SPATIALLY RESOLVED INFRARED IMAGING FOR BUILDING PERFORMANCE EVALUATION

by

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ABSTRACT OF THE THESIS

SPATIALLY RESOLVED INFRARED IMAGING FOR BUILDING PERFORMANCE EVALUATION

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Understanding the interior workings of buildings has become an increasingly important research topic as a growing population of people is living in urbanized environments. Infrared thermography has been used extensively for detecting building defects that affect energy performance. The focus of this project not only concerns building energy performance but also health and structure hazards. The first objective of this research study is to review the use of infrared thermography for building performance inspection and synthesize findings from existing studies to demonstrate the potential of infrared thermography for detecting and quantifying health and structure hazards. The second objective of this research study is to explore the effectiveness of integration of infrared thermography and spatial sensing methods for intelligent building hazard detection and evaluation. The proposed research methodology involves several

major components including design of data collection protocols, data fusion and intelligent extraction of building hazard related attributes, and field validation of proposed methods. The study was validated by surveying the health and safety performance of two multi-family buildings in a densely populated city in the Northeastern US, using the developed appraisal method that integrate infrared thermography with 3D point cloud data. The efficacy of integrated laser scanning and thermal imaging to determine housing-related health and structure-related issue was assessed. It is important to note that the research results reported in this study is part of a larger research effort aimed at developing quantitative understanding on the correlation between the defects inside the residential building and how they impact the residents' health and comfort in a systemic way.

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Chapter 1

Introduction

Florence Nightingale said “The connection between health and dwelling is one of the most important that exists”. The fact that people spend 50% or more of every day inside their homes make the housing environment one of the major influences on health and well-being. As the impact of buildings becomes increasingly apparent, two new fields called “Green Building” and “Health Homes” are gaining momentum.

Green Building, also known as green construction or sustainable building, refers to both a structure and the using of processes that are environmentally responsible and resource-efficient throughout a building’s life-cycle. As one of the major components of green building, energy consumption and efficiency have become issues of growing concern as both supply and demand are strained. In the United States, buildings’ heating and cooling use 37.3% of the total building energy consumption in 2010. With more than 134 million houses in the United States (U.S. Census Bureau 2010), this presents a tremendous opportunity to decrease energy consumption and reduce inefficiencies.

On the front of “Healthy Homes”, the history of researches linking housing and health can go back to more than 60 years ago by the American Public Health Association (APHA) Committee on the Hygiene of Housing. As a century-old concept, “Healthy Homes”, promotes a safe, decent, and sanitary housing for preventing disease and injury, has got increasing attention nationally. It is estimated that, in the United States, millions of home occupants are exposed to moderate or even severe health and safety hazards such as roofing structural problems, heating and plumbing deficiencies, leaks, and pest problems that are associated with a wide range of health issues from injuries to respiratory illnesses.

To promote green building and healthy home, there is a great need to understand the performance of hundreds of millions of existing building stocks. Given the sheer number of these buildings and homes, cost-effective, non-destructive, and non-invasive methods that can detect and evaluate building performance are game changes. Recently, with the development of thermal infrared technologies, Infrared Thermography has been increasingly used as a valuable tool for quick inspecting and performing non-destructive testing for building elements, detecting where the building deficiencies are and monitoring how energy is leaking from envelope. Problems that can be identified in a building through thermal infrared imaging include cracks, lack of insulation, damage door and window seals, and building-up of moisture (Vidas and Moghadam 2013). Successful inspection may lead to addressing these issues, along with achieving refinements in building design, which will ultimately improve building environment and energy performance.

Despite the recent advance in standardizing infrared thermography based building inspection, the effectiveness of infrared thermography still relies heavily on correct and rapid interpretation of visual displays of thermal images. Correct and rapid interpretation of thermal images requires considerable experience and can be assisted by a systems view of building structures. For many building professionals, infrared thermography interpretation is a very subjective process, and there are very few, if not none, software tools for automated interpretation of thermal images. Furthermore, interpretation of thermal images often happens in a context with limited geometric information on the building being investigated. As a result, spatial patterns of surface temperature anomaly cannot be easily visualized to detect interrelated building system defects. In many cases, accurate estimation of building defects and hazards often requires multiple trips to carry out geometric survey of susceptible building areas (Alba et al. 2011; Laguela et al. 2012).

At the same time, reality capture technologies such as RGB-D cameras, Structure from Motion (SFM), and laser scanners, have become main stream practices in interior and exterior modeling. RGB-D cameras are novel sensing systems that can capture RGB images along with per-pixel depth information. Originally developed for the purpose of gaming and human computer interface, RGB-D cameras have also shown promises in mapping of small-scale environments. Structure from Motion is the process of estimating three-dimensional structures from 2D image sequences (Agarwal et al. 2011). Comparing to Structure from Motion, RGB-D cameras allow the capture of reasonably accurate mid-resolution depth and appearance information at high data rates and at a very low cost. Light Detection and Ranging (LiDAR) a relatively new class of survey instrument that have been available on the market for about ten years and has become a popular and increasingly used technology for providing as-built and inventory data in building inspections.

There are opportunities in integrating infrared and spatial sensing technologies into a unified platform for systematic and quantitative assessment of building performance from the perspectives of both green building and healthy home. Previous studies have predominately focused on building defects impacting energy performance. Few studies have been devoted to understand which features related to building performance (energy performance and building hazards) can be reliably extracted from the fused 3D and infrared data, and also to which agree these extraction processes can be automated.

The purpose of this research project is to investigate integration of spatial and infrared sensing for systematic detection of building defects that are quantitative in nature and indicative in understanding issues related to both green building and healthy home. Sensing fusion and pattern extraction methods are developed in this project with a goal to expand these methods to crowd sourced approaches. The analysis framework developed in this study was validated on two multifamily high-rise buildings to demonstrate its effectiveness in building performance diagnosis and its potential in gathering high quality data sets that can be correlated to other healthy home indicators such as indoor air quality, etc.

This thesis consists of two standalone papers. The first paper provides a systematic review of existing research in infrared building hazard detection. The second paper concerns the effectiveness of integration of infrared thermography and spatial sensing methods for intelligent building hazard detection and evaluation.

Chapter 2

Infrared Thermography for Building Hazard Detection: A Review

2.1 Introduction

Green Building, also known as green construction or sustainable building, refers to both a structure and the using of processes that are environmentally responsible and resource-efficient throughout a building's life-cycle. As one of the major components of green building, energy consumption and efficiency have become issues of growing concern as both supply and demand are strained. In the United States, buildings' heating and cooling use 37.3% of the total building energy consumption in 2010. With more than 134 million houses in the United States (U.S. Census Bureau 2010), this presents a tremendous opportunity to decrease energy consumption and reduce inefficiencies. On the front of "Healthy Homes", the history of researches linking housing and health can go back to more than 60 years ago by the American Public Health Association (APHA) Committee on the Hygiene of Housing. As a century-old concept, "Healthy Homes", promotes a safe, decent, and sanitary housing for preventing disease and injury, has got increasing attention nationally. It is estimated that, in the United States, millions of home occupants are exposed to moderate or even severe health and safety hazards such as roofing structural problems, heating and plumbing deficiencies, leaks, and pest problems that are associated with a wide range of health issues from injuries to respiratory illnesses.

There is an opportunity emerging as a side benefit from the recent focus on energy efficient buildings. That effort has spurred much research into the development of non-destructive and non-invasive technologies for building energy performance inspection. For example, Infrared Thermography (IRT) is a popular technology used for diagnosis of building defects. While these technologies have their primary focus on improving energy efficiency, they brings new opportunities for identifying and diagnosing various housing-related health and safety hazards; many of these hazards are interrelated or interacting threats to healthy living.

The purpose of this paper is to provide a systematic review of existing research in infrared building hazard detection. The paper begins with discussion of health and structure hazards in buildings and homes, followed by a review of current research in building defect detection with infrared thermography technologies.

2.2 Green Building and Healthy Homes

Building performance (structure performance and indoor air quality) and residents' health symptom are two major fields that judge how suitable a building is for living. As the impact of buildings becomes increasingly apparent, two new fields called "Green Building" and "Health Homes" are gaining momentum.

The primary focus of green building movement is on designing and constructing a structure and the using of processes that are environmentally responsible and resource-efficient throughout a building's life-cycle. The U.S. Environmental Protection Agency listed the 5 principles for a green building, which are Sustainable Site Design, Water Quality and Conservation, Energy and Environment, Indoor Environmental Quality, Materials and Resources (Table 1). On the one hand, as one of the major components of green building, energy consumption and efficiency have become issues of growing concern as both supply and demand are strained. In the United States, buildings' heating and cooling use 37.3% of the total building energy consumption in 2010. With more than 134 million houses in the United States (U.S. Census Bureau 2010), this presents a tremendous opportunity to decrease energy consumption and reduce inefficiencies. On the other hand, green building also concerns "Indoor Environmental Quality", which clearly serves a tie to healthy homes.

As a century-old concept, "Healthy Homes", promotes a safe, decent, and sanitary housing for preventing disease and injury, has got increasing attention nationally. In 2013, the U.S. Department of Housing and Urban Development (HUD), the White House Council on Environmental Quality (CEQ), the Environmental Protection Agency (EPA), the Surgeon General, and the Department of Energy have introduced a collaborative initiative entitled Advancing Healthy Housing—a Strategy for Action. The program prompts federal agencies to support "pre-emptive actions" for reducing the number of US homes with health and safety hazards. Examples of resources that support this approach can be found in the form of guidance manuals and websites, training/education such as SolarOne's Workforce Lab program, and embedded within certification programs such as GREENGUARD or LEED. These resources are developed by professional organizations, federal and state agencies and nonprofit organizations and are frequently collaborative efforts. A few examples include HUD's Healthy Homes program, US EPA's Tips for Housing Managers and the NJ Department of Health Indoor Environments Program.

Table 1: Summary of green building components

Fundamental Principles of Green Building	Key Principles Description
Sustainable Site Design	Minimize urban sprawl and needless destruction of valuable land, habitat and green space, which results from inefficient low-density development.

	Encourage higher density urban development, urban re-development and urban renewal, and brownfield development as a means to preserve valuable green space. Preserve key environmental assets through careful examination of each site. Engage in a design and construction process that minimizes site disturbance and which values, preserves and actually restores or regenerates valuable habitat, green space and associated eco-systems that are vital to sustaining life.
Water Quality and Conservation	Preserve the existing natural water cycle and design site and building improvements such that they closely emulate the site's natural "pre-development" hydrological systems. Emphasis should be placed on retention of storm water and on-site infiltration and ground water recharge using methods that closely emulate natural systems. Minimize the unnecessary and inefficient use of potable water on the site while maximizing the recycling and reuse of water, including harvested rainwater, storm water, and gray water.
Energy and Environment	Minimize adverse impacts on the environment (air, water, land, natural resources) through optimized building siting, optimized building design, material selection, and aggressive use of energy conservation measures. Resulting building performance should exceed minimum International Energy Code (IEC) compliance level by 30 to 40% or more. Maximize the use of renewable energy and other low impact energy sources.
Indoor Environmental	Provide a healthy, comfortable and productive indoor environment for building occupants and visitors. Provide a building design, which affords

Quality	the best possible conditions in terms of indoor air quality, ventilation, thermal comfort, access to natural ventilation and daylighting, and effective control of the acoustical environment.
Materials and Resources	Minimize the use of non-renewable construction materials and other resources; Maximize the use of recycled content materials, modern resource efficient engineered materials, re-usable, renewable, sustainably managed, bio-based materials and resource efficient composite type structural systems wherever possible.
Data Retrieved from: US EPA Online http://www3.epa.gov/statelocalclimate/documents/pdf/12_8_what_is_green_GGGC.pdf	

HUD's Healthy Home Rating System (HHRS) was developed based upon the successful Housing Health and Safety Rating System (HHSRS), which can address key issues affecting health and safety due to conditions in the home, provides analysis of how hazardous a dwelling is and provides evidence and statistical information to assist assessors in making judgments. The HHRS provides a method of grading the severity of threats to health and safety in any dwelling, from house, self-contained flat/apartment, non self-contained flat/apartment, a room rented within a dwelling or house, to a room in a university hall or similar residential building and the means of access and shared or common rooms and facilities. There are 29 summarized hazards listed in the HHRS Hazards Summary Chart across four categories including Physiological, Psychological, Infection, and Safety (Table 2) (U.S. HUD).

Table 2: Healthy Home Rating System (HHRS) – Categorization of 29 hazards

Categorization	Hazard Type	
Physiological	1. Dampness and Mold 2. Excess Cold 3. Excess Heat 4. Asbestos and manmade fibers 5. Biocides	6. Carbon Monoxide 7. Lead-based paint 8. Radiation 9. Un-combusted fuel 10. Volatile
Psychological	11. Crowding and Space 12. Entry by Intruders	13. Lighting 14. Noise
Infection	15. Domestic Hygiene, Pests, and Refuse 16. Food Safety	17. Personal Hygiene 18. Water Supply
Safety	19. Falls in bath etc. 20. Falls on the level 21. Falls on stairs etc. 22. Falls from windows etc. 23. Electrical hazards 24. Fire hazards	25. Hot surfaces etc. 26. Collision/Entrapment 27. Ergonomics 28. Explosions 29. Structural collapse

The fact that people usually spend half of time or more everyday inside their homes making the housing environment one of the major influences on health and well-being. Nevertheless, in the United States, millions of home occupants are exposed to moderate or even severe health and safety hazards such as roofing or other structural problems, heating and plumbing deficiencies, leakages, and pest problems that are associated with a wide range of health issues from respiratory illness, SBS to injuries. Many of these home occupants have limited resources to detect these building and home hazards. There is a need for cost effective and non-intrusive technologies that can reliably detect and diagnose these hazards. Infrared thermography has been widely used for building performance inspection, in particular for detecting energy leakage from building envelope to quantify potential energy saving, identifying problems and deficiencies inside of the building. With the recent technological advance in infrared technology, infrared thermography is no longer an exclusive tool for building inspection specialist, and becomes accessible to the general public. The concept of using infrared thermograph as a cost effective building and home hazard detection method is intriguing. The central motivation of this review paper is to synthesize the studies in the field of using infrared thermography for building defect diagnosis in order to foster better understanding of the potential of infrared thermography for building and home hazard detection.

2.3 Infrared Thermography: Principles and Trends

2.3.1 The Principle of Infrared Thermography

Infrared Thermography (IRT) is the process of acquisition and analysis of thermal information from non-contact thermal imaging devices. Thermographic cameras can detect radiation in the infrared range of the electromagnetic spectrum and produce images of that radiation. Infrared light is one of the electromagnetic radiations (Figure 1) with a wavelength between 0.7 and 300 micrometers. Since infrared radiation is emitted naturally from any object with a temperature above absolute zero (-273.15 ℃ or 0 K) according to the black body radiation law, thermography makes it possible to see one’s environment with or without visible illumination. As shown in Figure 1, the infrared spectrum can be divided into five categories:

Near infrared (NIR), Short wavelength infrared (SWIR), Mid wavelength infrared (MWIR), long wavelength infrared (LWIR), and far infrared (FIR). The applications of infrared waves include: communications, thermal imaging, night vision, missile tracking, heating, and other uses in the field of astronomy, meteorology, spectroscopy, biological systems and so on.

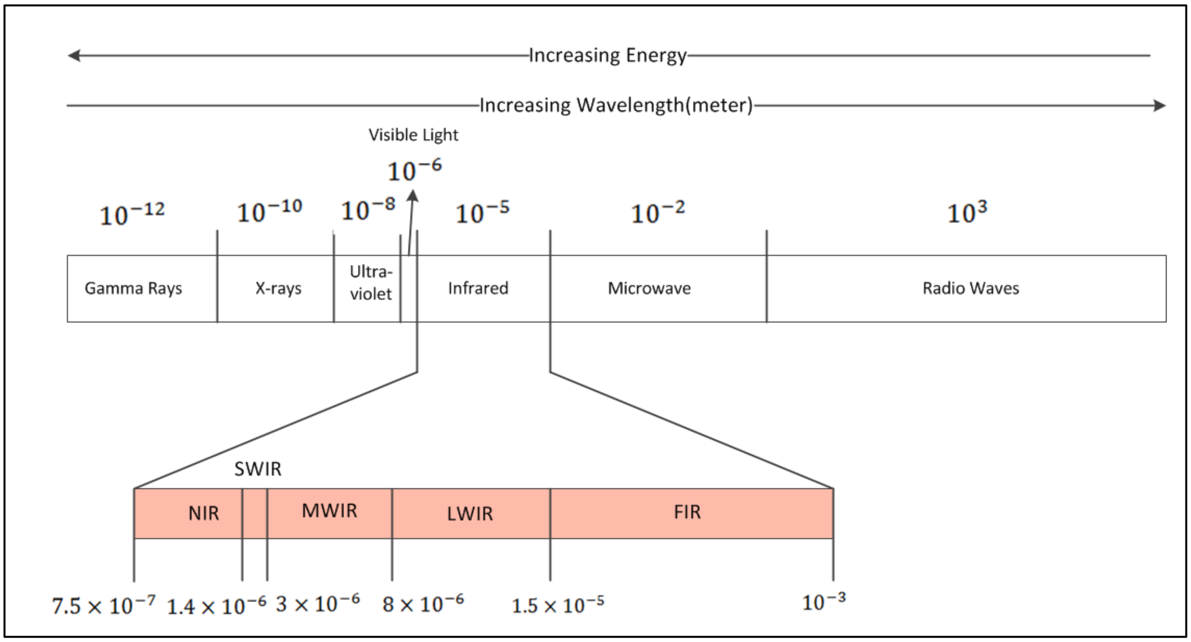


Figure 1: The electromagnetic spectrum

The energy of emitted radiation can be converted to temperature by means of the Stefan Boltzmann Law, which states that the power radiation by a material is directly proportional to the fourth power of its absolute temperature as:

$$q_{rad} = \varepsilon \sigma T^4 \quad (1)$$

where ε is infrared emissivity of the material, σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8}\ \mathrm{W\,m^{-2}\,K^{-4}}$), and T is the surface temperature of the material. Emissivity, ε, presents how efficiently a material transfers energy by radiation heat transfer. It is a unit value defined as the fraction of energy emitted relative to the radiation of perfect emitter or blackbody.

The amount of radiation emitted by an object increases with temperature; therefore, a thermal device can measure the emitted IR energy and converts it to digital temperature readout which allows one to see variations in temperature. Thus through an infrared device, those thermal patterns and heat signature can be captured and displayed as visible information to naked eyes. However, such temperature readings could be false due to the fact that the energy reaches a thermal sensor (Infrared camera) is a sum of energy emitted from the target and the energy emitted from surrounding environment and intercepted by the objects surface. In a simple term, the total energy emitted from the object is a combination of emitted energy, transmitted energy and reflected energy (Figure 2). The sum of emission is composed of absorption , reflection , and transmission , and the value is equal to one.

$$\%\text{Reflected} + \%\ \text{Tranmistted} + \%\ \text{Absorbed} = 100\% \qquad (2)$$

The absorption is the degree to which infrared energy is absorbed by a material, while, transmission is the degree that thermal energy passes through a material. In some case, if the object is opaque, the tranmissed energy become 0 and the emissivity and refectivity add together to be 100%. Reflection describes how much infrared energy is refected off a material. The sensor cannot distinguish between the energy emitted versus energy transmitted or reflected, so the temperature captured from infrared sensor is usually the “apparent” temperature.

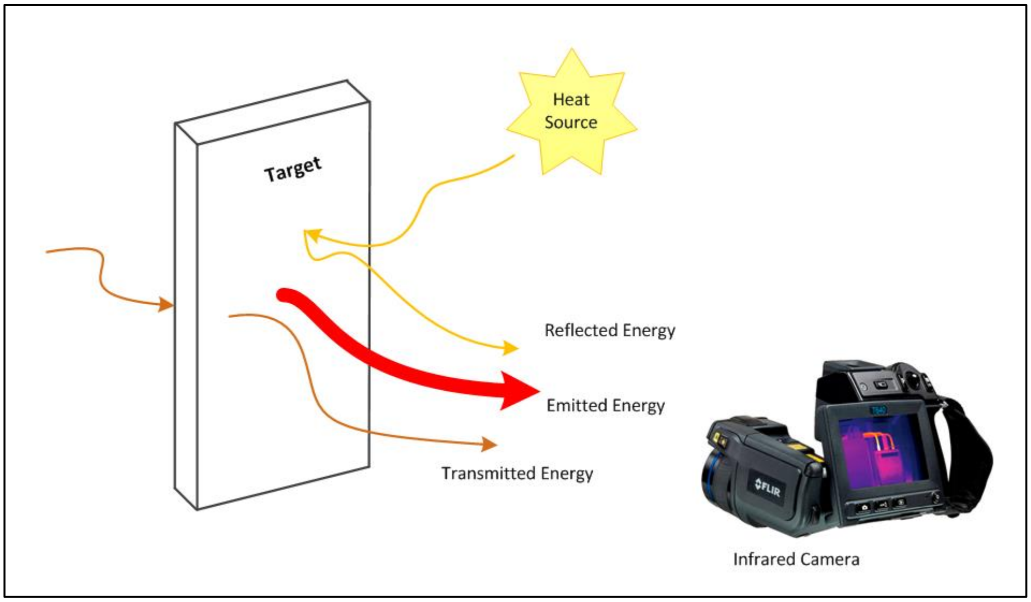


Figure 2: In addition to the radiation emitted from the target, the sensor also received reflected radiation

Subsurface anomalies in building structures, such as moisture and insulations, interrupt heat flow and produce localized differences in wall surface temperature. These localized variations in surface temperature in turn affect the amount of infrared radiation emitted from the surface, which are often detectable using an infrared camera. As discussed in the last paragraph, radiation measured by an infrared camera not only depends on the temperature of an object but also influenced by reflected radiation. To measure temperature accurately, it is therefore necessary to compensate for the effects of a number of different radiation sources. According to the FLIR Report on Buildings, object parameters required for accurate temperature measurement include emissivity of object, reflected apparent temperature, the distance between the object of interest and the camera, relative humidity, and atmosphere temperature (FLIR System AB. 2009). In addition to moisture and insulations, infrared thermography can also be employed to determine the heat losses in buildings (C.A. Balaras 2002), predict structure failures (M.R. Clark 2003), and other problems relating to humidity (V.De Luca 1996).

There are two types of thermography inspections: passive thermography and active thermography. The passive approach measures surface temperature differences of a structure during normal conditions, while the active approach generates the temperature differences of the structure using an external stimulus. External stimulus can be any kind of external heat sources, such as lamps, ovens, and hot packs (Kylili et al. 2014). Although the effectiveness of passive thermography can be complicated by weather and environmental condition, passive thermography, as a simpler and more rapid approach when compared with active thermography, is widely used in building diagnostics. In general, passive thermography has been used for structure inspection, electrical inspection, and mechanical inspection in the context of building performance inspection.

2.3.2 Infrared Camera Market

Thermography has a long history and had been used by firefighters to see through smoke, by maintenance technicians to locate overheating issues and section of power lines, by building construction technicians to see the thermal signatures to locate heat leaks. Although night vision and thermal imaging are both used to detect objects at night, they have different principles that night vision relies on at least a very low level of light and will not work in complete darkness. In the context of this research, our primary interest is thermal imaging cameras.

Although there are a number of components that contribute to the quality and cost of an infrared camera (thermal imaging camera), the two most important factors are detector resolution and thermal sensitivity. The detector resolution describes the number of pixels that can measure the temperature. The typical resolutions coming with a thermal imaging camera are 80×60, 160×120, 320×240, 640×480 and 1024×768. A 640×480 detector can produce an infrared image composed of 307,200 pixels. The thermal sensitivity is the least temperature difference an infrared camera can detect. A sensitivity of 0.02℃ means that the camera can distinguish between two surfaces with a two-hundredths of a degree temperature difference. In addition to detector resolution and thermal sensitivity, temperature range is also important. The temperature range of an infrared camera describes the maximum and minimum temperature that the camera can measure. A temperature range of -40℃ to +2000℃ means that camera can measure temperature from -40℃ to 2000℃. Table 3 provides a complete list of key parameters related to the performance of an infrared camera.

Table 3: Basic infrared camera parameters

Infrared Camera Characteristics	Description	Example
Resolution	Describe the number of pixels can be measure the temperature	640×480, means the infrared camera can produce an infrared image composed of 307,200 pixels
Thermal Sensitivity	Describe the least temperature difference one infrared camera can detect	sensitivity of 0.02℃ means that camera can distinguish between two surfaces with a two-hundredths of a degree temperature difference
Accuracy	Describe how accurate the temperature reading	An infrared camera with a +/-2% accuracy means the infrared camera is calibrated within a +/-2% of

	is.	reading
D/S Ratio	Distance-to-spot ratio. The distance-to-spot ratio is the size of the area being evaluated by the infrared camera as it relates to distance.	If the target to be measured is 5 inches in size, and the infrared thermometer has a D/S ratio of 8:1, then the maximum distance at which can reliably measure the temperature of the target is 40 inches. When the distance is farther than 40 inches, not only the target will be measure, but also the surrounding objects that falls within the “spot” will be measured at the same time.

The wavelength of an infrared camera often dictates its application areas. One means of categorizing infrared cameras is by spectral response. The most common design approach is to select a segment of infrared spectrum, and integrate the energy falling on the infrared detector for that segment. Many general-purpose cameras use a wideband 8 to 14 μm for measuring objects below 500 ℃ (Calex Electronics Limited). A narrow bans may be used for some special purposes and applications (e.g. gas detection).

When an infrared camera is used for building diagnosis, electrical inspection, and mechanical inspection applications, the spectral range usually goes from 7.5 to 14 μm. Infrared cameras used for optical gas imaging and furnace inspection usually have a different spectral range when compared with other thermal cameras. Depends on detailed applications, gas detection cameras can be divided for various applications such as oil and petrochemical application, manufacturing application, electric utility application, natural gas application, chemical application, furnace and boiler inspection application and independent lab testing (Table 4).

Table 4: Infrared cameras for optical gas imaging

Infrared Wave [µm]	Gas Detected	Gas Detection Application	Description
3.2 – 3.4	1-Pentene,Benzene, Butane, Ethane ,Ethanol , Ethylbenzene ,Ethylene , Heptane ,Hexane , Isoprene, MEK ,Methane , Methanol, MIBK, Octane , Pentane ,Propane,Propylene, Toluene ,Xylene,	Oil and Petrochemical; Manufacturing; Nature gas Detection; Chemical;	Detect spot leaks in piping, flanges and connections in petrochemical operations.
3.8-4.05	Gas from furnaces, heaters and boilers.	Furnace and boiler inspection	The camera with this infrared wave is specially designed to inspect industrial furnaces, heaters and boilers, which is equipped with a special mid wave "flame filter" that is

			specifically engineered for high temperature (up to 1500 ℃). It will help make inspection faster, work safer and avert unscheduled shutdowns.
4.2- 4.4	CO_2	Oil and Petrochemical; Manufacturing; Nature gas detection;	Visualize CO2 leaks during normal operation and keep operations safe.
4.52- 4.67	CO and Nitrous Oxide (N_2O); Ketene;Ethenone (C_2H_2O); Butyl Isocyanide; Hexyl Isocyanide; Cyanogen Bromide (CNBr); Acetonitrile (C_2H_3N); Acetyl Cyanide; Chlorine Isocyanate (CClNO); Bromine Isocyanate (CBrNO); Methyl Thiocyanate (C_2H_3NS); EthylThiocyanate; Chlorodimethylsilane(	Electric Utility;	Visualize CO or other harmful gases leaks from a safe distance without interrupting the operation.

	$(CH_3)_2SiHCl$; Dichloromethylsilane; Silane (H_4Si); Germane (GeH_4); Arsine (AsH_3);		
8-8.6	Refrigerant gas leakage	Refrigerant leak detection;	This type of infrared can detect refrigerant gas leakages in food production, storage and retail, air conditioning. The leakage can be detected without interrupting or shutting down the operation.
10.3–10.7	SF_6 (Sulfur Hexafluoride) Acetic Acid ($C_2H_4O_2$); Anhydrous Ammonia (NH_3); Chlorine Dioxide (ClO_2);Dichlorodifluoromethane "FREON-12" (CCL_2F_2); Ethyl Cyanoacrylate "Superglue" ($C_6H_7NO_2$); Ethylene (C_2H_4)	Manufacturing; Electric Utility; Chemical;	Detect SF6 that used in electrical substations at electrical power plants as insulator in circuit breakers and switchgear and magnesium production and semiconductor manufacturing.

Most infrared cameras have fewer pixels than common digital cameras. This is important as the resolution can influence measurement distance as well as image quality and accuracy. A higher resolution infrared camera can measure smaller targets at a large distance but still create sharp infrared images. Thus high-resolution cameras are required when surveying long-range targets or small components, especially for electrical and mechanical applications. For example, an infrared camera with a 25° lens and an 80×60-pixel detector will have a smaller spot measuring size than an infrared camera with a 25° lens and a 160×120-pixel detector. In general, there are four types of resolutions available on the market:

- Low resolution (As low as 60×60 pixels)
- Standard resolution (Typically 160×120 pixels)
- High resolution (From 320×240 pixels up to 640×480 pixels)
- Very high resolution (1024×768 or higher pixels)

Infrared cameras can also be varied in size. The general trend is with the rapid development in thermal technology, thermal devices become increasing affordable and portable. With the latest technology, the thermal cores become smaller and much less expensive. The FLIR One and Seek Thermal realized the fusion of smartphone and thermal camera. FLIR C2 and Seek Reveal(Figure 3) are the full-featured, pocked-sized, completely standalone camera that designed for a wide range of building, electrical and mechanical applications. In the past, thermography cameras are almost exclusive assets operated by professionals. This has changed since the introduction of miniature size smart phone-based infrared cameras. These cameras open the door to wide adoption of infrared thermography based building performance inspection by home owners and building operators, which will form the basis for a citizen science framework on building and home inspection.

Figure 3: Pocket-sized infrared cameras

(a)FLIR One for Android; (b) Seek Thermal for iPhone; (c) FLIR C2 ;(d) Seek Reveal

2.4 Infrared Thermography for Building Diagnosis

2.4.1 Building Defect Detection

Infrared technology has been increasingly used in building inspection to provide people with the distribution of temperature that allows building inspectors to see problems they would have missed through traditional assessment method. These problems include water penetration of walls and roof (Figure 4 and Figure 5), leaks in the plumbing, electrical problems, missing, improperly installed or damaged insulations, thermal bridges, and air infiltrations. While some of these problems are self-explanatory, the others, such as thermal bridge and air infiltration are not quite obvious to interpret. Detailed explanations of the symptoms of these problems are provided as the following.

As the most common defect that can be identified from infrared thermography, moisture issue has been confirmed not only impact the indoor humidity, but also human comfort and air quality (Rode et al., 2001; Simonson et al., 2002). Moisture areas are detectable to infrared thermography because a wet mass can retain the absorbed heat for a longer time than a dry mass and as a result of this the wet area takes a longer time to radiate the heat during the heating process. Figure 5 shows some examples of moisture intrusion detected by infrared thermography.

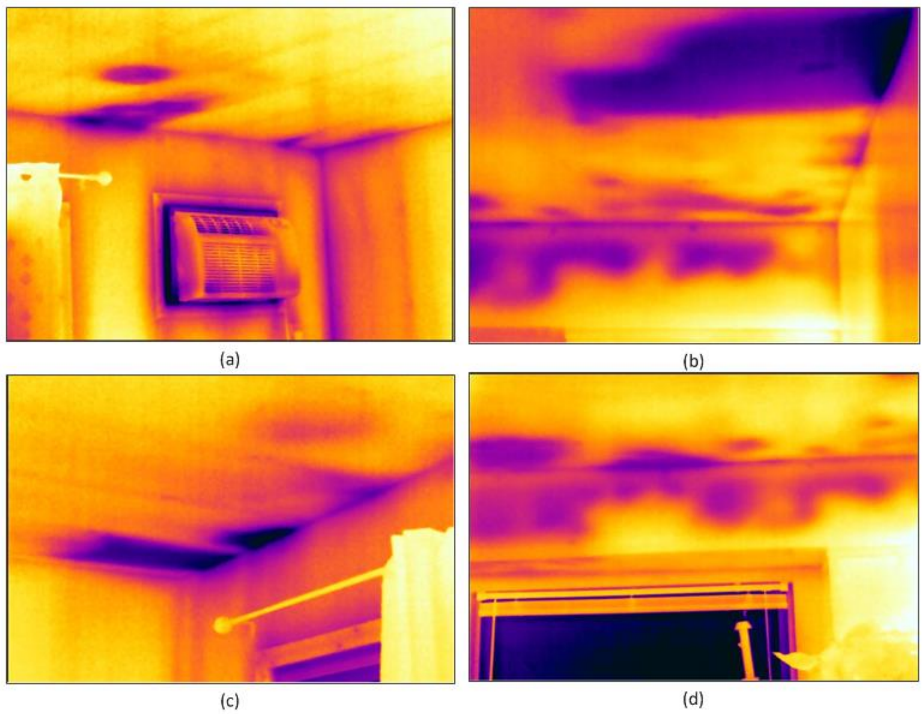


Figure 4: Infrared images taken in a simple apartment after a rainy day

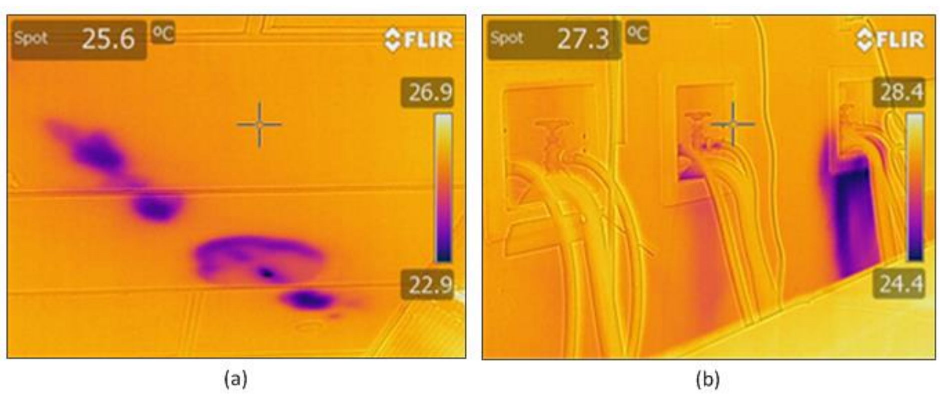


Figure 5: Thermography of interior wall surface with water leaking on the ceiling and in the wall

Thermal bridges, also called a cold bridge or heat bridge, are limited areas in the construction where heat flow is higher than the heat flow in the undisturbed area. They are usually caused by structural components that penetrate the insulation's thermal barrier. This creates a shot-circuit path for the heat flow, which cause unexpected heat transfer and energy waste. Possible consequences from thermal bridges are condensation of water vapor in buildings, especially the older buildings and significant energy loss. Several studies showed that thermal bridges may cause up to 30% of the extra-thermal losses through the envelope in winter, in this way increasing the energy consumption during heating season (Theodosiou and Papadopoulos 2008). Other effect of thermal bridges includes provide habitant for molds and fungi and produce bad indoor air quality conditions (Ascipne et al. 2013; GhaffarianHoseini et al. 2013). To quantify the extent of thermal bridge, temperature factor is used for the assessment of thermal bridge and air leakages. Kalamees (2007 and 2008) determined the typical places of air leakage and thermal bridge through the infrared camera and calculated the temperature factor at the internal surface ($f_{R_{si}}, -$). The temperature factor $f_{R_{si}}$ at the internal surface shows the relation of the total thermal resistance of the building envelope ($R_T, (m^2 \cdot K)/W$) to the thermal resistance of the building envelope without the internal surface resistance ($R_{si}, (m^2 \cdot K)/W$) and can be calculated with measured internal surface temperature ($T_{s,in}$, ℃), indoor temperature (T_{in}, ℃) and outdoor temperature (T_{out}, ℃) according to following equation (Hugo 2012, Kalamees 2007).

$$\frac{R_T - R_{si}}{R_T} = f_{R_{si}} = \frac{T_{s,in} - T_{out}}{T_{in} - T_{out}} \tag{3}$$

Studies related to temperature factor pointed out that the poor temperature factor related to poor insulation values and in their researches a level of grade was given: A temperature factor for Thermal bridges with $f_{R_{si}} \geq 0.65$ and $f_{R_{si}} \geq 0.61$ reflect good level and tolerable level, while when temperature factors are lower than 0.61, the detected air may include health risks or hazards (Kalamees 2008; Little 2011; Schock and Isokorb 2015).

Figure 6: Thermography of interior wall surface with thermal bridge in winter

Air leakage also known as infiltration is the unintentional or accidental introduction of outside air into a building, typically through cracks in the building envelope and through use of doors and passage (U.S. DOE 2012). Air leakage through windows and doors allow unwanted outdoor air to enter inside the building (infiltration) or indoor air to escape (exfiltration). Thus increasing the heat gains during the summer and heat lose during the winter. They are important in terms of building energy performance because it can reduce the effectiveness of insulation and significantly reduce the energy efficiency of the building through direct air intrusion. In addition, during the heating seasons, cold air drafts near the windows could cause thermal discomfort for residents, especially for children and occupants age 65 or above. Air leakage can occur in the junction of exterior walls, space between window/door jambs and framing, floors, electrical boxes or switches on the exterior wall. Air infiltration at electrical switches and outlets is one common issue happens in residential building, during heating season, leaks through electrical boxes and switches can cause comfort complaints and raise the risk of moisture problems in walls. Through the infrared camera, the cold air leakage can be easily point out around the window or a doorframe. Balaras and Argiriou (2002) pointed out that IR thermography can see the end results of the cold airflow, though it cannot see the cold air or measure the air temperature. Some of air infiltration examples are shown in Figure 7.

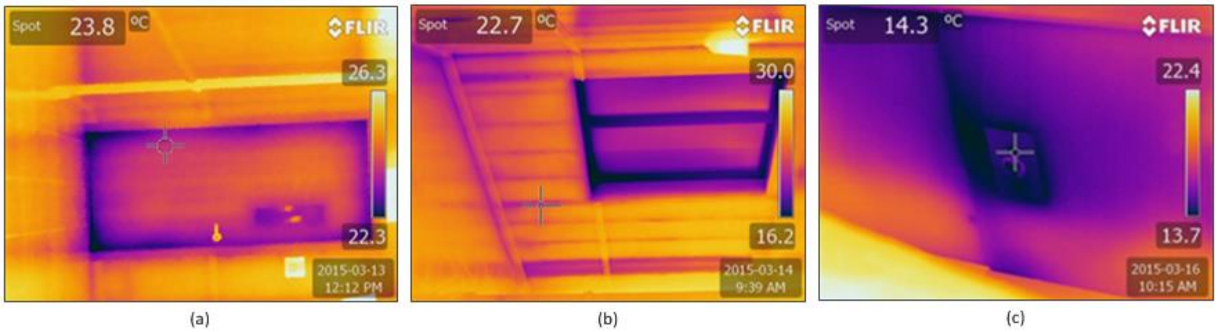
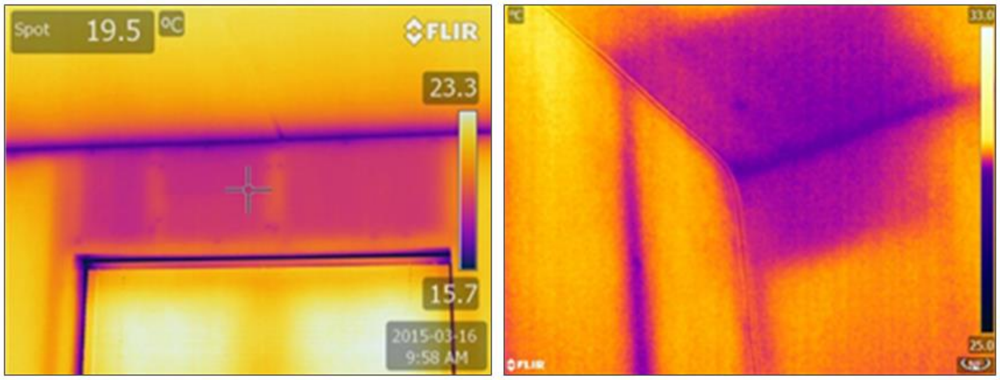


Figure 7: Thermography showing air infiltrations: (a) Cold air infiltration around the doorframe; (b) Cold air infiltration around the window; and (c) Cold air infiltration at wall socket

Thermal insulation reduces heat losses by conduction through the building envelope (i.e. wall, roof) during winter and heat gains during summer. Good thermal insulation can reduce the heating or cooling energy costs and improves indoor thermal comfort conditions by increasing the interior surface wall temperature in winter and by reducing it in summer. Missing or damaged insulation can be located when the thermography indicates a temperature difference of about 10 C between the internal and external surface temperature (Residential Energy Services Network, Inc. 2012; FLIR System AB. 2011). On a thermography, missing or poor insulation area will appears to be a light/dark colored patch with distinct edges the outline the problematic areas (Balaras and Argiriou 2002). Examples of missing insulation are shown in Figure 8.



(a) (b)

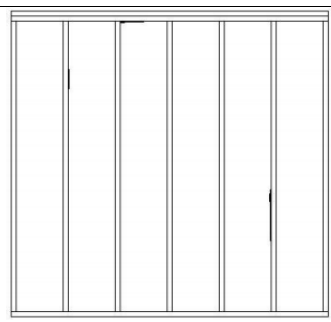
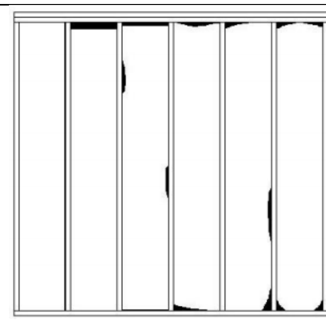
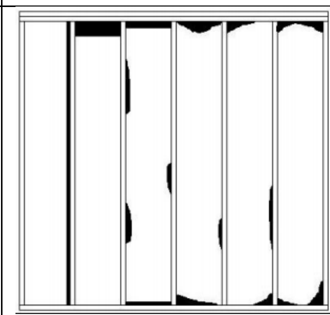
Figure 8: Thermography of interior wall surface with missing insulation

Assessing the performance of insulation in building construction is a particular interest topic as it can be used an important means to assess construction quality for new homes. ESNET or the Residential Energy Services Network is recognized national standards-making body for building energy efficiency rating and certification systems in the United States. In 2006, RESNET published a major revision of the HERS Standards, officially named the 2006 Mortgage Industry National Home Energy Rating Systems Standards. One important new feature in this standard was the grading of insulation installation quality. The rating result can be used for seeking to qualify for a program's label or certification, such as the ENERGY STAR new homes program. The rating result usually includes all the information about the building envelope, the heating and cooling systems, ventilation, water heating, lights, and appliances. The R-value of the insulation in all the insulated building assemblies (walls, ceilings, floors) can have a big effect on the rating result. Using a grade on the installation quality can help the rater develop the energy model of the home in a more accurate way. The HERS Standard defines a threshold, or boundary condition, that the installation must meet to be assigned to that level.

According to the HERS standard, the insulation installation quality can be split to two criteria: Missing insulation and Compression and incompletely filled areas. Missing insulation happens when a cavity in a building assembly has insulation installed in a way that leaves gaps, which can affect the amount of heat that flows across the building envelope. The increasing number of gaps led to a worse grade result in HERS. Description of Grade I, II and III and listed in follow table, images taken from HERS Standards. Compression and incomplete fill are the common problem with fiberglass batt insulation because the batts are often not cut to the proper size for the cavity, the detail description of Compression and incomplete fill grades are listed in Figure, information and images taken from HERS Standards.

Table 5: HERS Standard for missing insulation

Grade	Grade I	Grade II	Grade III
Description	Almost no gaps	Up to 2% missing insulation	2%-5% missing insulation
Interpretation	Grade I shall be used to describe insulation that is generally installed according to manufactures instructions and /or industry standards. To be graded as “Grade I”, the insulation material should uniformly fills each cavity side-to-side and top-to-bottom,	Grade II shall be used to describe an installation with moderate to frequent installation defects: gaps around wiring, electrical outlets, plumbing and other intrusions, rounded edges. Gaps and spaces running clear through the insulation amounting to no more than 2% of the	Grade III shall be used to describe an installation with substantial gaps and voids, with missing insulation amounting to greater than 2% of the area, but less than 5% of the surface area is intended to occupy. More than 5% missing

	without substantial gaps or voids around obstruction (such as blocking or bridging) and is split, installed, and/or fitted tightly around wiring and other services in the cavity.	total surface area covered by the insulation.	insulation shall be measured and modeled as separate, uninsulated surfaces.
Illustration	 Occasional very small gas are acceptable for "Grade I"	 No more than 2% of surface area of insulation missing is acceptable for "Grade II"	 The illustration represents the boundary conditions between Grade III and the situation whereby one must measure the uninsulated areas

The Grade III for missing insulation is designed as no more than 5% of the surface area of insulation missing is acceptable. For an installation that is worse than Grade III, the procedure specifies that the inspector must measure the insulated areas separately from the uninsulated areas and input them separately in software (Harley 2005). For example, a wall area of 200 square feet has 20 square feet of no insulation, the 20 square feet must be assigned as uninsulated cavity wall. In year 2010, RESNET adopted the guidelines for thermographic inspections of buildings and published the standard " RESNET Interim Guidelines for Thermographic Inspection of Buildings". This standard provides guidance on the use of infrared thermography for the inspection. In this standard, the definition of each Grade is slightly adjusted to apply for the use of infrared thermography. The following table shows the insulation grading standard for infrared thermography. Figure 9 shows the method for converting anomalies to insulation grading through infrared camera.

Table 6: HERS Standard for compression and incomplete fill

Grade	Grade I	Grade II
Description	2% or less	2%-10%
Interpretation	Compression or incomplete fill amounting to 2% or less, if the empty spaces are less than 30% of the intended fill thickness, are acceptable for "Grade I". To explain it, using 1000 square feet as example. No more than 20 square feet of each 1000 square feet can have this problem, and those 20	Compression or incomplete fill amounting to less than 10% of the area with 70% or more of the intended thickness (i.e., 30% compressed).

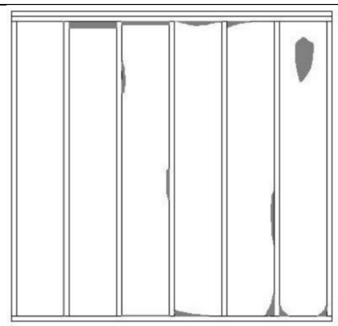
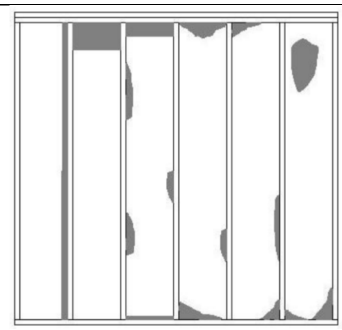
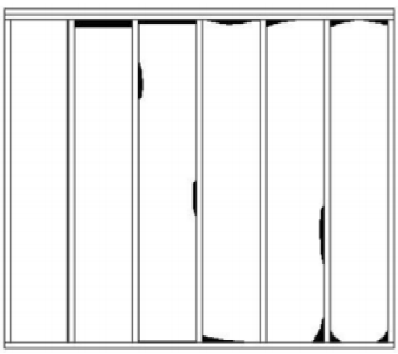
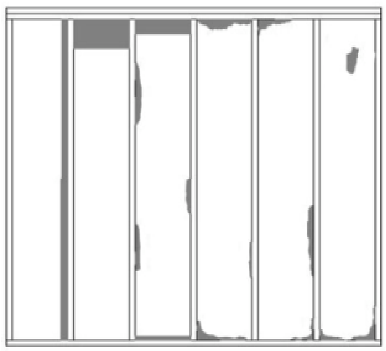
	square feet must be filled to at least 70% of their intended insulation depth.	
Illustration	 Compression or incomplete fill amounting to 2% or less, if the empty spaces are less than 30% of the intended fill thickness, are acceptable for “Grade I”.	 No more than 10% of surface area of insulation compressed or incomplete fill, by up to 30% (70% or more of intended thickness) is acceptable for “Grade II”.

Table 7: RESNET Interim Guidelines for thermographic inspection of Building Insulation Grading Standards

Grade	Grade I	Grade II	Grade III
Description	Grade I insulation installation cannot be verified using this infrared standard	Grade II must be insulation installed with anomalies found to be between ½% and 2% for all inspected walls, floors and ceilings of the building	Grade III must be an insulation installation having between 2% and 5% anomalies found for an inspected walls, ceilings and floors of the building enclosure
Illustration	NA		

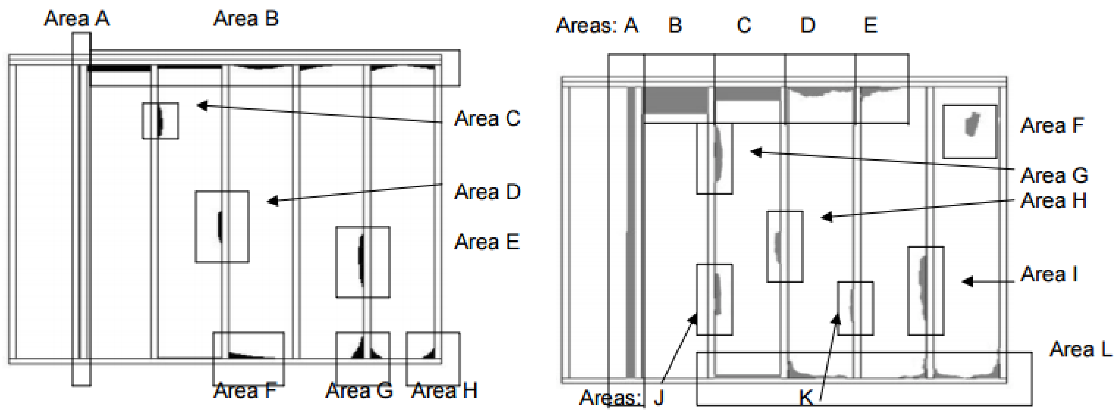


Figure 9: Grade II insulation grading example from RESNET Interim Guidelines for thermographic inspection of Building Insulation Grading Standards

2.4.2 Infrared Thermography Based R Value Estimation

As two major factors for insulation and heat loss measurement, R-value and U-value are widely used to describe the air-to-air behavior of a particular construction. The U-value, which is also known as the overall thermal transmittance coefficient (Unit:W/m^2K), is a measure of the overall rate of heat transfer. An R-value (Unit:m^2K/W) is a measure of the opposition to heat transfer offered by a particular building element, such as a wall, or by parts of the element. Although building regulations and codes (e.g. ASHRAE 90.1-2010, IECC 2012, IGCC 2012) use R-values or U-values as one mechanism to specify targets and limits for thermal insulation, there are other principal factor can also affect the rate of heat lost from a building. According to McMullan (2012), the principal factors that affect the rate of heat lost from a building are: Insulation of the building shell, exposed area of the building shell, temperature difference between inside and outside, air change rate, exposure to external climate, efficiency of service in the building and patterns of use of the building.

Extensive research effort has been devoted to estimate R (or U) value of building envelop systems based on infrared thermographic data. For example, many studies have investigated using point-based or 2D IR imaging for R value estimation (Haralambopoulos and Paparsenos 1998; Fokaides and Kalogirou 2011; Dall'o' et al. 2013; Nardi et al. 2014; Albatici and Tonelli 2010). Recent studies have also sought to use 3D thermographic methods for R value estimation (Ham and Golparvar-Fard 2014; Ham and Golparvar-Fard 2015). Based on the location of data collected, there are two ways of R/U-value that can be estimated. The first is to use only outdoor surface temperature of exterior walls (Dall'o' et al. 2013; Nardi et al. 2014; Albatici and Tonelli 2010, Haralambopoulos and Paparsenos 1998). The other way is to use indoor and outdoor surface temperature of exterior walls (Ham and Golparvar-Fard 2014, 2015; Fokaides and Kalogirou 2011).

To correctly calculate R-value using infrared thermographic data, rigorous calibration and estimation of parameters such as emissivity are of critical importance. Considering a steady state condition of heat transfer in building environments, thermal resistances (R-value) can be described with the following Equation (4-7). In the Eq. 4,

$$\frac{dQ}{dt} = \frac{A \times |T_{air,in} - T_{air,out}|}{R} \tag{4}$$

where $\frac{dQ}{dt}$ is the overall heat transfer rate through the area of a building surface (Area)A is the area of target building surface, R is the thermal resistance of the target area, and $|T_{air,in} - T_{air,out}|$ is the temperature difference between the air temperature inside and outside the building. The overall heat transfer (Q) in the building environment can be described as the combination of thermal convection and radiation. Eq. 5 describes the thermal convection

$$Q_{convective} = \alpha_{convective} \times A \times |T_{air,in} - T_{wall,in}| \tag{5}$$

where $\alpha_{convective}$ is the convective heat transfer coefficient. It can be calculated according to the Jurges' equation shown as Eq. 6. The equation calculates $\alpha_{convective}$ based on the wind velocity near the building element at the time of measurement. The wind velocity ν can be measured near the wall by a hot-wire anemometer.

$$\alpha_{convective} = 5.8 + 3.8054\nu \ (\nu < 5 \ \mathrm{m/s}) \tag{6}$$

The thermal radiation $Q_{radiation}$ can be calculated according to Eq. 7:

$$Q_{radiation} = \varepsilon \times \sigma \times A \times |T_{wall,in}{}^4 - T_{reflect,in}{}^4| \tag{7}$$

Where ε is the surface integral emissivity, σ is the Stefan-Boltzman constant $5.67 \times 10^{-8}\, W/m^2K^4$, $T_{wall,in}$ is the surface temperature of inside surface of the exterior wall and $T_{reflect,in}$ is the reflected temperature.

To measure the reflected temperature ($T_{reflect,in}$) and surface emissivity (ε), a piece of crumpled aluminum foil and a black tape are often used. There are two methods to determine reflected apparent temperature: Direct method and Reflector method. The reflector method has been used in many pervious researches (Haralambopoulos and Paparsenos 1998; Fokaides and Kalogirou 2011; Dall'o' et al. 2013; Nardi et al. 2014; Albatici and Tonelli 2010; Ham and Golparvar-Fard 2014 and 2015). The steps for direct method and reflector method are listed and described in the following Table 8. According to ASTM E-1862-97, reflected ambient temperature is the average temperature of the foil target, with the Infrared camera emissivity set equal to 1.0 (Figures 11 and 12). To estimate the emissivity, a piece of black tape ($\varepsilon = 0.95$) was fixed on the target wall. With picture in picture function and spot/ box measurement function, the exact temperature of the target in the area of the known emissivity can be captured real-time during the inspection. For reflected temperature and emissivity estimation, it is of vital importance for the aluminum foil and black tape to be in thermal equilibrium with the target to measure.

Table 8: Direct method and reflector method for apparent temperature estimation

Steps	Direct Method	Reflector Method
1	Look for possible reflection sources, considering that the incident angle = reflection angle.	Crumble up a large piece of aluminum foil and uncrumble the aluminum foil to attach it to a piece of cardboard of same size.
2	If the reflection source is a spot source, modify the source by obstructing it using a piece of cardboard.	Put the piece of cardboard in front of the object you want to measure, the side with aluminum foil face the infrared camera.
3	Measure the radiation intensity (which equals to apparent temperature) from the reflecting source using the setting: Emissivity = 1.0; Distance to Object = 0;	Set the emissivity to 1.0.
4	Measure the radiation intensity using one of the methods show in Figure 10 (a)(b)	Measure the apparent temperature of the aluminum foil and write down the result (Figure 10 (c) and Figure 11).
Note	Using a thermocouple to measure the reflected apparent temperature is not recommended for two important reasons: • A thermocouple does not measure radiation intensity;	Method used by: • Haralambopoulos and Paparsenos (1998) • Fokaides and Kalogirou (2011) • Dall’o’ et al. (2013) • Nardi et al. (2014)

	• A thermocouple requires a good thermal contact to the surface, usually by gluing and covering the sensor by a thermal isolator;	• Albatici and Tonelli (2010) • Ham and Golparvar-Fard (2014 and 2015)

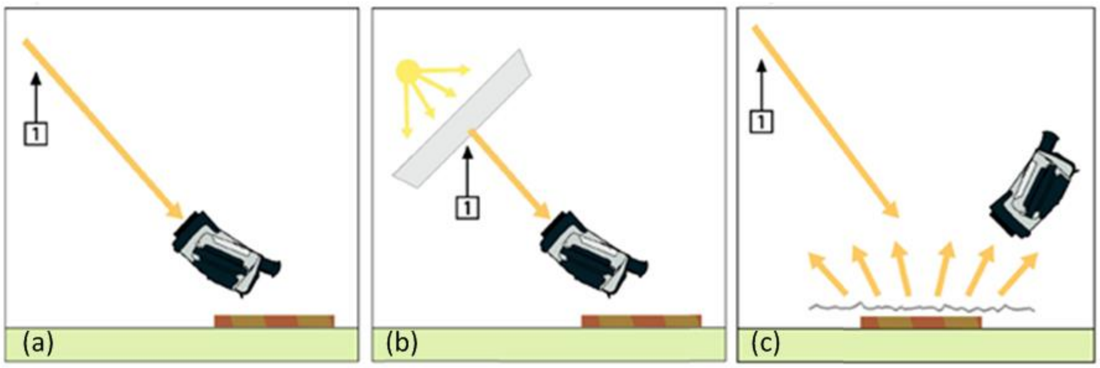


Figure 10: Ways to measure the radiation intensity

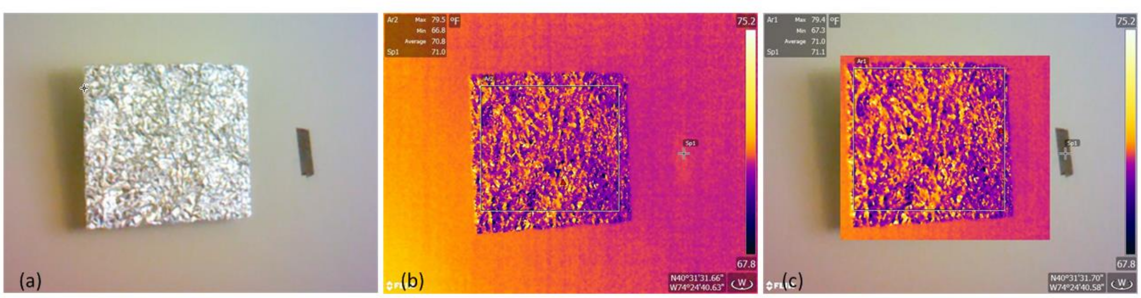


Figure 11: Measuring reflected temperature and emissivity

Table 9: Determining the emissivity of the target

Steps	Determining the emissivity
1	Select a place to put the sample. Determine and set the reflected apparent temperature according to the previous procedure (Table and Figure).
2	Put a piece of electrical tape with known high emissivity on the sample
3	Heat the sample as least 20K above room temperature. Heating must be reasonably even.
4	Focus and auto-adjust the camera and freeze the image.
5	Adjust Level and Span for the best image brightness and contrast
6	Set emissivity to that of the tape (usually 0.97)
7	Measure the temperature of the tape using isotherm, spot or box avg measurement functions.
8	Record the temperature and move your measurement function to the sample surface
9	Change the emissivity setting until you read the same temperature as recorded in the previous measure step 8.
10	Record the emissivity.

Once $Q_{radiation}$ and $Q_{convective}$ are calculated, R value can be calculated using the following equation 8. It can be seen that most of the values involved in Equation 8can be estimated using infrared thermography, temperature meter, and wind gauge.

$$R = \frac{|T_{air,in} - T_{air,out}|}{\alpha_{convective} \times |T_{air,in} - T_{wall,in}| + \varepsilon \times \sigma \times |T_{wall,in}{}^{4} - T_{reflect,in}{}^{4}|} \quad (8)$$

2.4.3 Synthesis of Existing Studies

Thermal infrared imaging can detect and provide the visual displays of the amount of infrared energy emitted, transmitted, and reflected by an object. As a useful tool, it has been used for many professions since variations in emitted energy in the infrared spectrum provide information concerning surface temperature and thermal properties of objects. In particular, infrared thermography is well suited for detecting temperature abnormality caused by change of material thermal property or the presence of latent moisture.

In the past few years, infrared thermography has emerged as a widely used method for building inspection because of its potential for contributing to energy efficiency, occupant health protection, occupant comfort, and green building development. Specifically, infrared thermography has been successfully used for building material evaluation (Titman 2001, Barreira and Freitas 2007; Meola 2007; Wyckhuyse and Maldague 2001; Forster 2007; Maierhofer et al. 2003), detecting construction defects such as air infiltration, missing insulation, and thermal bridges (Balaras and Argiriou 2002, Tony Colantonio 2007, Kalamees et al. 2008, Bianchi et al. 2014; Wrobel and Kisilewcz 2008; Grinzato et al. 1998; Li et al. 2000), moisture detection and mapping in building structures (Colantonio , Kominsky et al. 2007, Lerma et al. 2011, Gayo and De Frutos 1997; Grinzato et al. 1998; Jenkins et al. 1982; Ludwig et al. 2004; Moropoulou et al. 2002; Tobiasson and Korhonen 1985; Wild et al. 1998, Kominsky et al. 2007), building energy diagnostics(Vavilov 2010, Ham and Golparvar-Fard 2014, Fokaides and Kalogirou 2011), and pest detection in housing structures (Bruni 2004; Grossman 2005a; Grossman 2005b). The advantage of infrared thermography over other building inspection methods is mostly related to its ability of offering noncontact, non-destructive, and wide area detection of subsurface defects which can be caused by moisture intrusion, construction quality, and pest.

The effectiveness of infrared thermography can be further improved if reliable metrics of measuring the extent of various defects can be developed as they allow quantitative assessment of building performance or the quality of building construction. This has motivated extensive studies on developing and validating different metrics that can be derived from infrared thermography data. For example, Temperature Factor (TF) has been proposed and used to measure the extent of thermal bridge (Heinrich and Dahlem 2000; Bianchi et al. 2014) and air infiltration (Balaras and Argiriou 2002; Kalamees 2007; Heinrich and Dahlem 2000). Use of infrared thermography scanning to estimate R or U value of building envelops is another intriguing application and has attracted considerable attentions (Haralambopoulos and Paparsenos 1998; Fokaides and Kalogirou 2011; Dall'o' et al. 2013; Nardi et al. 2014; Albatici and Tonelli 2010; Ham and Golparvar-Fard 2014 and 2015). Last but not the least, moisture level has been used to diagnose moisture issues in buildings (Balaras and Argiriou 2002; Kominsky et al. 2007), and insulation level has been proposed to evaluate missing insulation problems (Balaras and Argiriou 2002).

Of particular interest is that the recently revised HERS standard (HERS 2006) also provides detailed procedures for assessing insulation installation quality. According to the standard, missing insulation can be classified into three grades including Grade I (Almost no gaps), Grade II (Up to 2% missing), and Grade III (2%-5% missing). The Grade III for missing insulation is designed as no more than 5% of the surface area of insulation missing is acceptable. For an installation that is worse than Grade III, the procedure specifies that the inspector must measure the insulated areas separately from the uninsulated areas and input them separately in software (Harley 2005). In year 2010, RESNET adopted the guidelines for thermographic inspections of buildings and published the standard “RESNET Interim Guidelines for Thermographic Inspection of Buildings” (RESNET 2010). This standard provides guidance on the use of infrared thermography for the inspection. In this standard, the definition of each Grade is slightly adjusted to apply for the use of infrared thermography.

Despite the recent advance in standardizing infrared thermography based building inspection, the effectiveness of infrared thermography still relies heavily on correct and rapid interpretation of visual displays of thermal images. Correct and rapid interpretation of thermal images requires considerable experience and can be assisted by a systems view of building structures. For many building professionals, infrared thermography interpretation is a very subjective process, and there are very few, if not none, software tools for automated interpretation of thermal images. Furthermore, interpretation of thermal images often happens in a context with limited geometric information on the building being investigated. As a result, spatial patterns of surface temperature anomaly cannot be easily visualized to detect interrelated building system defects. In many cases, accurate estimation of building defects and hazards often requires multiple trips to carry out geometric survey of susceptible building areas (Alba et al. 2011; Laguela et al. 2012).

At the same time, reality capture technologies such as RGB-D cameras, Structure from Motion (SFM), and laser scanners, have become main stream practices in interior and exterior modeling. RGB-D cameras are novel sensing systems that can capture RGB images along with per-pixel depth information. Originally developed for the purpose of gaming and human computer interface, RGB-D cameras have also shown promises in mapping of small-scale environments. Structure from Motion is the process of estimating three-dimensional structures from 2D image sequences(Agarwal et al. 2011). Comparing to Structure from Motion, RGB-D cameras allow the capture of reasonably accurate mid-resolution depth and appearance information at high data rates and at a very low cost. Light Detection and Ranging (LiDAR) a relatively new class of survey instrument that have been available on the market for about ten years and has become a popular and increasingly used technology for providing as-built and inventory data in building inspections. In principle, either of these reality capture technologies can be combined with infrared thermography to produce 3D thermography data (Table 10).

Table 10: Current Building Point Cloud Generation Methods for 3D Thermal Building Model

	RGB-D camera	SFM	Laser Scanner
Related Studies	Vidas et al. 2013; Weinmann et al. 2012; Vidas and Moghadam 2013;	Golparvar-Fard and Ham 2013;	Wang et al. 2012; Costanzo et al. 2014; Lagüela et al. 2012(a,b); Demisse et al. 2015; Alba et al. 2011; Borrmann et al. 2012; González-Aguilera et al. 2012

Infrared thermography analysis has become one of the most reliable tools for building defects detection; however, the current IR inspection and assessment are primarily qualitative and mainly rely on the energy auditor’s experience and knowledge. The identification and interpretation of the hot spots or cold spots of numbers of unordered thermal images are time-consuming and labor-intensive. Not to mention, without a proper benchmark or degree to judge the quality of a building’s performance, the auditor’s subjective idea only may lead to an inadequate refection of a building's structure and energy performance. With reasons above, there is a need of finding a way to level the condition of the building structure with all different types of detects (e.g. moisture issue, insulation issue, thermal bridge, air leakage, R/U-value) and building's basic information gathered together for an integral building performance estimation. Also, there is less research about the correlation between the defects inside the residential building and how they impact the residents' health and comfort in a systemic way. Starting from pervious researches, this paper concerned using statistical methods to get a better understanding of the effect of housing-related health and safety hazards on occupants' health and the relationship between building condition and human comfort.

Table 11 provides a quick summary of various studies in using infrared thermography for building defect diagnosis. Various indicators have been used in these studies to quantify the extent of building defects.

Table 11: A summary of infrared thermographic studies for building defect detection

Traditional 2D Infrared Building Envelope Inspection		Variables
Moisture Issue	Balaras, C. A., & Argiriou, A. A. (2002); Kominsky, J. R., Luckino, J. S., & Martin, T. F. (2007).	Moisture Level
Thermal Insulation Problem	Balaras, C. A., & Argiriou, A. A. (2002).	Insulation Level
Air leakages	Balaras, C. A., & Argiriou, A. A. (2002); Kalamees, T. (2007); Heinrich, H., & Dahlem, K. (2000);	Temperature factor for air leakage

Thermal Bridge	Heinrich, H., & Dahlem, K. (2000); Bianchi, F., Pisello, A. L., Baldinelli, G., & Asdrubali, F. (2014)	Temperature factor for thermal bridge
R-value or U-value	Haralambopoulos and Paparsenos (1998) Fokaides and Kalogirou (2011) Dall'o' et al. (2013) Nardi et al. (2014) Albatici and Tonelli (2010) Ham and Golparvar-Fard (2014 and 2015)	Average R-value by each apartment unit; R-value by room;

It can be noted that many of the defects investigated in these studies have connections to the hazards listed in the Healthy Home Rating System. More specifically, these connections are described in Table 12.

Table 12: Connections between defects in building envelops and home hazards

Building Envelop Defects	Connection to Home Hazards
Moisture Issue	HHRS – Physiological: Dampness & Mold; HHRS – Infection: Domestic Hygiene, Pests, and Refuse
Thermal Insulation Problem	HHRS – Physiological: Excess Cold; Excess Heat
Air Infiltration	HHRS – Physiological: Excess Cold; Excess Heat; Carbon Monoxide; Volatile organic compounds
Thermal Bridge	HHRS – Physiological: Excess Cold; Excess Heat
R-value or U-value	HHRS – Physiological: Excess Cold; Excess Heat

2.4.4 Factors Affecting Validity of Infrared Thermography Results

Infrared thermography is a sophisticated technology which can be easily used incorrectly. There are several major factors that could impact the validity of infrared thermography results. First, environmental conditions including temperature differences between indoor and outdoor environment, wind speed, high dew or rainy day, time of day, and reflection, can impact infrared thermography results significantly. Table 13 listed detailed effects of various environmental conditions on the validity of infrared thermography inspection results.

Table 13: Environmental conditions affecting the validity of infrared thermography

Environmental Conditions	Effects on the Validity of Infrared Thermography Inspection Results
Temperature Differences between indoor and outdoor air and Season	Heat conducted through wall is related with the temperature differences between external and internal wall. When indoor and outdoor temperature difference is limited, defects area could not get enough temperature differences to stand out from surrounding normal area, and finally lead to a doubtful and inaccurate building diagnose result. To keep the indoor environment in a comfort zone, the indoor temperature will always stay around 75 F. As a result of this, a high temperature differences between indoor and outdoor air will only occur during summer (high outdoor temperature) and winter (low outdoor temperature), which make summer and winter two best time for infrared-based building inspection.
Wind Speed	Convective heat losses depend on the wind velocity. High winds will

	enhance heat transfer from the surface and higher convective heat losses can reduce the surface temperature.
High dew or rainy day	Water or ice on the surface of the envelope can mitigate temperature variation and cause false reflection, so high dew, rain and snow should be avoided during building inspection.
Time of day	Defects beneath the surface usually have a different conduction rate and react differently with surrounding area during the heating (morning) and cooling (night) process. Usually, early morning inspections are best for building inspection because too much sunlight may wreak havoc and make feat refection on the building fa çade. Also, the inspection during morning can assured the adequate temperature difference between indoor and outdoor.
Reflection	Refection from heat or cold source could create a false refection in the infrared imaging.

It can be noted that the temperature difference between indoor and outdoor is another important factor to consider as it is the power pushing heat flow through a building's envelope (wall or ceiling). Low Delta-temperatures lead to indiscernible thermal patterns. In general, when there is larger temperature difference between indoor and outdoor environments, more accurate thermography inspection results can be achieved. Due to this reason, summer and winter are particularly suitable for infrared-based building inspection. Wind effects can also influence the thermal imaging results by enhancing the heat transfer from the surface which leads to high convective heat losses and reduces the temperature of structure surfaces. Rains and snows are two common weather conditions that may occur during summer and winter. They can benefit or impede infrared imaging based inspection. For example, infrared thermography should not be applied immediately before or during rainy weather condition, while rain occurs one or two days before the inspection is beneficial. Water migration in many buildings and roof leaks have short resident times, therefore, there is always an optimum time window to detect leaks and moisture problems in building envelops.

One of the most insidious limitations with infrared thermography is false reflection. Heat signatures captured by an infrared camera could be the reflection of a warmer adjacent building, surround trees or even the colder atmosphere. The reflections from these objects make it difficult for operators to discern if the thermal pattern is from true surface reflection or it is just a false reflection. This makes it challenging to locate true defects if they are masked by false reflection.

2.5 Conclusions

Extensive research effort has been devoted to using infrared thermography for detecting defects and hazards in building systems. As a non-destructive and non-intrusive inspection technology, it offers a compelling method to measure an array of hazard parameters related to high performance building system and healthy homes. The potential of infrared thermography methods for detecting home hazardous conditions has been further amplified with the rapid development of data collection methods. The general outcomes from these improvements are more data collected in less time, richer information, and automation in data interpretation. Challenges remain in using the technology in an optimum setting and in data interpretation. Future research on these directions would greatly benefit wider adoption of infrared thermography technology, which will greatly reduce the cost of improving the performance (energy efficiency and healthy homes) of a large number of existing building stocks.

Chapter 3

Spatially Resolved Infrared Imaging for Building Performance Evaluation

3.1 Introduction

Understanding the interior workings of buildings has become an increasingly important research topic as a growing population of people is living in urbanized environments. Building deficiencies not only affect the energy performance but also the occupants and residents' comfort in a life-cycle. Despite the increasing attention has been paid to building performance, the conventional process of building inspection and energy audit are time-consuming and requires certain level of expertise and experience.

With the development of thermal infrared technologies, Infrared Thermography has been increasingly used as a valuable tool for quick inspecting and performing non-destructive testing for building elements, detecting where the building deficiencies are and monitoring how energy is leaking from envelope. Problems that can be identified in a building through thermal infrared imaging include cracks, lack of insulation, damage door and window seals, and the building-up of moisture (Vidas and Moghadam 2013). Successful inspection may lead to addressing these issues, along with achieving refinements in building design, which will ultimately improve building environment and energy performance. However, due to the characteristic of 2D thermal imaginings, the thermal data collected during building inspection are usually lack information in geometry, location and orientation of objects and difficult to estimate precise dimension and location the defects. Once combined with LiDAR data, 3D thermal model can be generated and harnesses the advantages of both 2D thermal imaging and 3D point cloud. In a 3D thermal model not only the building thermal defects can be visually detected and precisely located, the R-value of the building envelope and heat losses can also be quantified give the availability of surface measurements.

The proposed research explored the effectiveness of integration of infrared thermography and spatial sensing methods for intelligent building hazard detection and evaluation. The proposed research methodology involves several major components including design of data collection protocols, data fusion and intelligent extraction of building hazard related attributes, and field validation of proposed methods. The study was validated by surveying the health and safety performance of two multi-family building in a densely populated city in the Northeastern US., using this new appraisal method that integrate infrared thermography with 3D point cloud data. The efficacy of integrated laser scanning and thermal imaging to determine housing-related health and structure-related issue was assessed. It is important to note that the research results reported in this study is part of a larger research effort aimed at developing quantitative understanding on the correlation between the defects inside the residential building and how they impact the residents' health and comfort in a systemic way.

The paper starts with a review of relevant work followed by description of research methodology used in this research. The research methodology includes design of data collection protocols and fusion of thermographic and LiDAR data for intelligent hazard data extraction. Field validations using two multi-story multi-family buildings are then described. Finally, the paper presents result and discussion.

3.2 Related Work

Infrared thermography detects and provides visual displays of the amount of infrared energy emitted, transmitted, and reflected by an object. It has been used as a useful tool for many professions since variations in emitted energy in the infrared spectrum provide information concerning surface temperature and thermal properties of objects. In particular, infrared thermography is well suited for detecting temperature abnormality caused by change of material thermal property or the presence of latent moisture (Table. 14). For most common applications, the useful portion of the infrared spectrum lies in the 0.72 to 12 μm. For ordinary objects that operate at room temperature, long wavelengths will be of interest to observe since high temperature bodies emit more in the short wavelengths (Maldague 2002).

As discussed in the last chapter, infrared thermography has been widely used for building inspection because of its potential for contributing to energy efficiency, occupant health protection, occupant comfort, and green building development. Specifically, infrared thermography has been successfully used for building material evaluation, detecting construction defects such as air infiltration, missing insulation and thermal bridges, moisture detection and mapping in building structures, building energy diagnostics ,and pest detection in housing structures (Table 14). The advantage of infrared thermography over other building inspection methods is mostly related to its ability of offering noncontact, non-destructive, and wide area detection of subsurface defects which can be caused by moisture intrusion, construction quality, and pest.

Table 14 : Application of Infrared Thermography for Building Diagnosis

Applications for Infrared Thermography	Related Studies
building material evaluation	Titman 2001; Barreira and Freitas 2007; Meola 2007; Wyckhuyse and Maldague 2001; Forster 2007; Maierhofer et al. 2003
Detect construction defects	Balaras and Argiriou 2002; Tony Colantonio 2007; Kalamees et al. 2008; Bianchi et al. 2014; Wrobel and Kisilewcz 2008; Grinzato et al. 1998; Li et al. 2000
moisture detection	Colantonio ; Kominsky et al. 2007; Lerma et al. 2011; Gayo and De Frutos 1997; Grinzato et al. 1998; Jenkins et al. 1982;

	Ludwig et al. 2004; Moropoulou et al. 2002; Tobiasson and Korhonen 1985; Wild et al. 1998; Kominsky et al. 2007;
building energy diagnostics	Vavilov 2010; Ham and Golparvar-Fard 2014; Fokaides and Kalogirou 2011;
pest detection	Bruni 2004; Grossman 2005a; Grossman 2005b

The effectiveness of infrared thermography can be further improved if reliable metrics of measuring the extent of various defects can be developed as they allow quantitative assessment of building performance or the quality of building construction. This has motivated extensive studies on developing and validating different metrics that can be derived from infrared thermography data (Table 15). For example, Temperature Factor (TF) has been proposed and used to measure the extent of thermal bridge (Heinrich and Dahlem 2000; Bianchi et al. 2014) and air infiltration (Balaras and Argiriou 2002; Kalamees 2007; Heinrich and Dahlem 2000). Use of infrared thermography scanning to estimate R or U value of building envelops is another intriguing application and has attracted considerable attentions (Haralambopoulos and Paparsenos 1998; Fokaides and Kalogirou 2011; Dall'o' et al. 2013; Nardi et al. 2014; Albatici and Tonelli 2010; Ham and Golparvar-Fard 2014 and 2015). Last but not the least, moisture level has been used to diagnose moisture issues in buildings (Balaras and Argiriou 2002; Kominsky et al. 2007), and insulation level has been proposed to evaluate missing insulation problems (Balaras and Argiriou 2002).

Of particular interest is that the recently revised HERS standard (HERS 2006) also provides detailed procedures for assessing insulation installation quality. According to the standard, missing insulation can be classified into three grades including Grade I (Almost no gaps), Grade II (Up to 2% missing), and Grade III (2%-5% missing). The Grade III for missing insulation is designed as no more than 5% of the surface area of insulation missing is acceptable. For an installation that is worse than Grade III, the procedure specifies that the inspector must measure the insulated areas separately from the uninsulated areas and input them separately in software (Harley 2005). In year 2010, RESNET adopted the guidelines for thermographic inspections of buildings and published the standard "RESNET Interim Guidelines for Thermographic Inspection of Buildings" (RESNET 2010). This standard provides guidance on the use of infrared thermography for the inspection. In this standard, the definition of each Grade is slightly adjusted to apply for the use of infrared thermography.

Despite the recent advance in standardizing infrared thermography based building inspection, the effectiveness of infrared thermography still relies heavily on correct and rapid interpretation of visual displays of thermal images. Correct and rapid interpretation of thermal images requires considerable experience and can be assisted by a systems view of building structures. For many building professionals, infrared thermography interpretation is a very subjective process, and there are very few, if not none, software tools for automated interpretation of thermal images. Furthermore, interpretation of thermal images often happens in a context with limited geometric information on the building being investigated. As a result, spatial patterns of surface temperature anomaly cannot be easily visualized to detect interrelated building system defects. In many cases, accurate estimation of building defects and hazards often requires multiple trips to carry out geometric survey of susceptible building areas

At the same time, reality capture technologies such as RGB-D cameras, Structure from Motion (SFM), and laser scanners, have become main stream practices in interior and exterior modeling. Light Detection and Ranging (LiDAR) as a relatively new class of survey instrument has been increasingly used for providing as-built and inventory data in building inspections. In principle, 3D thermography data can be generated once these reality capture technologies are combined with infrared thermography.

Though Infrared thermography analysis has become one of the most reliable tools for building defects detection, the current IR inspection and assessment are primarily qualitative and mainly rely on the energy auditor's experience and knowledge. The identification and interpretation of the hot spots or cold spots of numbers of unordered thermal images are usually time-consuming and labor-intensive. Not to mention, without a proper benchmark or degree to judge the quality of a building's performance, the auditor's subjective idea only may lead to an inadequate refection of a building's structure and energy performance. With reasons above, there is a need of finding a way to level the condition of the building structure with all different types of detects (e.g. moisture issue, insulation issue, thermal bridge, air leakage, R/U-value) and building's basic information gathered together for an integral building performance estimation. Also, there is less research about the correlation between the defects inside the residential building and how they impact the residents' health and comfort in a systemic way. Starting from pervious researches, this paper concerned using statistical methods to get a better understanding of the effect of housing-related health and safety hazards on occupants' health and the relationship between building condition and human comfort.

3.3 Research Methodology

The proposed research explored the effectiveness of integration of infrared thermography and spatial sensing methods for intelligent building hazard detection and evaluation. The proposed research methodology involves several major components including design of data collection protocols, data fusion and intelligent extraction of building hazard related attributes, and field validation of proposed methods. It is important to note that the research results reported in this study is part of a larger research effort aimed at developing quantitative understanding on the correlation between the defects inside the residential building and how they impact the residents' health and comfort in a systemic way (Figure 12).

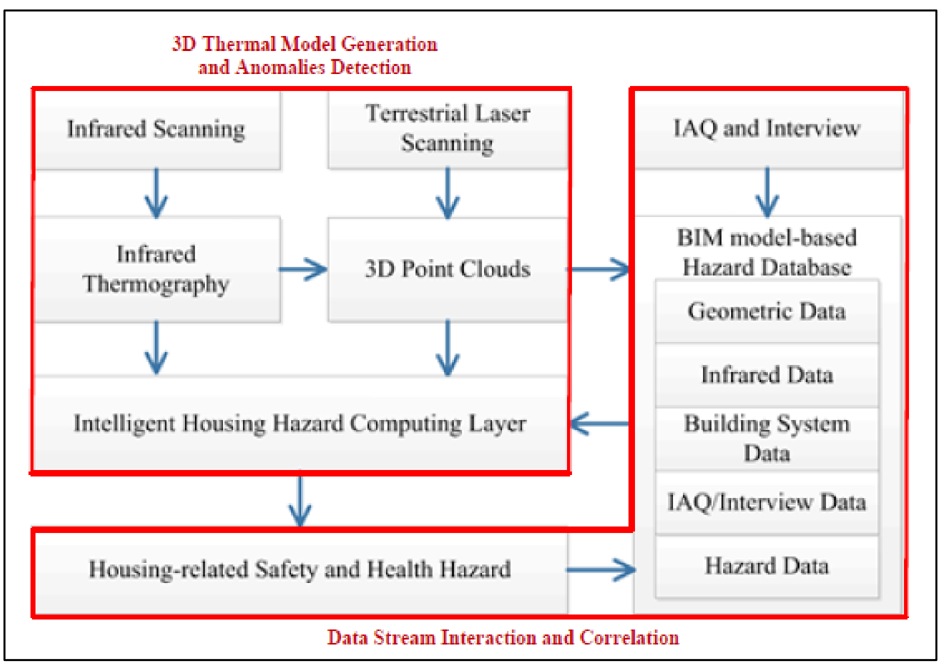


Figure 12: An integrated approach for housing-related hazard detection and management

3.3.1 Design of Data Collection Protocols

To understand how infrared thermography and its variants can be used for detecting building hazards, in particular those impacting occupants' health, it is imperative to draw connections between what can be measured from infrared thermography and what are considered as hazards to healthy homes. As a century-old concept, "Healthy Homes", promotes a safe, decent, and sanitary housing for preventing disease and injury, has got increasing attention nationally. HUD's Healthy Home Rating System (HHRS) was developed based upon the successful Housing Health and Safety Rating System (HHSRS), which can address key issues affecting health and safety due to conditions in the home, provides analysis of how hazardous a dwelling is and provides evidence and statistical information to assist assessors in making judgments. The HHRS provides a method of grading the severity of threats to health and safety in any dwelling, from house, self-contained flat/apartment, non-self-contained flat/apartment, a room rented within a dwelling or house, to a room in a university hall or similar residential building and the means of access and shared or common rooms and facilities. There are 29 summarized hazards listed in the HHRS Hazards Summary Chart across four categories including Physiological, Psychological, Infection, and Safety (Table 15) (HUD, The Healthy Homes Program Guidance Manual 2012).

Table 15: Healthy Home Rating System (HHRS) – Categorization of 29 Hazards

Physiological	Psychological	Infection	Safety
1. Dampness & Mold 2. Excess Cold	11. Crowding and Space 12. Entry by	15. Domestic Hygiene, Pests, and	19. Falls in bath etc. 20. Falls on the level 21. Falls on stairs etc.

3. Excess Heat 4. Asbestos and manmade fibers 5. Biocides 6. Carbon Monoxide 7. Lead-based paint 8. Radiation 9. Un-combusted fuel 10. Volatile organic compounds	Intruders 13. Lighting 14. Noise	Refuse 16. Food Safety 17. Personal Hygiene 18. Water Supply	22. Falls from windows etc. 23. Electrical hazards 24. Fire hazards 25. Hot surfaces etc. 26. Collision/Entrapment 27. Ergonomics 28. Explosions 29. Structural collapse

A close examination of the above table and the capabilities of infrared thermography as reviewed in the Relevant Work section suggest several connections. These connections are summarized in Table 16. These detectable defects are quantified using metrics proposed by previous studies and building rating standards. In summary, a list of data to be collected or computed is provided in Table 17. We assume the subjects of interest in this research are apartments in multi-story buildings.

Table 16: Connections between defects in building envelops and home hazards

Detectable Building Defects	Connection to Home Hazards
Moisture Issue	HHRS – Physiological: Dampness & Mold; HHRS – Infection: Domestic Hygiene, Pests, and Refuse
Thermal Insulation Problem	HHRS – Physiological: Excess Cold; Excess Heat
Air Infiltration	HHRS – Physiological: Excess Cold; Excess Heat; Carbon Monoxide; Volatile organic compounds
Thermal Bridge	HHRS – Physiological: Excess Cold; Excess Heat
R-value or U-value	HHRS – Physiological: Excess Cold; Excess Heat

Table 17: Data attribute list

Attribute Type	Variables	Description	Value/ Unit
Apartment Location Information	Floor	The floor number of the apartment unit and the total floor number	(Number 1)/(Number 2) Number 1: apartment floor number Number 2: total floor number
	Corner	Describe the location of the apartment unit	1: in the corner 0: other

	Inner Garden	Describe the location of the apartment unit	1: face the inner garden 0: other
Thermal Comfort	Real-time indoor air temperature	Describe the average indoor air temperature taken from moisture meter during data collection	Unit: ℉
	Real-time indoor air relative humidity	Describe the average indoor air relative humidity taken from moisture meter during data collection	Unit: %
	Real-time thermal comfort level	Real-time thermal comfort level calculated from ASHRAE Comfort Zone	1: for in the cold area of comfort zone (Left side of the Comfort Zone) 2: for in the comfort zone (Inside of the Comfort Zone) 3: for in the hot area of comfort zone (Right side of the comfort Zone)
	Dew Point	Dew point temperature estimated from real-time	Unit: ℉

		average temperature and relative humidity	
Thermal Infrared and Scan Data	Temperature Factor - Thermal Bridge	The temperature factor of thermal bridge area.	Unit: NA Higher value stands for better condition
	Temperature Factor- Air Leakage	The temperature factor of air leakage area	Unit: NA Higher value stands for better condition
	Missing or poor insulation area	Describe the area missing or poor insulation in square feet	Unit: Square Feet
	Missing or poor insulation percentage	Describe the percentage of the area missing or poor insulation out of the whole exterior wall of the apartment.	Unit: %
	Insulation Grading	The insulation grading calculated based on the Insulation Grading Standard designed by RESNET.	Insulation Grading Standards designed by RESNET Grade I: not infrared detectable anomalies; Grade II: insulation installed with anomalies found to be between 0.5 % and 2%

			for all inspected walls Grade III: An insulation installation having between 2% to 5% anomalies found for all inspected walls Worse than Grade III: The condition that insulation installation having more than 5% of the anomalies found for all the inspected walls
	Insulation Level	Describe the insulation level of the apartment unit when the temperature differences do not meet the requirement for RESNET Standard.	1: good condition 2: fair condition 3: poor condition
	Average R-value	The minimum R-value of the exterior wall area in one room in the apartment unit	Unit: W/m^2K
	Hot Water Riser poor insulated	Whether or not the apartment has hot water riser poor	1: Yes 0: No

		insulated in the apartment	

In Table 17 the temperature factor $f_{R_{si}}$ at the internal surface shows the relation of the total thermal resistance of the building envelope (R_T, $(\mathrm{m}^2 \cdot \mathrm{K})/\mathrm{W}$) to the thermal resistance of the building envelope without the internal surface resistance (R_{si}, $(\mathrm{m}^2 \cdot \mathrm{K})/\mathrm{W}$) and can be calculated with measured internal surface temperature ($T_{s,in}$, ℃), indoor temperature (T_{in}, ℃) and outdoor temperature (T_{out}, ℃) according to following Equation 8 (Hugo 2012, Kalamees 2007)

$$\frac{R_T - R_{si}}{R_T} = f_{R_{si}} = \frac{T_{s,in} - T_{out}}{T_{in} - T_{out}} \qquad (8)$$

For the temperature factor, several limit values or guidelines have been set. The following table 18 lists the guidelines for temperature factor for thermal bridge on wall base on the Finnish instructions regarding housing health (Asumisterveysohje 2003).

Table 18: Guidelines for the temperature factor for thermal bridge on wall

Temperature Factor Range	Description
$f_{R_{si}}$<0.61	Includes healthy risks or hazards and should be repaired
$f_{R_{si}}$ 0.61 ~ 0.64	Possibility for health hazards or structure risks, the details/structure must be checked and repairing necessity should be classified
$f_{R_{si}}$ 0.65 ~0.69	Includes obvious hydrothermal defects or faults but fulfils the requirements of the housing health

$f_{R_{si}}$ 0.70 ~0.74	Fulfils of the requirements of the good level, no risks in dwellings with low occupancy
$f_{R_{si}}$ 0.75 ~0.80	Includes some risk in dwellings with high occupancy and low occupancy
$f_{R_{si}}$ over 0.81	Tolerable level

The R-value in Table 18 is estimated using Eq. (9). Its principle is that the overall heat transfer (Q) in the building environment can be described as the combination of thermal convection and radiation.

$$R = \frac{|T_{air,in} - T_{air,out}|}{\alpha_{convective} \times |T_{air,in} - T_{wall,in}| + \varepsilon \times \sigma \times |T_{wall,in}{}^4 - T_{reflect,in}{}^4|} \quad (9)$$

where ε is the surface integral emissivity, σ is the Stefan-Boltzman constant$5.67 \times 10^{-8}\ W/m^2K^4$, $T_{wall,in}$ is the surface temperature of inside surface of the exterior wall and $T_{reflect,in}$ is the reflected temperature.

3.3.2 Fusion of thermographic and LiDAR data and Intelligent Hazard Data Extraction

Figure 13 shows the detailed workflow for producing 3D thermographic data. Table 19 provides further explanation of the steps shown in Figure 13.

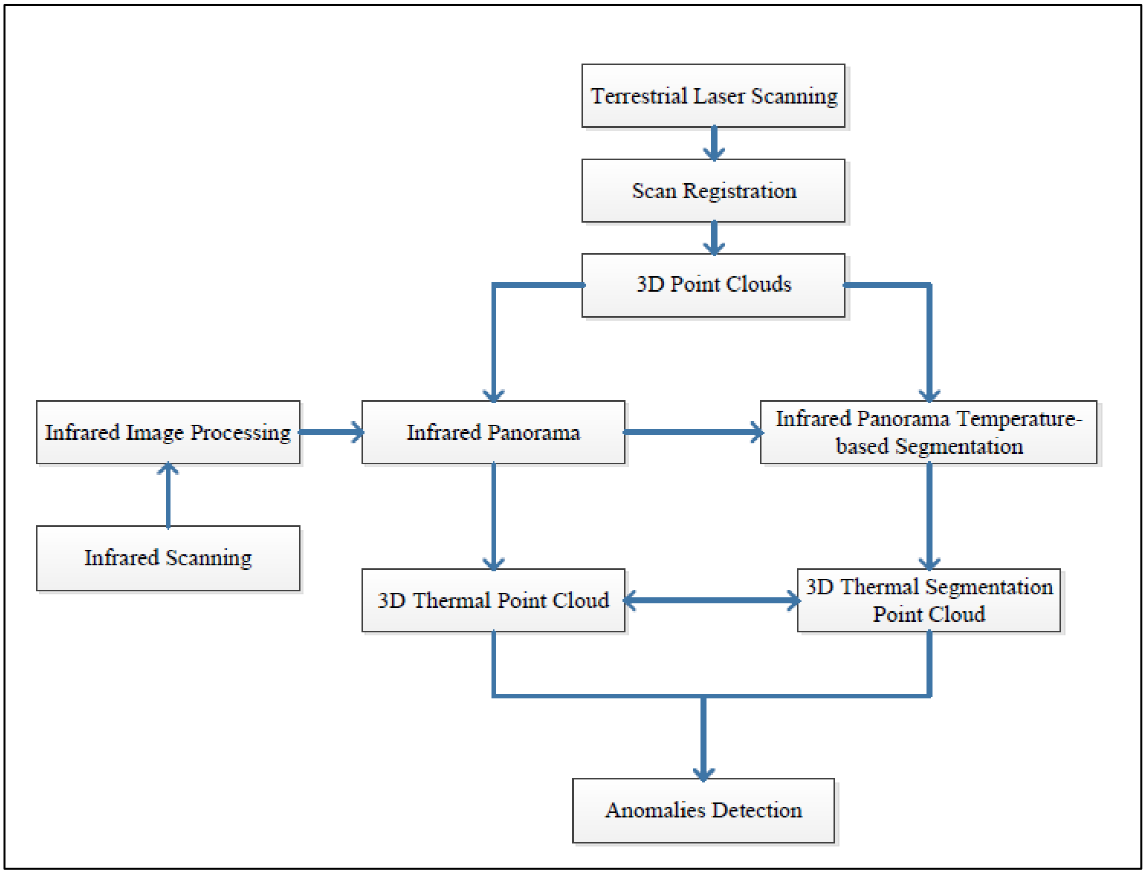


Figure 13: 3D thermal model generation and anomalies detection

Table 19: 3D thermal model generation process and description

Steps	Description
Infrared Scanning	Infrared data (images or videos) collection through infrared camera.
Terrestrial Laser Scanning	Collect raw terrestrial laser scans through laser scanner.
Infrared Image Processing	Read raw infrared images with FLIR SDK and transfer images to temperature matrix for temperature rescale and color palette modification.
Terrestrial Laser Scan	Register raw terrestrial laser scans into one point cloud file.

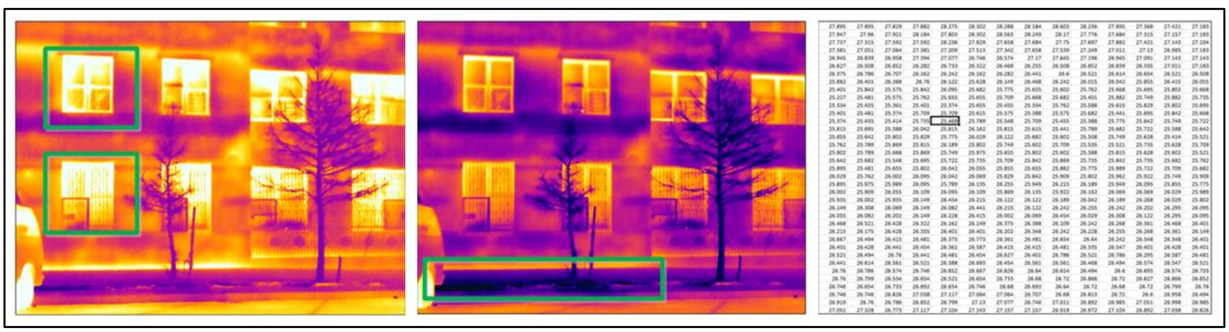
Registration	
Output 3D Point Clouds	Transfer the registration result to 3d point clouds.
Infrared Image Panorama	Automatic infrared images stitching for the infrared images with overlaps.
Infrared Panorama Temperature-based Segmentation	Automatic infrared panorama segmentation to segment areas with different temperature into pieces.
Infrared Panorama Projection	Project infrared panorama on the point cloud to generate a 3D point cloud with temperature information.
Infrared Panorama Segmentation Projection	Project infrared segmentation result on the point cloud to generate a 3D point cloud with segmentation information.

Infrared Scanning: In this research, the collected infrared data are images and videos. Infrared images taken through FLIR infrared camera are special .jpg format images that not only have color information but also temperature information for each point in the image. There are two types of videos that can be collected by an infrared camera: (1) color only video (2) video with pixel temperature information.

Terrestrial Laser Scanning: We used the FARO laser scanners for raw data collection. To provide sufficient 3d information of the building, one or more scans were collected per room (Figure 14).

Figure 14: 3D view of scanned living room and bathroom

Infrared Image Processing: This step involves converting infrared image data into data matrix that preserve temperature information (Figure 15).



(a) (b) (c)

Figure 15: Same infrared image with different temperature scale and its temperature in matrix

(a: 23.2 ℉ ~ 40.4 ℉; b: 31.8 ℉ ~ 40.87 ℉)

Terrestrial Laser Scan Registration and output 3D point clouds: In this step, scan data are registered and converted into a common point cloud format.

Infrared Image Stitching (Panorama): This step involves stitching infrared images into a panoramic image that can later be used to project to point cloud data. The steps for RGB image stitching include: (1) Feature Detection: identify image features (2) Feature Description: extract feature descriptor for each feature (3) Feature Matching: find candidate matches between features (4) Feature Correspondence: find consistent set of (inlier) correspondences between features.

RGB image stitching usually have the problem with color correction and matching (Tian et al. 2002, Doutre and Nasiopoulos 2009, Xiong and Pulli 2009), while, infrared images do not have this problem because the temperature of the same location usually stays constant during the inspection. Infrared images of the same location usually can be easily adjusted to the same color and can have a good match with each other even without color correction and matching. However, as shown in the infrared image processing step, infrared images may loss texture and pattern information with different temperature scales and temperature palettes. This could lead to the difficulty to detect image features useful for image stitching (Figure 16).

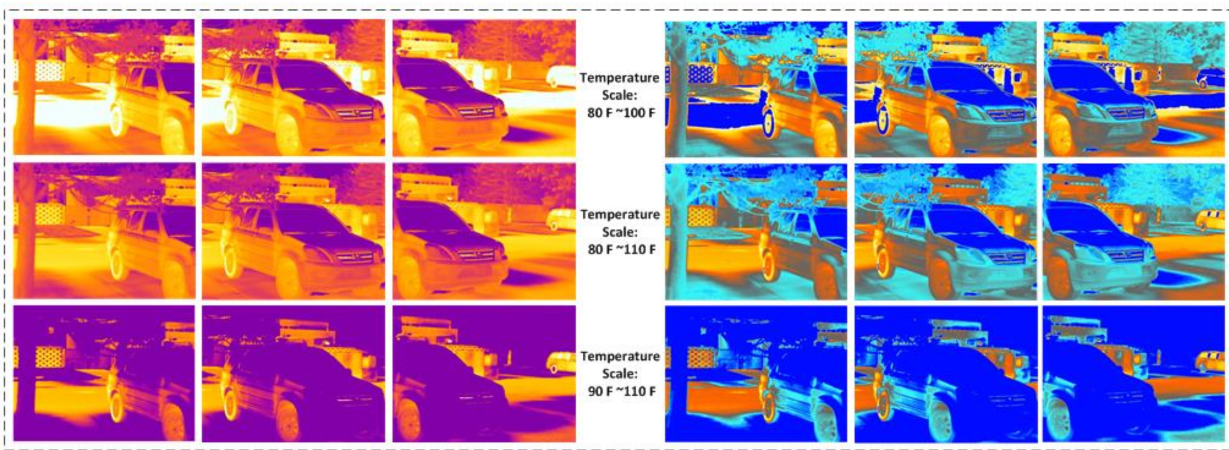


Figure 16: The effect of temperature scale and color palette on infrared images

Figure 17: Feature points detected in three infrared images

To address this issue, our approach tries different temperature scales and finds the best result in terms of number of feature points, matched points, and inliers. Once the transformation between images with highest inliers was calculated, these images can be combined to form a panoramic image which can be transferred to any color scale and color palette with a fixed transformation (Figure 17).

Figure 18: Matched SURF points, including outliers

Table 20: The effect of temperature scale on the number of inliner points

	Temperature Scale 80 ℉ ~100 ℉	Temperature Scale 80 ℉ ~110 ℉	Temperature Scale 90 ℉ ~110 ℉
Inlier Points between First and Second Image	30	34	36
Inlier Points between Second and Third Image	77	48	51

The same approach can also be applied to indoor infrared images although interior infrared images usually have fewer feature points and inlier points. Figure 19 shows an example of combining several interior infrared images.

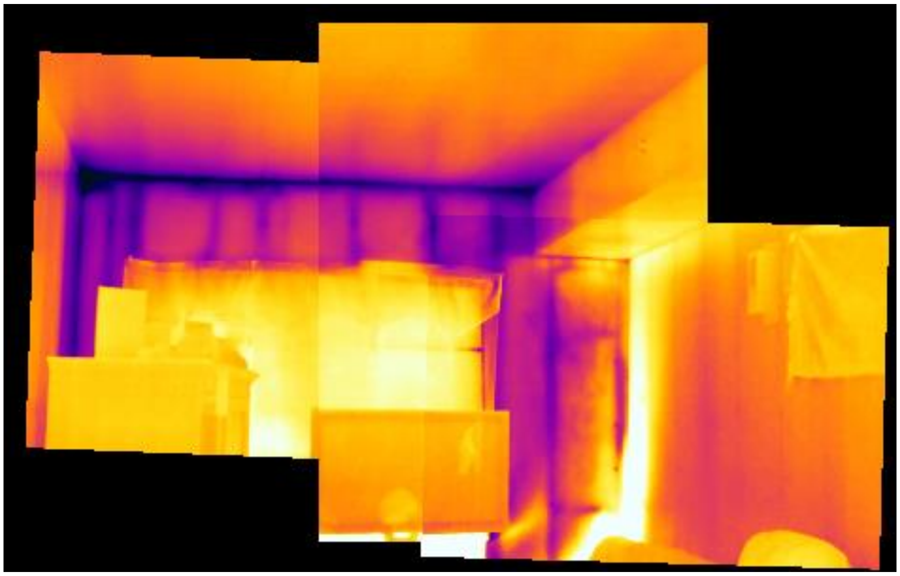


Figure 19: Automatic indoor infrared image stitching result

Infrared Temperature-based Segmentation: In this step, the result of temperature based segmentation and threshold based segmentation is compared (Figure 20 and Figure 21). Although several recent studies have used threshold methods to locate cold and hot spots in infrared images (Vidas et al. 2013, Ham and Golparvar-Fard 2014), temperature based segmentation can isolate the areas with different temperature easily and lead to a better result. In this research, we applied the temperature based segmentation to both single infrared image and panoramic images. The results are shown in Figure 22.

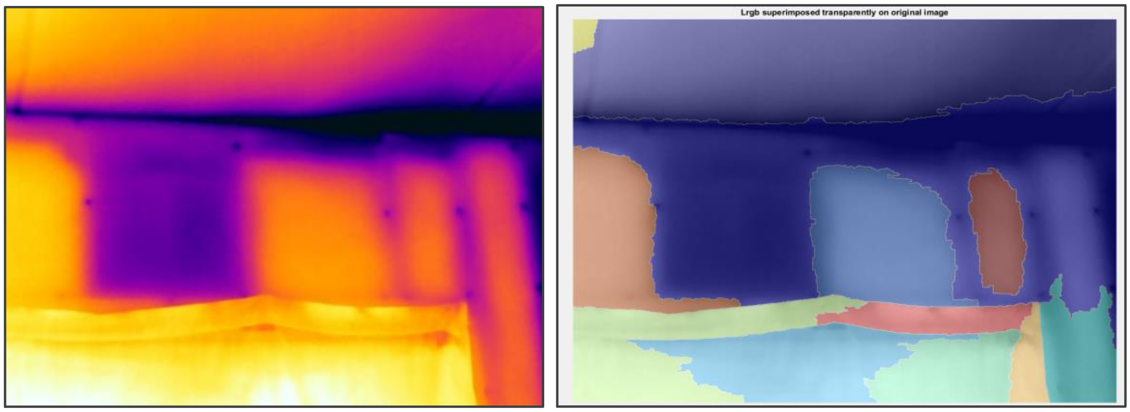


Figure 20: Infrared image and segmentation result

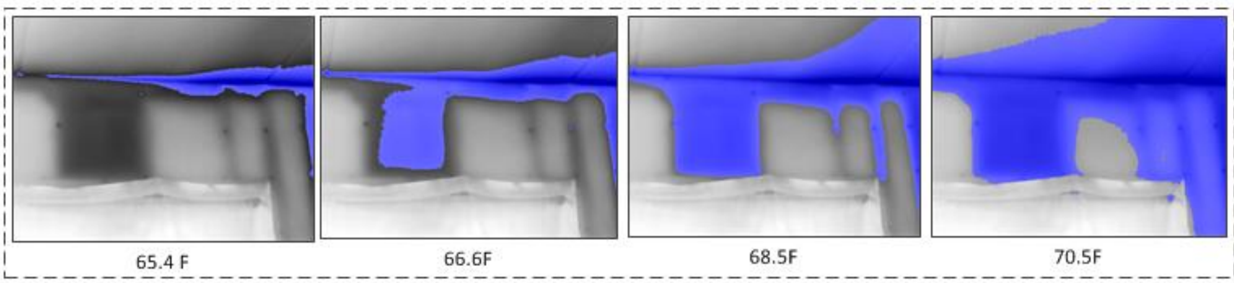


Figure 21: Infrared images with cold alarm

(blue area means temperature lower than threshold value)

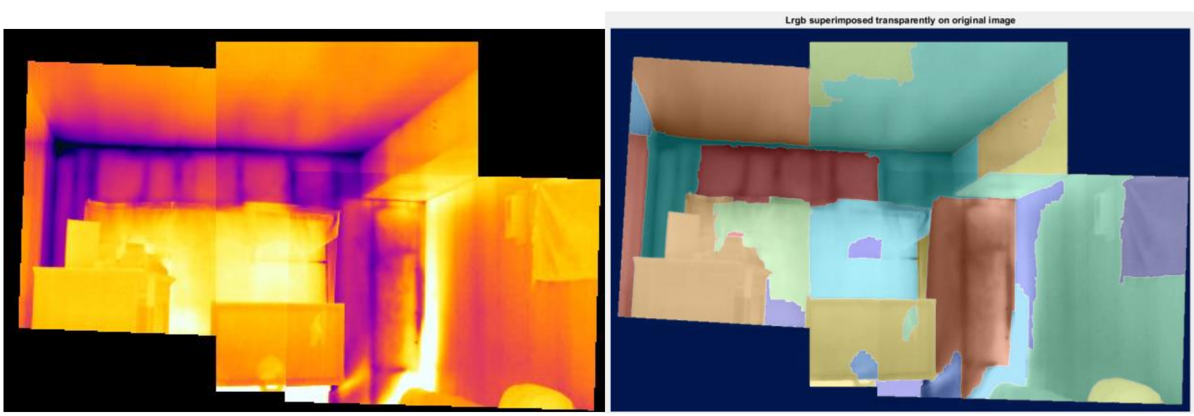


Figure 22: Indoor infrared image stitching and segmentation results

Infrared and Infrared Segmentation Project to 3D Point Cloud: In this step, infrared images and their temperature segmentation results are projected to the 3D point cloud. The principle behind the projection is to identify common points in both infrared images and point cloud data and compute the transformation between infrared images and point cloud data. Figures 23 and 24 show 3D thermal models of one building and an apartment as the result of data projection. Furthermore, if the infrared images are already segmented, this projection will lead to quick quantification of the size of different temperature areas (Figure 25).

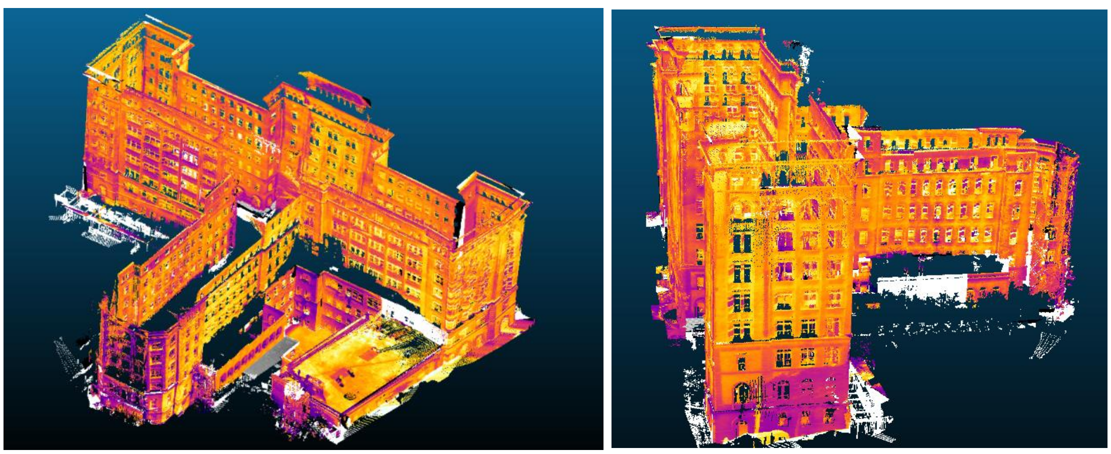


Figure 23: 3D thermal model of building exterior area

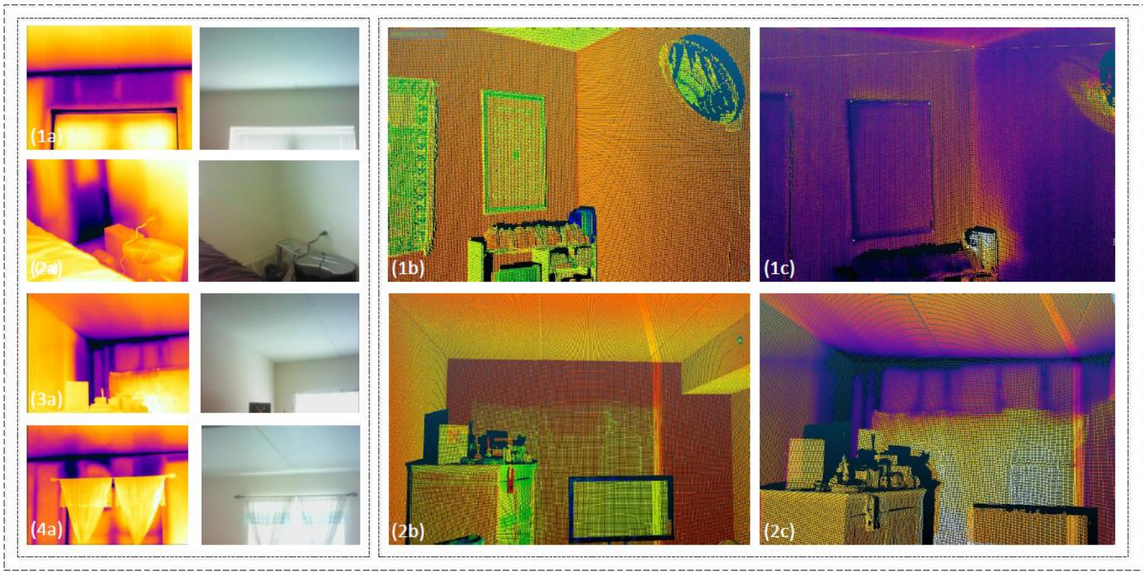


Figure 24: Raw data and 3D thermal point cloud

(a)Infrared thermography and digital images, (b) LiDAR point cloud, (c) 3D thermal point cloud

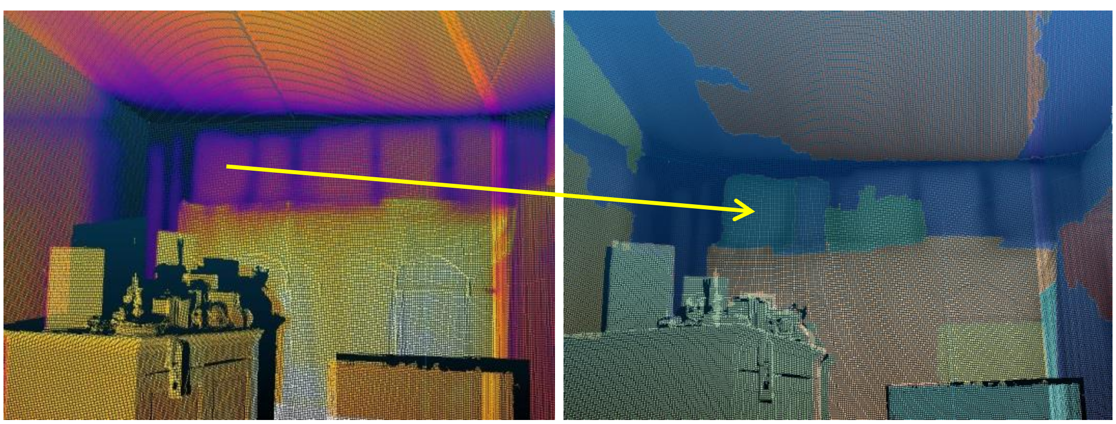


Figure 25: 3D thermal model and their paired 3D temperature-segmentation model

Point Cloud Segmentation: The 3D thermography data analysis process can be further facilitated by conducting segmentation of indoor scan data. The purpose is to divide scan data into subsets corresponding to different structural elements. One segmentation method that can be utilized is ransac based segmentation method. Figure 26 shows the segmentation results for one sample living room. It can be seen that all the structure elements and furniture are clearly segmented and marked out with different color.

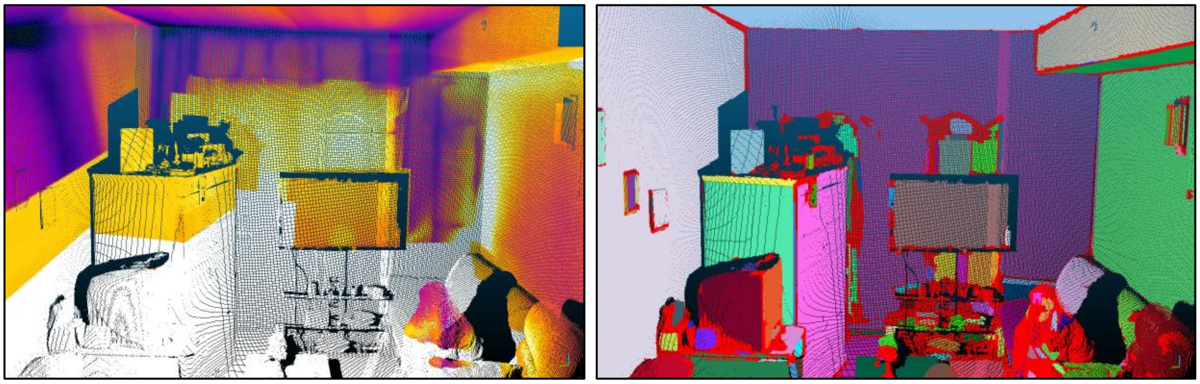


Figure 26: 3D thermal model and segmented 3D point cloud

Based on the segmented 3D thermal model, all the attributes that are relevant to building performances can be calculated and estimated. Table 21 lists all the data attributes collected from infrared data and 3D thermal data in this research.

Table 21: List of data attributes collected from 3D infrared thermographic data

Attribute Type	Variables	Description	Attribute Collection
Apartment Location Information	Floor	The floor number of the apartment unit and the total floor number of the building.	The floor number is collected base on the room number. For example, apartment 6E is located on 6^{th} floor. The total floor number can be used to know if one apartment is located on the top floor of the building.

	Corner	Describe the location of the apartment unit	This information is collected from floor chart.
	Orientation	Describe the location of the apartment unit	This information is collected from floor chart.
Thermal Comfort	Real-time indoor air temperature	Describe the average indoor air temperature taken from moisture meter during data collection	In each apartment, temperature data were collected by room from moisture meter during inspection. (Usually 8-20 values per apartment.)
	Real-time indoor air relative humidity	Describe the average indoor air relative humidity taken from moisture meter during data collection	Relative humidity data is collected from moisture meter by room during inspection. (Usually 8-20 values per apartment.)
	Real-time thermal comfort level	Real-time thermal comfort level calculated from ASHRAE Comfort Zone	Real-time thermal comfort level calculated from ASHRAE Comfort Zone base on the indoor temperature and relative humidity data. When the value is locate in the comfort zone chart, the apartment will be marked with “Comfort”. When the value is locate in the left side of comfort zone, the apartment will be marked with

			"Cold". Right side will be marked as "Hot".
	Dew Point	Dew point temperature estimated from real-time average temperature and relative humidity	Dew point temperature estimated from real-time average indoor temperature and relative humidity. Dew point value can be used to locate potential moisture issue.
Thermal Infrared and Scan Data	Temperature Factor-Thermal Bridge	The temperature factor for thermal bridge area	Measure the temperature factor for thermal bridge base on infrared data.
	Temperature Factor- Air Leakage	The temperature factor for air leakage area	Measure the temperature factor for air leakage area base on infrared data.
	Missing or poor insulation area	Describe the area missing or poor insulation in square feet	Measure the area missing or poor insulation in square feet base on the 3d thermal data.
	Missing or poor insulation percentage	Describe the percentage of the area missing or poor insulation out of the whole exterior wall	Calculate the percentage of the area missing or poor insulation out of the whole exterior wall base on 3d thermal data.

	Insulation Level	Describe the insulation level of the apartment unit	Describe the insulation level of the apartment unit.
	Average R-value	The average R-value of the exterior wall area in the apartment unit	Measure the average R-value of the exterior wall area in the apartment unit base on 3d thermal data and real-time environmental data.
	Hot Water Riser Overheating	Whether or not the apartment has hot water riser detectable by infrared camera.	Whether or not the apartment have hot water riser that detectable by infrared camera with temperature difference over 5 F with surrounding wall.

3.4 Field Validation

The proposed methods in this study are validated with two multi-family apartment buildings in Northeastern US. Building 1 was a historic building that transformed from an abandoned hospital built in 1926. Building 2 is one of the largest multi-family, Energy Star certified building. The building 2 was opened in 2009.

3.4.1 Data Collection Protocols

In this research, one infrared camera (FLIR T650sc) and one digital camera were used for data collection. The specification of T650sc camera is shown in the Table 22. The terrestrial laser scanner used to provide 3D data is a Faro Focus 3D scanner. The specification of the scanner is listed in Table 23.

Table 22: Specification for FLIR T650sc

Characteristics	Specifications
Thermal Imaging	
Performance	
Field of View/min. focus	25 °x 19 °/ 0.25m
distance	0.68 mrad
Spatial Resolution (IFOV)	<20 mK @ 30 ℃
Thermal Sensitivity	30 Hz
Image Frequency	Continuous, one shot or manual
Focus	Focal Plane Array (FPA), Uncooled microbolometer 640x480
Detector Type	pixels
Spectral Range	7.5 to 14 µm

Measurement Temperature Range Accuracy Measurement Analysis	 -40 ℃ to +150 ℃ +100 ℃ to +650 ℃ +300 ℃ to +2,000 ℃ ±1 ℃ or ±1% of reading Area; Line Profile; Automatic hot/cold detection; Isotherm;
Image Storage Type File Formats	 IR/visual images; simultaneous storage of visual and IR images Standard JPEG - including measurement data on memory card
Battery System	Lithium-Ion (field replaceable)
Environmental Specifications Operating Temperature Range Storage Temperature Range	 -15 to +50 ℃ -40 ℃ to +70 ℃
Data Communication Interfaces	USB-mini, USB-A, Bluetooth, Wi-Fi, Digital Video Output

Table 23: The specification of Faro Focus 3D Scanner

Characteristics	Specifications
Ranging Unit Unambiguity interval Range Focus 3DS 120	 153.29 m (503.57ft) 0.6m- 120m indoor or outdoor with low ambient light and

	normal incident to a 90% reflective surface
Range Focus 3dS 20	0.6m – 20m at normal incidence on >10% matte reflective surface
Measurement Speed(Pts/Sec)	122,000/244,000/488,000/976,000
Ranging error	±2mm at 10m and 25m, each at 90% and 10% reflectivity
Colour Unit	
Resolution:	Up to 70 megapixel colour
Dynamic colour feature	Automatic adaption of brightness
Deflection Unit	
Field of view (vertical/horizontal)	300 °/360 °
Step Size (vertical/horizontal)	0.009 ° (40,960 3D-Pixel on 360 °) / 0.009 ° (40,960 3D-Pixel on 360 °)
Max. Vertical Scan Speed	5,820 rpm or 97 Hz
Laser (optical transmitter)	
Laser power (cw Ø)	20mW (Laser class 3R)
Wavelength	905nm
Beam divergence	Typical 0.19 mrad (0.011 °)
Beam diameter at exit	Typical 3.0 mm, circular
Data Handling and Control	
Data storage	SD, SDHC™, SDXC™; 32GB card included
Scanner control	Via touchscreen display and WiFi
New WiFi (WLAN) access	Remote control, Scan Visualisation and download are possible on mobile devices with Flash

Multi-Sensor	
Dual axis compensator	Levels each scan; Accuracy 0.015°; Range ±5°
Height sensor Compass	Via an electronic barometer the height relative to a fixed point can be detected and added to ascan. The electronic compass gives the scan an orientation. A calibration feature is included.

To record environmental condition data, one moisture meter and one wind speed meter were used in this research. In this research, the moisture meter is used to provide data, including the outdoor ambient air temperature, indoor ambient air temperature, relative humidity of ambient air, and the relative humidity of building structures with possible moisture issues detected by infrared camera. The specification of the FLIR MR77 is listed in the following Table 24.

Table 24: Specification for FLIR MR77

Technical Summary	Range	Basic Accuracy
Pinless Moisture	0-99.9	Relative
Pinless Moisture Depth Max	0.75 inch (19mm)	-
Pin Moisture	0 to 99% WME	-
Relative Humidity	0 to 99% RH	±2.5% RH
Sensor Temperautre	-19 to 170 ℉, -28 to 77 ℃	±3.5 ℉, 2 ℃
IR Temperature	-4 to 392 F, -20 to 200 ℃	±3.5%
IR Distance to Spot Ratio	8 inches away: 1 inch spot size	-

IR Emissivity	0.95 (fixed)	-
Vapor Pressure	0 to 20.0 kPa	± 2%

Other Data Sources: In order to get real-time environmental data during data collection and one or two days before data collection, weather data from the closest weather station was downloaded to provide necessary weather information. The distance between two buildings and weather station are all within 2 miles. The following table displays the weather parameters captured from the weather station.

Table 25: Weather data from weather station

Environmental Factor	Factor Type	Units
Weather Condition	Daily	NA
Rain in Past Two Days	Daily	NA
Outside Temperature Range	Daily	℉
Real-time Outside Temperature	Real-time	℉
Outside Humidity Range	Daily	%
Daily Average Outside Humidity	Daily	%
Real-time Outside Humidity	Real-time	%
Average Wind Speed	Daily	Mph
Real-time Wind Speed	Real-time	Mph

3.4.2 Field Data Collection

Six data collection trips to Building 1were made during summer season from 6/30/2014 to 8/15/2014 to collect data on 15 apartment units. Four data collection trips to Building 2 were made during winter season from 3/14/2015 to 3/20/2015 to collect data on 16 apartment units. Data collected include infrared images, terrestrial LiDAR data, digital images, indoor humidity and temperature, interview data, indoor air quality data and real-time weather data from nearby weather station.

Table 26: Data sheet for building 1

Data Type	Equipment/ Data Source	Data Collected
Infrared Imaging	Infrared Camera: FLIR T650sc	500+ images
LiDAR Data	LiDAR Scanner: Faro Laser Scanner	300+ scans
Digital Image	Digital Camera: Sony NEX5r	1000+ digital images
Humidity and Temperature	Moisture Meter: FLIR MR77	100+ data
Wind Speed	Wind Speed Meter: Mastech MS6352A	15 units
Real-time Weather Data	From Weather Station	15 units

Table 27: Data sheet for building 2

Data Type	Equipment/Data Source	Data Collected
Infrared Imaging	Infrared Camera: FLIR T650sc	500+ images
LiDAR Data	LiDAR Scanner: Faro Laser Scanner	300+ scans
Digital Image	Digital Camera: Sony NEX5r	1000+ digital images
Humidity and Temperature	Moisture Meter: FLIR MR77	100+ data

Wind Speed	Wind Speed Meter: Mastech MS6252A	16 units
Real-time Weather Data	From Weather Station	16 units

During post-processing, all the data are grouped into three categories: (1) Exterior Area; (2) Common Area; and (3) Apartments.

(1) Exterior Area Data Collection

LiDAR data, infrared data, digital images that cover the whole exterior part of the building were collected. This includes exterior walls and roofs. Figure 27 (a) is the point cloud after scan registration. Figure (b) is the exterior wall of the building; the thermal image shows the heat loss at floor slabs. Figure (c) is the digital image taken for the exterior wall area with possible Air Conditioner water leakage issue. Figure (d) is the example of temperature and humidity data collection on site during inspection.

Figure 27: Exterior area data collection

(2) Common Area Data Collection

In building 1, common areas are basement, corridor, electrical room, fire pump room, gas meter room, head start room, commercial kitchen, laundry room, and stairs and telephone equipment room. In building 2, common areas include boiler room, corridor, electrical room, cellar garage, janitors closet, laundry, mechanical room, recycle room, and stairs and telephone communication room. Figure 28 shows the example of different types of collected data. Figure (a) is the raw scan data taken in head-start room. Figure (b) is infrared image of laundry room showing water leakage inside of the wall. Figure (c) is the digital image taken in the head-start room. Figure (d) is the example of temperature and humidity data collection in the corridor during inspection. During post-analysis these temperature and humidity data are extracted and input into excel.

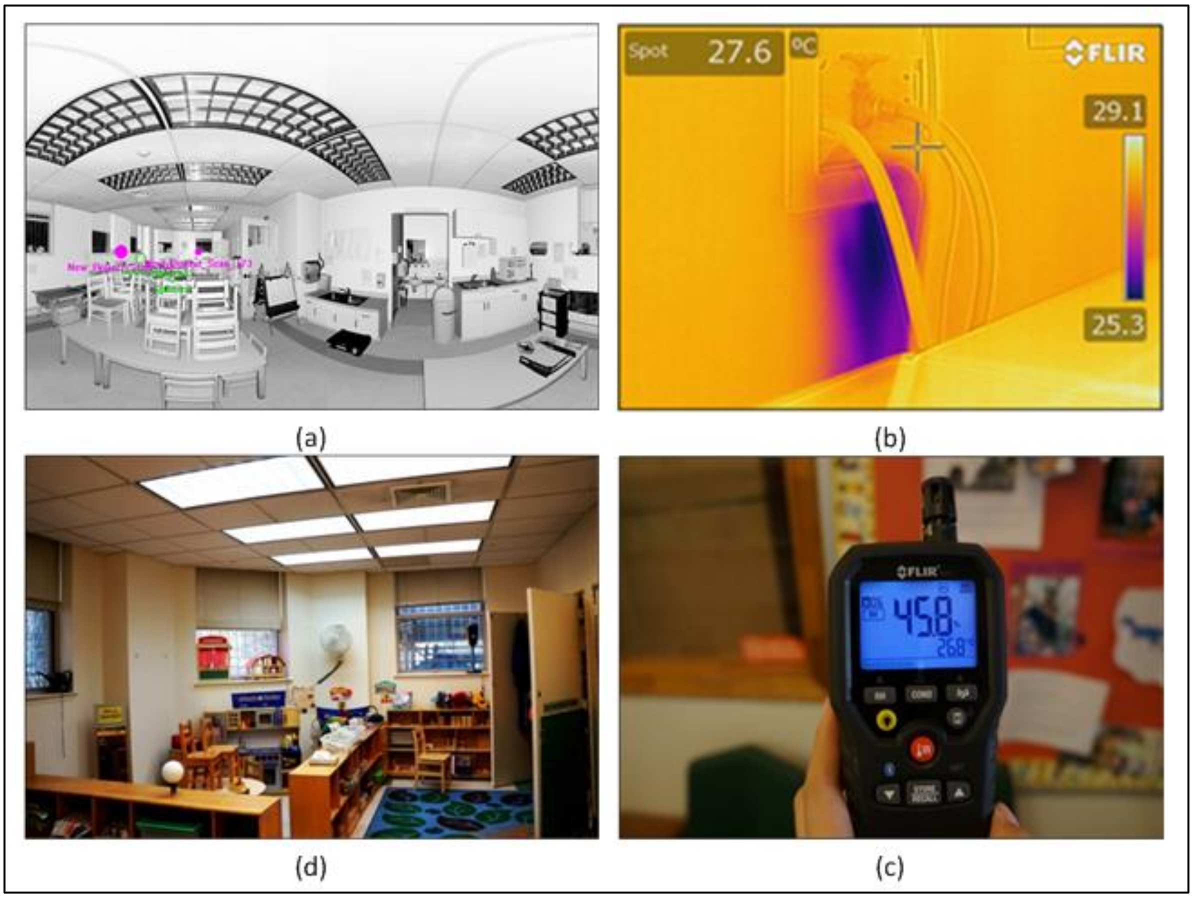


Figure 28: Common area data collection: (a) The raw scan data taken in head-start room; (b) Infrared image of laundry room showing water leakage inside of the wall; (c) Digital images taken in the head-start room; and (d) Examples of temperature and humidity data collection in the corridor during inspection.

(3) Apartment Data Collection

31 apartment units were selected for detail analysis in building 1 and building 2. Apartment types include studio, one bedroom, two-bedroom, and three-bedroom apartments.

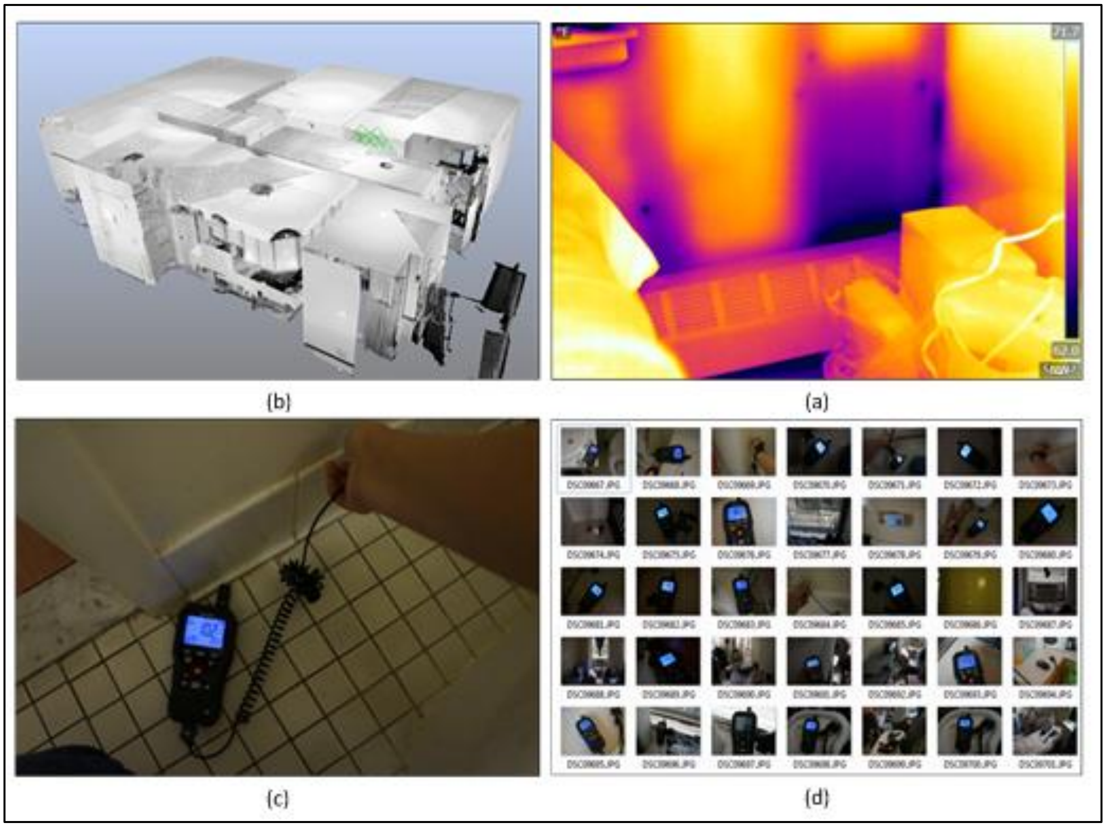


Figure 29: Example of apartment data: (a) Registered point cloud of six raw scans for one apartment; (b) Infrared images of bedroom showing poor/lost insulation in the exterior wall; (c) Using moisture meter to verify the moisture issue detected by infrared camera; (d) Temperature and humidity data collected in one apartment during inspection.

For each apartment, 8-30 groups of moisture data were collected randomly. During post-analysis, these temperature and humidity data are extracted and inputted into Excel by apartment to generate average temperature, average humidity and temperature variation information.

(4) Environmental Condition Data Collection

Environmental condition data were captured from moisture meter, wind speed meter and weather station nearby. Available data from weather station includes: temperature, relative humidity, wind speed and wind speed direction for every 4 minutes (Figure 30).

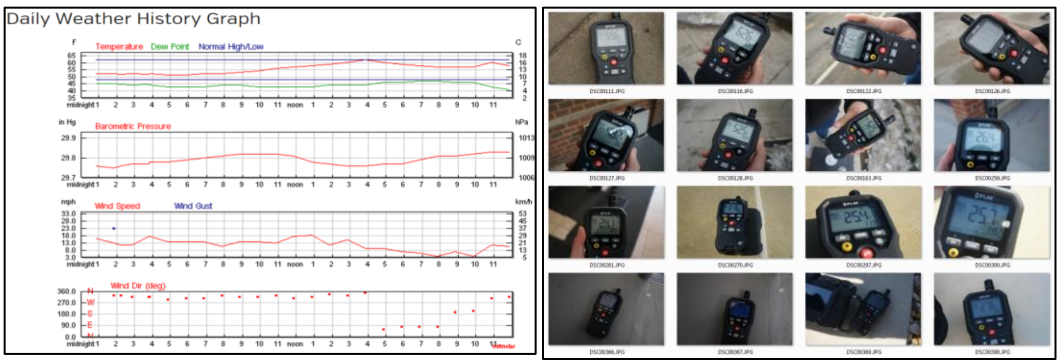


Figure 30: Real-time outdoor temperature and humidity captured from weather station and moisture meter

3.5 Results and Discussion

3.5.1 Defect Detection Results

A total of 1609 infrared images were captured for 31 apartments in two buildings after field data collection. These infrared images are integrated with LIDAR data to generate 3D thermography data. The integrated data are used to identify defects and locate these defects in 3D thermal model. The major types of defects detected from this process are described in the following. As discussed previously, there are many different types of defects that can be identified and located through thermal imaging. These defects include poor or missing insulation, moisture issue, air leakage or air infiltration, thermal bridge, and hot water riser overheating.

Poor or missing insulation: Poor or missing insulation can impair the thermal performance of building components significantly. Through infrared cameras, improperly installed or damaged insulation will appear as a patch with well-defined edges that outline the problematic areas (Balaras and Argiriou 2002) (Figure 31). In this case study, almost one half of 31 apartments have this type of issue. In order to obtain sufficient poor insulation information, a minimum temperature difference is required during inspection. According to the RESNET Interim Guidelines for thermographic inspections of building and FLIR thermal imaging guidebook, the minimum inside and outside temperature difference of the wall surface is 10 ℃/18 ℉ and for a period of 4 hours is recommended.

The field data collection for building 1 and building 2 were done during 6/30/2014 to 8/15/2014 and 3/14/2015 to 3/20/2015. There is a challenge for obtaining sufficient temperature difference during spring and summer inspection with only half of target apartments equipped with unit air conditioner. This results in inadequate temperature differences. Because of this situation, there may be potential poor insulation areas that cannot be detected during field trips. After all the missing and poor insulation areas are detected and located, 3D thermal point cloud was used to calculated the areas of anomalies. The RESNET Insulation Grading Standard was used to grade the insulation condition of each apartment.

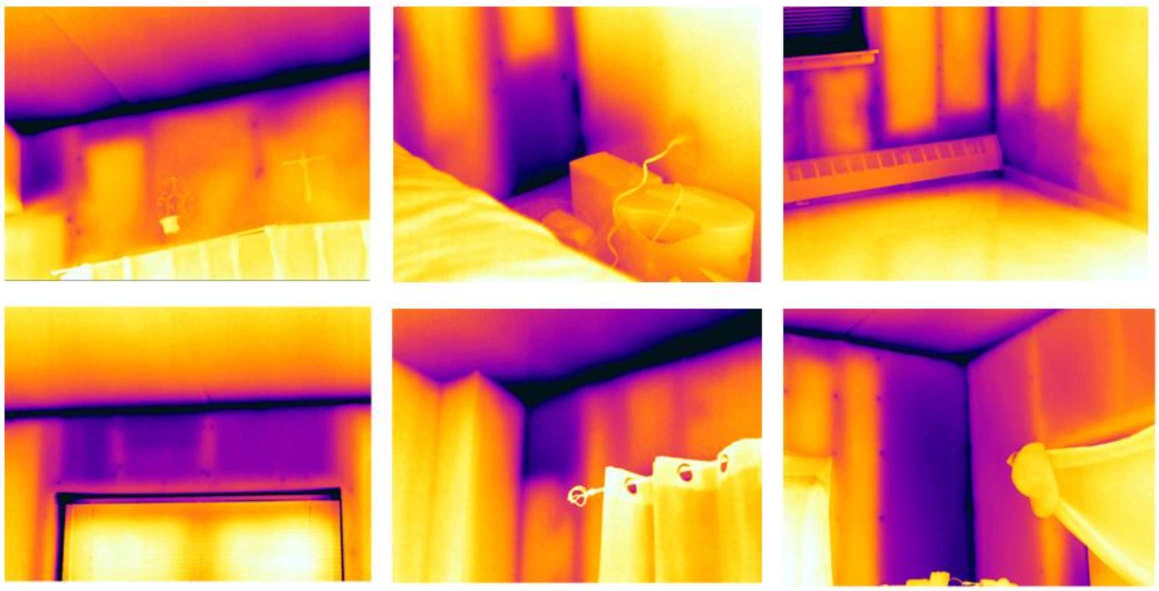


Figure 31: Poor or missing insulation issues

(Sections with missing or poor insulation are indicated by the cooler colors)

Moisture Issue: Moisture is the most common form of deterioration detected in a building. Locating moisture through infrared thermography is relatively straightforward since water has high thermal conductivity and heat capacity. Moisture in building envelop systems could be the result of air infiltration. This is because air infiltration allows warm moisture air going through wall assembly systems and condensing and accumulating at cold spots. These condensations can lead to reduced insulation value, mold growth, and structure element deterioration. The following shows examples of moisture issues detected in the studied buildings (Figure 32).

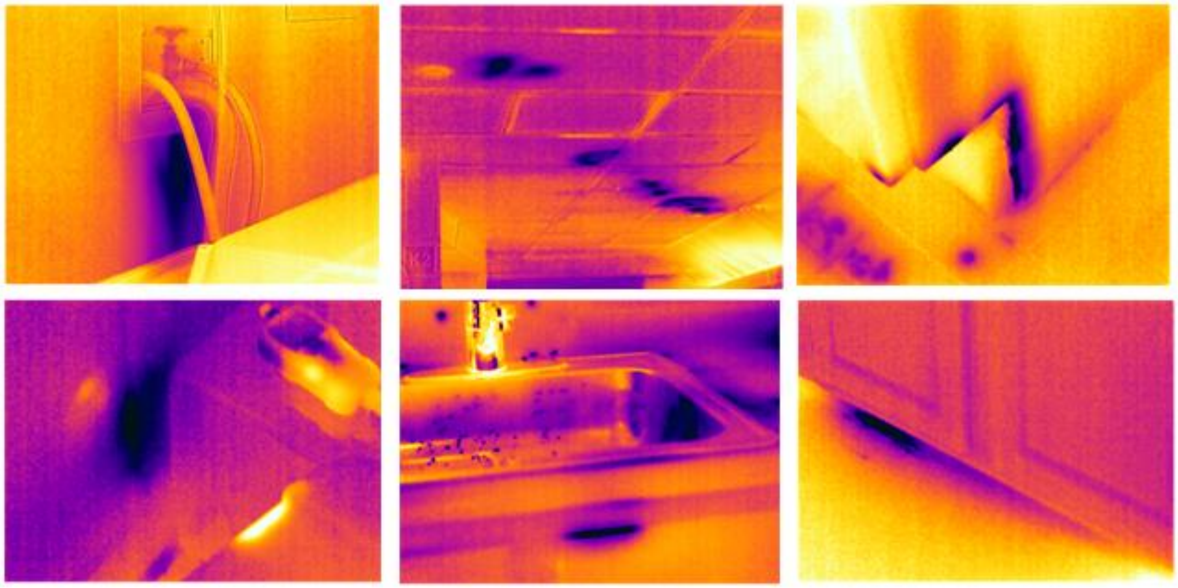


Figure 32: Moisture issues

Air infiltration: Air infiltration can lead to high energy consumption and condensation in building envelop systems. Although adequate air exchange is essential for occupants' health, many buildings have a far greater rate of air exchange than what is necessary. Air infiltration is usually caused by poor design and/or construction which allows air to move across thermal perimeters. It is recommended that air infiltration inspection works better when indoor air flow is controlled. This can be achieved using a blow door device or controlling air flow settings in HAVC systems. In the context of this project, both are not feasible. In this study, air leakage issues are detected mostly in wall assembly systems (Figure 33). In building 2, some of power outlet on the exterior wall became a point of cold-air entry in apartments. In the worst case, it was observed that an outlet has a temperature of 55 ℉ while the indoor and outdoor temperatures are 75 ℉ and 40.5 ℉, respectively (Figure 34).

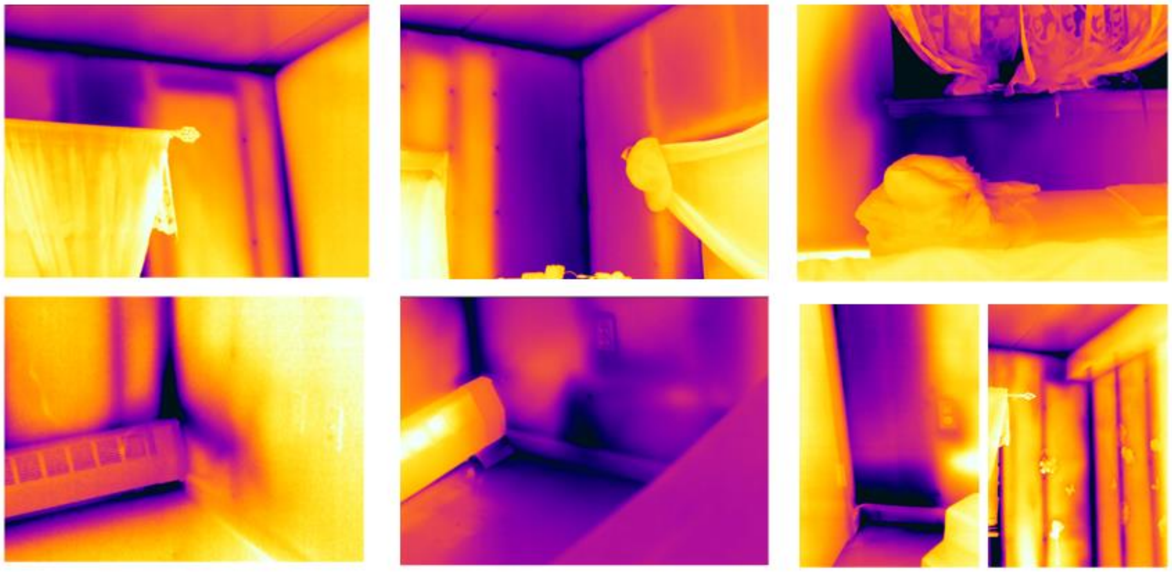


Figure 33: Air infiltration examples

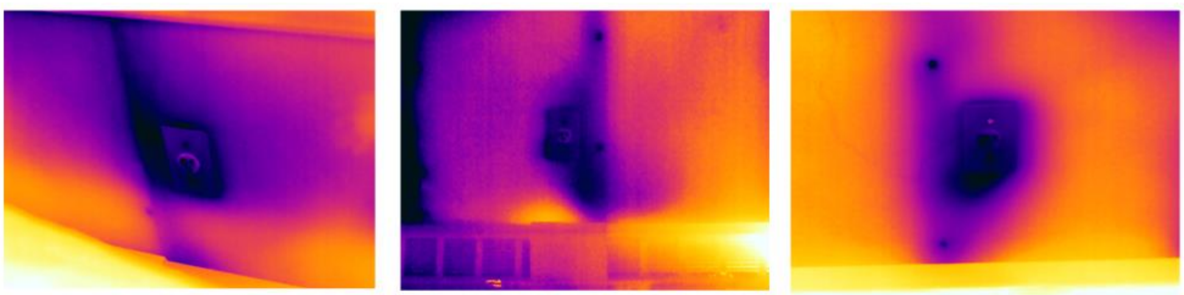


Figure 34: Cold air infiltration through wall sockets

Thermal bridge: Thermal bridges are the elements or areas that are characterized by high thermal conductance with respect to the homogeneous multilayer envelope structure. Thermal bridges can lead to an increase of energy requirement for heating up to 30% of the extra-thermal losses through building envelope during winter season (Theodosiou and Papadopoulos 2008). In the context of this research, numerous examples of thermal bridge were detected and evaluated (Figure 35).

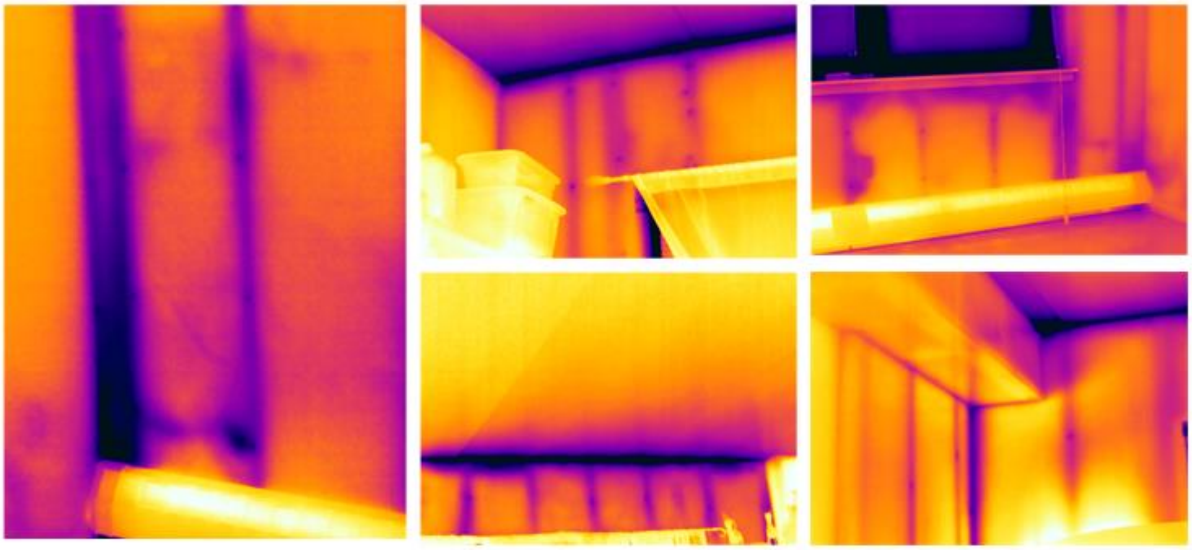


Figure 35: Thermal bridge issues with two buildings

Hot water riser poor insulated: During field data collection for building 2, we noticed some of the hot water riser pipes are not well insulated (Figure 36). The highest temperature difference between the wall cover the riser and surrounding wall in a same room can reach to 13.2 ℉. In this particular building, three out of fifteen apartments had a temperature difference of 10 ℉ in this case, and seven of fifteen apartments had the temperature difference higher than 5 ℉, and 66% of apartments had the temperature difference higher than 4 ℉. Insulating the pipes that carry hot water can help reduce the convective heat loss from pipes and increasing the delivered water temperature for end use apartments. On the other side, if the heat gain from poor insulated hot water pipes cannot be controlled, it may lead to overheating issue in the room.

Figure 36: Issues with hot water risers

3.5.2 Apartment Condition Grading Results

Based on the calculated data, the RESNET Insulation Grading Standard and R-value were used to grade the insulation condition of each apartment. The RESNET Insulation Grading for Thermographic Inspections of Building classify insulation condition into three categories:

- Grade I: no anomalies found through infrared camera
- Grade II: 0.5% to 2% for all inspected walls
- Grade III: 2 % to 5% for all inspected walls

In this study, the conditions of some apartments are far worse than Grade III. We added Grade IV to describe the situation when more than 5% of anomalies were found through infrared camera. According to the RESNET Standard, at least a 10 °F temperature difference between indoor and outdoor environments is required for applying the standard. However, most of data collected for building 1 during summer do not meet this requirement. As a result of this, an insulation level was designed to grade the insulation condition for building1. The RESNET standard was adopted for building 2. The insulation level has three levels:

- Level 1: for good condition that no insulation anomalies is detectable;
- Level 2 for fair condition with small insulation issue;
- Level 3 for poor condition with large detectable insulation issue;

3.5.3 Summary of Apartment Attributes

The conditions of studied apartments are summarized in the following tables.

Table 28: Extracted attributes for building 1(part one)

Attribute	Apartment Unit Information	
Apartment List	Top Floor	Corner
H1	0	1
H2	0	1
H3	1	1
H4	0	0
H5	1	1
H6	0	0
H7	0	0
H8	1	1
H9	0	1
H10	0	1
H11	0	1
H12	0	1
H13	1	1

H14	0	1
H15	0	1

Table 29: Extracted attributes for building 1 (part two)

Attribute	Thermal Comfort				Thermal Infrared Data	
Apartment List	Real-time Indoor Air Temperature	Real-time Indoor Air Relative Humidity	Real-time Thermal Comfort Level	Indoor Air Temperature Variation	Insulation Level	Moisture Level
H1	81.5	56.47	3	1.08	1	1
H2	82.28	50.09	3	3.78	2	1
H3	82.87	54.83	3	2.34	3	2
H4	82.9	56.22	3	7.56	1	1
H5	82.46	50.03	3	7.92	2	2
H6	84.02	50.19	3	4.5	1	1
H7	81.14	46.7	3	10.26	1	1
H8	80.66	47.578	2	3.96	2	2
H9	81.2	46.43	3	0.18	1	1
H10	81.56	44.53	2	6.84	1	1
H11	79.34	50.5875	2	4.32	2	2
H12	82.9	56.22	3	2.88	1	1
H13	83.876	48.52	3	0.36	3	1
H14	78.14	43.66	2	1.08	2	2

H15	77.68	43.56	2	3.24	1	1

Table 30: Attribute descriptions for building 1

Type	Attribute	Value	Description
Apartment Unit Information	Top Floor	Top (1); Other (0);	The apartment unit is on the top floor or not
	Corner	Corner (1); Other (0);	The apartment unit is in the corner of the building or not
Thermal Comfort	Real-time Indoor Air Temperature	Number (°F)	Average indoor air temperature from the moisture meter during inspection
	Real-time Indoor Air Relative Humidity	Number (%)	Average indoor air relative humidity from the moisture meter during inspection
	Real-time Thermal Comfort Level	Cold (1); Normal (2); Hot (3)	Thermal Comfort of the indoor environment base on the real-time indoor air temperature and relative humidity
	Indoor Air Temperature Variation	Number (°F)	The variation of the indoor air temperature in one apartment unit
Thermal Infrared	Insulation Level	1 = good condition; 2 = fair condition;	Describe the insulation condition of the apartment unit

Data		3=poor condition;	Level 1: for good condition that no insulation anomalies is detectable through infrared camera Level 2 for fair condition with small insulation issue; Level 3 for poor condition with large detectable insulation issue;
	Moisture Level	1 = good condition; 2 = fair condition; 3=poor condition;	Describe the moisture condition of the apartment unit Level 1: for good condition that no moisture anomalies is detectable through infrared camera Level 2 for fair condition with small moisture or non-structure element issue; Level 3 for poor condition with large detectable moisture issue;
Note: the temperature factor for thermal bridge and air leakage, R-value and RESNET Insulation Grading can only be calculated with a temperature difference below 10 ℉ between indoor and outdoor Although the RESNET Insulation Grading cannot be used for building1, an insulation level was applied in this case. Insulation Level defined here has three levels:			

- Level one for poor insulation condition:
- Level two for fair insulation condition:
- Level three for good insulation condition:

Table 31: Apartment information for building 2 – Exterior wall area

Attribute	Room Type	Bedroom 1	Bedroom2	Bedroom3	Living Room	Total Area
H1	1	81.1176	80.666	NA	93.524	255.3076
H2	1	81.1176	80.666	NA	93.524	255.3076
H3	2	64.4907	71.991	NA	111.033	247.5147
H4	3	72.7393	94.847	NA	84.574	252.1603
H5	1	81.1176	80.666	NA	93.524	255.3076
H6	1	81.1176	80.666	NA	93.524	255.3076
H7	1	81.1176	80.666	NA	93.524	255.3076
H8	5	70.1334	71.543	84.14	91.421	317.2374
H9	1	81.1176	80.666	NA	93.524	255.3076
H10	4	82.6608	NA	NA	102.316	184.9768
H11	1	81.1176	80.666	NA	93.524	255.3076
H12	3	72.7393	94.847	NA	84.574	252.1603
H13	4	82.6608	NA	NA	102.316	184.9768
H14	1	81.1176	80.666	NA	93.524	255.3076
H15	1	81.1176	80.666	NA	93.524	255.3076
H16	1	81.1176	80.666	NA	93.524	255.3076

Room Type:

Type 1: Typical two-bedroom apartment

Type 2: Corner two-bedroom apartment

Type 3: Other Type of two-bedroom apartment

Type 4: One-bedroom apartment

Type 5: Three-bedroom apartment

Unit: Square Feet

All the dimension information was collected from point cloud data.

Table 32: Attribute list for building 2 (part one)

Attribute	Apartment Unit Information		
Apartment list	Top Floor	Corner	Face Inner Garden
H1	1	0	1
H2	0	0	0
H3	0	1	1
H4	0	0	0
H5	0	0	1
H6	1	0	1
H7	0	0	0
H8	1	1	0
H9	1	0	1
H10	1	1	1

H11	0	0	0
H12	0	0	0
H13	0	0	0
H14	1	0	1
H15	0	0	1
H16	0	0	1

Table 33: Attribute list for building 2 (part two)

Attribute	Thermal Comfort				
Apartment list	Real-time Indoor Air Temperature	Real-time Indoor Air Relative Humidity	Real-time Outdoor Air Temperature	Real-time Thermal Comfort Level	Indoor Air Temperature Variation
H1	76.1	37.68	45.8	2	4.68
H2	76.865	39.21	45.65	2	0.72
H3	78.91077	46.45	46.8	3	3.78
H4	77.846	30.33	39	2	8.64
H5	75.38	42.26	40.45	2	7.74
H6	81.905	29.55	43.75	3	3.96
H7	75.66286	35.01	45.6	2	2.7
H8	78.815	36.47	47.2	3	3.78
H9	75.09714	31.9	39.1	2	6.3
H10	77	24.9	39.85	2	0.9
H11	71.672	25.06	40.75	2	4.32

H12	75.74	29.13	44.85	2	2.88
H13	78.26	27.98	45.6	2	1.98
H14	85.03	24.57	33.2	3	7.02
H15	76.82	30.82	33.95	2	2.34
H16	75.92	41.7	32.4	2	5.76

Table 34: Thermal infrared data for building 2 (part one)

Attribute	Dew Point	Dew Point Warning	Thermal Bridge Temperature	Thermal Bridge-temperature factor	Air Leakage Temperature	Air Leakage Temperature Factor
H1	53.7	0	64.5	0.6	61.5	0.5
H2	55	0	68.3	0.7	67	0.7
H3	59.6	0	67.2	0.6	66.7	0.6
H4	52.8	0	74.3	0.9	67.2	0.7
H5	54.6	1	64.3	0.7	55.1	0.4
H6	56.5	0	75.2	0.8	64.3	0.5
H7	52.3	0	66.8	0.7	64.5	0.6
H8	55.9	0	66.9	0.6	58.4	0.4
H9	50.6	0	73.4	1	63.7	0.7
H10	50	0	67.7	0.7	58.1	0.5
H11	44.7	0	73.4	1.1	73.3	1.1

H12	50.2	0	74	0.9	70.9	0.8
H13	52.3	0	74.5	0.9	72.6	0.8
H14	57.9	0	79.7	0.9	68.5	0.7
H15	51.9	0	71.2	0.9	64.3	0.7
H16	54.9	0	71.1	0.9	66	0.8

Table 35: Thermal infrared data for building 2 (part two)

Attribute	Missing Insulation Area (sf)	Missing Insulation Area (%)	Insulation Grading	R-value	Hot Water Riser Temperature Difference	Hot Water Riser poor insulated
H1	1.4	0.55%	2	0.53	5.2	1
H2	3.6	1.41%	2	0.67	4.1	0
H3	13	5.25%	4	1.97	0	0
H4	0.65	0.26%	1	0.9	13.2	1
H5	36.5	14.30%	4	0.3	5.9	1
H6	1.79	0.70%	2	1.21	1.2	0
H7	0.99	0.39%	1	0.54	0	0
H8	2.63	0.83%	2	0.85	12.6	1
H9	4.21	1.65%	2	1.13	0	0
H10	36.3	19.62%	4	0.31	0	0
H11	9.32	3.65%	3	4.06	10.2	1

H12	9.018	3.58%	3	2.01	6.2	1
H13	1.13	0.61%	2	1.52	0	0
H14	0.45	0.18%	1	2.7	7.2	1
H15	5.89	2.31%	3	1.68	4.3	0
H16	3.3	1.29%	2	2.09	3.9	0

Table 36: Attribute description for building 2

Attribute	Value	Description
Top Floor	Top (1); Other (0);	The apartment unit is on the top floor or not
Corner	Corner (1); Other (0);	The apartment unit is in the corner of the building or not
Face Inner Garden	Face Inner Garden (1); does not (0)	The apartment unit faces the inner garden or not
Real-time Indoor Air Temperature	Number (℉)	Average indoor air temperature from the moisture meter during inspection
Real-time Indoor Air Relative Humidity	Number (%)	Average indoor air relative humidity from the moisture meter during inspection
Real-time Outdoor Air Temperature	Number (℉)	Average outdoor air temperature during inspection from local weather station

Real-time Thermal Comfort Level	Cold (1); Normal (2); Hot (3);	Thermal Comfort of the indoor environment base on the real-time indoor air temperature and relative humidity. ASHRAE Comfort Zone was used for Standard.
Indoor Air Temperature Variation	Number (℉)	The variation of the indoor air temperature in one apartment unit
Dew Point	Number (℉)	Dew point temperature calculated from air temperature and humidity
Dew Point Warning	Yes (1); No (0);	Exterior wall temperature under dew point or not
Thermal Bridge Temperature	Number (℉)	Minimum thermal bridge temperature in the apartment unit
Thermal Bridge Temperature Factor	Number (0-1)	Describe the Thermal bridge condition; the higher the better
Air Leakage Temperature	Number (℉)	Minimum air leakage area temperature in the apartment unit
Air Leakage Temperature Factor	Number (0-1)	Describe the Air Leakage; the higher the better
Missing Insulation Area	Number (Square Feet)	Describe the accumulated area of missing insulation in one apartment unit

(sf)		
Missing Insulation Area (%)	Number (%)	Describe the percentage of accumulated area of missing insulation in one apartment unit out of total exterior wall area
Insulation Grading	Grade I; Grade II; Grade III; Worse than Grade III;	Insulation Grading Standards designed by RESNET Grade I: not infrared detectable anomalies; Grade II: insulation installed with anomalies found to be between 0.5 % and 2% for all inspected walls Grade III: An insulation installation having between 2% to 5% anomalies found for all inspected walls Worse than Grade III: The condition that insulation installation having more than 5% of the anomalies found for all the inspected walls (Note: in this case the total inspected exterior wall area was used as denominator instead of all the inspected walls, ceiling and floors of the building enclosure, because for multi-family building the only enclosure is the exterior wall)
R-value	Value (W/m^2K)	The calculated R-value for one apartment's worst condition room

Hot Water Riser Temperature Difference	Value (°F)	The temperature difference between hot water riser and surrounding wall
Hot Water Riser poor insulated	Yes (1); No (0)	Infrared detectable hot water riser under the wall with a temperature over 5 °compare to surrounding wall
Note: the temperature factor for thermal bridge and air leakage can only be calculated with a high temperature difference between indoor and outdoor		

The extracted building condition data show there are large variations in apartment conditions (Figure 37 and Figure 38). Some apartments have significant deficiency in building insulation, which could impact occupants' thermal comfort and lead to other building hazards such as indoor quality issues. These quantified building performance attributes form the basis to correlate with other data streams. Statistical analyses can be applied on these data streams to understand their correlations.

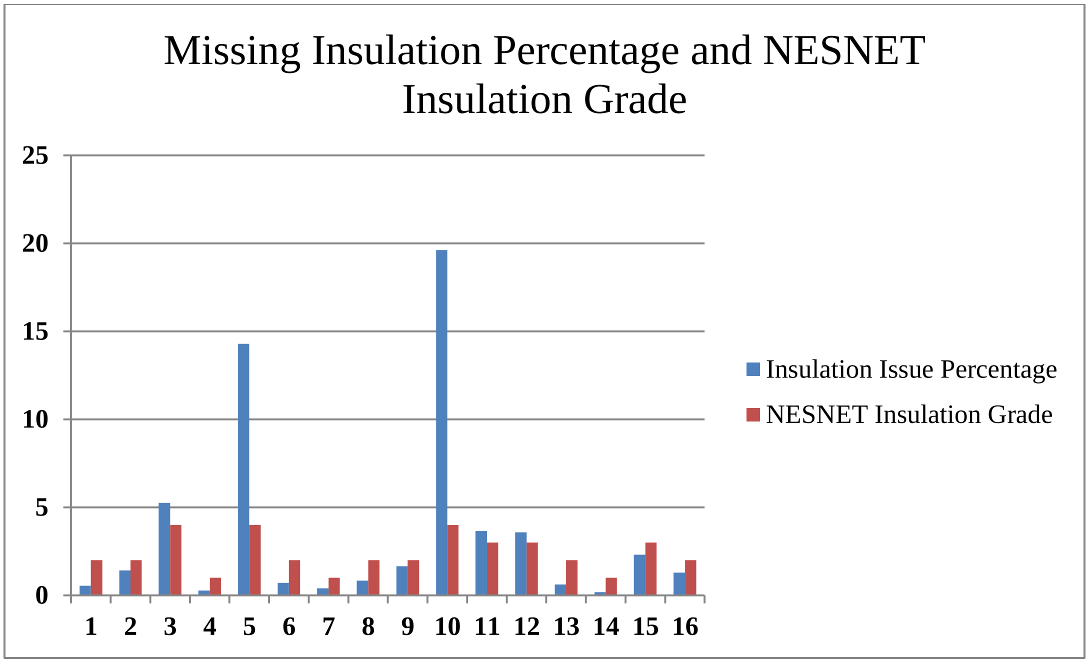


Figure 37: Summary of insulation condition for building 2

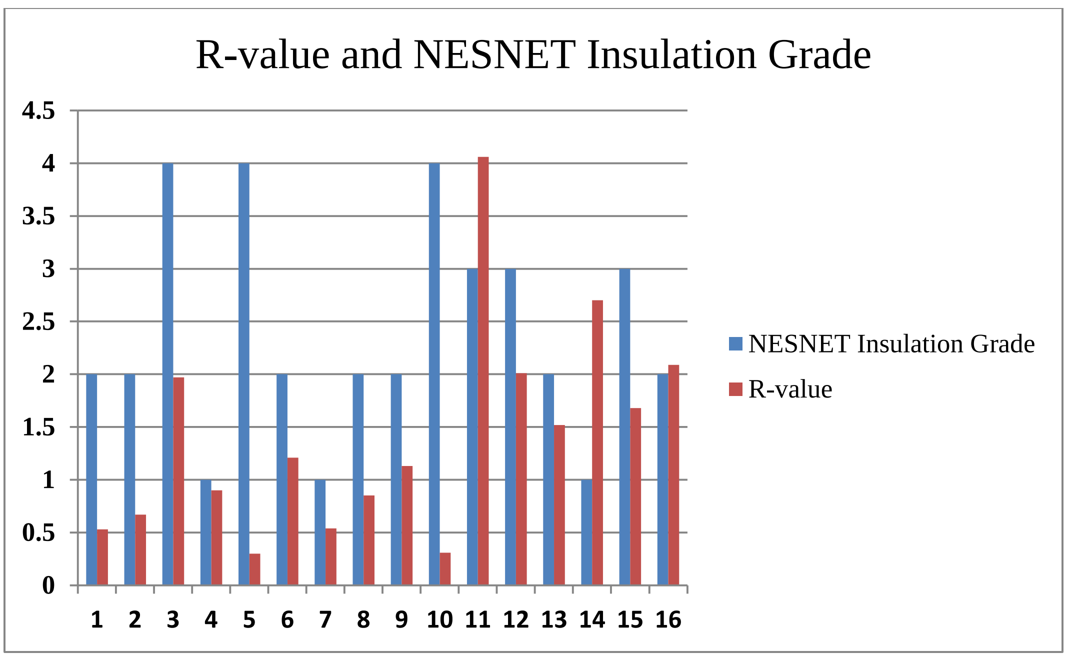


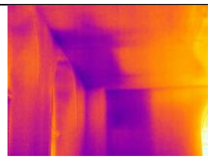
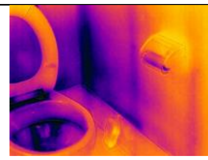
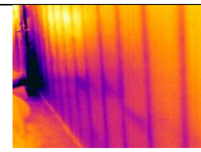
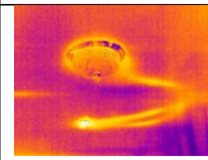
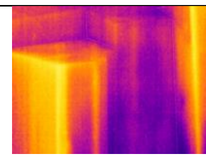
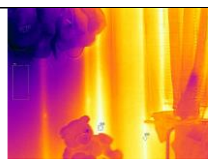
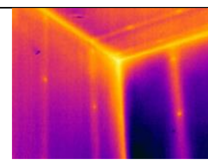
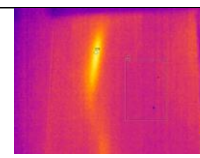
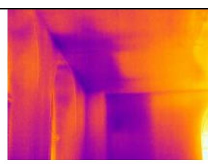
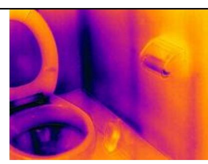
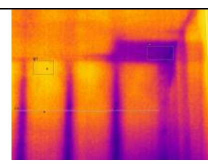
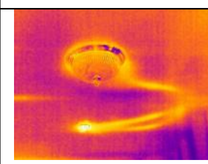
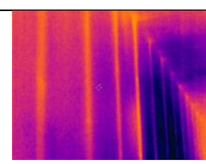
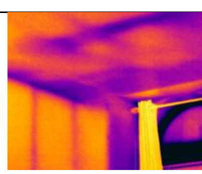
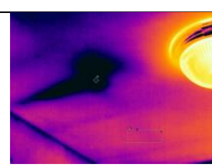
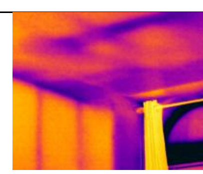
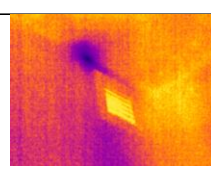
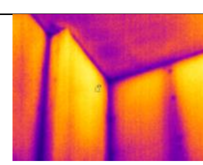
Figure 38: Summary of R-Value and NESNET Insulation Grade for building 2

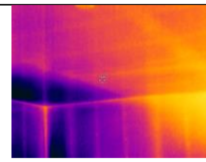
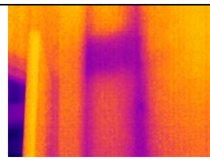
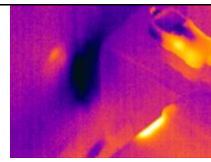
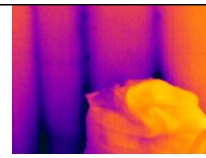
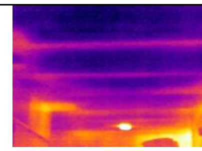
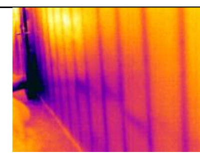
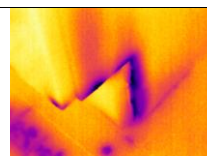
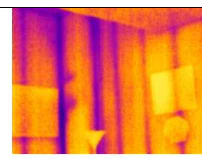
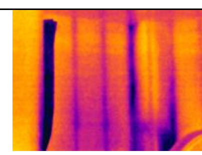
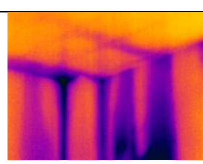
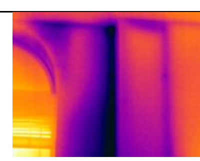
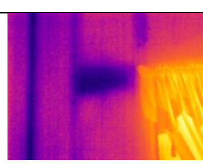
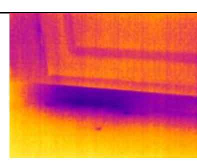
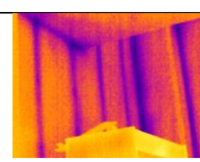
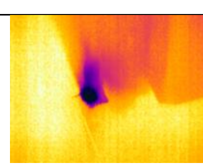
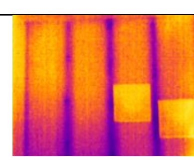
3.6 Conclusions and Future Research

This study explored the integration of infrared thermography and laser scanning for building hazard detection. The integration allows quick and objective measurement of common building defects that are relevant to healthy home. A systematic method that consists of infrared and laser scan data collection, data fusion, and data analysis was developed. The proposed approach was validated on two large multi-family multi-story buildings. A total of 31 apartments were surveyed and analyzed according to several quantitative metrics including moisture issue, thermal bridge, air infiltration, and missing insulation. The evaluation shows varied conditions in these apartments, some of them having alarming concerns on thermal performance and hazardous conditions. The field study shows the proposed method can generate systematic measures that can be used to gauge the performance of the apartments and potentially these data can be correlated with other condition data such as indoor air quality data to gain better understanding how these factors correlate with each other. Future research can be devoted to integrating with other data streams to evaluate the predictive power of the features quantified in this research. Also, the question on how to scale the algorithms used in this research to other lower quality sensors, such as those smart phone based infrared sensors, would be another promising direction.

Appendix A

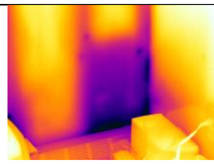
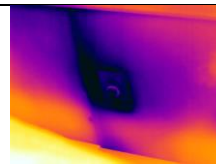
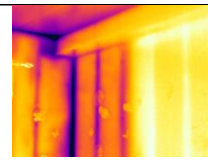
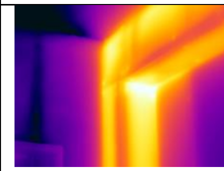
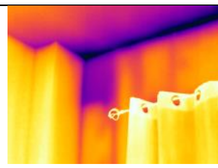
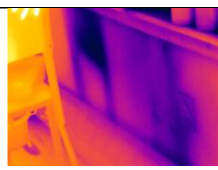
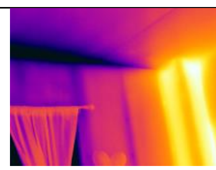
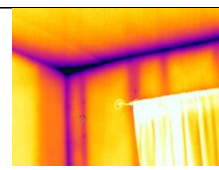
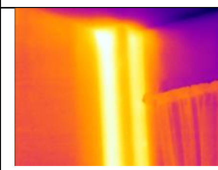
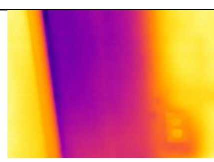
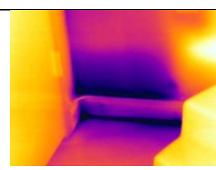
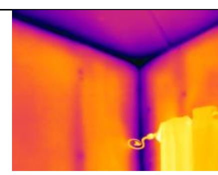
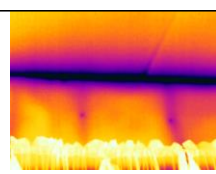
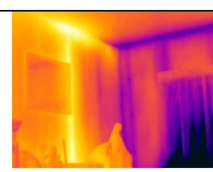
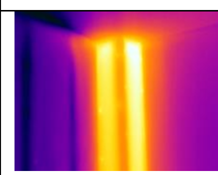
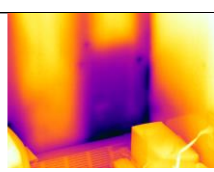
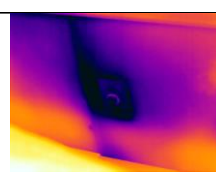
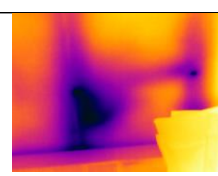
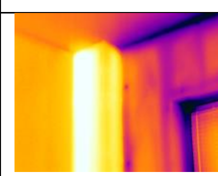
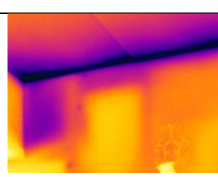
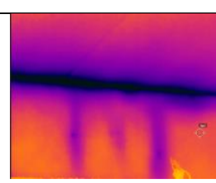
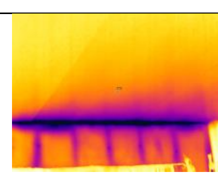
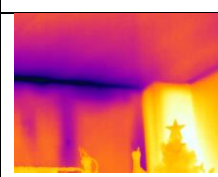
Building Defects Example in Building 1

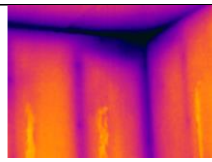
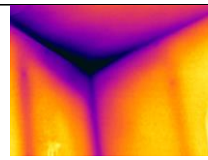
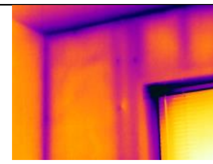
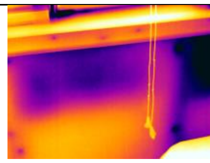
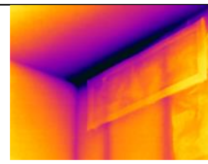
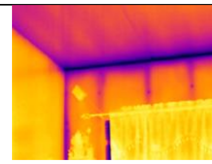
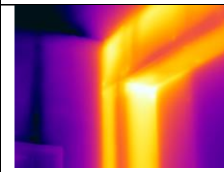
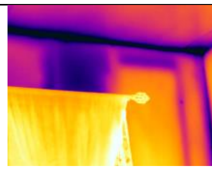
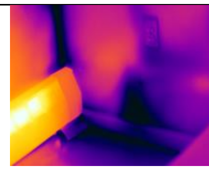
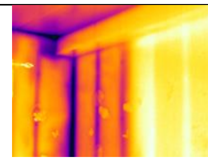
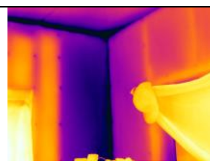
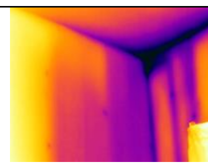
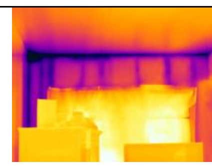
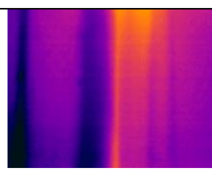
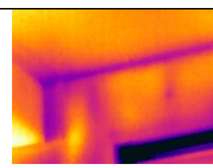
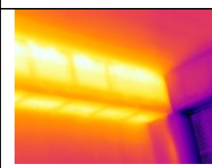
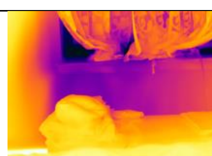
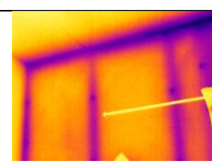
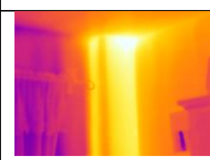
Apartment Number	Insulation	Moisture	Thermal Bridge	Electric Wire
Example				
H1				
H2				
H3				
H4				
H5				
H6				

H7				
H8				
H9				
H10				
H11				
H12				
H13				
H14				
H15				

Appendix B

Building Defects Example in Building 2

Apartment Number	Insulation	Air leakage And Air infiltration	Thermal Bridge	Hot Water Riser
Example				
H1				
H2				
H3				
H4				
H5				
H6				

H7				
H8				
H9				
H10				
H11				
H12				
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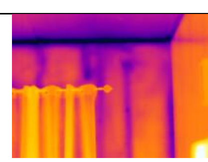
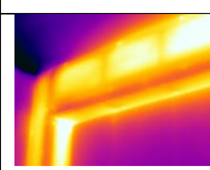
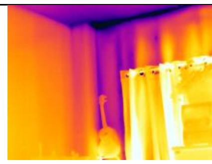
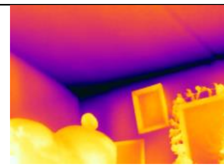
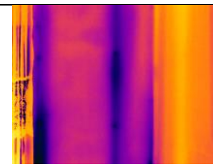
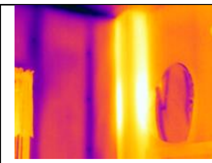
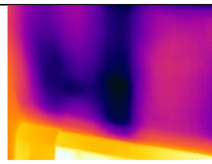
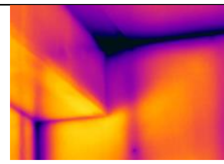
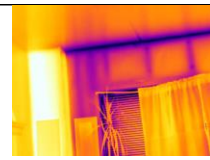
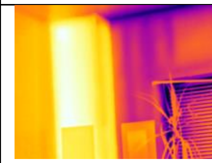
H14				

H15				
H16				

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