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## DRONE-ASSISTED ROOF INSPECTIONS: ADVANCING STRUCTURAL MONITORING AND MAINTENANCE OF FLAT ROOFS IN URBAN ENVIRONMENTS

### ІНСПЕКТУВАННЯ ПОКРІВЕЛЬ ЗА ДОПОМОГОЮ ДРОНІВ: УДОСКОНАЛЕННЯ МОНІТОРИНГУ ТА ОБСЛУГОВУВАННЯ ПЛОСКИХ ДАХІВ В УМОВАХ МІСЬКОГО СЕРЕДОВИЩА

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**Abstract.** Flat roofs comprise a modest share of Ukraine's overall housing sector, yet they dominate many multi-apartment developments due to Soviet-era construction approaches favoring flat concrete structures. Despite early concerns regarding snow accumulation and water management, modern engineering practices and retrofitting methods have validated the long-term viability of these rooftops, especially in dense urban areas such as Dnipro. Concurrently, the adoption of drones for roof inspections represents a noteworthy advancement, leveraging high-resolution RGB imaging, thermal sensors, LiDAR, and AI-driven analytics to detect structural defects more accurately and efficiently than conventional techniques [1]. Real-world applications underscore the benefits of drone-collected data in municipal energy audits, insurance claim assessments, and routine building maintenance [5]. Although regulatory and safety considerations remain pivotal, recent innovations suggest a continued rise in drone-based evaluation, particularly as the technology evolves toward multi-sensor fusion and possible autonomous operations [6]. As sustainable architecture gains momentum, flat roofs are increasingly suitable for installations such as green spaces and solar arrays, further amplifying the need for consistent, high-quality inspections [4]. Consequently, drone deployment not only enhances safety and cost-effectiveness but also addresses emerging demands for energy efficiency, sustainability, and proactive urban renewal.

**Key words:** flat roofs, drones, AI-driven analysis

### Introduction.

Flat roofs, while constituting a relatively small portion of Ukraine's overall residential building sector, serve as a dominant architectural feature within numerous multi-apartment housing developments. This imbalance can be traced back to Soviet-era urban planning principles, which mandated the widespread adoption of flat concrete roofs to expedite large-scale residential construction projects in burgeoning metropolitan centers. Notably, these construction strategies facilitated the rapid creation of standardized housing units, thereby accommodating the influx of urban



populations. Although pitched roofs have maintained their prevalence in more rural, privately owned dwellings—often due to cultural traditions and perceived efficiency in sloped design for snow management—larger cities typically exhibit a far denser landscape of flat-roof structures. In particular, the Dnipropetrovsk (Dnipro) region, widely recognized for its extensive industrial base and accelerated pace of urban growth, is home to numerous Soviet-era residential complexes featuring these flat rooftops. According to recent data, flat roofs comprise over 30% of the total roof area nationwide, a figure that can surpass 40% in some of the more urbanized oblasts, such as Dnipropetrovsk.

Early design considerations for these structures primarily emphasized straightforward construction and cost reduction, with climate and snow loads also exerting considerable influence on building methods. In earlier decades, the risk of snow accumulation and thermal inefficiency led to skepticism regarding the suitability of flat roofs in regions prone to severe winters. However, contemporary engineering advancements, ranging from improved waterproofing membranes to high-grade insulation materials, have demonstrated that flat roofs can remain structurally sound and energy-efficient, even under harsh climatic conditions. Despite these improvements, existing Soviet-era buildings often require significant renovations, including the installation of robust waterproofing systems and advanced insulation upgrades to meet modern standards. The recent rise in sustainable construction practices has further increased interest in flat roofs, as they offer accessible and versatile surfaces for rooftop gardens, solar panel arrays, and communal recreational spaces. Consequently, these flat-roof designs, once primarily viewed as a practical byproduct of high-density housing demands, now align more closely with contemporary values of sustainability and efficient resource utilization.

Despite the enduring prevalence of pitched roofs in single-family developments—largely due to longstanding architectural traditions and the perception that angled roofs effectively shed snow and rain—flat roofs have cemented their status in metropolitan regions. Their role in defining Ukraine’s skyline is evident, particularly within sprawling housing estates dating back to the Soviet period. Urban renewal initiatives



have increasingly turned their attention to these older, flat-roofed buildings, prioritizing not only structural integrity but also energy conservation. Consequently, design interventions frequently entail retrofitting older roofs with modern insulation materials, implementing cutting-edge waterproofing coatings, or installing environmental features like green roofs. As urban revitalization efforts accelerate, experts predict that flat roofs will remain a central focus of reconstruction and modernization measures, perpetuating their longstanding influence on Ukrainian residential architecture.

**Technological Advancements in Roof Inspection.** In parallel, drones have rapidly emerged as an essential tool for roof inspections (figure 1), providing notably higher levels of efficiency, accuracy, and safety compared to manual, on-site methods.



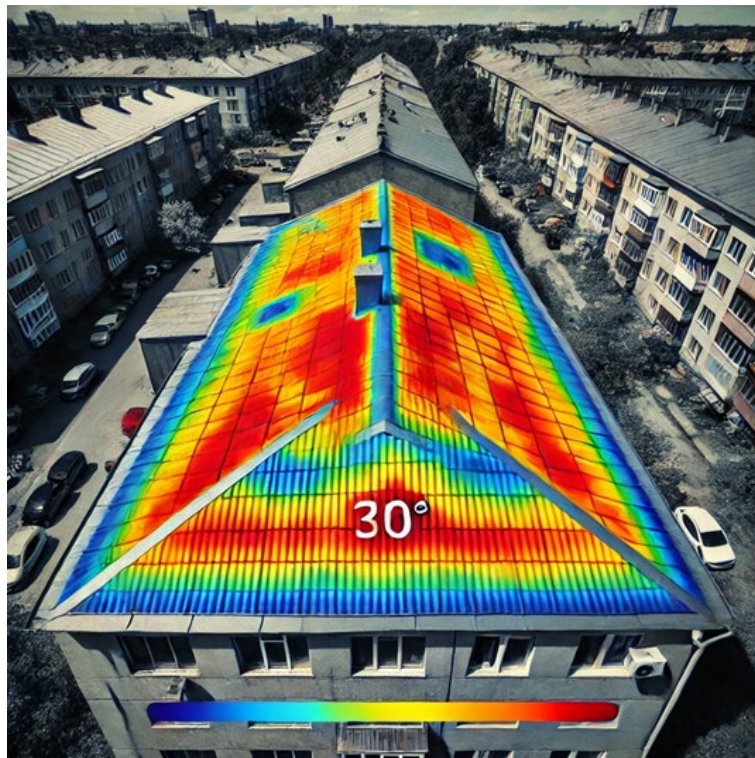
**Figure 1 - Drone-Based Roof Inspection Setup**

Over the past few years, scientific research—particularly from 2022 to 2025—has investigated the deployment of various sensors, including thermal imaging, light detection and ranging (LiDAR), and artificial intelligence (AI)-driven systems, to identify a range of defects on both flat and sloped roofs [2,3]. Traditional high-resolution RGB cameras still play a critical role in visual examinations, but advanced



AI algorithms increasingly automate the detection of missing shingles, cracks, deteriorations in waterproofing layers, and other forms of structural damage [1]. Incorporating these sensor types has shown remarkable promise in revealing issues that might be invisible during typical walk-through inspections, such as concealed moisture beneath roof surfaces or areas suffering from localized heat loss [4]. Moreover, LiDAR-based three-dimensional mapping has provided engineers and building managers with invaluable insights, aiding in the detection of subtle deformities or slight sags that may signify impending structural weakness [7].

Notably, real-world case studies underscore the practicality of drone-enabled analyses. Municipal energy audits, for instance, have leveraged thermal drone imaging to pinpoint regions of excessive heat transfer, suggesting inadequate insulation or hidden leaks [5] (figure 2).



**Figure 2 - Sample Thermal Imaging Results**

Similarly, insurance companies have adopted automated drone surveys to expedite claim assessments following storm damage, enhancing both speed and the consistency of evaluations. These examples illuminate the potential for integrating



drone-collected data into existing workflows, streamlining documentation, and offering a more objective basis for decision-making. Furthermore, researchers have increasingly focused on developing methodologies that combine photogrammetry, thermal scans, and deep learning systems, leading to greater precision in identifying small-scale anomalies and establishing robust protocols for further analyses [2,3].

Comparisons across multiple studies reveal that no single sensor or analytic technique is universally superior. Instead, a multi-faceted approach—often blending RGB imagery, thermal imaging, and LiDAR capabilities—delivers a more complete assessment by capturing different types of roof-related defects. AI-based data processing enhances these techniques further by rapidly compiling, organizing, and analyzing large volumes of visual and thermal inputs. This level of streamlined automation not only reduces the time required to draw conclusions but also helps reduce potential human error inherent in manual inspections. Over time, it is anticipated that such AI-driven processes will become even more sophisticated, potentially incorporating real-time data analytics that deliver near-immediate feedback to inspection teams on the ground.

However, as drones become more prevalent, stringent attention to regulatory and safety protocols remains paramount. Operators must comply with aviation regulations governing drone altitude, flight paths, and permitted operational areas, as well as maintain respect for privacy rights in residential and industrial contexts [8]. In certain jurisdictions, additional certifications or permission from civil aviation authorities may be required, emphasizing the importance of well-defined standard operating procedures. Beyond legal aspects, safety guidelines ensure that drones do not pose hazards to bystanders or risk collisions with other airborne or terrestrial obstacles. Consequently, professional operators often invest in flight simulation training, risk assessments, and ongoing technical audits to maintain a high standard of operational reliability [9]. In combination, these precautions foster both public trust and the continued integration of drone services into critical infrastructure assessments. Compare the methods of traditional and drone-based roof inspections, as highlighted in the **Comparison of Inspection Methods** (table 1).



**Table 1. Comparative overview of manual and drone-based inspection methods, highlighting advantages of multi-sensor drone setups.**

<b>Inspection Parameter</b>	<b>Manual Inspection</b>	<b>Drone Inspection (RGB)</b>	<b>Drone Inspection (RGB + Thermal + LiDAR)</b>
<b>Data Collection Speed</b>	Low (scaffolding, time-consuming)	Moderate (faster than manual, but single sensor)	High (simultaneous multi-sensor capture)
<b>Safety</b>	Moderate risk (fall hazards)	Lower risk, but requires flight safety measures	Very low risk, minimal human exposure
<b>Cost</b>	Varies (labor-intensive)	Moderate equipment/labor cost	Higher initial outlay, but cost-effective long-term
<b>Depth of Analysis</b>	Dependent on inspector's experience	Visual anomalies only	Comprehensive (thermal, structural mapping)
<b>Suitable for Large Roof Areas</b>	Challenging (time & manpower)	Improved coverage	Excellent coverage with multi-sensor data
<b>Detection of Hidden Damage</b>	Usually requires specialized tools or invasive checks	Limited (visual only)	High (thermal detects moisture, LiDAR detects sagging)

Analyzing specific advantages reveals a compelling case for widespread drone adoption in roofing and structural inspections. In challenging or hazardous environments, drones offer a safer alternative to placing human inspectors on precarious scaffolds or unsteady surfaces. Advanced imaging tools—comprising high-definition and thermal cameras—deliver comprehensive data sets that enable early detection of minute defects, culminating in more timely maintenance interventions (figure 3).



**Figure 3 - Drone LiDAR Point Cloud Visualization**

Expedited survey timelines further improve project efficiency by reducing the logistical complexities associated with multi-person teams and heavy equipment. Cost savings in labor, transportation, and materials further strengthen the argument for transitioning to aerial inspection methods. Drones also foster standardized data collection practices, thereby facilitating longitudinal studies that track incremental changes in a building's structural health. This advantage extends to other indoor scenarios, where specialized sensors can detect floor unevenness or minute damage under raised floors, mitigating disruptions and ensuring smoother commercial or industrial operations [7].

Further supporting these trends, integrating AI-assisted processing into drone workflows automates many data analytics tasks, including digital modeling and predictive assessments of potential failure points. By doing so, it narrows the gap between data collection and actionable insights, allowing facility managers to implement targeted interventions more swiftly. Additionally, LiDAR enables the creation of high-fidelity 3D maps, which can then be used to measure or compare structural shifts with prior data sets. This granular level of detail is invaluable for long-



term asset management, as it fosters predictive maintenance strategies instead of reactive solutions. AI-driven platforms can further categorize the severity of identified faults, suggesting immediate repairs where critical weaknesses are found, or scheduling lower-priority repairs at a later time. This logical, hierarchy-based approach to maintenance has the potential to significantly extend the lifespan of roofs, reduce unplanned downtime, and optimize resource allocation in large-scale property portfolios [3].

Meanwhile, the integration of drones within Ukrainian contexts holds especially high relevance given the widespread presence of Soviet-era multi-apartment buildings and the growing emphasis on sustainable, modernized urban living. Flat roofs, in particular, stand to benefit from routine inspections that identify the early onset of leaks or structural fatigue, thereby preventing more costly interventions down the line. In regions like Dnipropetrovsk, where flat rooftops often exceed 40% of total roof coverage, drone-based monitoring represents a proactive strategy for local authorities and private owners alike. Also, as green initiatives steadily gain traction, these same rooftops may eventually house communal gardens, renewable energy arrays, or additional spaces for recreation, thereby amplifying the importance of regular, precise inspections to maintain safety and optimize functionality. Beyond their immediate utility, drone technologies contribute to a broader transformation of Ukraine's urban environment, one that emphasizes resilience, adaptability, and efficient resource management.

### **The Future of Drone-Based Roof Inspections.**

Looking forward, the evolution of drone applications will likely extend to fully autonomous flight operations supported by multi-sensor fusion, effectively consolidating thermal, RGB, LiDAR, and potentially new sensor modalities into a single, cohesive inspection platform [6]. As AI capabilities advance, it is anticipated that such systems will not only detect and classify defects but also predict their future progression and recommend preventive measures. These developments could radically shift current paradigms of building maintenance, particularly in high-density urban centers where time and access constraints frequently hinder large-scale inspection





programs. Additionally, as regulatory frameworks adapt to support commercial drone usage, further integration of unmanned aerial vehicles into municipal planning and private enterprise will become increasingly seamless [8]. Ultimately, this synergy of technology, regulation, and architectural innovation has the potential to reshape how societies manage and maintain their built environments, with Ukraine—owing to its unique roofing landscape—positioned at the forefront of these transformative processes.

**In conclusion**, drones have already proven invaluable for enhancing the safety, efficiency, and comprehensiveness of roof inspections, whether for Soviet-era flat rooftops or contemporary pitched designs. Their ongoing adoption within urban environments, complemented by AI-powered diagnostics and multi-sensor data acquisition, underscores a broader shift toward proactive, data-driven building management strategies. Over time, these methods promise to reduce the incidence of catastrophic roof failures, promote sustainable property development, and equip municipal authorities with the tools necessary to upgrade aging housing infrastructure. As the body of research from 2022 to 2025 and beyond continues to expand, it is becoming increasingly clear that drone technology will serve as a linchpin for the next generation of architectural upkeep and renewal. In this context, Ukraine’s significant population of flat-roofed structures, combined with the global momentum toward green architecture and automated inspections, exemplifies the critical intersection of tradition and innovation. Through careful regulation, sustained research, and evolving best practices, drone-enabled roof assessments are poised to remain a cornerstone of structural evaluation well into the future.

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**Анотація.** Плоскі дахи складають невелику частину загального житлового сектору України, проте вони домінують у багатьох багатоквартирних забудовах завдяки підходам будівництва епохи Радянського Союзу, які сприяли використанню плоских бетонних конструкцій. Незважаючи на початкові занепокоєння щодо накопичення снігу та водовідведення, сучасні інженерні практики та методи ретрофітингу підтвердили



довготривалу життєздатність цих дахів, особливо в густонаселених міських районах, таких як Дніпро. Водночас використання дронів для інспекції дахів є суттєвим досягненням, оскільки воно використовує високоякісне RGB-зображення, теплові сенсори, LiDAR та аналітику на основі ШІ для точнішого і ефективнішого виявлення структурних дефектів порівняно з традиційними методами [1]. Реальні приклади застосування підкреслюють переваги даних, зібраних за допомогою дронів, у муніципальних енергетичних аудитах, оцінці страхових вимог і щоденному обслуговуванні будівель [5]. Хоча регуляторні та безпекові аспекти залишаються важливими, останні інновації вказують на зростаюче використання дронів для оцінки, особливо через розвиток технологій до мультисенсорного злиття та можливих автономних операцій [6]. Зі зростанням популярності сталого архітектурного підходу плоскі дахи стають дедалі більш придатними для встановлення таких об'єктів, як зелені зони та сонячні панелі, що ще більше підкреслює необхідність проведення постійних і якісних інспекцій [4]. Отже, використання дронів не тільки підвищує безпеку та економічність, але й відповідає на зростаючі вимоги до енергоефективності, сталого розвитку та проактивного міського відновлення.

**Ключові слова:** плоскі дахи, дрони, аналітика на основі ШІ