Simulating Invisible Light: Adapting Lighting and Geometry Models for Radiant Heat Transfer

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ABSTRACT
Thermal radiation, being the infrared spectrum of electromagnetic radiation, shares many characteristics with visible light, and thus is highly dependent on surface geometry. Much research effort has been dedicated to characterizing the behavior of visible light in the built environment and its impact on the human experience of space. However, longwave infrared radiation’s effect on the human perception of heat within the indoor environment is still not well characterized or understood within the design community. In order to make legible the embodied effect of radiant surfaces’ geometry and configuration, we have developed a Mean Radiant Temperature simulation tool which is based on a raytracing technique and accounts for the detailed geometry of the human body and its surrounding environment. This paper is meant to provide an overview of the geometric characteristics of radiant heat transfer with a dual purpose: 1. the integration of these principles into a Mean Radiant Temperature simulation technique in order to better characterize radiant energy exchanges and 2. the development of architectural design strategies based on these principles, which are tested in a case-study prototype. The MRT simulation method and results for the experiment are discussed.

Author Keywords
Longwave Radiation; View Factor; Raytracing; Mean Radiant Temperature.

ACM Classification Keywords
I.6.1 SIMULATION AND MODELING

1 MOTIVATION AND BACKGROUND
Radiant heat transfer may account for more than half of the thermal comfort for occupants in the built environment [14]. Investigation of radiant systems into building are critical for energy savings, since nearly 20% of the total energy demand in the United States is used for heating and cooling the buildings in 2018 [7]. With heightened interest in radiant heating and cooling systems due to their increased efficiency over air systems [11], it has become imperative to develop a simulation tool that makes the consequences of radiation heat exchange legible to designers.

The main method to characterize the radiant heat exchange between a body and its surroundings is its representation within the comfort heat balance as Mean Radiant Temperature (MRT). MRT has been taken into account in several thermal comfort model indexes such as predicted mean vote (PMV) and physiological equivalent temperature (PET). Nevertheless, there is a fundamental ambiguity regarding the concept because of the degree of geometric complexity which it represents [9]. The definition of mean radiant temperature in the 2017 version of ASHRAE-55 standard is “uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure” [1]. The calculation of MRT thus involves the proportion of radiation transferred between every portion of the surface on the human body and all surrounding surfaces, weighted by the view factor between them. Because of its complexity, abstraction and simplification methods for MRT representation have been employed.

While all other environmental comfort variables (air temperature, relative humidity, and air velocity) are dependent on the medium of air, MRT is independent of the air and is in fact a complex representation of the exchange between the body and the surrounding surface geometry and its variable material characteristics and energetic states. A temperature abstraction is necessary to enable direct comparative engagement by researchers and practitioners with the effects of radiant heat transfer in space. Still, the result of using MRT as the only metric for radiation impact on comfort, has led to a generalization and lack of appreciation of the importance of geometry in how it is spatially resolved. Therefore, it is critical to reconsider the fundamental physics of radiant heat transfer for what they are: infrared radiation is part of the same electromagnetic spectrum as the light we see, yet at longer wavelengths.

In this paper, we are proposing an improved method to simulate MRT by building upon existing literature. To highlight its advancements beyond the conventional methods, we reviewed the state-of-the-art approaches qualitatively, and provide a case study where we demonstrate improved MRT accuracy by implementing our method to a recent project in Singapore. Additionally, contemporary 3D-
modeling tools allow for a rigorous representation of the body’s surface geometry, as opposed to its abstraction into a platonic shape or a point in space.

2 SIMULATION TECHNIQUE

In the following section, existing methods of geometric representation of light and the human body are described and adapted towards the radiant heat transfer simulation.

The definition of MRT co-evolved along with the mathematical model for view factor. Since 1966 when mean radiant temperature was first defined in a standard by ASHRAE, the continual wording changes from “solid body” which abstracts the human body as a solid sphere to “human body” as well as from “environment” to “enclosure” show the increasing consciousness towards the inherent geometric complexities of both human body and the surrounding environment [2]. At an early stage of its evolution, the definition of MRT was equivalent to mean spherical irradiance, using a small black sphere at the test point to replace human body. The mean radiant temperature $T_r$ at a point $P$ can be derived from the Equation (1), where view factors $F_{p-s}$ between the point $P$ and all the surroundings are used to weigh the surface temperatures $T_i$:

$$T_r^4 = \sum_{i=1}^{n} T_i^4 F_{p-i} \quad (1)$$

Equation (1) is very commonly considered the equivalent mathematical representation of MRT and widely used among textbooks, standards and design guidelines [1] although the underlying assumption is that the human body is viewed as an infinitesimal point.

The improvement proposed here over the series of simplifications historically applied to MRT, is based on state-of-the-art methods used in existing literature and can be considered within three categories: the determination of view factors, adopting ray-tracing techniques from visible light simulation, and using more detailed body geometry. We will first review the most relevant recent advancements within each respective sector before presenting our method in the subsequent sections.

2.1 Determination of View Factors

Rather than simplifying the human body to a single point, there are several successive alternative methods for calculating view factors in a more precise way. One is the Fanger-Rizzo method, which mainly analyzes the geometric relationship in a Cartesian coordinate system. Fanger provided the graph of view factors based on tabulated data for a standing or seated human body and a surrounding rectangular plane based on experimental data, which was further developed by Rizzo into algorithms that automatically compute view factors between seated or standing occupant and the orthogonal surfaces of the Cartesian coordinates. Rizzo further developed algorithms to automatically compute the view factor based on Fanger’s data [3].

Nusselt Analog is another commonly used method in determining view factors between a point and the surrounding non-orthogonal surfaces. It was first developed by Nusselt to achieve the figure-factor integral. The Nusselt analog utilizes a unit-radius hemisphere centered at the point of interest on which the target surface is projected. Then if the projected surface on the hemisphere is projected onto the plane at the bottom, the measurement of solid angle which is needed for view factor is simplified to the calculation of areas on the plane [9]. As is shown in Equation (2), the view factor $F_{p-s}$ from the point $P$ to the surface $S$ is a function of the projected area $S_2$ on the plane at the bottom of the hemisphere.

$$F_{p-s} = \frac{S_2}{\pi} \quad (2)$$

Based on the Nusselt Analog method, a method named “Numerous Vectors (NV)” has been proposed in recent years [10]. Rather than projecting surfaces by the Nusselt method, the NV method utilizes the vectors emanating from the center point directly. The next step followed is to distribute points on the unit sphere spatially evenly. Every point on the surface of the sphere is connected to the centered point forming vectors of every direction in a certain resolution. The radiation flux represented by the vectors is thus traced backwards to hit the surrounding surfaces. The view factor can be calculated by Equation (3), where $F_{p-s}$ is the view factor of the desired point $P$ to a surface, $N^i_k$ is the count of the rays hit the surface and $N$ is the total number of rays.

$$F_{p-s} = \frac{N^i_k}{N} \quad (2)$$

The use of vectors allows for a sufficiently accurate and convenient calculation in computer simulation, as the he NV method makes the vector-based representation of view factors feasible and this is the reason for its widely combination with simulation tools. However, the use of this method in the past has been limited to the outdoor MRT and the human body was considered as a small black sphere [16]. Related to this method, the ray-tracing technique can be further used to trace the continual radiant interreflections between multiple surfaces.

The NV method is adapted in the simulation technique proposed in this paper (see Fig. 1).

![Figure 1: Numerous Vectors method for calculating the view factor.](image-url)

2.2 Raytracing Technique

The comparison study between visible light and infrared radiation is not rare. The research on the flow of light used
the concepts of scalar and vector illumination since 1960s [13]. Many simulation tools in the computer graphics field have been specifically developed to track visible light in the through raytracing methods. Those simulations include specular, diffuse and directional-diffuse reflection and transmission with specialized operators for each of them. The lighting simulation and rendering system named RADIANCE is the most widely used light rendering systems in the past two decades [30].

The shortwave radiation includes direct, diffuse and reflected light fluxes. When the raytracing technique was first used in the two-pass method, the diffuse part of interreflections was still calculated according to the radiosity method, introduced by Cohen and Greenberg [15], using a simplified coefficient for diffuse contributions. Along with the development of computing capability, diffuse emissions have been incorporated into Monte Carlo simulations of heat transfer and renderings [30],[32].

The RADIANCE rendering equation, which is conducted iteratively for multiple bounces, provides pixels brightness representation of test points based on energy passing through them [30]. It characterizes energy passing through a point in a specific direction, where outgoing radiance from a point on a surface is calculated in terms of incoming radiance over the projected view hemisphere of that point. This is based on the principle of conservation of energy:

$$\varepsilon + \rho + \tau = 1$$

(3)

where $\varepsilon$ is the portion of radiation absorbed/emitted, $\rho$ is the portion of radiation reflected and $\tau$ is portion of radiation transmitted.

For MRT simulation, a test point on the human body can be calculated as the origin for raytracing. If we consider raytracing of four bounces (Fig. 2), the perceived radiant temperature $T_r$ for a point 0 on the body would be:

$$T_{r0}^4 = \varepsilon_1 T_1^i + \rho_1 (\varepsilon_2 T_2^i + \rho_2 (\varepsilon_3 T_3^i + \rho_3 T_4^i))$$

(4)

where $T_i$ is the surface temperature at point $i$, $\varepsilon_i$ is the surface emissivity fraction and $\rho_i$ is the surface reflectivity fraction. Note that $\tau$ was dropped since the energy transmitted through the point does not affect the point’s radiant temperature. However, in this equation, for non-opaque surfaces, $\varepsilon + \rho$ does not equal 1.

Equation 4 only accounts for specular reflections. For diffuse interreflections, a caching system as used in RADIANCE [30] must be used or the simulation process would require exponentially more computational power.

While reflections between surfaces can be either diffuse or specular, all emissions from a terrestrial surface are diffuse and their intensity is distributed according to the Lambertian cosine law:

$$I = I_0 \cos \varphi$$

(5)

where $I$ is the radiant intensity (w/m² sr) $I_0$ is the radiance normal, i.e., perpendicular, to the emitting surface, and $\varphi$ is the angle between the emission direction and the normal to the emitting surface. The maximum intensity is in the direction of the normal to the surface and decreases in proportion to the cosine of the angle between the normal to the surface and the emission direction [31]. We use this equation to calculate the intensity of emission for each vector representing a direction of diffuse heat flux from a body to an environment. Fig. 3 visualizes the Lambertian Cosine law in 3D space, as used in our MRT simulation, treating emitted heat fluxes as vector emanating from a sample point on a Lambertian surface. In the context of our raytracing method, we may think of MRT as the mean of all the surface temperatures intersected by the heat flux vectors emitted from all the sample points on the human body.
We thus have as our MRT equation for N body segments:

\[
T_{\text{MRT}} = \sqrt{\int \sum_{j} \cos \theta \frac{v_i}{N v_i^2} \frac{dA_j}{N_a}}
\]

where \(N_a\) is the number of subdivisions of the body surface; \(dA_j\) is the fractional area of the body surface with centroid point \(j\) out of the full body area; \(N_v\) is the number of vectors emitted from point \(j\), \(\theta\) is angle between the emitted vector and the normal to the emitting surface; \(T_r\) is the perceived radiant temperature at point \(j\) after multiple bounces, calculated according to Equation 4.

Fig. 4 shows a sequential comparison of the method utilized in RADIANCE as compared to the algorithm used in our own method for calculating MRT.

### 2.3 Body Geometry

Accounting for mean radiant temperature precisely is largely limited to the body geometry complexity. For thermal comfort calculation, body surfaces of different body parts are related to specific condition of metabolic heat production, sweat evaporation, cloth covering. Furthermore, the body geometry model determines also the body position and movement. All these factors are given major focus in the rising research of localized thermal comfort [35]. Several different methods for simplifying the body geometry model are listed and compared in Table 1.

As described in section 2.1, the simplification method commonly used for body geometry is to assume the human body as a single point [4]. The computational workload is largely alleviated when the view factors between a point and surrounding surfaces needs to be calculated as opposed to complex body geometry.

Apart from view factor calculation, another parameter directly related to the human body geometry, is called projected area factor. The projected area factor is the ratio of the projected area of the human body on the surrounding surface to the “effective radiation area,” which is defined as the surface area of the human body directly involved in radiation transfer. These two values are required for the computation of the MRT. In the case of abstracting the human body into a point in a sphere, the projected area factor can be derived from a solid angle method.

In order to obtain the projected area factor of the human body when projected on its surroundings, Fanger utilized the parallel ray method with the aid of a photographic method. Silhouettes were used in many studies for the comparison of body shape [24]. The body posture (standing or seated), the body shape (for each gender separately) and the clothing condition were taken into account during the experiment. Since the average body shape given as samples varies, different results can be derived in different experiments [28].

Other studies utilized physical models with simple outlines representing the standing and seated human body for experiments [17].

Another prevailing method is to simplify the human body as a single solid figure. This method is also applicable for the derivation of view factors by numerical integration of projected area factor. A seated person is simplified into a sphere, a box or a cube, while a standing person is simplified into a cylinder or an oval cylinder. The projected area factors and the resulting view factors calculated based on these shapes are compared in terms of accuracy [29].

Before the aid of 3D models, manikins were used for thermal experiments. The physical manikin at [6] consists of 16 body segments and each segment is controlled and monitored for calculating the heat transfer. As the increasing computing power contributes to continually emerging simulation tools, different software adopt the simplification method of different degree, since the complete accounting of all view factors between every surface of the human body and the surrounding surfaces is not feasible. Among current simulation tools, there is only a small portion of software have detailed body geometry model including definable human body shape and position [12,21]. One commonly used method to simplify the human body geometry is to abstract different parts of the body into similar solid figures such as cylinders, spheres and cuboids. Many studies divide the human body into 16 to 18 segments for demonstrating the
different sensitivities towards thermal radiation and perception on these segments. One example is the ThermoSEM model representing the human body with 18 cylinders and 1 sphere, each of which has detailed layers for calculating heat transfer between different depth of the body [22]. Despite these simplifications have greater accuracy than previous methods.

<table>
<thead>
<tr>
<th>Method</th>
<th>Level of Detail</th>
<th>View Factor Method</th>
<th>Cases</th>
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<tr>
<td>Point</td>
<td>Single point</td>
<td>Equation for the view factor between a</td>
<td>Chung 2010</td>
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<td>point and a surface</td>
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<td>silhouettes</td>
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<tr>
<td>Single shape</td>
<td>A cube, box, sphere for seated person;</td>
<td>Solid angle method using the projected</td>
<td>Vorre 2015</td>
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<td></td>
<td>a cylinder or an oval cylinder for a</td>
<td>area factor to derive the view factor</td>
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<td>standing person</td>
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<tr>
<td>Several</td>
<td>Around 16-18 segments of cylinders,</td>
<td>Solid angle method using the projected</td>
<td>Miyana 2001, Schellen 2013</td>
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<tr>
<td>solid</td>
<td>spheres and cuboids</td>
<td>area factor to derive the view factor</td>
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<td>Mesh</td>
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<td>Discretized for test points</td>
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Table 1. Evaluation of simplified body models that can be used to calculate the view factor between the human body and the surrounding surfaces.

In Huizenga et al [34], the authors demonstrate how to derive view factors for MRT from a discretized 3D model. In fact, it has been possible to use detailed body geometry model for decades in ubiquitous 3D modeling software. However, currently available MRT simulation tools still lack detailed body geometry model to achieve necessary resolution demanded by localized thermal comfort research, especially for longwave radiation.

Fig. 7 (from the following case-study) shows the simulation we have developed to integrate 3D-modeled human body geometry into an MRT analysis. For digital simulations, there is no reason to use simplified geometries of cubes or cylinders, since in today’s 3D environment, even free-from or highly complex surfaces can be discretized. Using a human body mesh, discretized into triangular segments, with test points at the center of each triangulated mesh, we generate vectors according to Lambertian emissions as shown in Fig. 3, and use raytracing to obtain the radiant temperature for each test point, which can be added and averaged to receive the final MRT per equation 6. We are even able to obtain the effective radiation area of the body using the ray-tracing method, checking for self-intersections of the body which shade it from the surrounding environment (Fig. 5). As seen in Fig. 5, each area of the body may be exposed to the radiant environment to a different degree, depending on the body’s position and clothing.

3 CASE-STUDY
We employed the simulation method for an experimental radiant cooling pavilion we built in Singapore. Radiant cooling panels using an infrared transparent membrane to protect sub-dewpoint cooling surfaces from condensation (cite ASR) are the primary envelope in a specific geometric configuration to maximize radiant cooling. Experimental data is collected allowing the simulation to be validated and better understand the design of surfaces that influence more precisely the effect on the MRT of the occupant.

The pavilion was constructed at the United World College, Southeast Asia in Singapore from August to October 2018. The pavilion is enclosed by ten 1.2m x 2.1m (4’ x 8’) panels; two horizontal panels at the top and eight vertical panels, with north and south facing entrances. The surface of the panels are cooled down by chilled water from custom variable speed chillers to provide radiant cooling. For discussion of the special cooling panel, refer to our previous work [25,26].

For the MRT simulation technique, the relevant parameters are: active cooling panel temperature: 18.7°C; surrounding ground temperature: 39.2°C; non-active pavilion surface average temperature: 31.3°C; Air Temperature: 29.6°C; Skin/clothing average Temperature:30°C.
3.1 Methods for Case-Study Simulation

Two MRT simulations are conducted: The MRT Gradient Map and Full-Body Simulation and Validation:

The MRT Gradient Map uses a single point abstraction of the body, to provide an MRT gradient map for the full space. For this first method, a grid of 750 points is created on a plane at a fixed height of 1m above the floor. At each location on this grid, 1,280 geodesically distributed rays emanate. They intersect the surfaces around them, with assigned known surface temperatures, and the temperature value at each intersection is averaged and recorded as the mean radiant temperature at each point on the grid. A color gradient is then created based on the MRT values. This method used the numerous vectors technique described in the previous section and ray-tracing with multiple bounces for reflective surfaces and Lambertian distribution. The main goal of this first simulation is to evaluate the effect of view factor of radiant surfaces on the perception of comfort at different points in space.

The Full-Body Simulation and Validation provides a detailed human body geometry mesh, where the centroid of each subdivided triangulated part of the body is used as a test point (Fig. 7). A geodesic hemisphere with Lambertian distribution (Fig. 3) is then created and the vectors emanating from the test point are ray-traced through multiple bounces, registering surface temperatures and emissivity/reflectivity/transmissivity values for each intersection. The result is computed based on Equation 6 where the numerous vector method replaces the analytical view factor, and each test point is weighted against its triangulated subdivision on the body to receive the final MRT. We check for a total MRT of the full body as well as local radiant temperature of different zones in the body.

In order to validate the results, an empirical method of sensing MRT is compared to the simulation. A pyrgeometer, a device compiled of, a set of 6 radiometers (Apogee, SL-510-SS; 0.12 mV per W/ m²; 1% measurement repeatability; 6% calibration uncertainty; +/- °C) oriented orthogonally measuring radiant flux in all 6 cardinal directions, is used. The cubical set of 6 radiometers is considered the ground truth for the measurement of MRT since the sensing element is not sensitive to convection, unlike black globe measurements commonly used [26]. These 6 values were averaged and comprise the MRT at the measurement location.

However, in order to achieve a true comparison of the pyrgeometer reading to the simulation. It is again necessary to abstract the body back to a point in space with geodesic sphere around it, similar to the 6 faces of the device. Naturally, the pyrgeometer is not able to include the view factor of the body upon itself or the body geometry. Therefore, for the second simulation, two results are given - one for a full body, and one for a single point in space - which could be informative for the significance of the body geometry for MRT calculations.

3.2 Results for Case-Study Simulation

The MRT Gradient Map results are shown in Figure 10. It was achieved with relatively low-computational time compared to full-body simulation and provides a reasonable estimation of the change in radiant heat transfer intensity through the space of the pavilion due to the differences in the view factor of the active cooling pavilion and hot surrounding surfaces. As expected, once the simulation point is not covered by the active surfaces, the MRT rises significantly. The range of MRT in the space varies by 10°C from 21°C in the most internal corners to 31°C in the most externally exposed areas.
point or cylinder are not good estimates of the real geometry. A result differed from simulating the variable view factor influencing heat transfer at different locations. Still, this is different than the single point simulation due to perceived by different zones of the body in this scenario. The result of 24.5°C assumps sometimes used, yielded a much closer MRT geometry but not including the skin surface as part of the effective radiation area influenced by other parts of the body or has a very different effective radiation area. A simulation considering the body geometry but not including the skin surface as part of the environment, closer to the cylinder or other geometry assumptions sometimes used, yielded a much closer MRT result of 24.5°C. Fig. 11b shows the radiant temperature as perceived by different zones of the body in this scenario. Still, this is different than the single point simulation due to the variable view factor influencing heat transfer at different points. Therefore, for most of the body, the ceiling cooling panels have a smaller view factor than for the pyrgeometer. This demonstrates how simplifications of the body geometry into a point or cylinder are not good estimates of the real radiant heat experienced by a body.

4 CONCLUSION

MRT is an abstraction of radiant heat transfer that enables its direct integration into thermal comfort calculations and their temperature-centric considerations. The inherent complexity is challenging, and though the MRT simplification can be useful it can often mischaracterize actual heat transfer and thermal comfort conclusions. In essence, radiant heat transfer is measured in watts, and those are derived from the energetic state of surfaces, represented by their various temperatures. MRT is a proxy to this, an averaged abstraction that doesn’t represent any real measured temperature but serves to unify the variations of surrounding surface temperatures into one mean variable. But in this process the complexity of view factors and geometry that also vary throughout space is often lost. In this paper, methods of light rendering simulations have been integrated into an MRT simulation to enable more complex geometry consideration, and a detailed model of the human body geometry was used instead of a single-point or platonic form abstraction to fully consider the impact of current simplifications. The cooling pavilion case-study provided a unique opportunity to study the influence of various geometric properties of architectural enclosures on the thermal sensation of the human body. The simulation results for that space demonstrated the significance of the proposed MRT simulation improvements. An important take-away of this study is that we should stop thinking about MRT as we do of air temperature. Air temperature is an environmental variable, an intensive property of the material which describes its energetic state under normal pressure conditions, easily measured by simple temperature sensors. MRT, is a representation of the wave interaction of our body with other surfaces through infrared radiation. As part of the spectrum of electromagnetic radiation, we may consider MRT in a similar manner to the concept of radiance- it is a representation of how our body is “illuminated” by all the emissions and reflections of invisible light from the terrestrial and celestial objects surrounding it.

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