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Towards IoT-assisted Non-Intrusive Monitoring of Thermal Variation on Building Envelope

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Abstract—Miscellaneous surface damages and air leakages through building components significantly affect energy consumption as well as the thermal comfort of inhabitants in building. Formal thermal inspection of built environment by professionals is expensive and intrusive, often inconclusive and inconvenient, which also requires a lot of parameter tuning. Besides, non-intrusive monitoring with low-cost sensors and thermal images can provide data-driven knowledge of the thermal properties of built surfaces and also helps in accelerating the process of thermal inspection by professionals. We introduce novel quantitative approaches based on non-intrusive temperature and humidity sensor data as well as thermal images which simultaneously learn spatial and temporal thermal characteristics from different places in the inside built environment and provide data-driven thermal variation analysis for identifying potential damage-prone and air-leaking areas in order to reduce energy loss through building components.

Index Terms—Building envelope, Sensors, Thermal images, Thermal condition, Non-intrusive monitoring, Machine learning

I. INTRODUCTION

Recurrent or non-recurrent changes in temperature and humidity, such as excessive heat gains or loss, superfluous moisture on external and internal surfaces of building, can cause undesirable damage on building envelope over time. Air passing through the surface cracks, windows, doors, roofs, etc. causes additional energy consumption for heating and cooling. In residential buildings of the USA, 51% of total energy consumption contributes to space heating and cooling [1] and 31% energy loss occurs through different building components, such as poorly insulated walls, ceiling, and roofs [2]. Conventional thermal monitoring inside a built environment requires deploying intrusive equipment, tuning lots of parameters as well as building metadata. Besides, professional thermal inspection sometimes remains inconclusive due to the support from data-driven knowledge and resource limitations. The extensive invention of IoT devices in recent days, opens wide opportunities for predictive maintenance in buildings. In this paper, we present the overview of our developed flexible non-intrusive building envelope monitoring frameworks which can provide data-driven knowledge to the building inhabitants to understand the thermal characteristics of inside the built environment using cheaply available IoT devices. We introduced

machine learning based novel frameworks using temperature-humidity sensors as well as thermal and moisture images for analyzing the thermal variance over different indoor spaces without knowing any building metadata. This eventually helps the residents to identify the potential damage-prone and air leakage areas for further investigation.

II. CONTRIBUTIONS

We contributed in the following aspects of non-intrusive thermal monitoring of inside built environment.

A. Longitudinal thermal data acquisition

One of the most important and vital challenges in building envelope monitoring is collecting longitudinal thermal condition data. Collecting thermal images from inside and outside the built environment involves several issues related to setting up cameras, device safety, maintaining consistency of frames, preserving the privacy of inhabitants etc. In our works, we attempted to deal with these issues by collecting temporal temperature and humidity data as well as longitudinal thermal images. We propose a novel systematic approach for collecting and pre-processing thermal images from an indoor built environment in uncontrolled setup with our developed android based smartphone application. We develop a novel thermal image dataset with the annotation of different building components i.e., walls, doors, windows, ceiling, and ventilators which helps in exploring precise thermal variation over different places. We plan to release our dataset soon which surely can help the researchers with more resources in this area.

B. IoT-assisted thermal variation

Following two subsections present the overview of our developed IoT sensors based scalable and interpretable frameworks for thermal variation analysis.

1) *Temperature sensor based thermal variation*: We introduced an unsupervised temporal clustering algorithm to learn temporal representations of thermal conditions over different inside surfaces of the built environment using low-cost temperature-humidity sensors [3]. We obtained the thermal condition data i.e., temperature, humidity, dew point, and heat index from thermo-hygrometers deployed on different surfaces

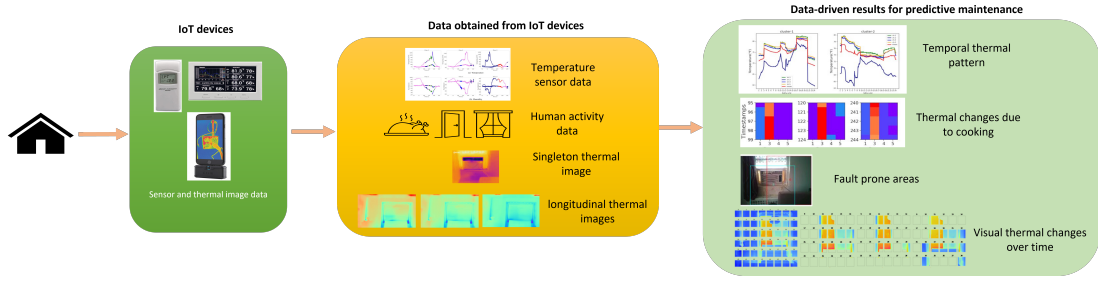


Fig. 1. Overall idea of thermal variation in inside built environment

for three different residential buildings. Our proposed temporal clustering provides the pattern of thermal conditions for different inside surfaces during different outdoor weather conditions and outperforms in achieving higher clustering metrics. We also measured the thermal response of indoor surfaces which indicates the time and amount of thermal condition changes for each indoor surface in response to outside thermal condition changes.

2) *Thermal image based thermal variation:* Prolonged analysis of the indoor built environment with thermal imagers can assist in identifying energy-leaking areas and potential damage-prone areas precisely. We experimented with both singleton and longitudinal thermal images for detecting air leakages and thermal variation. We proposed a symbolic aggregated approximation (SAX) based method for identifying different types of wall insulation problems from the temperature variation over different segments of thermal image [4]. We achieved 75% accuracy using this approach for finding fault-prone areas captured in the thermal image. Later, we experimented with longitudinal thermal images to analyze the spatial and temporal thermal variation over different building elements i.e., doors, windows, walls, etc more accurately. We presented the spatial and temporal relations among image pixels from sequential thermal images of the corresponding region with graph [5]. Here, we focused on the static temporal thermal images captured from a region to analyze the thermal characteristics. In further extension of this work, we plan to incorporate the visually observed structural connection among different building components and present them in a high-level spatio-temporal graph. In order to analyze the thermal condition of one building component, we consider including the thermal status of other neighboring building components which affect the corresponding component. We detect spatial and temporal thermal anomalies which provides the data-driven knowledge of potential air leakage and damage-prone areas for further inspection.

C. Activity based thermal variation

In residential homes, inside thermal condition is greatly affected by human activities along with the outside weather. Different human activities such as cooking, opening doors, and windows change the inside thermal condition. We studied how cooking activities affect the thermal condition inside the

built environment [6]. Our proposed recurrent neural network based algorithm recognizes cooking events from temperature sensors with 93% accuracy. It can differentiate the thermal changes due to cooking from diurnal temperature changes for outside weather. We also analyzed the temperature changes for using different number of cooking stoves. However, we avoided other thermal condition changing activities (i.e., open doors or windows) during cooking in order to analyze the sole impact of cooking activities on inside thermal condition changes.

Figure I presents the overall summary of our works on thermal variation analysis in inside built environment.

D. Conclusion

In this research, we attempted to deal with several issues in thermal variation analysis of building envelope, such as longitudinal data collection, scalability, incorporating structural information, and contextual interpretation. We introduced generalized frameworks to build thermal profile for different surfaces with low-price temperature sensors and smartphone-associated thermal cameras using no building metadata. This will be helpful in developing sustainable non-intrusive remote monitoring of building envelope for energy efficiency.

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