From Point Cloud to 4D Thermal Model: Leveraging In-Situ Measurements from a Low-Cost Mobile Mapping System in Rabat, Morocco

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Abstract

Thermal imaging provides valuable insights into building performance and urban environmental dynamics, yet integrating thermal data with 3D models remains challenging, particularly with limited equipment. This paper presents a comprehensive workflow from point cloud acquisition to 4D thermal model creation using a novel low-cost mobile triple-camera system in Rabat (Morocco). The methodology leverages a unique configuration with a central thermal camera positioned between two RGB cameras. First, terrestrial laser scanning data is processed to create 3D models suitable for thermal analysis and future microclimate simulations. The exterior orientation of RGB images is determined using Structure from Motion (SfM), then transferred to thermal imagery through the fixed geometric relationship between cameras, followed by a semi-automatic point- and line-based matching algorithm, achieving a spatial accuracy with average deviations of 2.9 cm for control points. Temperature data extracted via the FLIR SDK is projected onto the 3D model using ray-casting, with a weighted integration method resolving overlapping data based on view angle quality. The resulting spatiotemporal model enables analysis of dynamic thermal behaviour, revealing how vegetation and architectural elements can influence facade temperatures throughout the day. This framework creates spatially continuous ground truth data for upcoming comparisons with LASER/F simulation outputs, establishing a robust validation methodology for future urban planning scenarios.

1. Introduction

Urban environments are experiencing unprecedented thermal stress due to climate change and rapid urbanization, making the understanding of building thermal behaviour and urban heat dynamics increasingly critical for sustainable city planning and energy management. In this context, accurate thermal monitoring and modelling of urban surfaces, particularly building facades, becomes essential for developing effective mitigation strategies and optimizing building performance.

Traditional thermal analysis methods in urban environments often rely on discrete point measurements or satellite-based thermal imaging. While these approaches offer valuable insights, there is still a need to capture the complex thermal heterogeneity present at the building scale, where local variations in surface materials, architectural features, vegetation presence, and microclimatic conditions create intricate thermal patterns that evolve throughout the day. The integration of thermal data with detailed three-dimensional geometric models presents a promising avenue for comprehensive thermal analysis, enabling researchers and practitioners to understand not only the spatial distribution of surface temperatures but also their temporal evolution.

The integration of thermal imagery with 3D models faces several technical and methodological challenges. First, thermal infrared (TIR) sensors typically exhibit lower spatial resolution compared to visible spectrum cameras, complicating the precise registration of thermal data onto the geometric model. Second, the spectral differences between thermal and RGB imagery make traditional feature matching techniques less effective. Third, mobile acquisition systems introduce additional complexity through varying viewpoints, lighting conditions, and potential motion blur, necessitating robust calibration and registration methodologies.

This research addresses these challenges by developing a comprehensive methodology for creating four-dimensional (spatiotemporal) thermal models from point cloud data and mobile-acquired thermal imagery. The primary objectives of this study are:

- To develop a cost-effective mobile acquisition system capable of synchronized thermal and RGB data collection, utilizing a novel triple-camera configuration.
- To establish a robust geometric registration workflow that leverages Structure from Motion (SfM) techniques for RGB imagery and extends them to thermal data using a hybrid registration process combining point-based and line-based feature matching.
- To create quantitative 4D thermal models that preserve original radiometric values and enable temporal analysis.

This paper presents a complete workflow from data acquisition to 4D thermal model creation and validation. The methodology presented in this study builds upon the foundations established in the TIR4sTREEt project in Strasbourg (France) (Lecomte et al., 2024; Marie et al., 2024), while addressing the specific characteristics of the Rabat study site. Following this introduction, Section 2 provides a review of related work in thermal-3D integration and mobile mapping systems. Section 3 describes the study area characteristics and data collection procedures. Section 4 presents the developed methodology, including geometric processing, calibration procedures, registration techniques, and thermal mapping algorithms. Section 5 analyses the results, including accuracy assessment and thermal pattern analysis. Section 6 discusses the findings. Finally, Section 7 concludes the paper and outlines future

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research directions, including the planned validation against LASER/F (LAtent, SEnsible, Radiation / Fluxes) microclimate simulation outputs.

2. Related works

The integration of thermal imagery with 3D geometric models represents an evolving field at the intersection of photogrammetry, computer vision, and thermal engineering. This multidisciplinary domain has witnessed significant technological advances over the past two decades, driven by increasing demand for accurate thermal analysis in urban environments, energy auditing applications, and climate change adaptation strategies. The following review examines the key developments in thermal-3D integration, from foundational geometric modelling techniques to advanced multi-modal registration methods, highlighting achievements and persistent challenges motivating the current research.

2.1 3D Geometric Modelling for Thermal Applications

The foundation of thermal-3D integration starts with geometric modelling techniques that can accurately represent urban environments. The introduction of terrestrial laser scanning (TLS) revolutionized the field by enabling millimeter-level accuracy in 3D acquisition, creating detailed point clouds that serve as the basis for comprehensive urban modelling.

Advanced processing techniques for point cloud data have evolved to address the specific requirements of various levels of detail. Plane extraction algorithms, particularly those based on RANSAC (RANdom SAmple Consensus) and region growing approaches, enable the identification of planar surfaces that correspond to building facades, roofs, and other architectural elements (Schnabel et al., 2007).

The creation of mesh models from point clouds presents specific challenges when the resulting geometry must interface with microclimate simulation software. Many thermal simulation packages, such as LASER/F (Kastendeuch et al., 2006), require geometric inputs with specific characteristics, for instance: planar elements, convex polygons, and optimized face counts that balance computational efficiency with geometric accuracy. This constraint has driven the development of specialized mesh generation algorithms that prioritize thermal simulation compatibility while preserving geometric features.

2.2 Mobile Mapping Systems for Thermal Data Acquisition

Mobile mapping systems for thermal data collection have evolved from handheld devices to multi-sensor platforms. The development of mobile, human-operated systems has enabled more detailed data collection with greater positional control and the ability to optimize viewpoints for specific analytical requirements. Middel et al. (2023) developed a mobile panoramic thermal imaging system using a FLIR Duo Pro R dual-sensor camera that simultaneously captures thermal and RGB imagery, demonstrating significant improvements in thermal exposure modelling accuracy. However, these and many other existing systems rely on expensive integrated thermal-RGB cameras, limiting their accessibility for research applications with limited budgets.

The temporal aspect of thermal mapping requires a sampling strategy that captures relevant thermal dynamics while maintaining practical feasibility for field deployment with limited personnel, time and equipment. Diurnal thermal cycles in urban environments exhibit complex patterns influenced by solar geometry, weather conditions, thermal mass of building materials, and microclimatic effects. Effective temporal sampling must balance the need for comprehensive temporal coverage with logistical constraints of mobile data collection.

2.3 Thermal Imaging Integration Approaches

Several distinct approaches have emerged for integrating thermal imaging with 3D geometric data, each with specific advantages and limitations.

2.3.1 Thermal Point Clouds: Thermal point clouds represent an alternative approach for combining three-dimensional geometric data with temperature information, achievable through either direct integration of thermal sensors with laser scanning systems or post-processing fusion techniques. Lecomte et al. (2022) developed a methodology for generating 3D thermal point clouds of buildings and trees by combining TIR images with TLS data. Their approach involves georeferencing thermal images and colorizing point clouds through projection.

Ramón et al. (2022) have highlighted the potential and limitations of current thermal point cloud methodologies. While they offer the theoretical advantage of direct thermal-geometric correspondence, they remain limited by several critical factors: (1) the significant cost of integrated thermal-geometric sensors, (2) lower point density due to thermal sensor resolution constraints, and (3) difficulty in achieving comprehensive surface coverage due to sensor positioning limitations. Most importantly, these approaches do not enable direct comparison with simulation outputs, as the point-based thermal data cannot be readily compared with the mesh-based geometric models required by microclimate simulation software. These limitations highlight the continued relevance of image-based thermal mapping approaches that can leverage high-resolution geometric models while preserving quantitative thermal information.

2.3.2 Texture-Based Thermal Mapping: The earliest approaches to thermal-3D integration treated thermal imagery as simple texture overlays on geometric models. Borrmann et al. (2012) developed a method to project thermal images onto 3D building facades, creating visual representations of thermal distribution. These texture-based methods provide intuitive visualization of thermal patterns, but they remain fundamentally limited for temperature analysis. The thermal information is encoded as RGB values rather than preserved as quantitative temperature data.

2.3.3 Quantitative Thermal Data Integration: Recognition of the limitations inherent in texture-based approaches led to the development of methodologies that preserve the quantitative nature of thermal measurements. Natephra et al. (2017) introduced a significant advancement by integrating time-stamped thermal data with Building Information Modelling (BIM) systems, creating what can be termed as "4D thermal BIM". Their methodology extracts RGB values from thermal images through planar pixel grids and converts these to actual temperature values using calibrated thermal cameras. This approach enables both visualization and quantitative analysis while incorporating the temporal dimension.

The work by Natephra et al. (2017) represents a paradigm shift from visualization-oriented to analysis-oriented thermal mapping. By preserving radiometric values and maintaining temporal relationships, their methodology enables advanced thermal studies including energy performance assessment, thermal comfort evaluation, and validation of building energy models. However, their approach was primarily demonstrated in controlled indoor environments and small-scale building components, leaving questions about scalability to complex urban environments.

A significant recent advancement in thermal-3D integration involves the use of UV coordinate systems to establish precise pixel-to-facet mapping relationships. Marie et al. (2024) developed a methodology that creates exact correspondences between 2D thermal image pixels and 3D mesh facets, enabling thermal information transfer while preserving original radiometric values. Temperature data is stored as exploitable scalar fields directly associated with the mesh geometry.

2.4 Advanced Registration and Calibration Techniques

The field of thermal-3D integration has evolved through the development of advanced registration and calibration techniques that specifically address the unique characteristics and limitations of thermal imaging systems.

2.4.1 Multi-Modal Image Registration: One of the core challenges in thermal-3D integration lies in accurately registering thermal imagery with 3D building models. Iwaszczuk & Stilla (2017) developed a line-based model-to-image matching methodology specifically designed for thermal imagery. Their approach finds correspondences between building edges, then co-registers the images and the 3D building model through robust estimation of exterior orientation parameters. This line-based approach includes camera pose refinement techniques, uncertainty modelling for both image features and 3D building models, and outlier detection methods.

2.4.2 Geometric and Radiometric Calibration of Thermal Systems: Geometric calibration of thermal cameras requires consideration of thermal contrast rather than visual contrast. Alternative calibration targets have been developed, including heated/cooled patterns and materials with different thermal emissivity characteristics. For instance, Macher & Landes (2022) created a specialized calibration target composed of squares of two materials with significantly different emissivity - aluminium foil and black stickers - to increase thermal contrast for effective corner detection in infrared images.

Radiometric calibration involves the accurate measurement of temperature values and requires consideration of material emissivity and reflected temperature effects. Various approaches to thermal accuracy validation have been explored, including comparison with calibrated reference thermometers, blackbody radiation sources, and thermal reference standards. Macher & Landes (2022) conducted radiometric calibration validation experiments using the FLIR T560 thermal camera with black body references (Mikron M345 and Landcal P80P), finding temperature differences ranging from -0.10°C to 0.46°C across the tested temperature range of -2°C to 40°C.

2.5 Validation and Quality Assessment

The use of distributed temperature sensors, such as thermocouples or data loggers, provides ground truth thermal measurements for validation of thermal mapping results. However, careful consideration must be given to differences in measurement principles and spatial sampling between contact and remote sensing methods.

Our methodology builds upon these advancements while addressing new challenges. The system presented in this paper features a unique setup where a dedicated TIR camera — without an integrated expensive RGB sensor — is positioned between two low-cost RGB cameras. This led to the development of a hybrid registration process, combining SfM from RGB imagery with optimized point- and line-based feature matching for thermal-to-3D correspondence. Additionally, another constraint had to be considered, because the produced mesh model must be tailored to microclimate software outputs for future comparison between measurements and simulations.

3. Study Area and Data Collection

The research was conducted in Hay Riad, a residential district in Rabat, Morocco (33°57'N, 6°51'W), selected for its representative urban morphology and diverse thermal characteristics. This location offers several advantages for thermal mapping research: (1) Mediterranean climate with pronounced diurnal temperature variations, (3) diverse vegetation patterns including both Mediterranean species and palm trees characteristic of North African urban environments, and (3) varied solar exposure conditions due to building orientation and height differences. Building materials include painted concrete facades, metal elements, and glazed surfaces, each exhibiting distinct thermodynamic and radiative properties.

High-resolution geometric data was acquired using TLS to provide the foundational 3D geometry for thermal mapping. The mobile thermal acquisition system (Figure 1) consists of three imaging devices mounted on a rigid aluminium framework: one FLIR TAU2 thermal camera positioned centrally, flanked by two GoPro HERO4 RGB wide angle cameras providing stereoscopic coverage. The FLIR TAU2 features a 640×512-pixel resolution with a 13 mm focal length, and 45°×37° field of view, with a thermal range of -25°C to 100°C. The GoPro HERO4 cameras capture 4:3 format images at 12 MP resolution (4000×3000 pixels) with a 122° horizontal field of view, and 3 mm focal length. The geometric configuration maintains fixed 20 cm baselines between the central thermal camera and each RGB camera, with all devices oriented parallel and synchronized for simultaneous image acquisition. This configuration enables redundant spatial referencing while maintaining system portability and cost-effectiveness. The entire system is mounted on a wheeled cart platform, maintaining consistent camera height (1.5 m above ground). Power supply is provided by an on-board portable power bank.

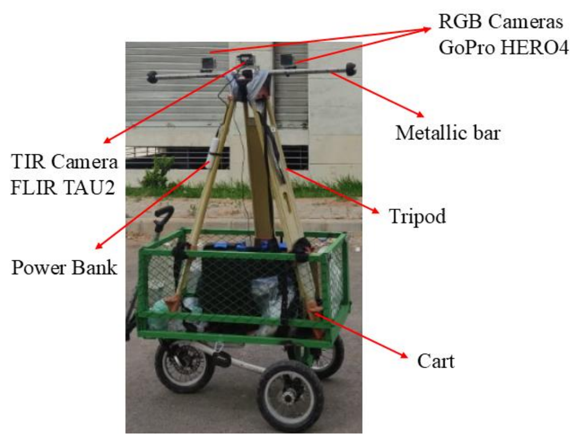

Figure 1. Mobile triple-camera acquisition system.

Temporal coverage was achieved through systematic data collection over nine days during July and August 2024. Data acquisition occurred at 1.5-hour intervals from 07:00 AM to 07:00 PM local time, providing 9 temporal samples per day. The acquisition protocol followed a stop-and-go methodology, with synchronized cameras programmed to capture images at one-minute intervals throughout each route. Route completion typically required 40 minutes, during which the synchronized imaging system automatically recorded thermal and RGB data. The data collection campaign resulted in acquisition of over 3,500 thermal images and 7,000 RGB images.

Validation of thermal imaging accuracy was achieved through deployment of nine miniature temperature data loggers (Plug&Track iButtons) distributed across building facades. These devices provide continuous temperature measurements at 5-minute intervals with 0.5°C accuracy. Thermobutton placement was strategically designed to sample diverse thermal conditions including direct solar exposure, partial shading, and complete shade conditions. Each logger was mounted using thermally conductive adhesive to ensure good thermal contact with building surfaces while minimizing solar heating of the device itself. Logger positions were surveyed using total station measurements.

4. Methodology

The methodology presented in this study encompasses a comprehensive workflow from point cloud acquisition to 4D thermal model creation. The approach is structured into four main components: (1) 3D geometric modelling from point clouds, (2) image processing and thermal-geometric registration, (3) 4D thermal mapping and (4) validation.

4.1 3D Geometric Modelling

The initial point cloud data was processed to extract detailed 3D surface envelopes of buildings (Figure 2). This approach ensures that the resulting geometric models meet the specific requirements for thermal analysis and future microclimate simulations using LASER/F.

4.1.1 Building Mesh Creation and Optimization: The 3D modelling of buildings was performed at Level of Detail 3 (LOD3) to capture architectural features that significantly influence thermal behaviour, including balconies, window recesses, and projecting elements. Autodesk Revit was used to model the basic elements. The resulting model cannot be directly imported into LASER/F. Only external surfaces of 3D volumetric components must be retained, with each planar element isolated and differentiated based on constituent materials. This separation enables proper material characterization. This step is done using Technodigit's 3DReshaper.

A specialized MATLAB processing pipeline was implemented to ensure mesh compliance with simulation software requirements. The topology correction process addresses three principal mesh categories:

- Convex-shaped meshes: Simplified using convex polygons
- Concave-shaped meshes: Decomposed into convex polygons or remeshed
- Meshes with holes: Remeshed with growth rates applied according to the smallest segment

The correction algorithm ensures that each mesh element is planar and convex, with faces as large as possible to minimize computational overhead while maintaining geometric accuracy. For triangulated surfaces, triangles are optimized to approach equilateral geometry, as simulation calculations are performed at triangle barycentre.

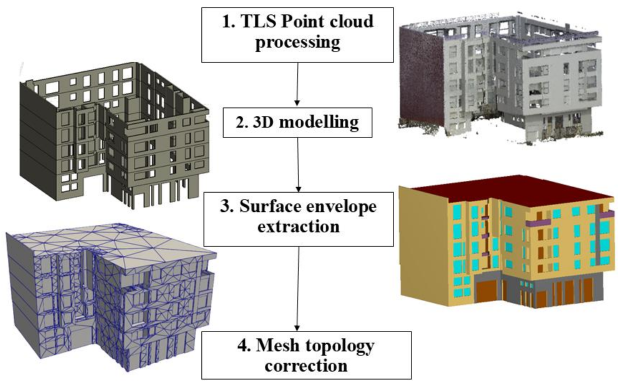

Figure 2. Developed pipeline for 3D modelling of buildings.

4.1.2 Vegetation Modelling: Tree crown modelling utilized a hybrid approach to balance geometric accuracy with computational efficiency (Figure 3). The methodology addresses the limitation of traditional convex envelope approaches that tend to overestimate foliage volume by implementing a two-stage process.

Initial processing generates a concave envelope that closely follows foliage tortuosity from the tree crown point cloud, providing an accurate representation of the complex three-dimensional structure of vegetation. Subsequently, a convex envelope is generated and adjusted to match the volume of the reference concave envelope, creating a volume-corrected convex representation. This hybrid approach provides more accurate Leaf Area Density (LAD) calculations while maintaining computational compatibility with simulation software.

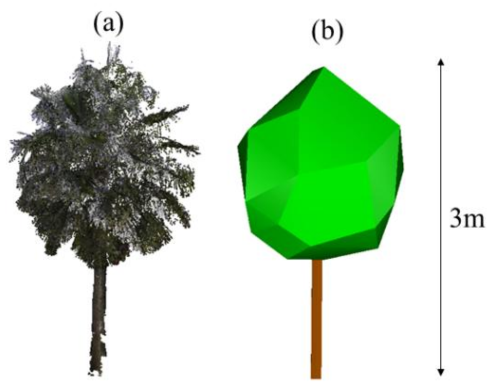

Figure 3. (a) Palm tree point cloud (b) corresponding convex crown and cylinder for the trunk.

4.2 Geometric Calibration and Registration

4.2.1 Camera Calibration: Geometric calibration of the thermal camera was performed using a custom-designed low-cost aluminium checkerboard pattern (Macher & Landes, 2022). This specialized calibration target addresses the unique characteristics of thermal imaging, providing intrinsic parameter estimation. Standard photogrammetric calibration procedures were applied to the stereo RGB cameras, establishing both intrinsic parameters and the stereo baseline geometry.

4.2.2 Multi-Modal Registration Process: The multi-modal registration strategy leverages the fixed geometric configuration of the camera system to derive exterior orientation parameters for thermal images based on RGB SfM results, while addressing the spectral differences that make direct thermal alignment challenging. Exterior orientation parameters for the RGB cameras are first obtained using automated SfM processing, which capitalizes on the higher spatial resolution and visual richness of RGB images to produce pose estimates. The thermal camera's initial orientation is then inferred by applying the known rigid transformation between the RGB and TIR sensors.

To assess the quality of the initial alignment, RGB-to-TLS alignment accuracy was evaluated by performing space resection of RGB images using well-distributed control points extracted from the TLS point cloud, yielding an initial photogrammetric registration error of 3.5 ± 1.2 cm. Cross-modal RGB-to-thermal alignment error was assessed through a two-step process: first, points were manually identified in RGB images and their coordinates recorded. Second, the pre-calibrated transformation was applied to these RGB coordinates. These predicted thermal coordinates were then compared with the actual coordinates of the same features manually identified in the thermal images. This yielded an initial transformation error of 7.2 ± 2.1 cm.

After this initial alignment, a hybrid approach combines manual 2D–3D correspondences with semi-automated line-based feature matching (Figure 4). Distinctive structural features visible in both modalities are used to constrain camera pose. Line segments are automatically extracted from thermal images using the Line Segment Detector (LSD), with automated fallback to Hough Transform in low-contrast cases. These lines are computationally matched with projected 3D mesh edges based on angular similarity (<11°), spatial proximity, and length coherence, followed by interactive user validation of uncertain matches to eliminate false correspondences.

Final geometric accuracy of the thermal-to-3D model alignment was quantitatively validated through an independent set of correspondence points, achieving an average spatial error of 2.9 cm.

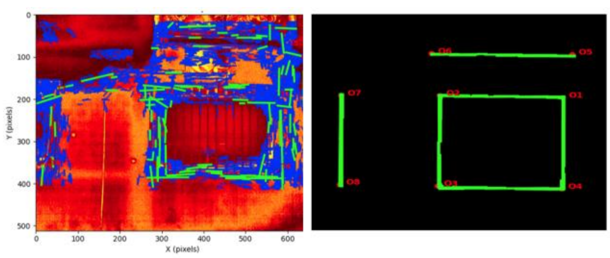

Figure 4. Left: TIR image with overlaid detected line segments; Right: 3D model with user-selected 2D-3D correspondence points (red) and the final detected line segments (green).

4.3 4D Thermal Mapping

Actual surface temperature data is extracted directly from TIR images using the FLIR SDK API, preserving radiometric accuracy, similar to the approach employed by Marie et al. (2024). Acquisition timestamps are maintained throughout the processing pipeline to enable temporal analysis.

The thermal mapping algorithm implements a ray-casting approach to project temperature data onto the 3D geometric model. Camera parameters derived from the registration process enable the projection of thermal pixels onto corresponding 3D surface elements through geometric ray tracing, establishing precise correspondences between two-dimensional thermal information and three-dimensional geometric surfaces.

For overlapping thermal images covering the same surface areas, a weighted integration method resolves conflicts by prioritizing data based on multiple criteria. For instance, view angle quality is assessed by calculating the angle between the camera viewing direction and the surface normal vector, with perpendicular views receiving higher weights due to their superior thermal measurement accuracy and reduced reflection effects. Spatial proximity to surface normal is automatically evaluated to favour measurements acquired at optimal viewing geometries. Image recency provides temporal prioritization for dynamic thermal analysis, particularly important when multiple thermal acquisitions are performed over time periods where surface temperatures may vary due to changing environmental conditions such as solar heating, wind patterns, or building system operations. This temporal weighting ensures that the most recent thermal measurements are preferentially retained when multiple images capture the same surface area.

Each mesh facet is associated with a population of pixels, with each pixel containing thermal information. Finally, a spatial-statistical approach identifies anomalous temperature values by analysing local neighbourhoods within the 3D thermal field. The filtering process operates on two levels to ensure data quality and reliability. Temperature values exceeding three standard deviations from the local mean are considered as statistical outliers, along with any null values resulting from incomplete thermal data coverage.

However, a critical challenge arises with mesh elements located along the edges, which are only partially covered by thermal mapping and consequently contain insufficient temperature information. To address this limitation, the percentage of null values within each mesh element is quantified. This quality metric distinguishes between two sources of high standard deviation: genuine thermal inhomogeneity versus edge effects caused by mesh topology and incomplete texture coverage. Elements with high standard deviation but low null value percentages indicate actual temperature variation, while those with both high standard deviation and high null value percentages reflect geometric artifacts. The acceptable maximum proportion of null values must be empirically determined based on the specific mesh resolution and thermal coverage requirements, ensuring that only mesh elements with sufficient thermal data density are retained for analysis while maintaining spatial continuity of the thermal field.

4.4 Validation Framework

A dual validation framework was implemented: first, the accuracy of TIR imagery in depicting surface temperatures was verified through direct comparison with point measurements from the thermobuttons deployed on the facades. These provide independent temperature measurements for assessing the accuracy of thermal imaging results. Second, the correct transfer of thermal values from TIR imagery to the 4D model was validated by comparing surveyed thermobutton positions in the 4D model with their corresponding placements in the thermal images, represented as 10×10 averaged pixel values. This dual verification process confirms both the thermal accuracy of the imaging system and the geometric precision of the 4D modelling methodology, ensuring that temperature values are correctly transferred from the thermal imagery to the three-dimensional model through the developed workflow.

5. Results

This section presents results from two representative days with contrasting weather patterns: July 24, 2024 (extreme heat wave conditions) and August 7, 2024 (partially cloudy conditions), analysed across three time periods (07:00 AM, 01:00 PM, and 05:30 PM local time).

5.1 Diurnal Thermal Dynamics Analysis

5.1.1 Extreme Heat Wave Day: During early morning hours under clear sky conditions, the facade exhibited minimal thermal variation with temperatures ranging primarily from 28°C to 32°C across the surface (Figure 5a). The thermal distribution appeared relatively uniform, with subtle temperature gradients primarily influenced by residual thermal storage from the previous day. Shaded areas created by architectural projections and vegetation showed temperatures approximately 2-3°C lower than exposed surfaces, indicating the beginning of diurnal thermal differentiation.

Peak solar exposure period (Figure 5b) revealed thermal heterogeneity across the facade, with temperatures ranging from 35°C to 47°C. The northern and north-eastern facades of the building experienced intense solar heating, with directly exposed wall surfaces reaching maximum temperatures of 47°C. Significant thermal contrasts were observed: balcony-shaded areas maintained temperatures of 35-38°C, and tree shadows created distinct cooling zones with temperatures 8-10°C lower than adjacent sun-exposed surfaces. Window areas displayed intermediate thermal signatures (40-42°C) compared to surrounding wall surfaces due to their metal grids.

Late afternoon conditions (Figure 5c) showed sustained elevated temperatures ranging from 31°C to 43°C, demonstrating significant thermal inertia of building materials. While direct solar intensity decreased, surface temperatures remained elevated due to accumulated thermal energy throughout the day. The thermal gradient between shaded and exposed areas persisted but showed slight reduction compared to midday conditions, with differences of 6-8°C.

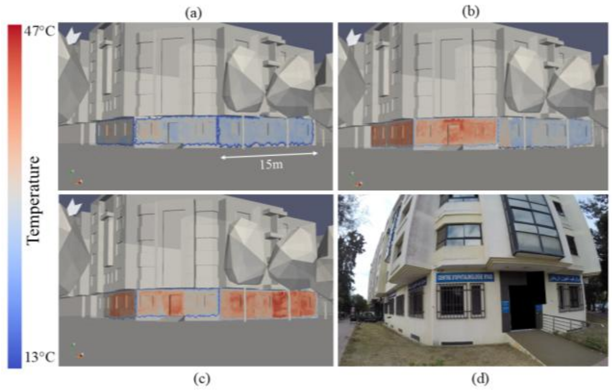

Figure 5. 4D thermal mapping results for July 24 at (a) 07:00 AM, (b) 01:00 PM and (c) 05:30 PM; (d) RGB image of the building.

5.1.2 Moderate Temperature Day: Morning facade temperatures (Figure 6a) ranged from 26°C to 30°C, showing reduced thermal variation compared to the conditions of July 24. Cloud cover probably created dynamic shading patterns that intermittently reduced solar heating, resulting in more moderate thermal gradients. Temperature differences between shaded and exposed areas were limited to 2°C.

Intermittent cloud cover significantly moderated peak temperatures, with the facade displaying a range of 32°C to 40°C at midday (Figure 6b). The thermal distribution showed reduced thermal contrast between shaded and exposed areas (4-6°C difference), more uniform temperature distribution across the facade surface, and tree shadows still creating observable cooling effects, though less pronounced than under clear sky conditions.

Late afternoon temperatures (Figure 6c) ranged from 28°C to 38°C, showing accelerated cooling compared to July 24 conditions. The reduced thermal accumulation throughout the day resulted in faster heat dissipation, with evening temperatures approaching morning values more rapidly than observed during heat wave conditions.

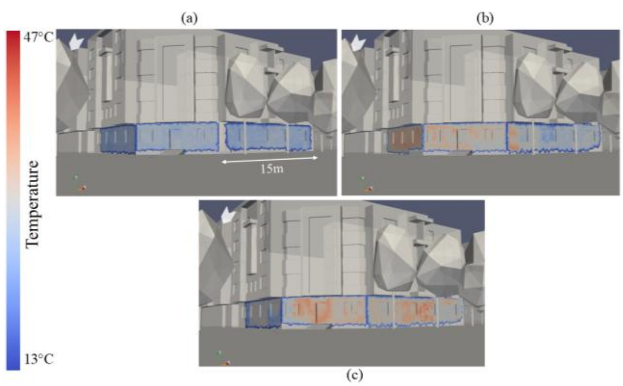

Figure 6. 4D thermal mapping results for August 7 at (a) 07:00 AM, (b) 01:00 PM and (c) 05:30 PM.

5.2 Thermal Mapping Validation and Accuracy Assessment

The validation process comprised two complementary assessments:

5.2.1. TIR-Thermobutton Comparison: a 10×10-pixel window was selected in each thermal image to correspond to the portion of the wall surface located near a thermobutton (accuracy: ±0.5°C). For the TIR images, the emissivity was set at 0.95, an approximate value used for urban facade materials, including validation work over Strasbourg where this emissivity value has been shown to introduce temperature variations of less than 0.24°C when varied within the typical urban material range of 0.85-0.95 (Roupioz et al., 2018).

To assess the consistency between the TIR imagery and the reference temperature measurements, the temperature values from the corresponding 2D image pixels were compared with the thermobutton data. The temperature logger data was down sampled to match the exact timestamps of the thermal image acquisitions. This TIR-thermobutton validation analysis revealed maximum root mean square error (RMSE) values of 1.2°C under clear sky conditions and 0.9°C under partially cloudy conditions. The improved accuracy under partially cloudy conditions is likely due to reduced atmospheric thermal turbulence and more stable radiometric conditions.

The thermobutton consistently recorded slightly higher temperatures than both the raw TIR imagery and the derived 4D model values throughout the observation period (Figure 7d). This discrepancy is likely attributable to a combination of factors, including radiometric corrections applied to the thermal images, solar radiation effects on the exposed surface of the thermobutton, and possible thermal inertia in the contact sensor. Despite this systematic offset, temperature trends and temporal dynamics remained strongly correlated between the methods.

5.2.2. 4D Model Thermal Data Transfer Accuracy: The comparison between raw TIR image ROI values and their corresponding temperature projections within the 4D thermal model showed excellent agreement. The mean temperature difference between the thermal image ROI and the 4D model was 0.1°C, with a standard deviation of 0.05°C. These minimal differences demonstrate that thermal data is correctly transferred from the 2D thermal images to the geometric mesh without significant loss of accuracy.

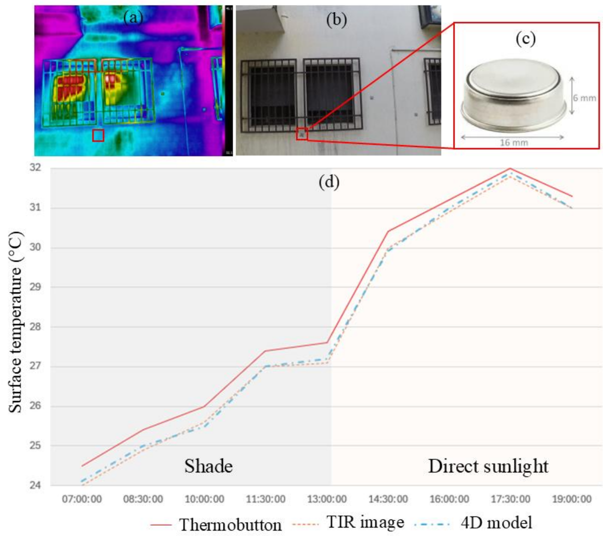

Figure 7. (a) TIR and (b) RGB images showing thermobutton placement, (c) thermobutton sensor, (d) comparison between thermobutton measurements, TIR and 4D model-derived surface temperatures. Temperature data were down sampled to correspond with TIR image acquisition times.

6. Discussion

The hybrid registration approach developed in this study represents a substantial improvement in thermal-3D integration methods. The methodology builds upon the quantitative thermal integration frameworks while extending it to complex outdoor urban environments. The preservation of radiometric values throughout the processing pipeline enables quantitative analysis capabilities that are not possible with texture-based approaches. The systematic temporal sampling strategy provides sufficient temporal resolution while maintaining spatial flexibility. The 4D thermal analysis revealed thermal dynamics that would not be possible to capture with discrete point measurements or satellite-based thermal imaging. The ability to quantify how vegetation and architectural elements can influence facade temperatures throughout the day provides insights for urban planning and building design applications.

The achieved geometric accuracy of 2.9 cm average deviation of control points compares favourably with existing photogrammetric thermal mapping systems. The validation of thermal imagery against ground truth temperature measurements demonstrates thermal accuracy (RMSE ≤ 1.2°C) suitable for engineering applications and simulation validation.

Several limitations of the current methodology must be noted. The mobile data collection approach, while providing more spatial coverage, introduces inevitable temporal offsets. For rapidly changing thermal conditions, this offset may introduce uncertainties in comparative analysis across different facade orientations. Furthermore, the current methodology does not allow for the segmentation of the dataset into thermally stable time intervals, which prevents the development of a truly dynamic model capable of adapting to real-time thermal variations and transient conditions.

The 3D modelling process involves level-of-detail considerations that may not capture all architectural features present in the thermal imagery. This geometric abstraction may result in loss of thermal information for fine-scale architectural

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elements that are visible in the thermal imagery but not adequately represented in the 3D mesh.

The current methodology has been demonstrated on individual building facades, raising questions about scalability to neighbourhood or district-level thermal mapping. The data processing workflow, while highly accurate, requires manual quality control steps that may limit application to larger study areas.

7. Conclusion

This research successfully demonstrates a comprehensive methodology for creating 4D thermal models through integration of TLS and mobile thermal imaging. The key contributions of this work include the development of a cost-effective mobile triple-camera system that achieves satisfying geometric accuracy (2.9 cm average deviation) while maintaining thermal radiometric precision (RMSE ≤ 1.2°C). The hybrid registration approach, combining SfM processing with line-based feature matching, successfully addresses the spectral differences between thermal and RGB imagery. The ray-casting thermal projection algorithm with weighted integration successfully resolves overlapping thermal data while preserving original radiometric values, enabling quantitative thermal analysis capabilities that surpass existing texture-based approaches.

The established methodology creates a foundation for several promising research directions. The primary intended application of this methodology involves validation of LASER/F microclimate simulation outputs. The spatially continuous ground truth data provided by the 4D thermal mapping creates opportunities for detailed comparison between measured and simulated thermal behaviour.

Future research should explore automatization approaches to enable larger-scale applications while maintaining accuracy standards. The development of automated quality control procedures could significantly reduce processing time for district-level thermal mapping. Extending the temporal analysis and the measurement campaigns to encompass seasonal variations would provide a more comprehensive understanding of annual thermal dynamics, supporting long-term urban planning and climate adaptation strategies.

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