Zurich, June 15-17 2016
Sustainable Built Environment (SBE) Regional Conference

Expanding Boundaries:
Systems Thinking for the Built Environment

SPHERICAL MOTION AVERAGE RADIANT TEMPERATURE SENSOR (SMART SENSOR)

E. Teitelbaum[1]*, J. Read[2], F. Meggers[3,4]

[1]Civil and Environmental Engineering, Princeton University, USA
[2]Waterloo Architecture, University of Waterloo, CAN
[3]School of Architecture, Princeton University, USA
[4]Andlinger Center for Energy and the Environment, Princeton University, USA
*Corresponding author; e-mail: eteitelb@princeton.edu

Abstract

Mean radiant temperature accounts for roughly 50% of an occupant's level of perceived comfort, however building controls and HVAC complaints are typically centred on air temperature. With the proliferation and acceptance of radiant technologies, which heat and cool more effectively, as well as problems with radiant asymmetry in zoned air delivery systems, the need for radiant temperature information is increasing. Accurate radiant temperature measurements from industry standard black globe thermometers are dependent on precise understanding of convective air movements. Directional cameras are very expensive with limited field of view. Our research has developed a novel mean radiant temperature sensor, coupling cheap electronic components and geometric weighting algorithms to provide spatially resolved mean radiant temperature measurements for any point in a defined space. Specifically, a LIDAR range finder is coupled with precise servos and a narrow field of view radiant temperature sensor, which allow spherical coordinates of radiant temperature readings to be recorded. This approach to visualizing and measuring directionality of radiant temperature could directly impact building climate controls. The device has been used with our research to record the mean radiant temperature of an outdoor pavilion, where standard black globe thermometers were unsuccessful, as well as to spatially assess the mean radiant temperature in office spaces deemed uncomfortable by occupants. The results presented in this paper will pull from results of concurrent studies to provide calibration, comparison, and spatial data for the SMART Sensor, as well as the geometric justification of the data.

Keywords:
Mean Radiant Temperature; Sensors; Thermal Imaging; Arduino

1 INTRODUCTION AND MOTIVATION

The field of Building Physics in the United States and abroad is continuing to embrace and improve (1) radiant systems, (2) precision control algorithms, and (3) thermal comfort metrics. Many advances have been made in these fields in the past decades, however the primary mode of improvement is frequently on the research side, with many ingrained practices remaining unchanged and ripe for new technology development. From poor thermostat performance to overlooked urban comfort, we have addressed issues 1, 2 and 3 with a new device to provide quick and inexpensive data on thermal conditions in our built environment. The system will not only enable increased comfort, but also help increase building heating and cooling performance, by far the largest part of the energy demand of a building helping to make buildings responsible for 40% of CO_2 emissions in the USA according to the US Department of Energy [1].

Our system is a non-contacting mean radiant temperature sensor, which is instrumental in addressing items 1, 2, and 3 above. Standard equipment for such measurements is often expensive, subject to heat loss due to convection

DOI 10.3218/3774-6_115, ISBN 978-3-7281-3774-6, http://vdf.ch/expanding-boundaries.html

to air, and gives very little information aside from the overall mean radiant temperature [2]. Conventional approaches include black globe thermometers, technology that has been unchanged for nearly a century [2], or rely upon expensive instruments that have an extremely limited resolution [3,4]. Our SMART Sensor provides spatially resolved radiant temperature information, which is applicable to research, construction, and comfort controls domains. The SMART Sensor technology is not subject to heat losses or gains due to convection from wind or diffusers, making the technology universally deployable and more desirable than a black globe radiant temperature sensor, the industry standard. Such novel sensing allows for greater control capabilities for radiant exchange, for which there are many guidelines [5].

The SMART Sensor is an extension, combination and novel application of several technologies: a 5° field of view (FOV) Melexis radiant temperature sensor, a 2° FOV LIDAR Lite rangefinder, and two servos that swing the sensors through space in a spherical shell motion powered by a single microcontroller. At each point, temperature, distance, axial, and azimuthal readings are recorded. These values are then post-processed to provide information including air temperature, radiant temperature, and directional information. These are all essential for a true thermal comfort assessment or controls algorithm, but difficult to obtain with standard sensors. Additionally, as opposed to conduction and convection, which are superficially and volumetrically oriented processes; radiant heat transfer has a geometric component as well. For example, two occupants in the same room will not perceive the same mean radiant temperature, as they will experience surfaces and objects with different view factors. Therefore, the net energy balance with the inclusion of the radiant component, responsible for 50% of one's thermal comfort, cannot be precisely measured for an arbitrary number of locations in a room with one measurement. From spatial data obtained from the SMART sensor, the MRT can be approximated for any point in a room from a single measurement.

2 METHODS

The system development includes the device as well as the algorithms associated with post-processing of the data. The SMART sensor represents a novel implementation of components, a narrative behind placement and construction, and important algorithms for data processing.

2.1 Components

The SMART Sensor is controlled by an Arduino Yun microcontroller, which sends data via a serial communication to a receiver. This data can be used in real time to visualize a space, or for further post processing by a user in a software such as Matlab. Images in this paper were created via this route. The Yun microcontroller was chosen as there is a built-in SD card slot, allowing data to be written to the SD card as well allowing for portable operation without computer assistance.

The servos deployed in the sensor's operation are manufactured by Parallax, and include a continuous rotation servo and a 180° servo. The continuous rotation servo is calibrated prior to use, determining the rotational velocity and using a timed control to provide a precise angular rotation. The 180° servo is simpler in operation, as its angular position is controlled by an internal mechanical system, with a program-specified angle. The azimuthal and rotational angles are calculated and reported to allow for plotting of the space in spherical coordinates. To calculate object distance, the SMART sensor has a LIDAR Lite module, is able to determine distances between 0-40m with accuracy of ±0.025m and can take up to 500 readings per second.

The infrared temperature sensor used is a Melexis MLX90614 5° FOV non-contacting temperature sensor. The accuracy of the sensor is ±0.5 °C for an ambient temperature of 0-50 °C and object surface temperature of 0-60 °C. Within this range, accuracies are typically better with an accuracy of ±0.1 °C from 20-30 °C, which includes the majority of temperatures in the building physics domain. When taking readings of the sky, accuracy goes down to ±1 °C. The functional range of the sensor is -70 to 380 °C.

2.2 Data Processing

This data is recorded in a string and sent via serial as a 4-tuple as (distance, rotational angle, azimuthal angle, temperature). This allows data to be reproduced as a 3 dimensional representation, or with only temperature data as a spherical shell representing the net radiant heat flux through a spherical control volume around the sensor. Both approaches offer useful interpretations.

For the sensor, surface temperature is known for each point in a spherical mesh, with a desired weighted average of all readings. The problem is a simple geometric weighting transformation, which requires only knowledge of the mesh. By transforming to Cartesian coordinates first, a geometric weighting algorithm can compress each vertical column into a single data point, creating a line over which all values are equal which can then be averaged. In Fig. 1 below, this is accomplished for an image where the author's outline is clearly observed. The average from the top of Fig. 1 gives an MRT of 21.9 °C.

G. Habert, A. Schlueter (eds.): Expanding Boundaries © 2016 vdf Hochschulverlag AG an der ETH Zürich
DOI 10.3218/3774-6_115, ISBN 978-3-7281-3774-6, http://vdf.ch/expanding-boundaries.html

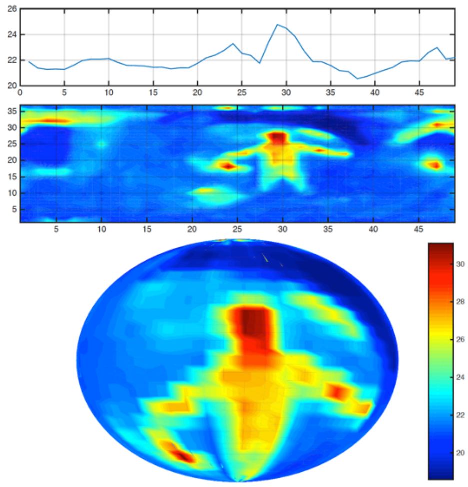

Fig. 1: Spherical information (bottom) Cartesian map (middle) to weighted distribution (top).

2.3 Case Studies

The sensor has been deployed in research by the Princeton C.H.A.O.S. Laboratory in campus and other experimental settings. There are many unique opportunities for such a novel sensor, and future studies will examine the capabilities and limitations of the sensor. This section contains brief descriptions of current applications of the sensor technology

Thermoheliodome

An experimental radiant cooling pavilion developed and built in summer 2014 by C.H.A.O.S. Lab, required a precise measurement of the MRT observed by an occupant at the focal point of the structure's geometry. The SMART sensor was developed for this application, as convective losses in an outdoor setting are large and inaccurately correlated with black globe thermometer readings. In fact, black globe thermometer readings were imprecise and noisy. Data was recorded and used in conjunction with air temperature to calculate the operative temperature inside the space, which informed calculations regarding performance of the structure compared to other cooling technologies.

Office Assessments

A case study was performed in the Princeton University School of Architecture, where comfort complaints were investigated using an air temperature sensor as well as the SMART sensor. Results were not scientifically analysed, however were able to be used to inform solutions, such as when a thermostat setpoint change was necessitated versus window shading or duct configuration changes.

Comparison to IR cameras

Additionally, the SMART sensor was compared to top of the line high FOV infrared imaging cameras. While the two sensors are in two different domains as far as imaging and analysis, the two were compared to demonstrate the trade-off between resolution and spatial data with regard to thermal comfort.

3 RESULTS

Initial prototyping and calibration has led to a successful prototype operation and a patent disclosure. Fig. 2 shows a prototype of the SMART sensor, equipped with LIDAR Lite and an infrared non-contacting temperature sensor. The binocular-like portion is the LIDAR Lite element, and the smaller cylinder underneath is the 5° FOV non-contacting temperature sensor. They are held tightly in place with adequate separation as to not interfere. The rigid construction ensures reproducible results.

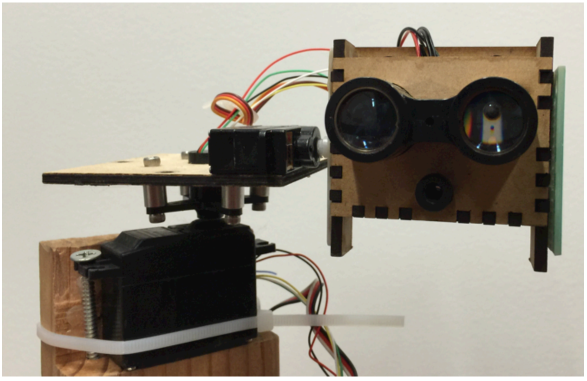

Fig. 2: SMART Sensor prototype.

3.1 Thermoheliodome

As mentioned in the methodology, the SMART sensor was initially developed to measure MRT in outdoor cooling pavilions. In this scenario, insensitivity to convection is essential. The sensor was able to produce reliable measurements, and produce a 3D point cloud of the Thermoheliodome (Fig 3c). The values were particularly enlightening because the site was adjacent to a building, and the MRT measured inside was clearly influenced by a warm wall on the adjacent building. The warm temperatures shown in Fig. 3b are caused by this wall. While the MRT data was taken from an earlier sensor prototype than the one described in this paper, it was spatial information from the SMART sensor that fully described how the difference between air temperature and MRT was created by the wall outside of the pavilion.

G. Habert, A. Schlueter (eds.): Expanding Boundaries © 2016 vdf Hochschulverlag AG an der ETH Zürich
DOI 10.3218/3774-6_115, ISBN 978-3-7281-3774-6, http://vdf.ch/expanding-boundaries.html

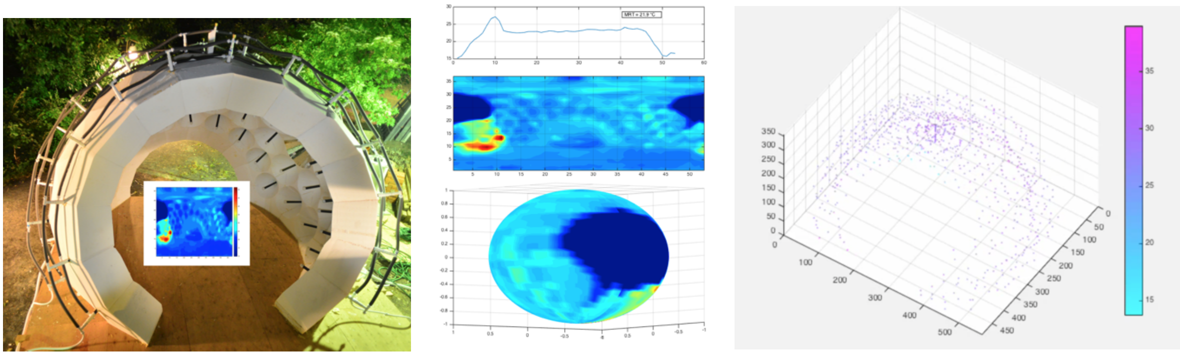

Fig. 3a-c: a (left) – Photo of sensor data in a dome-shaped radiant cooling pavilion; b (middle) – Temperature data plotted and weighted to provide radiant temperature, compared with air temperature; c (right) – A spatially resolved image of the pavilion with locations represented in colour corresponding to the temperature reading.

The spatial information provides a strong understanding of view factors, shading, and important surface temperatures. In the case of the Thermoheliodome, the data suggests repositioning the dome such to avoid incident re-radiation from the adjacent heated wall. While the sensitivity of the dome's geometry relative to the sun path prohibits this, the information is instructive nonetheless.

3.2 Office Assessments

This experiment was used as a demonstration of the utility of the SMART Sensor. Thermal maps of offices were examined and occupants were informed of any changes in behaviour or system controls that were informed by the images.

Fig. 4 shows an image taken from the Princeton University School of Architecture IT office. Warm regions increase the MRT of an occupant seated at the main desk to 28.9 °C. The air temperature is also high, 28 °C, implying an air side issue, rather than only a radiant component to the comfort complaint. In fact, this evidence prompted contacting building facilities, where it was learned that a cooling coil was broken at the time of the study.

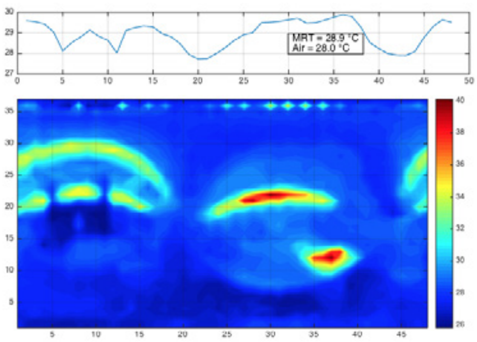

Fig. 4: Server room and IT Office.

Fig. 5 shows an exterior office on the ground level, with a large window with poorly sealed operable symmetric window panels on either side, shown in the middle of the figure. The MRT in this space is 20.6 °C, compared to a comfortable air temperature of 21.5 °C. This data implies comfort could be improved by installing shutters to reduce the amount of cold surface area in the space. Increasing the air temperature is not possible, as there are other rooms controlled by the same setpoint in the hall that would become overheated.

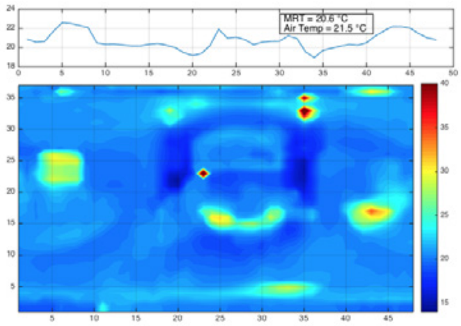

Fig. 5: Exterior Ground Floor Office.

3.3 Comparison to IR Camera

Information from our sensor was also compared to a high-resolution thermal camera, the E60 manufactured by FLIR, with a 45° wide angle lens. The purpose of FLIR's camera is primarily diagnostics and other documentation, as well as detailed non-contacting temperature profiles. As far as resolution, the E60 is far superior. However, while the E60 gives detailed information per particular views, even a 45° FOV lens represents a small fraction of the space's surface area when viewed from the same point as the SMART sensor is set up. Compared to a 90° FOV, representing approximately one octant, a 45° FOV image from the same point in space will only contain 17% of the overall surface area. Therefore, assuming there are 8 octants making up the SMART sensor's image, 46 non-overlapping images would be required to reproduce the SMART sensor's image with the E60. In reality, this is the worst-case scenario, as there are many geometric ways to reduce this number. This comparison is still instructive.

G. Habert, A. Schlueter (eds.): Expanding Boundaries © 2016 vdf Hochschulverlag AG an der ETH Zürich
DOI 10.3218/3774-6_115, ISBN 978-3-7281-3774-6, http://vdf.ch/expanding-boundaries.html

Additionally, from one revolution of the SMART sensor, mean radiant temperature data can theoretically be calculated for each point in the space since the room is plotted in a 3D geometry. The E60 or similar cameras would be limited to a spherical approach (i.e. Fig. 3b rather than Fig. 3c) Even in this scenario, splicing photos together to create a sphere (i.e. going from a Cartesian map to a spherical globe) is difficult since edges are poorly defined compared to standard visual spectrum images used in splicing applications. As the Melexis sensor values compare well to a calibrated FLIR E60 as shown in Fig. 6, the authors believe the SMART sensor is the best way to obtain mean radiant temperature information.

Fig. 6: SMART Sensor point cloud (left) with components shown in comparison to images of the same features from a FLIR E60 (middle and right).

4 DISCUSSION

There is a vast application potential across the thermodynamics research and building physics domain. The system is borne from the Internet of Things (IoT) revolution, which seems to self-catalyse novel sensing devices. The NEST thermostat for instance is a novel device in which users set comfort levels remotely from their house, maximizing comfort and minimizing energy use and costs, but still depending on single air-temperature sensing alone. Our system would allow a radiant component of thermostat controls, which would allow for even greater savings with technologies similar to the NEST. Large companies such as Honeywell are currently embracing the Industrial IoT and using 3D modelling technology to enhance user experiences. The SMART sensor fits with this motif.

Aside from the Internet of Things hype, thermal imaging manufacturers have been extending the infrared imaging market to standard consumers, by making more affordable products that connect to smart-phones, or producing other standalone pocket-sized peripherals. Our system fits squarely in this new field, and is a prime example of the expansions of available information to improve building controls and performance. A typical thermal camera costs upwards of USD $1000, largely due to the expensive glass to filter visible light and allow IR through. The expensive glass in turn also limits the field of view because making wide-angle lenses like fisheye lenses is not economically feasible. Our system solves this in an inexpensive manner by panning a $35 single sensor around a space and reconstructing the full surface digitally.

A single sensor is promising, but a set of sensors may be the long-term solution in terms of producing the surface temperature map of a space. For instance, in a building controls application, it may not be pertinent to introduce a moving part to perform such a central operation. Therefore, the SMART sensor in its current iteration may be limited to a one-time building controls calibration use, whereas an implementation with a set of fixed sensors may be the permanent solution. However, the novelty of having MRT data for each point in a space is a hugely useful starting point from a radiant system controls standpoint.

5 CONCLUSIONS AND FUTURE WORK

Future research includes producing a more compact, watertight enclosure and allow for more research and work to be performed on the post-processing of the data. The end goal would be a sleek, compact product that comes with an application package that seamlessly allows analysis of any space. New rapid prototyping systems for small scale milling of parts and PCBs and 3D printing will be acquired along with a larger set of sensors to test and deploy the device. Additionally, research as part of a larger controls project informed by data from a SMART sensor would be a promising area.

6 REFERENCES

1. U.S. Department of Energy (DOE), “2011 Buildings Energy Data Book“ Prepared for the DOE Office of Energy Efficiency and Renewable Energy by D&R International, 2011.

2. Spagnolo, Jennifer, and Richard De Dear. "A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia." *Building and environment* 38.5 (2003): 721-738.

3. Thorsson, Sofia, et al. "Different methods for estimating the mean radiant temperature in an

G. Habert, A. Schlueter (eds.): Expanding Boundaries © 2016 vdf Hochschulverlag AG an der ETH Zürich
DOI 10.3218/3774-6_115, ISBN 978-3-7281-3774-6, http://vdf.ch/expanding-boundaries.html

outdoor urban setting." *International Journal of Climatology* 27.14 (2007): 1983-1993.

4. H¨oppe P. 1992. A new procedure to determine the mean radianttemperature outdoors. Wetter unt Leben 44: 147–151.

5. Wessel, D. J. "Ashrae fundamentals handbook 2001 (si edition)." *American Society of Heating, Refrigerating, and Air-Conditioning Engineers* 31 (2001).

G. Habert, A. Schlueter (eds.): Expanding Boundaries © 2016 vdf Hochschulverlag AG an der ETH Zürich
DOI 10.3218/3774-6_115, ISBN 978-3-7281-3774-6, http://vdf.ch/expanding-boundaries.html