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A scoping review of non-destructive testing (NDT) techniques in building performance diagnostic inspections

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HIGHLIGHTS

- Non-Destructive Testing (NDT) techniques can be utilized to conduct envelope diagnostics for standardized energy audits.
- Six NDT techniques are analyzed for their compatibility with building envelope auditing.
- A tool was developed and is presented to identify hybrid workflows between different NDT techniques.
- Hybrid workflows can be created between different NDT techniques to conduct standard envelope energy audits.

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ABSTRACT

Understanding building envelope thermodynamics is an essential foundation of building sciences, mainly due to the envelope's role as a boundary layer for exterior environments, as well as a container and regulator of internal microclimates. This paper presents a scoping literature review of select Non-destructive Testing (NDT) techniques for building envelope scanning and surveying for thermodynamic diagnostics. The investigation focuses specifically on reviewing six NDT techniques: Ground Penetrating Radar (GPR), Light Detection and Ranging (LiDAR)/Laser Scanning, Thermography, Ultrasound, Close-Range Photogrammetry and Through Wall Imaging Radar (TWIR). The aim is to identify knowledge gaps in terms of their use in accurately characterizing envelope compositions for further integration in Building Energy Modeling (BEM). Each technique was evaluated according to set categories imbibed from the American Society of Heating, Refrigerating, and Air Conditioning Engineering (ASHRAE) Standard 211P that showcase the technique's ability to extract various relevant information. A framework is then developed to inform users on how to use hybrid NDT-based workflows applied in building envelope energy audits. The paper concludes by discussing possibilities of utilizing NDT in large-scale audit automation, BEM integration, and developing built environment policies focusing on increasing existing building performance through retrofitting design.

Contents

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1. Introduction

One of the biggest challenges facing the built environment is its substantial impact on climate change and the energy sector. Almost two-thirds of electricity (76%) and 40% of total energy consumption in the United States is consumed by buildings [1]. This puts the onus on designers, builders, contractors, and all other professionals that work in the building sector to find immediate and effective solutions to decrease this consumption and help combat the ever-growing threat of climate change. One avenue to achieve substantial carbon reductions is by diagnosing existing building stocks through energy audits. Energy audits allow for the quantification and optimization of individual building performance at an isolated level and can also expand to urban scale analysis of neighborhoods and districts. The identification of building envelope component performance is critical for a comprehensive energy audit [2]. Built wall components are traditionally examined through visual inspection or collection of samples [3]. This entails a labor-intensive, time-consuming, and costly destructive process of disassembly or drilling to be able to extract samples from the different layers of the wall [4]. To be comprehensive, this process must be repeated at different discrete sections of a wall, and when repeated continuously may cause permanent damage to the inspected surface. As the need to enhance and streamline building energy retrofits is evident for application on a wide scale, the question that presents itself is: how can built environment professionals inspect, assess, and document building envelopes using fast, low cost, and nondestructive means?

Non-Destructive Testing (NDT) can provide a useful tool to extract information from buildings, which would aid researchers and building scientists in performing building audits for various applications. An NDT technique that can identify wall components can support averting the physical damage resulting from traditional sample collection processes [5], and thus, can benefit users greatly in the documentation phase. These techniques include photogrammetry, laser scanning, Ground Penetrating Radar (GPR), and thermography, which have been utilized in different applications [6]. Some of these techniques benefit from the fact that they do not necessarily require contact with the surface that is under inspection, while other contact-based NDT techniques can be utilized to further refine models built by remote techniques, by allowing a higher detail of subsurface inspection for a more accurate result [6]. Therefore, identifying the strengths and weaknesses of current NDT techniques and the compatibility of hybrid workflows may prevent inadequate use that could prove costly for any decisions built on inaccurate readings. This may also maximize the positive effect of those built on accurate ones [3].

This paper reviews the literature on various NDT techniques that are currently in use and develops a tool to organize this literature into nondestructive workflows for building façade audit purposes. Reviewing and assessing the strengths and limitations of each tool for performing audits on building envelopes becomes an essential reference to identify workflows that would help articulate a framework for large-scale building envelope assessment and retrofits.

2. Literature review methodology

This literature review aims to study existing research on NDT applications and identify gaps regarding their application in building envelope component identification. The goal of the paper is to create a cohesive tool that indicates the appropriateness of each NDT technique in the context of different categories related to building audits. These categories were imbibed from ASHRAE's Standard 211P for Commercial Building Audits. This standard puts the building envelope in the scope of energy audits among other systems [7]. The audit requires the following information to be provided about the envelope:

- Roof: Gross roof area-Condition of roof (Degradation, Moisture)-Exterior Material-Insulation level and R-Value (determined noninvasively).
- Wall: Gross wall area- Exterior Material- Insulation level and R-Value (determined noninvasively).
- Fenestration: Gross fenestration area-Fenestration wall ratio-Glazing frame type-Exterior Door Area and construction-Fenestration seals.
- Floors and Underground Walls: Floor-type and insulation - Underground floor area and insulation.
- Overall enclosure tightness: Infiltration/exfiltration and condition level.

Thus, to be able to conduct ASHRAE audits, it is imperative to gather envelope related data that is pertinent to its composition and construction. This data can be divided into physical properties, material properties, and condition properties of the envelope. Standard 211P requires other information as well such as Energy Use Intensity (EUI) which encapsulates the entire energy consumption of the building. This makes the performance of the envelope a factor in the audit and its thermal and moisture performance, which drives HVAC loads important properties to assess [8]. Accordingly, to encompass the necessary information required the following categories for evaluation of each NDT technique displayed in Fig. 1 are:

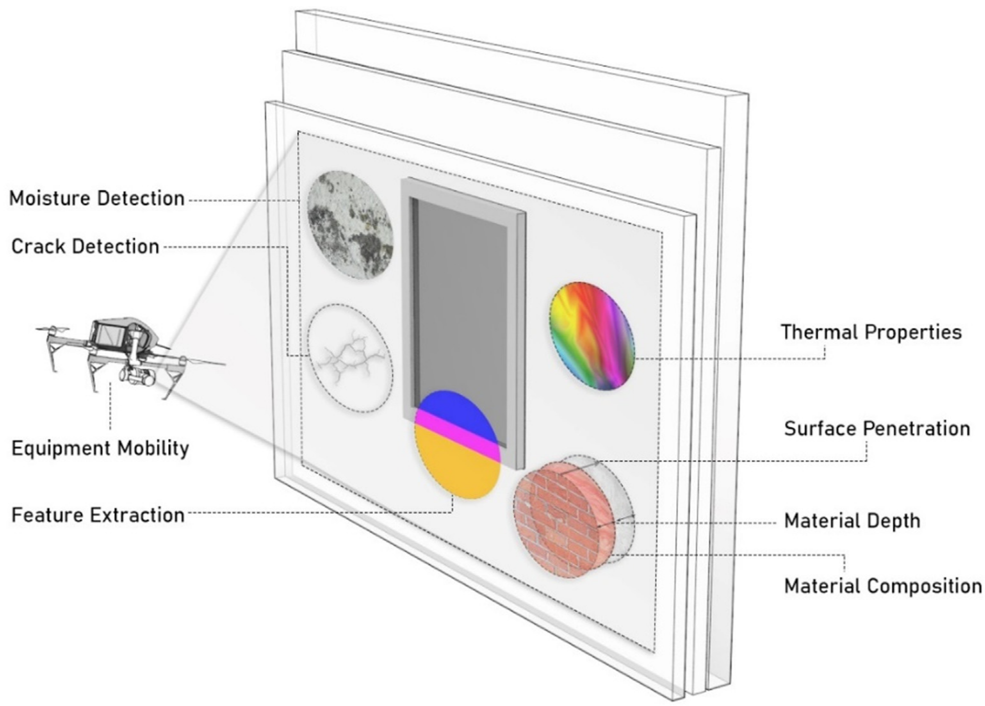

Fig. 1. Graphical representation of NDT evaluation categories in an example wall component.

Table 1
Final Search Terms.

Final Search Terms	
Inclusion Criteria	Corresponding Search Terms
Evaluation Type	Non-Destructive (Techniques OR Evaluation OR Testing)
Building Envelope	Building Envelope (Component OR Properties OR Attributes) Identification

- Surface Penetration: The ability to extract either only surface, subsurface, or both surface and subsurface information.
- Feature Extraction: The ability to identify building separate envelope components.
- Material Depth: Identifying material thickness of individual layers.
- Material Composition: Identifying the material's physical and dielectric properties.
- Thermal Properties Detection: Measuring the thermal performance of materials.
- Moisture Detection: Identifying the presence of moisture inside a wall assembly.
- Physical Defect Detection: Identifying cracks or anomalies in a building envelope.

These categories cover the technique's ability to extract the relevant information needed for a thorough envelope inspection. In the larger framework of a national policy on retrofitting buildings, the mobility and speed of the testing remain essential factors for practicality. As the ASHRAE 211P standard had specified information must be gathered for roofs, walls, and fenestrations, access to these elements of a building is crucial for a complete energy audit. Land-based mobile surveying equipment, such as tripods and road vehicles, offer versatility in terms of auditing building facades, with limitations regarding building height and poor access to roof areas. Unmanned Aerial Vehicles (UAVs), commonly referred to as drones, offer a medium for inspection that is increasingly common in the construction industry and has the potential to significantly speed up building inspection and documentation processes especially for inaccessible areas [9]. Thus, an additional category is therefore added to the assessment criteria that would assess the literature for NDT equipment mobility compatibility and is defined as such:

- Equipment Mobility: The ability to conduct the testing on-site for automation purposes using drones.

2.1. Literature Search procedures

According to the identified properties, a thorough search of the literature on different NDT techniques used in the building construction sector was conducted using the Georgia Tech Library database tool. The review was based on searching for the keywords seen in Table 1.

Accordingly, a sizeable body of literature most pertinent to the subject matter was gathered through searches utilizing the aforementioned Georgia Tech Library Database. The studies were screened by the authors and conducted according to the following steps: (1) Removal of duplicates and title screening (2) Abstract Screening (3) Initial full-text screening to identify studies examining building envelope properties using NDT techniques. A second round of screening was conducted by the authors to select only the subset that pertains to the criteria identified above that is convergent with the ASHRAE Standard 211P. Six techniques were accordingly selected that intersected repeatedly in the results of the keyword searches and the criteria subset concurrently which are*: Infrared Thermography, Ultrasound, Through Wall Imaging Radar, LiDAR/Laser scanning, Close-Range Photogrammetry*, and *Ground Penetrating Radar.* These NDT techniques represent commercially available and applied methods that were practically relevant to this paper's scope and purpose. Other techniques were identified such as *Geoelectric Mapping, Microgravimetry, and Magnetometry*. These, however, were deemed not suitable for this review as they find applications mostly in other fields such as geographical surveying and civil engineering applications [6].

Each NDT technique was evaluated according to these categories. The results were tabulated to indicate whether for each category there is:

1) "Direct Relevant Literature," showcasing an already established application of the NDT technique in this category in terms of building envelope audits.

2) "Indirect Relevant Literature," demonstrating that there is a similar application that has not been applied to on-site building envelope evaluation or provides only preliminary results or proof of concept.

3) "No Relevant Literature," which indicates that there was no direct or indirect relevant literature found for this category.

It is important to note that the literature on NDT applications for building envelopes is extensive and it is beyond the scope of this paper to cover it comprehensively. The paper seeks to provide references that are sufficiently representative of the application under evaluation. For this purpose, the identification of "direct relevant literature" requires at least 2 scholarly investigations that directly portray for the reader the presence of peer-reviewed literature that pertains to the particular property of the envelope under study. The articles that were selected are satisfactory contemporary examples that would mirror a successful use of the application in building envelope evaluation. Regarding "indirect relevant literature," finding at least one paper was considered sufficient if it has shown a promising application that can be tailored to building envelope evaluation based on shared scientific principles. This serves to present for the reader a window into possible future applications of NDT techniques that have not been explored yet.

3. Literature review and results

3.1. Infrared thermography (IRT)

IRT is a technique that measures the emitted and reflected infrared radiation from a target surface or object, and consequently, displays this image as a spectrum. It has been utilized as a technique to assess the condition of building envelopes and identify invisible defects. This technique offers the benefit of being remote and can be used from a distance of few millimeters to several kilometers and can identify one-dimensional heat flux sensing and emissivity [10]. In buildings, thermography is mainly used to detect thermal anomalies. These are points within an envelope where heat transfer occurs at an accelerated rate and allows for the specification for range and surface temperature evaluation [11].

It has been utilized in applications that allow the tracking of moisture-related problems inside wall assemblies as well [12]. Infrared imaging by nature is dependent on the emissivity of the surface [11], and reads the surface temperature, and therefore is not efficient on its own to identify subsurface building components. However, it has been used in tandem with impulse radars, GPR, acoustic, and radiography imaging to identify subsurface cracks and anomalies in various concrete and masonry structures [10] and thus extends its usability as a subsurface investigation tool.

3.2. IRT evaluation

The results tabulated in Table 2 demonstrate that direct relevant literature was found regarding the property of surface penetration of IRT as displayed by the process of extracting subsurface information such as insulation defects, as indicated by Taylor, Counsell, and Gill [13] and detecting subsurface structural building elements as shown by Barreira and de Freitas [5] and Lerma et al. [14]. IRT's ability to detect moisture has been displayed by Colantonio [12] Barreira and Almeida [15] through surface temperature readings and comparison, and the ability to conduct thermal readings which can be utilized to extract thermal properties as seen in the work conducted by Solla and Riveiro [6] and Taylor, Counsell, and Gill [13]. Undergoing drone flybys using IRT has been previously developed by Rakha et al. [16], Rakha and Gorodetsky [17], Omar and Nehdi [18] as well as using IRT images with specialized software for feature extraction with work conducted by Lagüela et al. [19] and Rakha et al. [16]. The ability to detect physical defects in the envelope has been showcased by Bauer et al. [20] which identified cracks using quantitative thermography that measure the delta T to determine cracks, Taylor, Counsell, and Gill [13] which utilized IRT to identify missing insulation in assemblies, and Rakha et al. [16] that utilized IRT to identify building envelope defects with up to 76% accuracy using drone flybys, Computer Vision (CV) and Machine Learning (ML) techniques.

Indirect relevant literature was identified regarding Material Depth detection in work conducted by X. Li et al. [21] using a two-sided set up to accurately measure stainless steel step wedges of varying thickness from 5.09 mm to 24.08 mm. Also, Holland and Reusser [22] showcased the ability of IRT for detecting thickness, roughness, and material composition using one-dimensional flash thermography techniques. Barreira and de Freitas [5] showed that infrared thermography can be utilized in identifying different material compositions according to the specific behavior of materials under infrared thermography that allowed differentiation. These techniques are a form of active thermography that requires

Table 2
Literature Review on Thermography.

	Surface Penetration	Feature Extraction	EquipmentMobility	MaterialDepth	Material Composition	ThermalProperties	Moisture Detection	Physical Defects
IRT Source	● (Taylor, Counsell, and Gill 2014) (Barreira and de Freitas 2007) (Lerma et al. 2007)	● (Rakha et al. 2018) (Lagüela et al. 2011)	● (Rakha and Gorodetsky 2018) (Rakha et al. 2018) (Omar and Nehdi 2017)	○ (X. Li et al. 2018) (Holland and Reusser 2016)	○ (Holland and Reusser 2016) (Barreira and de Freitas 2007)	● (Solla and Riveiro 2016) (Taylor, Counsell, and Gill 2014)	● (Colantonio 2008) (Barreira and de Freitas 2007)	● (Bauer et al. 2016) (Rakha et al. 2018) (Taylor, Counsell, and Gill 2014)

● Direct Relevant literature
○ Indirect Relevant literature
○No Relevant literature

Table 3
Literature Review assessment on Ultrasound.

	Surface Penetration	Feature Extraction	EquipmentMobility	MaterialDepth	Material Composition	ThermalProperties	Moisture Detection	Physical Defects
Ultrasound Source	● (Liñán et al. 2015) (García-Diego et al. 2012) (Shah and Ribakov 2010)	○	● (Mattar and Kalai 2018) (D. Zhang et al. 2018) (Skaga 2017)	● (Schickert 2005) (Pristov, Dalton, and Likins 2008) (Carino 2004)	○ (Afanasenko, Boev, and Kulakov 2019) (Dhekne et al. 2018)	○	○ (W. M. Healy and Van Doorn 2004) (W. Healy and Van Doorn 2007)	● (Shickert 2002) (Shah and Ribakov 2010) (Godinho et al. 2013)

● Direct Relevant literature
○ Indirect Relevant literature
○No Relevant literature

the applications of transient heat flow that allows the measurement and detection of said properties.

3.3. Ultrasound

Ultrasound is another NDT technique that is used for wall component surveying [3]. It utilizes relatively short wavelengths which enables the highly detailed assessment of concrete structures [23]. This technology can be used with Synthetic Aperture Focusing Techniques (SAFT) for imaging by sections through propagating waves to generate high-resolution images of areas under study in concrete structures and allow fault detection, duct localization, and measurement of the thickness of the material [23]. Thickness measurements are based on the resonant frequency described in the following equation:

1. $TH = \frac{Ws}{2F}$

where "TH" is the thickness in mm, "Ws" represents P-wave (summation wave generated by the depolarization front as it transits the atria) speed in m/s and "F" represents the dominant resonant frequency of the waveform in Hz [24]. This ability to identify the thickness of materials raises the eligibility of using radar and radio wave-based technologies for the identified purpose.

3.4. Ultrasound evaluation

In terms of evaluating Ultrasound on the categories set in the methodology, the tabulation in Table 3 demonstrates that direct relevant literature pertinent to ultrasound's ability for "Surface Penetration" has been explored by Liñán et al. [3], where readings in wood structures allowed the identification of material properties such as resistance capacity and deterioration. García-Diego et al. [25]investigated ultrasound techniques that were utilized for detecting brick joints behind wall paintings, and Shah and Ribakov [26] utilized ultrasound to detect and assess subsurface damage in concrete structures. The ability to conduct ultrasound testing on the fly for the "Equipment Mobility" category was demonstrated by Mattar and Kalai [27] with the development of a wall sticking drone that conducts contact-based ultrasound inspections of structures for corrosion detection. Also, D. Zhang et al. [28] demonstrated the development of an autonomous drone technique that utilizes ultrasound at a sufficient set distance to conduct NDT and determine structural integrity and corrosion. Finally, Skaga [29] tested glass fiber laminates in wind turbines for delamination defects to determine damage on a voltage–time graph first through testing a 27 mm sample with a handheld device and then with a UAV (Unmanned Aerial Vehicle) and reported promising results regarding the feasibility of the technique.

Regarding Material Depth detection, this was explored by Schickert [23] where the detection of concrete thickness, the position of subsurface tendon ducts, and corrosion using ultrasound was demonstrated. Pristov, Dalton, and Likins [24] utilized the "Resonance Method" to detect concrete thickness, and Carino [30] used the Impact-Echo method to detect concrete thickness using the American Society for Testing and Materials (ASTM) C1383 standard procedure. In regards to the detection of Physical Defects, Shickert [31] demonstrated ultrasound's ability to detect various physical defects in concrete such as cracks, honeycombing, micro-cracking, and voids in tendons. Shah and Ribakov [26] also investigated the ability to detect micro-cracking in materials showcased nonlinear ultrasonic and acoustic emission techniques. Godinho et al. [32] additionally explored two advanced numerical models to simulate and detect progressively severe defects in concrete and indicated promising results for the development of onsite evaluation techniques and equipment. All of which confirm ultrasound's ability and application in physical defect detection.

Indirect literature was identified regarding material composition as displayed by Afanasenko, Boev, and Kulakov[33], which utilized ultrasound for the detection of material discontinuities in the homogeneity of bimetals and thus identify differences in multilayered materials. Dhekne et al. [34] as well developed the use of ultrasound techniques to identify different types of liquids in a container. The ability to find identify the minute differences between liquids indicates the possibility of successfully adapting and applying the technology to non-homogenous building materials. Regarding moisture detection, W. M. Healy and Van Doorn [35] conducted a preliminary investigation in the use of ultrasound waves to detect moisture in samples of oriented strand board (OSB), gypsum, and pine and concluded that the initial results prove promising. This was followed by a patent by the same authors for a device that claims the ability to utilize ultrasound techniques to detect moisture in building envelopes W. Healy and Van Doorn [36].

Regarding the categories of "Feature Extraction" and "Thermal Properties" categories, no relevant direct or indirect literature was found.

3.5. Through wall imaging radar (TWIR)

TWIR technology is built on using electromagnetic waves to identify objects inside buildings and extract the physical characteristics of the objects inside to create scenes through the recording of the through the wall microwave scattering. This technology has garnered particular interest in military applications especially in room breaching events, and rescue operations in collapsed buildings. [37]. While this technology is intended to penetrate not just the surface but the wall assembly itself, the waves traveling must travel twice through the wall which attenuates the emitted waves.

Table 4
Literature review assessment on TWIR.

	Surface Penetration	Feature Extraction	EquipmentMobility	MaterialDepth	Material Composition	ThermalProperties	Moisture Detection	Physical Defects
TWIR Source	● (Yoon and Amin 2009) (Nkwari, Sinha, and Ferreira 2018) (Ren, Burkholder, and Chen 2015)	○	○	● (Protiva, Mrkvica, and MacHáč 2011) (Sévigny and Fournier 2014)	● (Nkwari, Sinha, and Ferreira 2018) (Sévigny and Fournier 2014)	○	○	○ (Yu et al. 2017) (Ren, Burkholder, and Chen 2015)

● Direct Relevant literature
○ Indirect Relevant literature
○No Relevant literature

Suggestions to use lower frequency radars (under 3 GHz) have been made to lessen the wall attenuation [37]. This suggestion would help establish the fact that the variation in wave attenuation could prove to be a starting point in creating unique markers for different wall materials and their ability to attenuate electromagnetic waves. Some challenges lie in that certain wall assemblies contain air gaps that can trap electromagnetic modes (field patterns of the propagating waves). This can prove problematic in the subsequent reading as it produces long time constant relaxations which can distort the clarity of the readings in the generated profiles [38].

3.6. TWIR evaluation

Evaluating TWIR, the results tabulated in Table 4 showcase direct relevant literature regarding the "Surface Penetration" property. Yoon and Amin [38] indicated that TWIR can be used to image behind the wall targets and mitigate radio wave clutter in different types of walls (solid wall, multilayered wall, and cinder block wall) through using spatial filters. Nkwari, Sinha, and Ferreira [37] show the ability of TWIR to image objects behind walls of unknown properties as well and Ren, Burkholder, and Chen [39] developed the usage of TWIR for identifying gaps in multilayered walls through microimages. In regards to material depth, Protiva, Mrkvica, and MacHáč [40] created a method that employs TWIR to detect the thickness and permittivity of materials in a wall through time-delay measurements only. Also, Sévigny and Fournier [41] developed the use of TWIR for front wall material characterizations and thickness detection in tandem with Light Detection and Ranging (LiDAR) that was used for front wall feature extraction. For the "Material Composition" category. Nkwari, Sinha, and Ferreira [37] indicated that tomography, which is described as an inverse scattering algorithm, can be utilized to identify the media electric property of the material This can aid in characterization, as well as using Linear Inverse Scattering Algorithms (LISP) which are used to detect wall properties while detecting behind the wall targets. Sévigny and Fournier [41] explored as well the use of TWIR for material composition identification in multilayered assemblies (vinyl/gypsum/wood studs, cinder block, brick, and cinder block, poured concrete, etc.).

Indirect relevant literature was identified regarding the "Physical Defects" category, where Yu et al. [42] indicated the use of Synthetic Aperture Radars (SAR), which most TWIR systems were developed for Y. C. Li et al. [43], to detect cracks in concrete structures. Ren, Burkholder, and Chen [39] had as well identified a fast imaging algorithm that can identify gaps and potential defects in multilayered assemblies.

There was no relevant literature identified for the categories of "Feature Extraction, Equipment Mobility, Thermal Properties, and Moisture Detection."

3.7. Light detection and Ranging (LiDAR)/Laser scanning

LiDAR and laser scanning are both techniques that utilize a laser beam to calculate the distance between the device and the target object, where if the measurement is repeated along an entire field of view the resulting point cloud would create a primitive 3D Model [6]. These readings are conducted using Mobile Laser Scanning (MLS) which consists of a Global Navigation Satellite System (GNSS) device, an Inertial Measurement Unit (IMU), and an RGB camera that is accurate to a millimeter-level with thousands of points/m^2 density [44]. While LiDAR and Laser Scanning are both similar in the mechanics of the process of gathering data, the fundamental difference between both lies in the principle governing this data gathering and how they interpret the reflected data. Laser Scanning utilizes the "phase-shift" principle which in effect compares the phase of the source with that of the reflected signal which produces higher fidelity models but is slower. While LiDAR utilizes the Time-of-Flight method that records the time it takes for the reflected signal to return to the source, which is faster but does not capture the smallest details [45]. These technologies have been

Table 5
Literature review assessment on LiDAR.

	Surface Penetration	Feature Extraction	Equipment Mobility	Material Depth	Material Composition	Thermal Properties	Moisture Detection	Physical Defects
LiDAR Source	○	● (Previtali et al. 2013) (Sévigny and Fournier 2014) (Susetyo, Hidayat, and Hariyono 2018)	● (Wood and Mohammadi 2015) (Espositoa et al. 2014)	○	○	○	○ (Suchocki and Katzer 2018) (Lerones et al. 2016)	● (Olsen et al. 2010) (Cho et al. 2018)

● Direct Relevant literature
○ Indirect Relevant literature
○No Relevant literature

Table 6
Literature review assessment on CRP.

	Surface Penetration	Feature Extraction	EquipmentMobility	MaterialDepth	Material Composition	ThermalProperties	Moisture Detection	Physical Defects
CRP Source	◦	● (Esmaeili et al. 2019) (Bitelli et al. 2006)	● (Wojciechowska and Luczak 2018) (Petti Fabio Massimo et al. 2018) (Esmaeili et al. 2019)	◦	◦	◦	◦	● (Jiang, Jáuregui, and White 2008) (Hampel 2010) (Alshawabkeh and El-Khalili 2013)

● Direct Relevant literature
○ Indirect Relevant literature
◦No Relevant literature

used in applications related to renovation, urban planning, agriculture, and security monitoring [46 47].

3.8. LiDAR evaluation

Evaluation of LiDAR, whose results were tabulated in Table 5, indicated that direct relevant literature was found in terms of "feature extraction" with work conducted by Previtali et al. [48] where the authors specified the use of LiDAR to extract highly detailed vector models of building facades. The process utilizes a segmentation approach and an ML technique that helps build the models based on previous architectural scenes and further integration with thermography data. Sévigny and Fournier [41] additionally showed the use of LiDAR for front wall feature extraction and differentiation between windows and walls to bypass window readings and speed up other processes. Susetyo, Hidayat, and Hariyono [49] and Kim, Shin, and Kim [50] both showcase methods for automatic feature extraction of building facades using LiDAR. Regarding equipment mobility, LiDAR has been utilized with drones for structural and building inspections as indicated by Wood and Mohammadi [51] and Espositoa et al. [52]. Physical defect detection has been demonstrated by Olsen et al. [53], who specified the use of terrestrial laser scanning to assess damage in structures, and by Cho et al.[54] who indicate the use of image processing techniques to identify cracks in structures from information extracted from terrestrial laser scanning data.

Indirect relevant literature regarding the use of laser scanning in moisture detection in building facades was identified. Suchocki and Katzer [55] state the "viability of the concept" through scanning porous construction materials and using image processing identifying properties such as roughness, color, and visible presence of water. Lerones et al. [56] showed the application of LiDAR for detecting moisture in heritage buildings by analyzing the laser reflectivity level off the surfaces. This method shows promise and should be explored further for accuracy testing and moisture depth penetration.

No direct or indirect relevant literature was identified regarding the categories of "Surface Penetration", "Material Depth", "Material Composition", and "Thermal Properties."

3.9. Close Range photogrammetry (CRP)

CRP is a technique used to create a 3D model (location, size, and depth) through the measurement and analysis of 2D images [57]. It utilizes a digital photographic camera that takes a set of images under controlled lighting to create the 3D model of the object under study [6]. Several types of cameras can be used which vary according to the purpose, from metric cameras that are specifically designed for CRP applications to semi-metric cameras. The latter are described as a mixture of a metric camera and commercially available off-shelf camera, which is for consumer purposes and can be used for amateur photogrammetry where the precision of the model generated is not a priority. [6] This technique has been utilized in applications in civil engineering for detection and modeling of cracks in material testing [58] as well as structural applications such as beam deformation [6] bridge deformation, geometry measurement, topographical studies and historic documentation [57].

3.10. CRP evaluation

In terms of evaluating CRP on the categories set in the methodology, the results recorded in Table 6 showcase direct relevant literature that was identified for "Feature Extraction," where Esmaeili et al. [59] demonstrated the usage of a UAV with CRP to extract local features of a wall to measure displacement in soil nail walls. Bitelli et al. [60] utilized UAV's as well where CRP was used to create highly detailed 3D models for archaeological sites. In terms of equipment mobility, CRP has been used in tandem with UAV's for different applications as displayed by Esmaeili et al. [59] as mentioned in the "Feature Extraction" category, by Wojciechowska and Luczak [61] for documentation of architectural monuments, and by Petti Fabio Massimo et al. [62] in the study of dinosaur track sites. Regarding "Physical Defects" Jiang, Jáuregui, and White [57] showed the use of CRP for identification of defects and cracks within bridge structures, and Hampel [58] indicated the use of CRP to detect cracks as small as 5 μm and other 2D and 3D fields of displacements, deformations and other defects in concrete.

No relevant direct or indirect literature was identified regarding the categories of "Surface Penetration, Material Depth, Material Composition, Thermal Properties, and Moisture Detection."

3.11. Ground Penetrating Radar (GPR)

This technology utilizes electromagnetic waves to conduct various studies and inspections of subsurface objects [63]. The technology requires a radar transmitter that transmits the electromagnetic waves and a receiver that collects the reflected signal. Measuring and analyzing this reflected signal would allow the characterization of the structure and localization of the subsurface objects [64]. It has been significantly used by structural engineers particularly in the inspection of rebar within cast concrete [64].

Historically, GPR traces its roots to the early 20th century when inventors Leimbach and Lowy filed for patents in 1910 for devices that utilize radio waves to detect targets buried beneath the ground [6]. Thus, the idea of emitting electromagnetic waves and measuring their reflections to detect subsurface objects is over a century old and well researched. The technology is most prominently used in civil and transport engineering applications such as roads, pavements, highways, bridges, tunnels, etc. Applications include GPR being used for the detection of underground cavities as well for detecting groundwater and pollution evaluation [65]. In structural applications, GPR has been utilized for building

Table 7
Literature review assessment on GPR.

	Surface Penetration	Feature Extraction	EquipmentMobility	MaterialDepth	Material Composition	ThermalProperties	Moisture Detection	Physical Defects
Ground Penetrating Radar (GPR)	●	○	○	●	●	◦	●	●
Source	(Giunta and Calloni 2000) (Johnston et al. 2018) (Queiroz et al. 2012)	(Lu, Pu, and Liu 2014) (Qin et al. 2016)	(Altdorff et al. 2013) (Chandra and Tanzi 2018)	(Giunta and Calloni 2000) (Johnston et al. 2018)	(Queiroz et al. 2012) (Alsharahi, Driouach, and Faize 2016) (Morris, Abdel-Jaber, and Glisic 2019)		(Hugenschmidt and Loser 2007) (Rodríguez-Abad et al. 2016) (Barone and Ferrara 2018)	(Giunta and Calloni 2000) (Johnston et al. 2018)

● Direct Relevant literature
○ Indirect Relevant literature
◦No Relevant literature

inspections, especially regarding reinforced concrete and the non-destructive location of the steel rebar inside as well as the pre- and post-tensioning stressing ducts. It has also been used in detecting deterioration and delamination on decks of bridges [65].

GPR has seen successful applications in the areas of geology and geoarchaeology, and architecture mostly with restoration projects that require the least invasive methodology in gathering information about the structure and composition of a building, especially those with little to no documentation. In that domain, GPR was successfully applied to the characterization of buildings with notable cultural and historical value for conservation and restoration projects [66]. GPR presents one of the most promising technologies due to its ability to accurately identify discontinuities between materials and recording them due to the different dielectric properties of each material [67]. It allows the determination of both the location and the nature of the discontinuity by measuring the time of arrival of the reflected pulses and the amplitude of each [67]. This presents a promising possibility as a technology capable of dealing with the two main issues to be tackled with NDT building envelope component evaluation, the thickness of the materials, and the differences between the properties of each.

3.12. GPR evaluation

The results of the GPR evaluation presented in Table 7, indicate direct relevant literature in terms of "Surface Penetration" as investigated by Giunta and Calloni [68], where GPR was used to assess the preservation of St. Peter's Basilica in the Vatican. This revealed information about the different wall elements and assemblies that otherwise would have been extracted through destructive analysis. Johnston et al. [69] indicated the use of GPR to identify voids and gaps in a wall assembly, and Queiroz et al. [70] displayed GPR's application in helping identify the media which exists within a sample block of concrete. In terms of "Material Depth" identification, both Giunta and Calloni [68] and Johnston et al. [69] indicated the applied use of GPR to detect the thickness of assembly samples under study. Concerning the category of "Material Composition" Alsharahi, Driouach, and Faize [71] 2016 and Queiroz et al. [70,71]showcased the use of GPR to identify the dielectric property of the materials under study. Morris, Abdel-Jaber, and Glisic [72] confirmed the ability to differentiate between understudy areas of a concrete bridge, where varying curing conditions resulted in unique material sensitivities that GPR was able to identify In terms of the "Moisture Detection" category, Hugenschmidt and Loser [73] indicated the ability to detect chlorides and moisture in concrete bridge decks. As well Rodríguez-Abad et al. [74] showcased the use of GPR to localize and identify moisture penetration depth in waterfront concrete structures. Barone and Ferrara [75] as well explored a similar application of moisture detection using GPR in terms of preservation of historical structures by measuring the electromagnetic sensitivity of materials.

Indirect relevant literature regarding feature extraction was identified with Lu, Pu, and Liu [76] and Qin et al. [77] as they both indicated the use of GPR to extract 3D features of underground buried objects, which potentially shows the technology's ability to extract both surface and subsurface features if applied and adapted to building facades. Similarly, In terms of equipment mobility, Altdorff et al. [78] showed the feasibility of using GPR mounted on a UAV for near-surface geophysical sensing. Chandra and Tanzi [79] explored as well the limitations of drone-based GPR due to propagation issues and suggested constraints which researchers should take note of when utilizing drone-based GPR. No relevant literature was found for the "Thermal Properties" category.

4. Discussion and conclusion

In order to facilitate cohesive building envelope energy audits using the categories identified in this work, the identification of hybrid workflows that can amalgamate the NDT techniques is needed. Standard 211P does not explicitly identify the procedures required to extract the needed information, and this research bridges the gap between the information required and how to gather it. What remains is to identify different workflows where the required information regarding the envelope can be nondestructively extracted. For that purpose, after assessing the literature and categorizing it using the three-classification system identified earlier, the following can be inferred in terms of the value of these findings for both practitioners and researchers:

- A category that has been rated ● indicates that the NDT technique is a candidate for use in the relevant category. This would provide an opportunity for practical applications and research to be conducted.
- A category that has been rated ▼ indicates that there exists a literature gap in the specific area that has research to back up a possible building audit hypothesis and presents an opportunity for researches to pursue further upon reviewing the relevant identified literature.
- A category that has been rated □ indicates the presence of a literature gap, but it would not clarify if the gap is the result of a current technological limitation of the NDT technique or a novel research gap that should be pursued by the researcher.

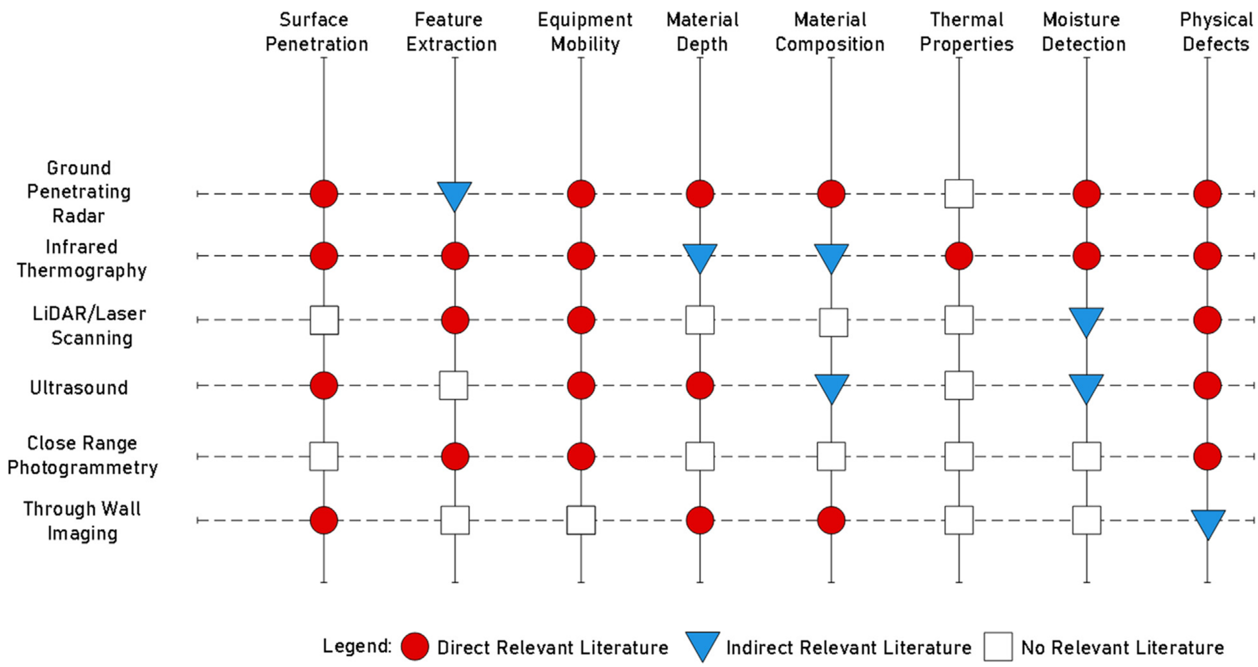

Fig. 2. Tool for literature assessment of NDT techniques and hybrid workflow identification.

Fig. 2 below compiles the results and establishes a matrix of relationships between the different NDT techniques for the user to identify hybrid workflows for various requirements and applications.

No NDT technique alone satisfies the entirety of the categories set for the building envelope energy audit. A hybrid workflow would then be required to extract and cover the entirety of the categories. Utilizing the tool, an example of an identified workflow that provides a comprehensive framework that covers all the categories previously indicated the following techniques: IRT, and GPR. This workflow among many possible others allows the reader to assess the different NDT techniques per criteria pertinent to building science and envelope audits and make inferences based on what they had measured. By identifying the strengths, potential areas of development, and weaknesses of the techniques, the paper aims to benefit both practitioners and researchers. The goal is to serve as an informative, and concise guideline that sets the stage for further experimentation.

4.1. NDT and BEM

The information extracted for building envelopes using NDT techniques can prove critical to building energy audits and the larger goal of streamlining retrofits. This would provide the base for inferring information about building wall assemblies such as Window to Wall Ratios (WWR), U-Values, insulation defects, moisture damage, air infiltration, and other building science metrics. The categories identified are pertinent to fundamental laws crucial to heat and mass transfer that form the crux of any computational BEM engine [80]. The EnergyPlus engine, for example, utilizes the following metrics for its "Material" object component*: Roughness, Thickness, Conductivity, Density, Specific Heat, Thermal Absorptance, Solar Absorptance, Visible Absorptance*. The "Wall" object as well utilizes components geometrical such as *Length, Height, Tilt Angle, Azimuth Angle* [81]. These properties can be identified using the categories described above either directly through measurement or material identification and subsequent inference. Thus, the information acquired through NDT techniques that cover the categories would prove significant to any present or future BEM engine. This would ensure the longevity of the research and its ongoing impact on the future.

The next step would be to streamline the reporting phase and integration of the information obtained into BEM. Creating tools that can automate reporting of results into BEM would accelerate building auditing processes and provide much higher fidelity models for more accurate simulation results. This can be approached from both a hardware and software point of view. The hardware approach would aim for the synthesis of hybrid tools that encapsulate different NDT techniques tailored for a specific purpose of building energy audits by conducting tests concurrently to save time and labor costs. This would prototype a different apparatus, with the ability to be carried on a drone, that can have different sensors tailored for a specific auditing purpose, built on the findings of the tool generated in this paper. The software approach would be through the process of data fusion. This would essentially mean translating the data collected automatically to formats such as IDF files with EnergyPlus, gbXML for Building Information Modeling (BIM) integration, and .rb files with OpenStudio. Brierly et al. displayed data fusion from NDT findings in an experiment using single pulse-echo ultrasonic testing on a titanium aerospace disk. The paper presented a framework for partial-automation of data analysis which averts the need for time-consuming manual labor of a skilled analyst [82]. Amassing a large database through automating the process of building energy audits using NDT techniques, as a result, would pave the way towards large scale computational simulations using BEM, which can help verify and quantify the feasibility of any retrofitting upgrades support policy, such as the Green New Deal [83]. Finally, the process is a feedback loop where after each retrofit it would be repeated after an amount of time when the energy codes have become even more stringent or newer materials and systems are in use. This would entail a new study of the literature and update of the tool synthesized in this paper, and a new round of documentation and simulation which would lead to new decisions and policies that befit current standards.

4.2. Mobility and NDTs

Building inspection and documentation automation are thus essential to allow for large scale integration. The results indicated that 5 out of the 6 NDT techniques can be integrated with drones that present opportunities for automation. Traditionally, surveyors would utilize different means of access to elevated parts of a building such as staging, rafting, ladders, scaffoldings, and rope access to conduct inspections [84]. Compared to traditional methods that require human labor with all the risks and costs associated with that, drones not costing more than $1500 or less can sufficiently conduct drone mapping and inspection [9]. Work by Rakha et al. indicated the idea of automating building thermography inspection using CV and ML on a drone. The researchers utilized edge detection and leakage segmentation algorithms to identify anomalies in an envelopes thermal pattern [16]. The integration of NDT with UAVs gave the user unique perspectives on the building envelope and aided in a whole building envelope audit. Thus, the ability to automate the data collection process becomes key in terms of large-scale retrofits, and NDT techniques with a proven drone-based component are viable candidates to lead that effort. Further research in creating multiple sensor gimbals for drones that integrate the hybrid workflows identified in the generated tool would expedite the auditing process and decrease flyby times and cost. The tool thus can act as a guideline for designers and manufacturers to create a holistic building envelope audit solution.

4.3. Summary and future directions

With the threat of climate change becoming more evident every day, and the implicit role the built environment has played in it the need for large scale retrofits is a necessity. NDT presents one solution for an equally large-scale building documentation process. This literature review had identified the different abilities of each NDT technique regarding categories pertinent to building energy audits. After a thorough literature review was conducted a tool was then developed from the reported results to help identify different workflows tailored to the purposes of the user. The tool as well identified literature relevant to each building category that saw the NDT technique being utilized in a similar non-building energy audit-related application, giving researchers insight on potential avenues to pursue in the field of NDT and increase the efficiency and scope of each. This tool evolves with the literature and should be updated whenever new literature is published to ensure its relevance for more potential hybrid workflows if identified. One category which each NDT technique was tested for, is its equipment mobility and integration with drones. Drones present an efficient, quick, and safe solution to conduct retrofits, and with their ability to be automated, expedite the retrofitting process immensely. The results confirmed that 5 out of the 6 NDT techniques have had successful drone integration, and thus confirms the eligibility of NDT to spearhead the retrofitting documentation process. Looking ahead, further automation of the data reporting process through data fusion would lead to direct integration into BEM simulations. This would allow for quick decision and policy-making, and validation, which would make the idea of large-scale national retrofits a tangible reality.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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