

MANAGERIAL PERSPECTIVES ON BUILDING MAINTENANCE THROUGH THE INTEGRATION OF NONCONVENTIONAL TECHNOLOGIES AND INNOVATIVE SOLUTIONS

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ABSTRACT: Building maintenance is undergoing a profound evolution, thanks to the integration of innovative technological solutions. The use of drones equipped with optical and thermal sensors, capable of integrating RGB imaging with infrared thermography and generating elaborate 3D models, opens new perspectives for the diagnosis and optimization of buildings. This method is not limited to the rapid detection of hidden defects and monitoring of energy performance, but also leads to a reduction in costs and risks associated with conventional inspections. At the same time, by detecting energy losses and improving decision-making, RGB-T 3D technology contributes to extending the lifespan of buildings and reducing carbon emissions. The paper analyzes the transition from the visible to the infrared spectrum, practical scenarios for using drones in audits and maintenance processes, but also the current limitations of these tools. Finally, the potential of three-dimensional aerial thermography to become a key element in modern building maintenance management is highlighted, with direct advantages for sustainability and the development of a more efficient and environmentally responsible built environment.
KEYWORDS: Innovative technologies, 3D thermography, Drone inspection, Building maintenance, Carbon emission reduction

1. INTRODUCTION AND THEORETICAL BASIS

During the operating phase of the building life cycle, a series of fundamental components can be highlighted: actual use, maintenance activities, repair interventions, replacement of damaged components, renovation actions and functional water and energy requirements [1]. This paper highlights the fact that, simultaneously with the advancement of the complexity and technological advancement of buildings, maintenance activities are becoming increasingly elaborate and well-planned maintenance strategies, implemented including through nonconventional and innovative methods such as three-dimensional thermal imaging and the use of drones, not only increase their lifespan, but also play an important role in reducing CO_2 emissions, improving energy efficiency and reducing adverse effects on the environment [1,2].

Based on the results obtained from multiple studies, buildings account for a significant share of approximately 40% of the total energy used globally and contribute a similar percentage of approximately 30% to total CO_2 emissions. [3] Of all the stages of a building's life cycle, the operation and maintenance phase is considered the most substantial in terms of negative environmental consequences, generating more than 70% of CO_2 emissions and energy requirements [3,4,5]. According to a study on the level of greenhouse gas emissions, carried out on a residential skyscraper in Hong Kong, approximately 213.03 t-CO_2-e per apartment and 4980 kg CO_2-e per square meter were estimated. The analysis of the distribution of emissions generated in this study, illustrated in Figure 1, shows that the major source is the operation and maintenance phase (85.82%), followed by the materials used in construction (12.69%), renovation works (1.14%), operations corresponding to the end-of-life phase-decommissioning (0.28%) and, to a very small extent, other factors (0.07%) [6].

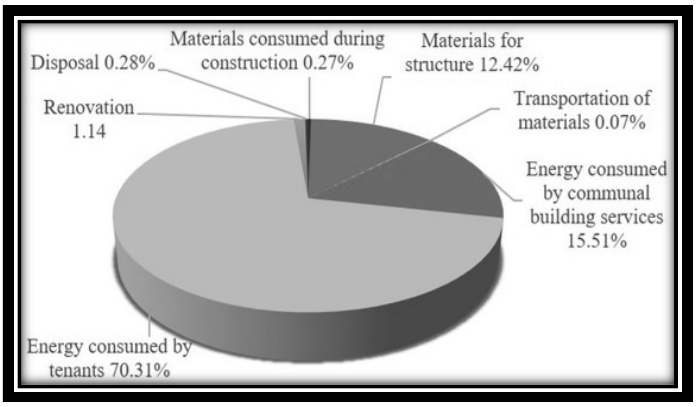


Figure 1. Share of greenhouse gas emissions of the residential

The present study proposes to explore nonconventional approaches to building maintenance, highlighting three-dimensional imaging technologies and their contribution to creating a more sustainable environment.

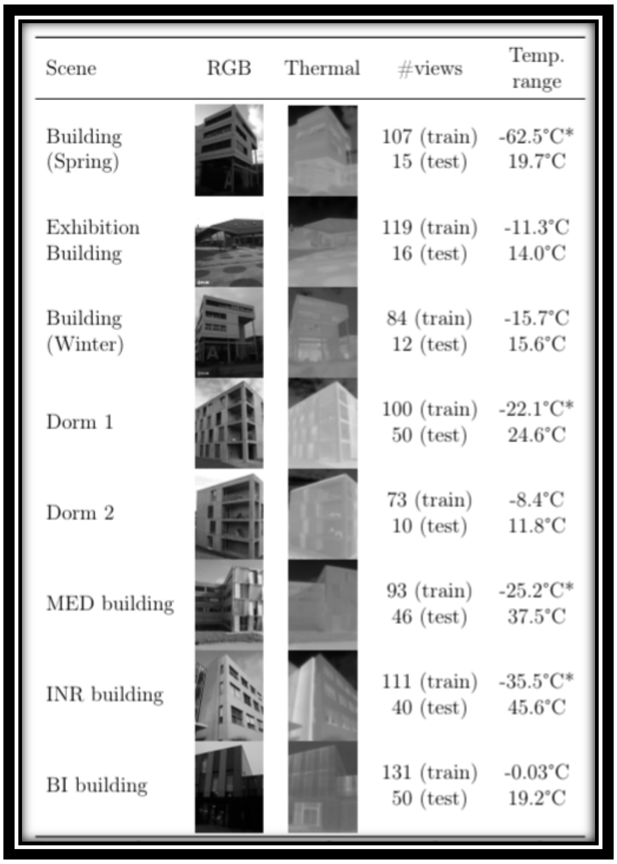
2. FROM THE VISIBLE TO THE INFRARED SPECTRUM: THE ROLE OF RGB AND THERMAL IMAGING

Although thermal imaging is frequently used in building performance monitoring, most current studies on the use of drones (UAVs) for thermal imaging are limited to interpreting two-dimensional (2D) data or developing 2.5D models of buildings, such as roofs or facades [8]. Recent developments in the use of unmanned aerial vehicles (UAVs), configured with thermography systems, have led to the development of accurate and rapid ways to analyze the thermal behavior of building envelopes and other building-related elements [9].

RGB imaging, based on the combination of the three fundamental elements of color: red, green, and blue, is a conventional method of collecting visual information, being constantly present in our daily lives. Drones equipped with such cameras generate images in natural colors, very close to the natural perception of the human eye. Due to this advantage, RGB technology is frequently used in fields such as aerial photography and high-altitude filming [10,11].

In contrast to RGB imaging, thermography focuses on recording infrared radiation from objects, reflecting the temperature distribution on the observed surfaces. Unlike conventional cameras, thermal sensors can operate independently of lighting conditions, which makes them extremely useful when thermal differences play a determining role in analysis and decision-making [10,11].

Figure 2 illustrates, as an example, a complex dataset consisting of RGB and thermal images of eight different building facades. This representation highlights both the number of frames used for training and testing the models and the temperature range specific to each scene. This organization allows for a detailed understanding of the structure of the dataset, highlighting not only the visual diversity of the facades, but also the thermal variability encountered during data collection. By associating RGB and thermal images, the figure highlights how complementary information can be harnessed to train building feature detection and analysis algorithms. Thus, this representation facilitates the interpretation of the dataset and provides a clear framework for evaluating the performance of the algorithms, taking into account the variable conditions under which the data were obtained and highlighting their relevance for practical applications in building facade inspection[12].



Scene	RGB	Thermal	#views	Temp. range
Building (Spring)			107 (train) 15 (test)	-62.5°C* 19.7°C
Exhibition Building			119 (train) 16 (test)	-11.3°C 14.0°C
Building (Winter)			84 (train) 12 (test)	-15.7°C 15.6°C
Dorm 1			100 (train) 50 (test)	-22.1°C* 24.6°C
Dorm 2			73 (train) 10 (test)	-8.4°C 11.8°C
MED building			93 (train) 46 (test)	-25.2°C* 37.5°C
INR building			111 (train) 40 (test)	-35.5°C* 45.6°C
BI building			131 (train) 50 (test)	-0.03°C 19.2°C

Figure 2. Experimental dataset comprising paired RGB-thermal images of eight building facades [12]

3. RGB-T 3D – AN NONCONVENTIONAL TOOL FOR ADVANCED DIAGNOSTICS OF BUILDINGS THROUGH DRONES

3D imaging is proving to be a valuable tool in numerous fields, from architectural and industrial design, to determining the condition of materials and artifacts, from medical applications to uses in entertainment (video games and cinema) and the enhancement of historical and artistic heritage (through the integration of emerging technologies such as virtual reconstruction or augmented reality) [13].

Figure 3. Md4-1000 UAV (Microdrones) fitted with thermal and RGB imaging sensors [13]

3D inspection technology involves, among other things, an nonconventional approach by analyzing RGB – thermal infrared (RGB-T) images using drones equipped with both thermal (TIR) and RGB cameras, such as the one in Figure 3, combining the collected data to produce detailed three-dimensional models of buildings.Through geometric and radiometric calibration, image distortions are corrected, and the 3D reference point clouds, generated from RGB photographs, are completed with temperature information from thermal images used for texture mapping. The end result is a complex 3D model, which facilitates the immediate identification of energy inefficiencies on roofs or facades, providing an innovative tool for preventive and sustainable building maintenance [8]. The application of 3D thermography, as in the example in Figure 4, is proving to be of major importance in areas such as structural diagnostics, energy performance analysis of buildings, inspection operations and monitoring processes. Also, the use of unmanned aerial vehicles (UAVs) allows the expansion and streamlining of these types of assessments [14].

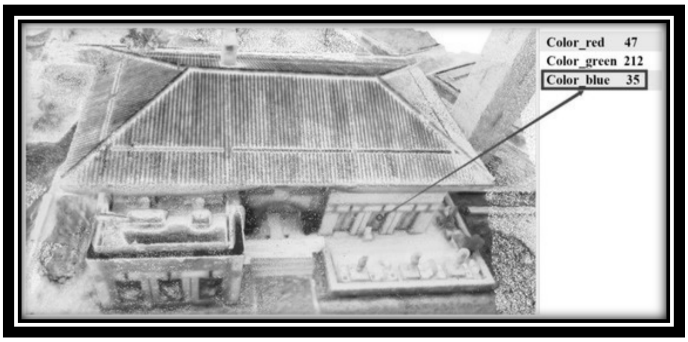


Figure 4. 3D Thermography Performed Using UAV [15]

4. THE CONTRIBUTION OF DRONES WITH OPTICAL AND THERMAL SENSORS IN OPTIMIZING BUILDING AUDITS

Specialized studies have shown that energy audits in the construction sector can generate considerable reductions in energy consumption, highlighting their essential role in optimizing and increasing the efficiency of buildings. The results obtained confirm not only the technological benefits, but also the economic and environmental advantages, underlining the role of these assessments in reducing carbon emissions [16].

In this direction, an innovative option is the use of drones equipped with optical and thermal sensors, which can transform the audit process into a fast, precise and sustainable solution [17].

This type of audit is based on the use of thermal information, obtained by identifying correspondence points in the 3D model generation process. However, in the case of thermal images with low clarity, determining similar features and locating these points becomes more complicated and generates limited accuracy. In contrast, high-quality RGB images, with superior resolution and clarity, provide a much more reliable basis for establishing correspondences and for effectively integrating visual and thermal data. Match points represent visible features in an image that can be recognized in other images of the same building, such as eaves edges, architectural details, window corners, or other color patches that serve as landmarks. The data fusion process is illustrated in Figure 5 [18].

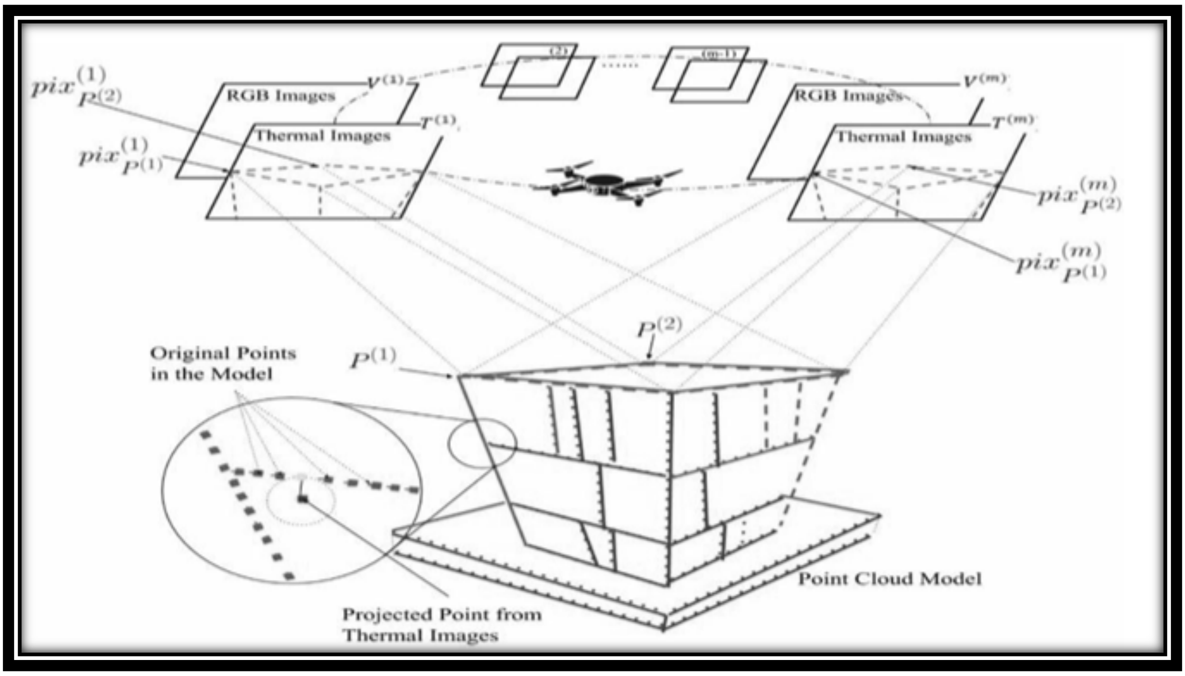


Figure 5. Schematic of the Data Fusion Process [17]

5. APPLICATIONS OF 3D THERMOGRAPHY WITH DRONES IN THE DIAGNOSTIC AND OPTIMIZATION PROCESSES OF BUILDINGS

New innovative remote verification technologies not only increase the efficiency of inspection operations within the maintenance process, but also manage to overcome the limits of classic technical examination methods by considerably reducing the exposure of responsible personnel to time, money and occupational health and safety costs, such as in verification operations on very tall buildings or difficult-to-access locations, such as the one in Figure These nonconventional alternatives bring together steps such as data collection and analysis, selection of relevant data and verification of compliance with regulations[17,19].

Figure 6. Skyscraper inspection procedures using drones [20]

The use of thermography via unmanned aerial vehicles can provide essential data on the appearance of cracks or possible detachment of various finishing layers on stone and concrete structures, as well as obtaining much more detailed information on the stage of degradation of exterior finishes and their evolution over time. By applying such checks, the thermal properties of building materials can be established, facilitating the assessment of the impact of the wear process on the energy performance of the materials used in the construction of buildings [21]. These technologies clearly highlight temperature imbalances in the analyzed buildings, allowing the graphic transposition of energy losses and the localization of areas with wet insulation on facades, roofs or other constructive elements [17]. As highlighted in Figure 7, the application of 3D thermographic modeling performed with drones allows for the accurate identification and characterization of defects, and the main areas of use, including those already mentioned, are presented in Table 1.

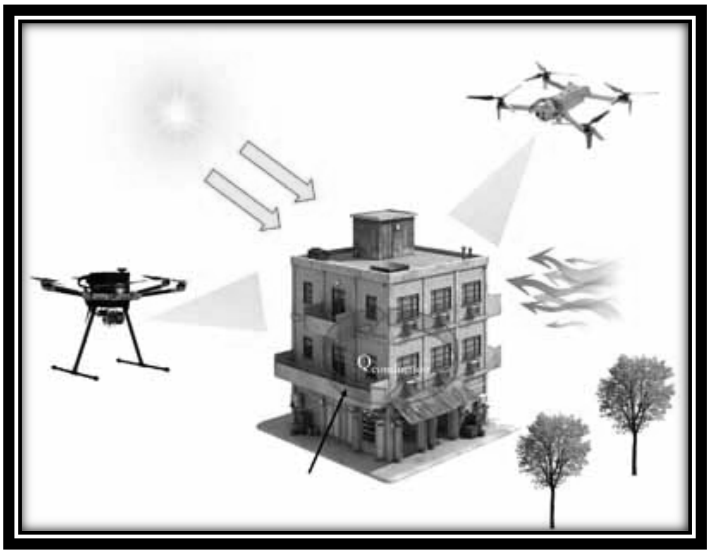


Figure 7. Detection and assessment of building defects and related equipment through 3D thermography using drones [22]

Table 1. Domains of application of drone-based thermographic inspections in building maintenance [23,24]

Scope	Observable defects/problems with UAV	Advantages and benefits
Building facade inspections	Thermal insulation deficiencies, moisture accumulation in the walls, water infiltrations that are difficult to visually identify, hidden wiring with possible defects, energy losses through leaky areas.	Early detection of problems reduces repair costs, improves the thermal comfort of the home and increases energy efficiency by eliminating heat loss
Checking the condition of roofs	Wet areas or areas affected by infiltration, structural degradation caused by water accumulation, identification of points vulnerable to corrosion or mechanical degradation	It allows a valid assessment of roofs that are difficult or dangerous to access, quickly identifies areas vulnerable to infiltration and eliminates the risk of accidents for the personnel responsible for the checks.
Assessment of the condition of electrical installations	Echilibru deficitar între faze, circuite supraîncărcate, siguranțe arse, contact electric imperfect sau slăbit, identificarea punctelor fierbinți care prevestesc avarii critice	Poor balance between phases, overloaded circuits, blown fuses, imperfect or loose electrical contact, identification of hot spots that predict critical failures.
Monitoring of photovoltaic panels	Module failures (cracked glass, defective diodes, overheating) cutiilor de conexiuni, the appearance of hot spots on the cells), wiring	It ensures rapid identification of faults before costly damage occurs, helps maximize renewable energy production and

Scope	Observable defects/problems with UAV	Advantages and benefits
	and connection problems (inverters, fuses, controllers), as well as installation deficiencies of the supporting structure.	extends the lifespan of photovoltaic installations.

6. DRONES AS TOOLS FOR REDUCING CARBON EMISSIONS. TYPES OF RGB-TI COMPLEMENTARY SENSORS

Regarding carbon emissions, according to [25], they are considerably reduced by the use of drones, taking as a benchmark the comparison between drones and helicopters regarding power line inspections:

- Replacing the helicopter with a drone and a gasoline car leads to a reduction of approximately 8.96 kg CO_2/km of inspected line;
- Switching from helicopter to drone and electric car brings an even clearer advantage, reducing emissions by 11.73 kg CO_2/km [25].

In the field of building maintenance, in addition to this RGB–TI combination, which is the basis of modern 3D thermography technology, UAVs can also integrate other high-performance sensors. For example, LiDAR sensors use laser beams to generate detailed three-dimensional models of the terrain and buildings, and GPS and RTK systems offer high-precision positioning, facilitating rigorous mapping of investigated areas and maneuvering drones in narrow or difficult-to-access spaces [26,27,28,29,30].

All these sensors are illustrated in Figure 8, as follows:

- RGB sensors (visible light sensors) –Figure 8a;
- LiDAR sensors – Figure 8b;
- Thermal imaging (TI) sensors – Figure 8c;
- GPS and RTK positioning sensors – Figure 8d;

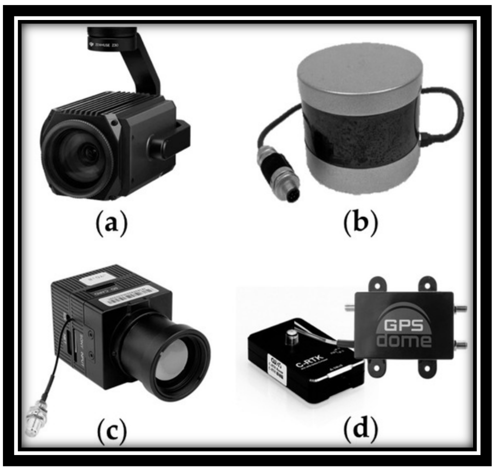


Figure 8. Illustrative sensor payloads for construction-focused UAVs include: (a) visible-spectrum (RGB) cameras; (b) LiDAR scanners; (c) thermal imaging sensors; and (d) satellite positioning modules such as GPS with RTK correction [27]

7. CURRENT LIMITATIONS OF THREE-DIMENSIONAL THERMOGRAMMYS CARRIED OUT WITH DRONES

Although UAVs offer significant advantages in maintenance and inspection activities, their use is still subject to certain technical limitations that may influence the accuracy and efficiency of the results, such as those listed in Table 2 [27].

Table 2. Technical and operational constraints in the use of UAVs for building inspection and maintenance [27,31,32]

Technical limitation (UAV)	Description	Result
Short flight time (20–30 min per battery)	The amount of information extracted in a single output is conditional. Operations can become fragmented, especially in large assemblies.	Incomplete coverage in a single session, longer working times
Limited distance/range and radio link	Limitations in maintaining connection with the controller/base over large areas or locations with poor connectivity	Uncovered areas, video/telemetry link drops, flight replays.
Adverse weather conditions (rain, strong wind, etc.)	Flying becomes difficult or unsafe and data quality may decline	Collection delays, unusable data series, rescheduled windows.
Limiting access to tight spaces/indoors (tunnels, narrow corridors)	The inability or difficulty of operating in areas with reduced visibility/signal.	Lack of data in critical areas; gaps in 3D/thermal models
Planning and operational constraints	The need to correlate UAV capabilities with field conditions and respect constraints (schedule, safety, regulations).	Reduced efficiency, operational risks, non-compliance

8. 3D THERMOGRAPHY: PERSPECTIVES AND CONCLUSIONS FOR MAINTENANCE MANAGEMENT

3D thermography with drones is an nonconventional diagnostic tool with real utility in building maintenance, allowing safe inspections in hard-to-reach areas and supporting structural, maintenance and energy audits. Integrated with a 3D-RGB model, it precisely fixes the thermal map on the model and accurately locates anomalies. Rapid identification of thermal bridges, infiltrations, insulation defects or equipment degradation allows targeted interventions that reduce consumption, and the replacement of scaffolding and repeated trips with short flights reduces emissions and, overall, the carbon footprint decreases [14,17,16, 18, 21,33].

The construction industry is at a turning point, facing significant challenges such as labor shortages, increasingly stringent safety requirements, and pressure to maintain profitability. In this context, the use of drones and advanced vision systems no longer represent hypothetical perspectives in building maintenance, but concrete and tested solutions capable of effectively addressing these challenges. Their impact is manifested not only in reducing costs, but also in increasing productivity, improving quality, and reducing risks associated with exploitation. However, the real contribution of these nonconventional technologies depends on how they are integrated into a coherent and coordinated plan based on data and advanced software. The constructions of the future are thus profiled as part of an intelligent ecosystem, where drones transmit real-time information to ground robots, and all processes operate synchronously through a central digital model, aligned with the overall project plan.This perspective paves the way for a safer, more efficient and more predictable construction industry. In order to convert this potential into a long-term competitive advantage, however, an integrated strategy is needed that connects technology, human resources and projects into a unified framework [34].

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