Review of Non-Destructive Techniques (NDTs) for Building Diagnostic Inspections

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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 container and regulator of internal microclimates. This paper presents a systematic literature review of the various Non-destructive Testing (NDT) for building envelope scanning and surveying for thermodynamic diagnostics. 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 NDT was evaluated according to set categories imbibed from ASHRAE Standard 211 that showcase the NDTs 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 NDTs in large-scale audit automation, BEM integration, and developing built environment policies focusing on increasing existing building performance through retrofitting design.

INTRODUCTION

One of the biggest challenges facing the built environment is its substantial impact on climate change and the energy sector. Almost two thirds (76%) of electricity and 40% of total energy consumption in the United States is consumed by buildings (US Department of Energy, 2015). 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.

In the US where 50% of buildings were built before 1970 (Güler, 2018) the need to retrofit these buildings is a massive undertaking that should be resolved if there ever is a serious push towards combating climate change and decreasing consumption to meet that end. The multi-trillion-dollar Green New Deal Bill sponsored in 2019 represents one such recent push, by calling to retrofit every single building in the United States to meet efficiency standards over the next 10 years (*Recognizing the Duty of the Federal Government to Create a Green New Deal*, 2019). Certain states have already recognized the importance of reducing the energy footprint of buildings and have passed bills in that regard. In 2019 New York passed a bill that requires the state to reduce emissions by 40% by 2030 and implement retrofits such as Green Roofs in buildings. Such an ambitious undertaking would require a critical amount of documentation of the current stock of buildings targeted to assess and apply the correct measures (New York City Council, 2019). Whether the Green New Deal bill passes or not, it still indicates that climate change is a national security threat to the United States (*Recognizing the Duty of the Federal Government to Create a Green New Deal*, 2019). Thus, the urgent need for retrofitting buildings is a challenge the US and other countries in the world have to deal with in the coming decades.

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 (Baechler et al., 2011). Built wall components are traditionally examined through visual inspection or collection of samples (Liñán et al., 2015). 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 (Jasiński et al., 2019). 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 (NDTs) 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 that can identify wall components can support averting the physical damage resulting from traditional sample collection processes (Barreira & de Freitas, 2007), 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 (Solla & Riveiro, 2016).

This paper systematically reviews the literature on various NDTs that are currently in use and develops a tool to organize that 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.

LITERATURE REVIEW METHODOLOGY

This literature review aims to study existing research on NDT applications and identify gaps regarding its application in building envelope component identification. Accordingly, a sizeable body of literature most relevant to the subject matter was gathered. A thorough study of the tools, methods, and applications used was utilized to identify gaps in the literature. The goal of the paper is to create a cohesive tool that indicates the appropriateness of each NDT in the context of different categories related to building audits. These categories were imbibed from ASHRAE's Standard 211 for Commercial Building Audits. Standard 211 puts the building envelope in the scope of energy audits among other systems (ASHRAE, 2018). The audit requires the following information to be provided about the envelope:

1. Roof: Gross roof area-Condition of roof (Degradation, Moisture)-Exterior Material-Insulation level and R-Value (determined noninvasively)
2. Wall: Gross wall area- Exterior Material-Insulation level and R-Value (determined noninvasively)
3. Fenestration: Gross fenestration area-Fenestration wall ratio-Glazing frame type-Exterior Door Area and construction-Fenestration seals
4. Floors and Underground Walls: Floor-type and insulation - Underground floor area and insulation
5. 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. Accordingly, the categories for evaluation of each NDT displayed in figure 1 are:

- 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 thermal emissivity of materials.
- Moisture Detection: Identifying the presence of moisture inside a wall assembly.
- Physical Defect Detection: Identifying cracks or anomalies in a building envelope.

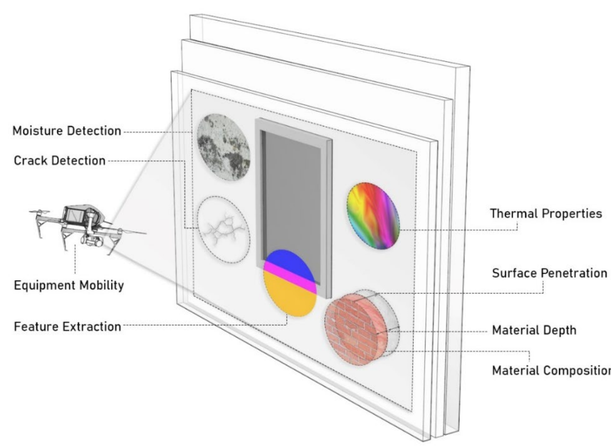

Figure 1 Graphical representation of NDT evaluation categories in an example wall component.

These categories cover the NDTs ability to extract the relevant information needed. 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 211 standard had specified information must be gathered for roofs, walls, and fenestrations, access to these elements of a building is thus crucial for a complete energy audit. Land-based mobile equipment, such as tripods and road vehicles, offer versatility in terms of 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 (Grubesic & Nelson, 2020). 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.

Regarding which NDTs are to be the subject of the assessment, 6 are identified for evaluation: Infrared Thermography, Ultrasound, Through Wall Imaging Radar, LiDAR/Laser scanning, Close-Range Photogrammetry, and GPR (Figure 2).

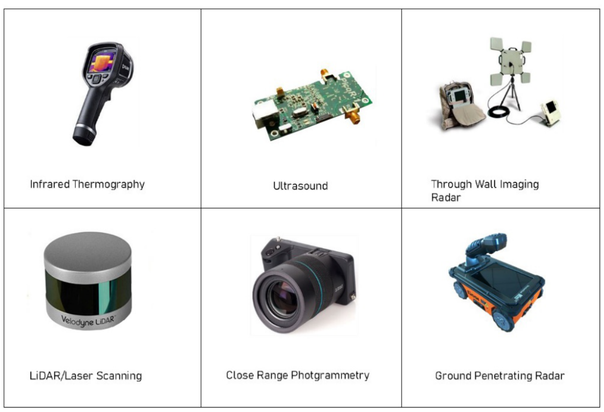

Figure 2 NDTs selected to be evaluated

Each NDT 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 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.

LITERATURE REVIEW AND RESULTS

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 (Clark et al., 2003). 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 (Wróbel & Kisilewicz, 2008).

It has been used in applications that allow the tracking of moisture-related problems inside wall assemblies as well (Colantonio, 2008). Infrared imaging by nature is dependent on the emissivity of the surface (Wróbel & Kisilewicz, 2008), 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 (Clark et al., 2003) and thus extends its usability as a subsurface investigation tool.

IRT Evaluation:

The results 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 et al., 2014) and detecting subsurface structural building elements as shown by (Barreira & de Freitas, 2007) and (Lerma et al., 2007). IRT's ability to detect moisture has been displayed by (Barreira & Almeida, 2019) through surface temperature readings and comparison, as well as the ability to conduct thermal readings that can be utilized to extract thermal properties as seen in the work conducted by (Solla & Riveiro, 2016). Undergoing drone flybys using IRT has been previously developed by (Omar & Nehdi, 2017; Rakha et al., 2018; Rakha & Gorodetsky, 2018) as well as using IRT images with specialized software for feature extraction (Lagüela et al., 2011; Rakha et al., 2018). The ability to detect physical defects in the envelope has been showcased by (Bauer et al., 2016) which identified cracks using quantitative thermography that measure the delta T to determine cracks, (Taylor et al., 2014) which utilized IRT to identify missing insulation in assemblies, and (Rakha et al., 2018) 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., 2018) 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 & Reusser, 2016) showcased the ability of IRT for detecting thickness, roughness, and material composition using one-dimensional flash thermography techniques. These techniques are a form of active thermography that requires the applications of transient heat flow that allows the measurement and detection of said properties.

Ultrasound

Ultrasound is another NDT that is used for wall component surveying (Liñán et al., 2015). It utilizes relatively short wavelengths which enables the highly detailed assessment of concrete structures (Schickert, 2005). 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 (Schickert, 2005). Thickness measurements are based on the resonant frequency described in the following equation: $TH = \frac{Ws}{2F}$ where "TH" is the thickness, "Ws" represents P-wave (summation wave generated by the depolarization front as it transits the atria) speed and "F" represents the dominant resonant frequency of the waveform (Pristov et al., 2008). This ability to identify the thickness of materials raises the eligibility of using radar and radio wave-based technologies for the identified purpose.

Ultrasound Evaluation:

In terms of evaluating Ultrasound on the categories set in the methodology, the results demonstrate that direct relevant literature pertinent to ultrasound's ability for "Surface Penetration" has been explored by (Liñán et al., 2015), where readings in wood structures allowed the identification of material properties such as resistance capacity and deterioration. (García-Diego et al., 2012) investigated ultrasound techniques that were utilized for detecting brick joints behind wall paintings, and (Shah & Ribakov, 2010) 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 & Kalai, 2018) with the development of a wall sticking drone that conducts contact-based ultrasound inspections of structures for corrosion detection. Also, (D. Zhang et al., 2018) 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, 2017) 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, 2005). (Pristov et al., 2008) utilized the "Resonance Method" to detect concrete thickness, and (Carino, 2004) 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, 2002) demonstrated ultrasound's ability to detect various physical defects in concrete. (Shah & Ribakov, 2010) also investigated the ability to detect micro-cracking in materials. (Godinho et al., 2013) additionally explored two advanced numerical models to simulate and detect progressively severe defects in concrete.

Indirect literature was identified regarding material composition as displayed by (Afanasenko et al., 2019), which utilized ultrasound for the detection of material discontinuities in the homogeneity of bimetals and thus identify differences in materials. Regarding moisture detection, (W. M. Healy & Van Doorn, 2004) 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 & Van Doorn, 2007).

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

Through Wall Imaging Radars (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. (Nkwari et al., 2018). 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. Suggestions to use lower frequency radars (under 3 GHz) have been made to lessen the wall attenuation (Nkwari et al., 2018). 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 (Yoon & Amin, 2009).

TWIR Evaluation:

Evaluating TWIR, the results showcase direct relevant literature regarding the "Surface Penetration" property. (Yoon & Amin, 2009) 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 et al., 2018) show the ability of TWIR to image objects behind walls of unknown properties as well and (Ren et al., 2015) developed the usage of TWIR for identifying gaps in multilayered walls through microimages. In regards to material depth, (Protiva et al., 2011) created a method that employs TWIR to detect the thickness and permittivity of materials in a wall through time-delay measurements only. In addition, (Sévigny & Fournier, 2014) 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 et al., 2018) 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 & Fournier, 2014) explored the use as well of TWRI 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., 2017) indicated the use of Synthetic Aperture Radars (SAR), which most TWIR systems were developed for (Y. C. Li et al., 2018), to detect cracks in concrete structures. (Ren et al., 2015) 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".

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 (Solla & Riveiro, 2016). 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 (Wang et al., 2019). 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 (San José Alonso et al., 2012). These technologies have been used in applications related to renovation, urban planning, agriculture, and security monitoring (Yang et al., 2016) (Bellian et al., 2005).

LiDAR Evaluation:

Evaluation of LiDAR indicated that direct relevant literature was found in terms of "feature extraction" in work conducted by (Previtali et al., 2013) 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 & Fournier, 2014) 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. (Kim et al., 2006; Susetyo et al., 2018) showcase methods for automatic feature extraction of building facades Regarding equipment mobility, LiDAR has been utilized with drones for structural and building inspections as indicated by (Wood & Mohammadi, 2015) and (Espositoa et al., 2014). Physical defect detection has been demonstrated by (Olsen et al., 2010), who specified the use of terrestrial laser scanning to assess damage in structures, and by (Cho et al., 2018) 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 & Katzer, 2018) 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. No direct or indirect relevant literature was identified regarding the categories of "Surface Penetration", "Material Depth", "Material Composition", and "Thermal Properties".

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 (Jiang et al., 2008). 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 (Solla & Riveiro, 2016). 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. (Solla & Riveiro, 2016) This technique has been utilized in applications in civil engineering for detection and modeling of cracks in material testing (Hampel, 2010) as well as structural applications such as beam deformation (Solla & Riveiro, 2016) bridge deformation, geometry measurement, topographical studies and historic documentation (Jiang et al., 2008).

CRP Evaluation:

In terms of evaluating CRP on the categories set in the methodology, the results showcase direct relevant literature that was identified for "Feature Extraction," where (Esmaeili et al., 2019) 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., 2006) 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., 2019) as mentioned in the "Feature Extraction" category, by (Wojciechowska & Luczak, 2018) for documentation of architectural monuments, and by (Petti Fabio Massimo et al., 2018) in the study of dinosaur track sites. Regarding "Physical Defects" (Jiang et al., 2008) showed the use of CRP for identification of defects and cracks within bridge structures, and (Hampel, 2010) 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".

Ground Penetrating Radar (GPR)

This technology utilizes electromagnetic waves to conduct various studies and inspections of subsurface objects (W. Zhang, 2014). 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 (Y. Zhang et al., 2014). It has been significantly used by structural engineers particularly in the inspection of rebar within cast concrete (Y. Zhang et al., 2014). GPR has been utilized for building inspections, especially regarding reinforced concrete and the nondestructive 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 (Pajewski et al., 2013).

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 (Ranalli et al., 2004). 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 (Dong & Ansari, 2011). 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 (Dong & Ansari, 2011). 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.

GPR Evaluation:

The results of the evaluation of GPR indicate direct relevant literature in terms of "Surface Penetration" as investigated by (Giunta & Calloni, 2000), 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., 2018) indicated the use of GPR to identify voids and gaps in a wall assembly, and (Queiroz et al., 2012) 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 & Calloni, 2000) and (Johnston et al., 2018) indicated the applied use of GPR to detect the thickness of assembly samples under study. Concerning the category of "Material Composition" (Alsharahi et al., 2016; Queiroz et al., 2012) showcased the use of GPR to identify the dielectric property of the materials under study. (Morris et al., 2019) 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 & Loser, 2007) indicated the ability to detect chlorides and moisture in concrete bridge decks. As well (Rodríguez-Abad et al., 2016) showcased the use of GPR to localize and identify moisture penetration depth in waterfront concrete structures. (Barone & Ferrara, 2018) 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 et al., 2014) as they 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 to building facades. In terms of equipment mobility, (Altdorff et al., 2013) showed the feasibility of using GPR mounted on a UAV for near-surface geophysical sensing. No relevant literature was found for the "Thermal Properties" category.

DISCUSSION

After assessing the literature and categorizing it using the three-tiered classification 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 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 or a novel research gap that should be pursued by the researcher.

Figure 3 below compiles the results and establishes a matrix of relationships between the different NDTs for the user to identify hybrid workflows for various requirements and applications.
Addressing the gaps in the literature, no NDT 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 cohesive framework that covers all the categories previously indicated the following NDTs: IRT, and GPR, outlined in dashed lines in Figure 3. This workflow and many possible others allow the reader to assess the different NDTs 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 NDTs, 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.
The information extracted for building envelopes using NDTs 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), R-Values, insulation defects, moisture damage, air infiltration, and other building science metrics. The categories identified are applicable to fundamental laws crucial to heat and mass transfer that form the crux of any computational BEM engine (Toulouevski & Ilyaz, 2010). 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* (U.S. Department of Energy, 2018). 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 NDTs that cover the categories would prove significant to any present or future BEM engine, ensuring the longevity of the research and its ongoing impact on future investigations.

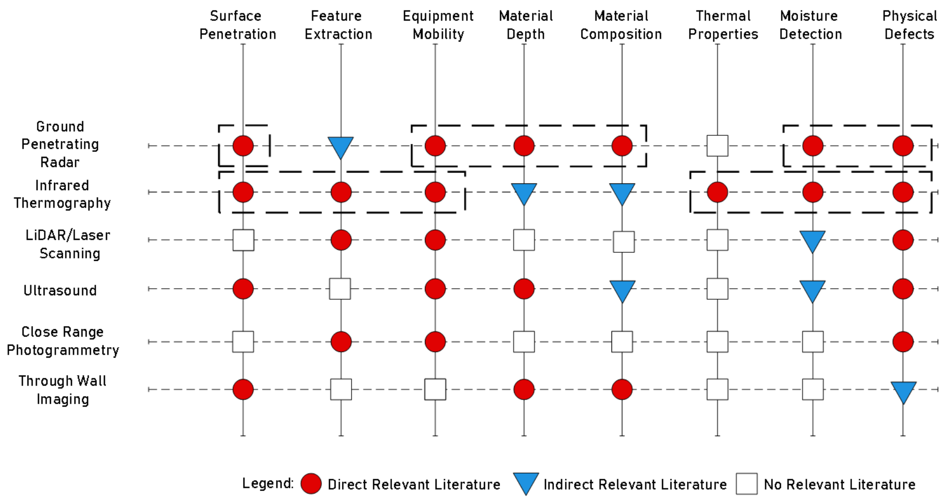

Figure 3 Tool for literature assessment of NDTs with a potential workflow identified with dashed lines.

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 NDTs tailored for a specific purpose of building energy audits by conducting tests concurrently to save time and labor costs. This would prototype different apparatuses 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 presents a framework for partial-automation of data analysis which averts the need for time-consuming manual labor of a skilled analyst (Brierley et al., 2014). Amassing a large database through automating the process of building energy audits using NDTs, as a result, would pave the way towards large scale computational simulations using BEM, which can help verify and quantify the feasibility of any policy such as the aforementioned Green New Deal.

CONCLUSION

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. NDTs present one solution for an equally large-scale building documentation process. This literature review identified the different abilities of each NDT regarding categories related to building energy audits. After a thorough literature review was conducted, a tool was developed from the reported results to help identify different workflows tailored to the purposes of the user. The tool identified literature relevant to each building category that saw the NDT being utilized in a similar non-building energy audit-related application, giving researchers insight on potential avenues to pursue in the field of NDTs 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 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 NDTs had drone integration, and thus confirms the eligibility of NDTs 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 policymaking, and validation, which would make the idea of large-scale national retrofits a tangible reality.

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