterior orientation parameters (position and orientation in a coordinate system) of TIR images (Macher and Landes, 2022) from the orientation of RGB images.

3D thermal models are proposed by many authors as 3D triangulated textured models (Previtali et al., 2013) or thermal point clouds. The latter are produced directly from TIR images (Grechi et al., 2021) or by colorizing a point cloud produced for

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instance from a laser scanner with the pixel value extracted from TIR images (Zhu et al., 2021).

Two categories of methodologies arise from the literature review: those adapted for the building modelling and those for the trees modelling. Indeed, most of the methodologies implemented in the literature have been validated for buildings but are not suitable for trees. In general, thermal point clouds of trees are produced from the fusion of several thermal laser scans taken independently. Each laser scan is previously colorized separately by projection of thermal information on the 3D points. Then, the different scans are merged to avoid any colorization problem related to the complex geometry of the tree (Hosoi et al., 2019).

Other authors exploit the spherical panoramic images taken from the laser scanner and use them as a reference image. Additional photographs can then be automatically aligned using matching algorithms. In this way, a link is created between the 3D data and photographs (Bruno et al., 2022). The same process of referencing is interesting when setting up a photogrammetric reference block. After the alignment of photographs and their georeferencing with control points, additional photographs can be automatically added to the block (Vincke et al., 2020). It is particularly interesting when dealing with several acquisitions of the same area over time, i.e., for monitoring purposes, as in our case.

3. 3D AND TIR DATA ACQUISITION

Numerous 3D geometric data of the study site have already been acquired in the last few years using various sensors (laser scanner, tacheometer). Regarding thermal information acquisition, a handheld imaging thermal camera has been used.

3.1 3D geometric data

After setting ground control points per polygonation with a total station and GNSS, the georeferenced point cloud of the whole site could be produced using static laser scanning systems. The resulting point cloud of the whole study area will serve in a further step as the geometric basis for the 3D thermal model. Table 1 presents a synthesis of the different point clouds acquired with their characteristics.

Acquisition system	Number of points	Site covering X-Y-Z (m)	RGB information
Faro Focus 3D X330	359 812 496	189 – 86 – 23	yes
Trimble X7	1 654 961 104	208 – 193 – 21	yes
GeoSlam Zeb-Revo RT	1 747 814	180 – 127 – 14	no
GeoSlam Zeb-Horizon	53 129 975	197 – 96 – 20	no

Table 1. Summary of the characteristics of the point clouds

The point clouds acquired with a mobile system show a lot of noise compared to those acquired with a fixed system. Moreover, the density of points is lower which make the 3D modelling of urban environment more difficult. Therefore, point clouds acquired with a static laser scanner are considered in the developed methodologies. It should also be noted that the point clouds were taken from a pedestrian perspective. The point density of the clouds at the rooftop level is thus lower.

3.2 Thermal infrared data

To acquire thermal data on a site, the use of an imaging TIR camera is appropriate. By detecting the electromagnetic radiation emitted by objects in the thermal infrared wavelength range, the IR sensor produces temperature matrices. These are transformed into thermal images via a colour scale.

In this project, the thermal infrared camera FLIR T560 equipped with a lens of 42° is used. It has the advantage of being equipped with a RGB sensor which acquires images in the visible part of the spectrum in addition to its infrared sensor. The IR sensor can measure temperatures between -20 °C and 120 °C with an accuracy of 0,3 °C. However, even if the infrared thermography sensors tend to improve, the resolution of TIR images remains lower than that of RGB images. In our case, TIR images have a resolution of 640 x 480 pixels and RGB images have a resolution of 2592 x 1944 pixels. The geometric and radiometric calibration of the camera used in this study was conducted in the work of Macher and Landes (2022).

4. DEVELOPED COMBINATION METHODOLOGIES

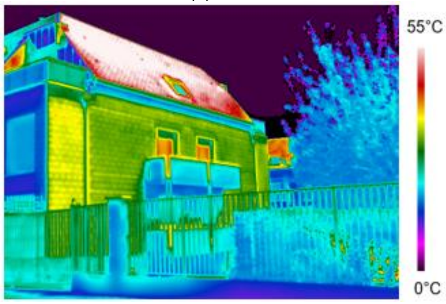
4.1 General approach

The use of textured meshes for thermal 3D models of buildings and trees is not satisfying. Indeed, textured meshes do not allow an easy access to temperature information on a specific point that’s why the creation of thermal point clouds was preferred in this study.

The detection and matching of points of interest is more difficult within thermal images than within RGB photographs. The production of 3D thermal point clouds based on IR images have a lower geometric accuracy than a point cloud acquired with a terrestrial laser scanner.

The solution thus chosen is to colorize a point cloud acquired from a static laser scanner with radiometric information extracted from TIR images. The general approach takes benefit of the ability of the thermal camera used for the study to take RGB images besides TIR images. Figure 1 shows a RGB photograph and a TIR image for the same camera position and orientation.

(a)



(b)

Figure 1. RGB photograph (a) and TIR image (b) of a building

The main idea of the developed methodologies is that, based on the orientations of RGB photographs and the relative position and orientation of RGB and TIR sensors, it is possible to deduce the exterior orientation parameters of TIR images. Then, TIR images can be projected on a georeferenced point cloud. Finally, a temperature information can be assigned to every 3D point. This constitutes what we call a 3D thermal point cloud. Thermal information provided by IR images are not directly usable. The thermal camera must be before all geometrically calibrated, and the thermal images must be recoded in a format suitable for the transfer of temperature values.

4.2 Pre-processing of thermal information

Thermal images are produced from a temperature matrix and a colour scale. Since the IR images are in colour, the pixel values correspond to a RGB code, not a temperature value. Thus, to easily retrieve the temperature information for each point, the temperature matrices must be recoded into a format suitable for transferring the thermal attribute values to the point cloud. The numerical count of the pixels of the images projected on the point cloud should allow to find the temperature value. For that purpose, the temperature matrices are transformed into a 16-bit mono-band image. This coding extends the range of values to 65536. Since the values in this range are positive and thermal values might be negative, the temperatures initially in Celsius degrees (°C) are converted into °Kelvin degrees (°K). Finally, to make the best possible use of this range of values, the data are expressed in centiKelvin. Thus, each temperature of the temperature matrix in °C is converted according to equation 1.

$$T\,(°cK\,) = (\,T\,(\,°C\,) + 273.15\,) \times 100 \qquad (1)$$

where T = temperature

A simple conversion can be carried out to retrieve the temperature value in °C of a given point in a thermal cloud. Specifically, the possible temperature values might lie between 0 cK and 65536 cK which corresponds to a temperature range of -273.15 °C to 382.21 °C.

4.3 TIR camera calibration

To geometrically correct the RGB photographs and TIR images, it is necessary to calculate their internal orientation parameters. Additionally, it is essential to calculate the relative parameters of translation and rotation between the RGB sensor and the TIR sensor. Those information are used for the positioning and orientation of TIR images based on RGB photographs.

4.3.1 Interior orientation: The interior orientation consists in the calculation of the coordinates of the main point and the distortion coefficients of the RGB photographs and TIR images. The objective is to facilitate the photogrammetric calculations but also to reduce the inaccuracies of georeferencing of the photographs. As explained by Macher and Landes (2022) in a previous study, a checkerboard was created specifically. It can be detected simultaneously in the visible and infrared range. The checkerboard is placed on the ground and several photographs are taken with the thermal camera mounted on a tripod.
The internal orientation parameters of the photographs are calculated thanks to the MATLAB (MathWorks) application Camera Calibrator. This application automatically detects the checkerboard tiles for the calculation of the desired parameters. During this calibration, the two sensors were considered individually. Thus, a second calibration step is necessary to calculate the relative position and orientation between the RGB sensor and the TIR sensor.

4.3.2 Relative position and orientation between RGB and TIR sensors: The objective is to calculate the position and orientation parameters of the TIR sensor with respect to the RGB sensor. These will subsequently deduce the parameters of exterior orientation of TIR images from the calculation of those of RGB photographs without having to detect and match points of interest on the thermal images.
To do this, the data acquisition consists in taking an RGB photograph and a homologous TIR image for each position and orientation of the thermal camera. Once the relative orientation is calculated for all RGB photographs and their corresponding TIR images, the translation and orientation parameters between the two sensors are calculated.
The parameters were calculated automatically in Metashape (Agisoft) through the alignment of the RGB photographs with their TIR images on pairs of photographs of a building. The acquisition distance was about ten meters. The angles to be calculated are very small. Thus, the greater the acquisition distance, the greater the precision of the calculations.

4.4 Methodology developed for buildings

The geometry of the buildings is very unlikely to change over time. Thus, since the point cloud of the study site is already available, the acquisition phase is limited to taking RGB photographs and TIR images with the thermal camera. Using a tripod, several pairs of images (RGB and TIR) are taken ensuring a sufficient coverage of 60% between RGB photographs. The use of a tripod avoids instabilities occurring when changing the mode of acquisition of the photographs (RGB mode to TIR mode). A camera mode allows to take simultaneously a RGB photograph and a TIR image but in this case, the RGB photograph is resampled, and its resolution is strongly decreased. In addition, the pairs of photographs are taken as perpendicular as possible to the façade. This condition facilitates their processing by the algorithms of detection and matching of points of interest.
Once the thermal data is prepared (recoloured images and temperature matrices converted to centiKelvin) in FLIR Research Studio (Teledyne), the data set is composed of a series of three layers: a RGB photo, a coloured TIR image and a temperature matrix coded in 16 bit.
In order to register both TIR and RGB images, the exterior orientation parameters of the TIR images are computed from the position and orientation of the RGB photographs as well as the relative offset parameters between the RGB sensor and the TIR sensor. For these steps, the photogrammetry software Metashape (Agisoft) is used and more particularly the multi-camera system option.
After detecting and matching points of interest, the RGB photographs are aligned and then georeferenced manually using ground control points. The position and orientation of the thermal images are determined using the offset parameters between the RGB and TIR sensor. The point cloud acquired with a static scanner of the building is imported and then colorized by projection of the thermal images. Finally, the temperature in centiKelvin of each point is converted back into °Celsius.
The result is a thermal point cloud as shown in Figure 5. For each point, in addition to its coordinates, several attributes are assigned: a RGB code corresponding to the visible range, a RGB code corresponding to the colour obtained from the thermal images and finally a temperature field in °Celsius. The methodology for buildings is schematized in the Figure 2.

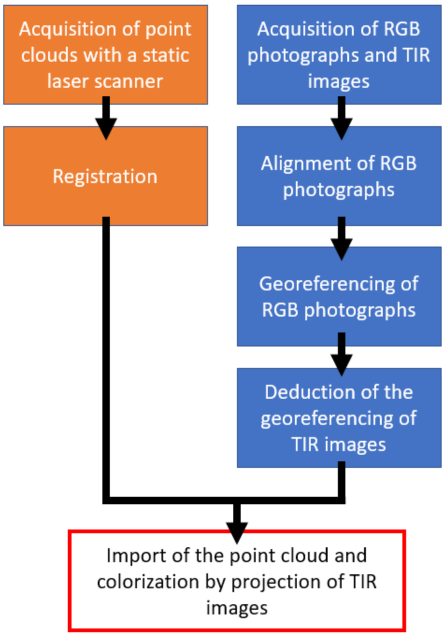


Figure 2. Diagram of the different steps for the methodology developed for buildings

4.5 Methodology developed for trees

With their leaves and roots, trees can get all the resources they need to grow. Deciduous trees also lose their foliage in autumn. In addition, in urban areas, some trees are pruned. All these reasons reflect a change in the geometry of the tree. Thus, the 3D geometric data must be acquired at several time to follow the 3D geometry of trees.
On the other hand, the geometry of a tree is complex because of its foliage and branching. A simple colorization by projection on a complete point cloud of a tree is not adapted. Indeed, points that do not correspond to any pixel of a thermal image might be colorized because of the projection of photogrammetric data on the entire depth of the cloud.
The approach implemented in this work aims to produce thermal point clouds for each laser scan and then merge them to obtain a complete 3D thermal model of the tree. This method is inspired by the studies of Yandún Narváez et al. (2016) and Hosoi et al. (2019).
The acquisition of geometric and thermal data consists of performing a laser scan with a static laser scanner and then standing approximately at the same location with the thermal camera mounted on a tripod to acquire RGB photographs and TIR images of the tree. This approach avoids the problem of colorization in depth since part of the field of view of the laser scanner corresponds to that of the thermal camera. This operation is performed several times around the tree to multiply the shots and avoid occlusions. The different laser scans are then registered and georeferenced. In addition, to obtain a dataset composed of a series of three layers as above, photogrammetric data are pre-processed.
The next step consists of the calculation of the exterior orientation parameters of the 3-layers images. For this, in a similar way to the coupling methodology proposed for buildings, it is necessary first to calculate the position and orientation of the RGB photographs to deduce those of the corresponding TIR images using the relative parameters between the two sensors of the camera.
Unlike buildings, the characteristic points of a tree are difficult to discern. Thus, the placement of points of interest on photographs taken around a tree is delicate, especially if no nearby building is visible on the pictures. The new idea implemented to overcome this problem is to use automatic algorithms to detect and match points of interest between the RGB photographs taken with the thermal camera and the referenced spherical panoramic photograph taken by the laser scanner during laser scanning.
For each laser scan and its corresponding set of 3-layers images, the link between the panoramic image from the scanner and the RGB photographs is performed. The multi-camera system approach allows to deduce the exterior orientation parameters of the TIR images. The point cloud of the laser scan is then imported and colorized. The colour associated to each point is determined by the common referencing system of the photogrammetric data and the point cloud.
Once all the laser scans have been processed, they are merged to obtain the whole thermal point cloud of the tree. In the same way as the method described for buildings, the temperature in centiKelvin is converted back to Celsius degrees. The methodology developed for trees is schematized in the Figure 3.

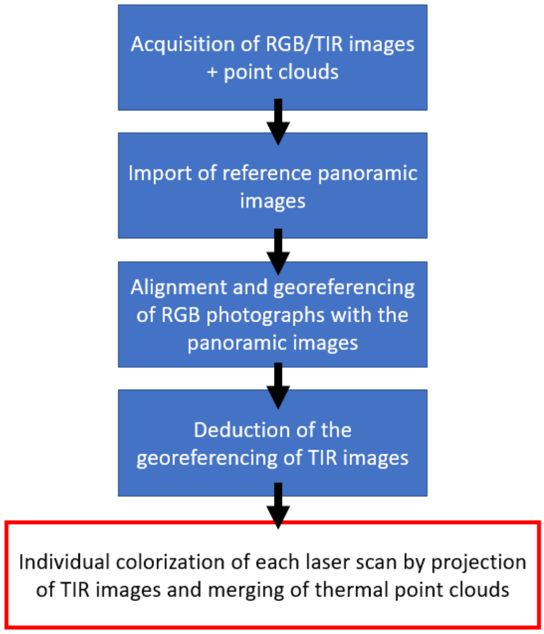


Figure 3. Diagram of the different steps for the methodology developed for trees

5. RESULTS OF FIRST EXPERIMENTS

As first experiments, previously presented methodologies were tested on a building and a tree. The radiometric evaluation of the results is difficult at that stage. Indeed, to assess the accuracy of the temperatures displayed on the models, it would be necessary to take the temperature at some remarkable points of the modelled elements with a thermal radiometer. However, this requires having access to the house, but these are private properties. For these reasons, while waiting to have the authorization to carry out this operation, the results are analysed mainly from a geometric point of view.

5.1 3D thermal modelling of a building

The building façade chosen for the 3D/TIR combination experiment is about 27 m long and 12 m high. Using a tripod, 36 pairs of photographs (36 RGB photographs and 36 TIR images) were acquired to cover the entire façade and ensure a high overlap between the RGB photographs. These were taken to be as perpendicular as possible to the facade.

Once the data is processed, the image triplets are imported into Metashape and the initial parameters are entered (interior orientation parameters of the two sensors and their relative offset parameters). In addition, masks are set up on the TIR images. These masks cover the whole of each image of the thermal dataset and are similar to black masks so that TIR images are not considered in future alignment calculations. A cloud of tie points is then automatically created through Structure from Motion (SfM) algorithms. To gain in accuracy, the calculations are then optimized: the tie point cloud is cleaned according to the point reprojection error criterion with a value of 0.5 pixels and the relative image orientation settings are compensated. This operation is repeated until the total reprojection error is about 0.5 pixels.

The next step consists in calculating the spatial transformation of the photogrammetric data using control points. The coordinates of these have been extracted from the available georeferenced point cloud of the street. These points correspond to points that are easily identifiable on the RGB photographs. A total of 26 points were used, i.e., 15 as control points and 11 as check points. These are evenly distributed throughout the building façade. The tie point cloud produced from the RGB photographs, and the distribution of the control points is shown in Figure 4. We can notice that the cloud of tie points covers the major part of the façade as well as the visible part of the roof. Since the alignment of the TIR images is voluntarily blocked during the calculations, the software does not allow to put check points on these images, even if they are in practice positioned and oriented in space via the translation and rotation parameters between the two sensors.

The standard deviation observed for the control points reaches 1.2 cm and that of the check points is 1.1 cm for the georeferencing of RGB photographs. These results are satisfactory in view of the accuracy associated with the point clouds from which the coordinates of the points are derived. The points with the largest error values are those difficult to discern on the photographs.

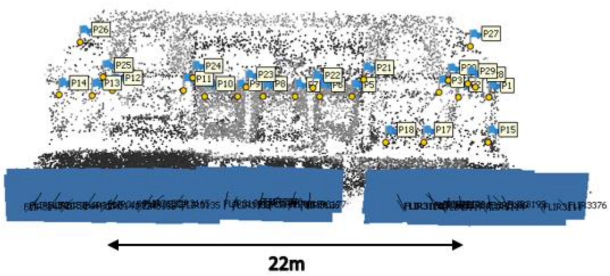


Figure 4. Tie point cloud of the façade as well as control points and check points

After importing the point cloud, all the photogrammetric data is projected onto it. When a pixel crosses points, colorimetric and thermal information are transferred. The resulting cloud is visible in Figure 5. Temperatures lie between 10 and 50 °C. The coolest temperatures correspond to the tiled part of the façade in the shade and the warmest temperatures to the tiles of the roof exposed to the sun. The thermal point cloud highlights the impact of sunlight on the façade, as well as the temperature of the different materials composing the facade. However, we can notice on the thermal point cloud some "overflows" coming from the colorization by projection (circled in yellow on Figure 6). This case appears when the angles of the photographs are not perpendicular to the façade or for some elements of the façade which are too thin. Another artefact is presented in the red circle on Figure 6. It is explained by the projection of a fence on the point cloud. This is due tie the fact that the point cloud was acquired prior to the photographs and the environment was modified between both acquisitions.

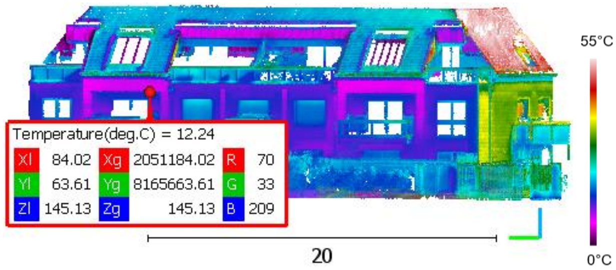


Figure 5. Thermal point cloud produced with the proposed methodology of combination – case of a building façade

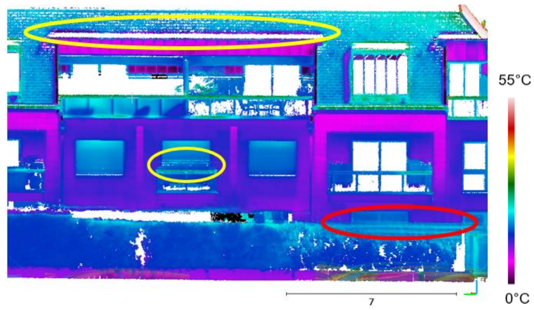


Figure 6. Visible errors in projection colorization. The elements circled in yellow correspond to "overflows" coming from the colorization by projection. The elements circled in red correspond to an element appearing on the photos but absent in the point cloud

Another important element to emphasize is the acquisition time of RGB and TIR photographs. This must be as short as possible to obtain a good consistency of temperature measurements. In our case, to obtain 36 pairs of photographs (RGB and TIR), the duration of data acquisition was about 40 min which represents about one pair of photographs per minute. For the study of a building, this time is acceptable. However, for the study of an entire street, this time is still long. The use of a reference photogrammetric block ensuring the necessary overlap beforehand might alleviate this problem and automate the georeferencing (Vinck et al. 2020).

5.2 3D thermal modelling of a tree

The tree studied in this work is a lime tree of the university garden of Strasbourg. It is about 8 meters high (Figure 7). Its branches are thick, and its foliage was dense at the time of the acquisition.

Figure 7. Tree under study. The environment around the tree is clear and a building façade is nearby.

In the data acquisition phase, five colour laser scans were performed at about 10 m all around the tree with the Zoller & Fröhlich IMAGER 5016 scanner. The locations of the tree and the scanner stations are shown in the Figure 8. The acquisition step of the scans was 6 mm at 10 m and the point clouds were registered with a cloud-to-cloud algorithm. In addition, the thermal camera was placed at the same location as the laser scanner to take pairs of RGB and TIR photographs of the tree. Approximately 10 pairs of tree shots were acquired for each laser scan and then transformed into a triplet of photographs as for the building methodology. The acquisition time for the geometric and thermal data was approximately 45 minutes.

Figure 8. Studied tree (circled in red) and scanner stations (blue discs)

The scans are then imported and processed one by one with their respective 3-layers images. Since the files of the laser scans performed with this scanner do not contain the spherical panoramic image acquired with the scanner camera, the images of the scans were produced via point projection. These images are positioned and oriented in space. An example of this type of panoramic image is shown in Figure 9.

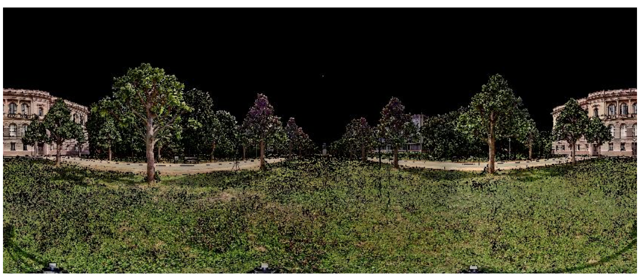


Figure 9. Spherical panoramic image by projection of coloured points on a sphere

The panoramic images of the laser scans are activated, and the 3-layers images are aligned on them via the RGB photographs. Thus, for each scan, a tie point cloud is produced and filtered as before. The point cloud acquired per scan is then loaded and colorized with the thermal images. Figure 10 presents the resulting point cloud for one scan station only.

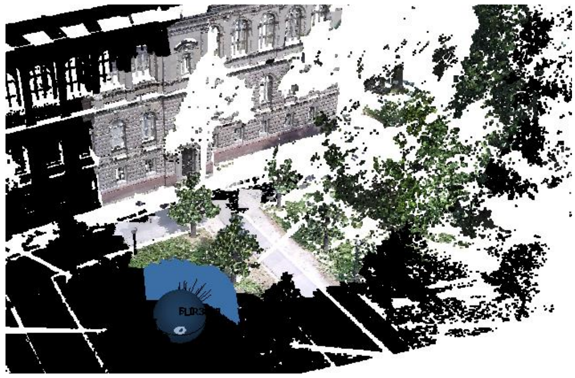


Figure 10. Colorized point cloud for a laser scan

To check the alignment of the RGB photographs with the panoramic images of the laser scans, six control points were placed on the different photographs. These correspond to remarkable points on the facade (window corners and doors) located a few meters away in the background.

The standard deviation obtained on the control points is about 3.5 cm. Since the points are located on a facade further away than the tree compared to the position of the scanner, the accuracy on the tree can be slightly better. Moreover, the spherical panoramic images used were constructed from the projection of the points, the raw photographs taken by the camera of the laser scanner are not available. Geometrical distortions might be induced by the creation of the spherical panoramic images from point clouds.

Finally, after merging the different colorized laser scans, a thermal point cloud of the tree is obtained. One can observe that the edge of the leaves seems much cooler than the rest of the foliage. Figure 11 illustrates the fact that the edge of some leaves is purple. These points have been coloured with pixel values of mixels. These mixels are pixels composed of the signal captured from the leaf and the signal captured from the sky with the thermal camera (so-called "edge effect", Boehler et al., 2003). The sky appears much colder on the thermal images; the temperatures associated with it are generally aberrant compared to the rest of the model. These points are removed via a scalar field filter. All points below 20 °C are removed from the model. Thus, points with an outlier temperature compared to the rest of the model are removed. This operation is performed on CloudCompare (EDF R&D) by indicating to the software the extreme values to consider. The resulting cloud can be seen in Figure 12.

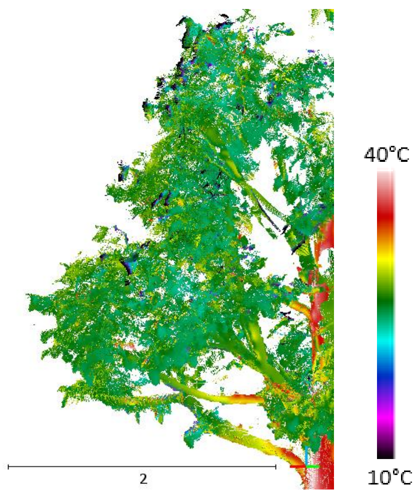
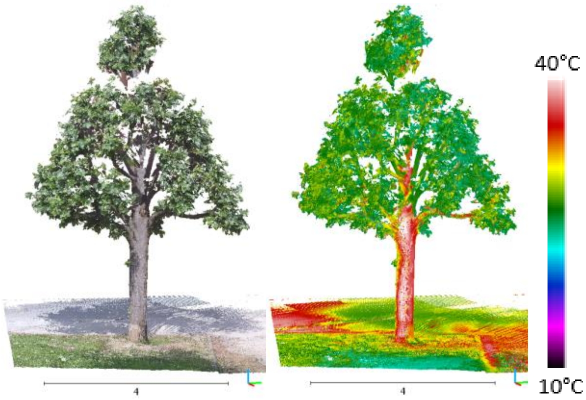


Figure 11. Points of leaves coloured by mixels



(a) (b)

Figure 12. RGB (a) and TIR (b) visualization of a thermal point cloud of a tree

During the acquisition of the data, the sky was clear, and the sun was shining. The shadow cast by the tree on the ground is clearly visible. Also, the side of the tree in the shade appears cooler than the side exposed to the sun. Finally, the point cloud presents partially acquired branches because of the lack of laser scanner stations during the geometric data acquisition phase (Figure 13).

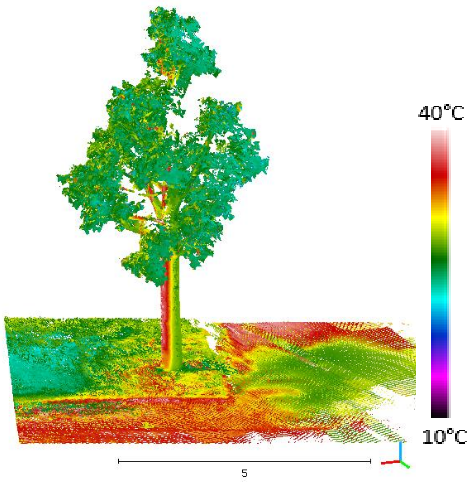


Figure 13. 3D thermal point cloud of a tree. Temperatures are between 20°C (for the leaves in the shade) and 38°C (for the trunk in the sun)

The RGB colorized point cloud is useful to better understand the temperatures distribution and to validate some interpretations, like for instance the shadow on the ground.

The tree cloud is composed of about 4 600 000 points. The points are spaced about 1 cm apart, which ensures a proper density to model overall the tree. Also, to combine the geometric and thermal data, each laser scan required about 15 minutes of processing time.

During the acquisition of the laser scans, the scanner used was also equipped with its own thermal camera (T-Cam) and was able to produce a thermal point cloud of the tree in parallel. A comparison between the two clouds was then made. Using the nearest neighbour method, the temperature of each point of the thermal cloud produced with the FLIR T560 camera was transferred to the cloud acquired with the scanner equipped with its thermal camera. Each point has then two temperature values, the thermal information was subtracted to obtain a temperature difference associated with each point. This comparison was performed on CloudCompare.

The average difference is 1.75 °C. This reflects the fact that the temperatures acquired with the FLIR T560 thermal camera are higher than the temperatures acquired with the T-Cam. A possible reason for this is the georeferencing error of the TIR images of the FLIR T560 camera. Finally, it is also important to highlight the fact that the T-Cam thermal camera has a lower geometric resolution and thermal accuracy than the FLIR T560 thermal camera.

6. CONCLUSION

In conclusion, the thermal 3D modelling of urban objects is required specifically on buildings and trees. The use of spherical panoramic images of laser scanners allows the automation of georeferencing of RGB images and TIR images. This approach is particularly interesting for trees, because the manual detection of points of interest in TIR images is difficult. In addition, the approach of using temperature matrices in centiKelvin as images allows to avoid a significant processing time compared to the use of look up table between the RGB code of a point and its associated temperature.

The thermal models presented in this paper are satisfactory. The urban elements are correctly modelled. However, it should be noted that the facades were relatively flat and that the building was not very high compared to a house with several floors. This architecture was therefore favourable to our calculations.

Concerning the tree, the conditions were also favourable. The acquisition distance allowed to take the whole tree with few photographs and the façade in the background also facilitated the calculations of the SfM algorithms.

In the future, to assess the limits of the developed methodologies, the methodologies will be extended to larger areas and to additional buildings and trees. In addition, a photogrammetric reference block will be set up to automate the georeferencing which is, at this stage, manual.

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REFERENCES

Grechi, G., Fiorucci, M., Marmoni, G.M. and Martino, S. (2021). 3D Thermal Monitoring of Jointed Rock Masses through Infrared Thermography and Photogrammetry. *Remote Sensing*, 13(5), 957.

Macher, H. and Landes, T. (2022). Combining TIR images and point clouds for urban scenes modelling. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLIII-B2, 425–431.

Hosoi, F., Umeyama, S. and Kuo, K. (2019). Estimating 3D chlorophyll content distribution of trees using an image fusion method between 2D camera and 3D portable scanning Lidar. *Remote Sensing*., 11(18), 2134.

Zhu, J. Xu, Y., Ye, Z., Hoegner, L. and Stilla, U. (2021). Fusion of urban 3D point clouds with thermal attributes using MLS data and TIR image sequences. *Infrared Physics & Technology*., 113, 103622.

Vincke, S. and Vergauwen, M. (2020). Geo-registering consecutive construction site recordings using a pre-registered reference module. *Remote Sensing*, 12(12), 1928.

Bruno, N., Mikolajewska, S., Roncella, R., and Zerbi, A. (2022). Integrated processing of photogrammetric and laser scanning data for frescoes restoration. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLVI-2/W1, 105–112.

Boehler, W., Bordas Vicent, M. and Marbs, A. (2003). Investigating Laser Scanner Accuracy. *CIPA International archives for Documentation of Cultural Heritage*. Vol XIX: 696-701

Yandún Narváez, F.J., Salvo del Pedregal, J., Prieto, P.A., Torres-Torriti, M. and Auat Cheein, F. (2016). LiDAR and thermal images fusion for ground-based 3D characterisation of fruit trees. *Biosystems Engineering*. Vol.151, pp479–494.

Previtali, M., Barazzetti, L., Redaelli, V., Scaioni, M. and Rosina, E. (2013). Rigorous procedure for mapping thermal infrared images on three-dimensional models of building façades. *J. Appl. Remote Sens.*, 7(1), p073503.