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# The SMART sensor: fully characterizing radiant heat transfer in the built environment

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Abstract. In a conventional indoor environment, thermal comfort is supplied by an air based distribution system. This system is controlled by an air temperature (and occasionally humidity) sensor, and the role of radiation in thermal comfort is often overlooked. In a typical indoor environment, slightly less than half of the heat occupants shed to maintain thermal comfort is lost to convection. The other portion is lost to radiation. We have developed the Scanning Mean Radiant Temperature (SMART) Sensor to fully characterize radiant heat transfer in the built environment. Combining surface temperatures and geometry allows us to produce 3D thermal point clouds which may be meshed to produce watertight surfaces. The view factor between occupants and environmental surfaces may be calculated, allowing us to accurately model radiative heat transfer. Additionally, this may be calculated for any location in the space, allowing us to map spatial variation of the mean radiant temperature from a single scan. In this paper, we use the SMART sensor to calculate the spatial distribution of mean radiant temperature over a range of environmental conditions. Its performance is validated using a net radiometer. The sensor demonstrates that there is frequently significant spatial variation of mean radiant temperature in typical indoor environments up to 4 °C.

#### 1. Introduction

Thermal comfort is determined by the combined effect of four environmental and two personal parameters: air temperature, humidity, velocity, thermal radiation, personal activity and clothing levels. [1] In typical building environments, more than half of the human body's total heat loss is due to radiative exchanges with the surrounding environment [2, 3, 4]; however, currently available building sensors are unable to measure this component. This has led to the systemic underestimation of its importance. Mean radiant temperature is a complex metric because it is explicitly defined in relation to human body and is dependent on both surface temperature distributions and spatial geometry. Consequently, it is not specific to a space but varies significantly depending on proximity to various surfaces and geometric occlusions. MRT is required to calculate thermal indices such as Predicted Mean Vote (PMV) [1], Physiologically Equivalent Temperature (PET) [5], and operative temperature [6]. However, researchers in academia and industry frequently assume that MRT is equal to air temperature [7]. The ASHRAE 55-2017 standard lists a series of conditions that must be satisfied for this assumption to be considered valid [6], but, in practice these requirements are rarely met. For example, widely used psychrometric charts and their prescriptive comfort zones [6] were developed under

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the assumption that MRT is equal to air temperature [8]. The exact ratio of convective to radiative heat transfer depends on the air temperature, air speed, and surface temperatures in the environment, which can dynamically change throughout the day. Additionally, increasing energy efficiency through occupancy or radiant-enhanced air temperature setbacks changes the relative importance of these modes of heat transfer. We have developed a new sensor to quantify impact of radiative heat transfer on thermal comfort. This is particularly valuable since it has been demonstrated that radiant temperature inputs are required for better model convergence[9] over primarily air based measurements [10].

#### 2. Methods

Our sensor, known as the Scanning Mean Radiant Temperature (SMART) sensor combines a LiDAR sensor and two radiant temperature sensors to spatially resolve surface temperatures into three dimensional thermal point clouds. The sensor rotates along two axes to capture a full sphere of data, measuring its position in polar coordinates at each location. These points are then converted to Cartesian coordinates representing every surface in the sensor's line of sight. These thermal point clouds are then meshed into watertight surfaces and used to calculate  $T_{MRT}$  every point in a room. Both temperature and spatial information are required to accurately measure  $T_{MRT}$ , since it is highly dependent on each surfaces view factor to an occupant, a concept that is abstracted using  $T_{MRT}$  as shown in equation 1. In this equation, A is the surface area of a person  $[m^2]$ ,  $T_{person}$  is the average temperature of the person [K],  $\varepsilon$  is the emissivity of the person and the surroundings, assumed to be equal [0.95], and  $\sigma$  is the Stephan-Boltzmann constant, [5.67 \* 10<sup>-8</sup> W m<sup>-2</sup> K<sup>-4</sup>]. Here,  $Q_{rad}$  is the radiant heat transfer in W between a surface and the hypothetical enclosure at  $T_{MRT}$ .

$$\frac{Q_{rad}}{A} = \varepsilon \sigma (T_{person}^4 - T_{MRT}^4) \tag{1}$$

Moving around a space with non-isothermal surfaces generates different  $T_{MRT}$  measurements since the view factor of each surface changes relative to the others. In normal building conditions, these non-isothermal surfaces could be caused by an exterior wall, single pane glazing, solar radiation gains, for example. This change is captured in the analysis of SMART sensor data, producing a thermal radiation map at each point in space calculating the view factor between each point in the volume and each surface element produced in the scan.

The definition of  $T_{MRT}$  in equation 1 can be updated to account for this spatial variability to calculate the MRT (°C) at any point in the space using equation 2.

$$T_{MRT} = \sqrt[4]{\sum_{S \in S} T^4 F_{P \leftrightarrow S}} - 273.15$$
(2)

Here, S is the set of environment surfaces, T is the temperature [K] of surface S, and  $F_{P\leftrightarrow S}$  is the view factor between the surface S and point P. The view factor must be calculated for each of the surfaces in the mesh in order to weight the corresponding surface temperature appropriately. Modeling the object of interest as a point allows the view factor  $F_{P\leftrightarrow S}$  to be calculated as the solid angle  $\Omega$  [sr] that the surface S subtends at the point P.

Creating a mesh from each x, y, z point in spherical coordinates as  $\theta, \phi, r$  provides a watertight volume within which the view factor of an arbitrary point to any triangular segment can be calculated using equation 3. This generalizable approach to view factor calculation can therefore yield a calculated mean radiant temperature at any spatial x, y, z point within the enclosure.

$$F_{P\leftrightarrow S} = \frac{1}{4\pi} \int \int_{S} \sin\theta \, d\theta \, d\phi \tag{3}$$



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**Figure 1.** A photo of the cubical pyrgeometer (a - left) array and the SMART sensor (b -right).



**Figure 2.** Plan drawings of (a - left) the large shared office space and the (b - right) small single occupant office, showing the distance between the SMART sensor and pyrgeometer, represented by a black circle and square, respectively.

To test the algorithm, a 3-axis pyrgeometer was placed at a fixed position at a known coordinate relative to the SMART sensor in two different spaces. The set of 6 pyrgeometers (each Apogee, SL-510-SS; 0.12 mV per  $W m^{-2}$ ; 1% measurement repeatability) were oriented orthogonally measuring radiant flux in all 6 cardinal directions. This pyrgeometer device is shown in figure 1a and the SMART sensor is shown in 1b. The SMART sensor has a LiDAR rangefinder (Garmin ®LIDAR-Lite v3; +/- 2.5 cm) and a 55° field of view (FOV) infrared thermal array (Melexis ®MLX90640; 24 x 32 pixels; +/- 1.5 °C) and a 5° FOV single point non-contacting infrared temperature sensor (Melexis ®MLX90614; +/- 0.3 °C). The single point sensor has a much higher accuracy than the array and was used to check the array measurements.

The two spaces were a large shared office space with small cubicles, and a small single person office. In the large office space, the SMART sensor and the 6-axis pyrgeometer were 8.71 meters apart, and in the single person office the two sensors were 1.8m apart. This is shown schematically in figures 2a and b. Locations at distances greater than the sensor dimensions were chosen to test the robustness of algorithms, but future validation work will use a more methodical distribution. In addition, having the sensors further from each other reduces mutual occlusion.

Data was collected continuously with the 3-axis pyrgeometer, reporting to a local server at 10 second intervals which were averaged over the course of a SMART sensor scan and is reported in the results. The thermal point cloud information from the SMART sensor was algorithmically processed remotely to provide a value for  $T_{MRT}$  at the location of the pyrgeometer cube, which we compare here. Data collection occurred overnight when the ambient outside temperatures dropped to approximately 18 °C.

#### 3. Results



Figure 3. Two dimensional slices representing the spatial variation of  $T_{MRT}$  in the large shared office space (left) and the single occupant office (right) shown in Figure 2. Note the temperature scales are shifted.

The SMART sensor data was meshed, processed and analyzed to produce two dimensional slices that illustrate the spatial variation of  $T_{MRT}$ . The large open plan office had significant spatial variation totalling almost 3 °C despite the mild conditions on the night of the experiment. The single occupant office was significantly smaller and only had 1.3 °C of  $T_{MRT}$  variation. The SMART sensor data was used to calculate the  $T_{MRT}$  at the location of the net radiometer in both datasets yielding Table 1. The cold spots are due to a cold window (left) and a table under a diffuser that becomes cooler (right).

	Calculated $T_{MRT}$	Net Radiometer $T_{MRT}$
Large Office	22.4 °C	22.6 °C
Small Office	24.0 °C	24.25 °C

**Table 1.** Comparison of  $T_{MRT}$  calculated from the SMART sensor data and measured using the Net Radiometer.

#### 4. Discussion

We hypothesize that comfort variation in the built environment and the challenges of predicting and maintaining thermal comfort can be partially attributed to a mismatch between point-based



Figure 4. A traditional comfort zone (red box) compared to the expanded psychrometric comfort zone (dark color gradient) [11]. Low air temperatures are allowed, so long as they are coincident with higher mean radiant temperatures which is not observed in the space.

signals and 3D comfort maps. While primarily characterized as a state of mind, physiologically comfort is influenced by the overlap of a radiatively, convectively, and conductively active heat engine positioned in an environment. This maps a 7 dimensional comfort parameter landscape to the body's skin. Simplifying comfort to a point in space greatly simplifies computational power and degrees of freedom for system intervention, however advances in sensors and spatial data structures has left the existing comfort framework oversimplified.

Data presented in this paper is from two representative experiments in rooms of different sizes and scales. Future work will provide more robust validation including higher spatial resolution of ground truth measurements and different room typologies. The results presented here are demonstrative of the sensor's capabilities to produce a spatialized MRT map from a single scan, an ability currently missing from the thermal comfort research tool set.

Figure 4 uses the expanded psychrometric presented at CISBAT 2017 [11] by Teitelbaum and Meggers to evaluate the data recorded by the SMART sensor. The expanded psychrometrics framework allows any air temperature and humidity on the psychrometric chart to be comfortable, so long as it is compensated for with an appropriate mean radiant temperature, as accounted for by an energy balance about the human body. The contour from 10 to 35 °C in figure 4 was calculated for a non-sweaty occupant at an office work metabolic rate of 1.2 met. The dark gradient shows the extent of the  $T_{MRT}$  range in the small office space, bounded by 20 to 60 %RH, the conditions often measured in the building. While the data could be used to reduce the air temperature setpoint locally, in reality the actual air temperature is too low uniformly to provide comfort around the entire space. In reality, achieving the required  $T_{air}$  to  $T_{MRT}$ separation of up to 8 °C to provide comfort at the colder air temperature points is difficult, and often the colder  $T_{MRT}$  measurements are coincident with colder  $T_{air}$  measurements. However, recent work has demonstrated methods for radiation and convection isolation, allowing design

freedom with both modes of heat transfer [12], requiring a refined analysis with data from the SMART sensor. Further work can be conducted to assess linkages between  $T_{air}$  and  $T_{MRT}$  with the SMART sensor.

#### 5. Conclusions

The SMART sensor data and algorithms allow us to determine the mean radiant temperature at any, and every, location in a space from a single scan. The sensor was able to calculate  $T_{MRT}$  at a location 8.71 m away within 0.2 °C despite variation of almost 3°C across the space. Future efforts will evaluate the SMART sensor's abilities across a wider range of environmental conditions and building spaces. Additionally, they will directly calculate the radiative heat transfer between the environment and a human body mesh rather than a single point. This will allow researchers to quantify the impact of different postures, clo values and body shapes without having to collect additional datasets.

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