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Automated mobile sensing: Towards high-granularity agile indoor environmental quality monitoring

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ABSTRACT

Indoor environmental quality (IEQ) is a critical aspect of the built environment to ensure occupant health, comfort, well-being and productivity. Existing IEQ monitoring approaches rely on sensor networks deployed at selected locations to collect environmental measurements, and are limited in scale and adaptability due to infrastructure cost and maintenance requirement. To enable high-granularity IEQ monitoring with agile adaptation to the dynamic indoor environment, we propose an "automated mobile sensing" system that dispatches a sensor-rich navigation-capable robot to actively survey the indoor space. Data collected in this fashion is sparse in the joint temporal and spatial domain, and cannot be used directly for IEQ evaluation. To deal with this special characteristics, we developed a spatio-temporal interpolation algorithm to capture the global trend and local variation in order to use the data efficiently to reconstruct the IEQ dynamics. We compared the performance of the automated mobile sensing with a dense sensor network in a laboratory where we measured the air-change effectiveness (ASHRAE standard 129) for four different conditions. Results indicate that automated mobile sensing is able to accurately estimate the parameters with a minimal sensor cost and calibration effort. Potential applications of this system include indoor thermal comfort, lighting, indoor air quality and acoustic monitoring, pollutant source identification, and building commissioning. We shared publicly the source codes for robot control, sensor setup, and interpolation algorithm to encourage comparison study and further development.

1. Introduction

Smart buildings are cyber-physical energy systems (CPES) that integrate sensing, data analytics, and control to provide essential services to the occupants. Buildings consume about 40% of primary energy in the U.S. and there is a fundamental drive for buildings to be *energy efficient* [1,2]. As people spend about 90% of their time indoors, they should also be *human-centric* by focusing on improving human health, comfort, well-being and productivity, and well-being [3–6]. This could be achieved effectively by monitoring and enhancing indoor environmental quality (IEQ), such as indoor air quality, thermal comfort, lighting and acoustics [7–9]. IEQ monitoring has been recognized as one of the fundamental strategies to obtain credits by various guidelines and rating systems, such as American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)/Chartered Institution of Building Services Engineers (CIBSE)/U.S. Green Building Council (USGBC) Performance Measurement Protocols for commercial buildings (PMP) [10] and Leadership in Energy and Environmental Design (LEED) [11]. For instance, environmental parameters (e.g., temperature, humidity) need to be continuously monitored when occupants take a "right-now" thermal comfort survey, according to AHSRAE/CIBSE/USGBC PMP [10]. LEED suggests CO_2 monitoring in all densely occupied spaces. In addition, IEQ assessment involves contaminants sampling in all occupied spaces, such as volatile organic compound (VOC) and particulate matter (PM) [11]. Guidelines, standards and rating systems recognize that more IEQ monitoring would be valuable but affordability constrain limits what is suggested to be used.

Due to complex indoor structures and dynamic environment, IEQ parameter distributions are often *inhomogeneous*, resulting in spatial variations in thermal environment and indoor contaminant exposure [12–14]. Furthermore, applications of personalized heating/cooling devices, aiming to reduce building energy use, augment such inhomogeneity [15–20]. Consequently, spatio-temporal monitoring of indoor environment can provide an comprehensive IEQ assessment.

Key challenges in the objective IEQ assessment of commercial buildings involve accurate, easy-to-use, and scalable sensing systems [21]. An effective approach is to implement wireless sensor networks; however, despite the continuous reduction in sensor cost and

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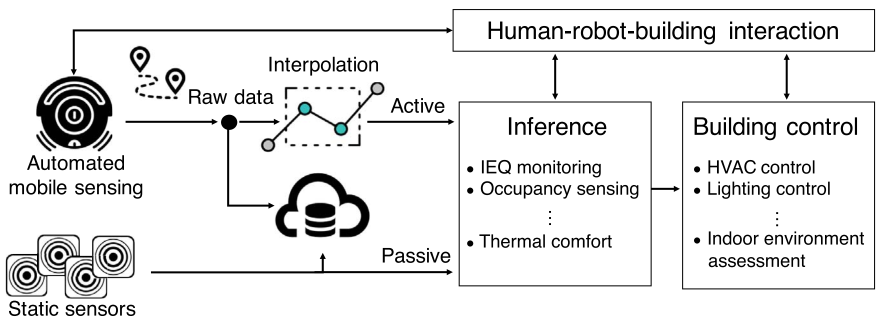

Fig. 1. Automated mobile sensing system overview. The robotic platform can either work alone or with static sensor network to actively estimate building context and facilitate building control.

simplification in deployment, infrastructure investment and maintenance might still remain a concern in the near future, especially when considering monitoring numerous IEQ variables simultaneously. Moreover, many sensors that require a significant amount of power (e.g., hot wire anemometer) can not easily become wireless. Additionally, buildings might undergo several renovations in their life-cycle, so *agility* is essential to adapt to the changing environment.

1.1. Main contributions and objectives

Differentiated from existing approaches of deploying static sensors for indoor monitoring, we propose a sensing paradigm of "automated mobile sensing" by leveraging a navigation-enabled sensing-capable mobile robot (see Fig. 1 for the overall architecture). This represents a paradigm of "active inference", where the robot can plan its path to take representative measurement samples at locations of interests, as compared to "passive inference" where the data collection is limited by the geolocations of static sensors.

From a data analytic perspective, unlike data from static sensors, the samples taken by the robot is highly sparse in time and space, as illustrated in Fig. 3. While existing interpolation mainly focuses on the spatial domain [22,23], we propose a data-efficient spatio-temporal (ST) interpolation method that extracts local and global trends and constructs an informative visualization of IEQ. Through experimental evaluations of zone air distribution effectiveness (air-change effectiveness, ACE), automated mobile sensing is compared with static sensing with a dense sensor network required by the ASHRAE standard 129 [24]. Note that the air-change effectiveness experiment is only used to demonstrate our novel platform, rather than to investigate possible factors that influence its value, for which we refer the readers to more established works [20,25–27]. It is, therefore, the objective of this paper to describe the novel "automated mobile sensing" system for indoor environmental quality monitoring, enabled by a sensor-rich navigation-capable robot to actively survey the indoor space.

2. Brief literature review

2.1. Indoor environmental quality assessment

IEQ assessment can be conducted using occupant surveys [5,28–30], personal monitoring [31–33], and sensor measurements [34–36]. Surveys provide subjective IEQ evaluation from occupant perspectives; however, survey design requires systematic effort to avoid bias and confusion, and the results can not be updated frequently due to user fatigue. Several online or mobile tools have been developed to allow users to vote their thermal or lighting preferences in real time [17,28]; however, the responses may reveal only subjective perceptions, like "the air is stale", but it rarely gives hints about the causes, such as increased indoor pollution caused by low outdoor air flow rate or unpleasant thermal environment due to malfunctioning mechanical systems.

Objective measurements, taken by static or mobile sensors during daily operation or performance commissioning, can accurately depict building environment and diagnose potential faults. Static sensors are deployed in a space to continuously monitor environmental parameters [1]; nevertheless, limited by cost, the deployment is often sparse in locations or absent, especially for expensive sensors like CO_2. In addition, while indoor environment is often inhomogeneous and unpredictable, the stationary sensors may not always be deployed in the optimal locations to reflect indoor environment. Personal monitoring systems, such as using infrared thermography [31] and physiological measurements [32,33,37] can offer assessment of individual comfort and inform building operation system of proper adjustments in real-time; however, they require users to be equipped with special instruments or sensors and may involve privacy concerns. For some IEQ parameters like indoor air quality, the effect on productivity and health may be long-term and cannot be readily captured by physiological measurements.

Mobile carts, such as an instrumented chair-like cart [34] and the IEQ cart [35,36] can hold multiple sensors to take measurements simultaneously at a given location. While the results are comprehensive, the carts often require considerable labor cost and manual navigation. Several studies exist to deploy robots for monitoring and identifying pollutants both indoor and outdoor [38–41]; however, the methods do not distinguish the global trend of physical parameters from their local variations, which might lower the estimation accuracy, and the results have not been validated against a ground truth, which requires a dense sensor network for comparison.

2.2. Continuous interpolation from discrete measurements

Data from static or mobile sensor measurements is highly sparse and requires interpolation for informative visualization. Spatial interpolation is a well-studied topic in geostatistical analysis and image processing communities, where methods like Kriging and Markov random field (MRF) are among the most prominent [22,23]. Kriging has also been combined with Gaussian MRF [42], Bayesian network [43], and principle component analysis [44] to improve the computational efficiency. In practice, this means that the algorithm can analyze a large amount of data within limited time span, thus enabling large-scale sensing.

Since Kriging is efficient with sparse data, it has been generalized to spatio-temporal interpolation [22,45]. Shape functions have also been introduced based on finite element mesh generation [46]. Variational Gaussian-process factor analysis is proposed to model the dynamics of spatio-temporal data [47]. Prior works assume multiple time series data from individual sensor stations, which requires continuity in time at a specific location; but the data from mobile sensing robot poses the challenge of high sparsity and non-continuity in time and space (Fig. 3).

Differentiated from existing interpolation methods, our method can efficiently capture spatial and temporal dynamics by constructing global and local trend estimators based on highly sparse data.