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Towards Physically Based Material Appearance in the Thermal Infrared Spectrum: A Short Survey

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Abstract

In the context of photorealistic rendering, global illumination mainly relies on material models from the visible spectrum, whereas thermal infrared signatures receive only little attention. This paper outlines physical principles for determining the temperature distributions within a 3D scene and with it the overall radiance reaching an IR sensor. Hitherto existing approaches for physically based rendering are surveyed. Supposing that those methods still can benefit from recent rendering concepts in visible spectrum, we point out possible transfers.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Color, shading, shadowing, and texture

1. Introduction

Photorealistic rendering implies complex descriptions for light propagation in a scene, but still rather guides the global illumination aesthetically by using idealized physical principles. While the well-known rendering equation of Kajiya [Kaj86] determines the radiance from an object's surface point for visible light wavelengths, other spectral ranges and attending factors such as absorption, transmission and thermal emission by a material are disregarded. In thermal image generation, these physical effects are essential for demonstrating the total emitted and reflected thermal energy of an object. Contrary to the visible spectrum, an object is a constantly radiating source of infrared energy whose characteristics strongly depend on its surface properties like temperature. This surface temperature relies on the material properties and environmental conditions. In particular, a long-term environmental history is crucial, including weather conditions and the interaction of dynamic objects.

Contribution This paper examines the feasibility of thermal infrared rendering as a survey of commonly used methods for temperature prediction and physically based thermal rendering. Recent techniques for performance optimized rendering in visible spectrum are deduced as potential future work on thermal infrared image synthesis. The focus of this paper is set on thermal and radiance modeling, while atmospheric and sensor modeling are neglected.

2. Thermal Infrared Imagery

The simulation of thermal infrared (TI) images can be divided into two tasks: the estimation of the temperature distributions of individual scene objects and the subsequent radiance evaluation for rendering based on those temperature distributions.

Temperature The temperature distribution of an object strongly depends on its individual material properties such as thermal conductivity or material density and relies additionally on the environmental history over a certain period of time, i. e. weather conditions as cloud coverage or solar altitude and position. Following [LILV17], the heat transfer rate Q describing the temporal evolution of the temperature T of an object over time t can in general be written as

$$Q = mc\frac{\mathrm{d}T}{\mathrm{d}t} = Q_{cond} + Q_{conv} + Q_{rad}\,, \tag{1}$$

taking into account the conductive, convective and radiative heat transfer rates Q_{cond}, Q_{conv}, Q_{rad}, object mass m and specific heat capacity c (note that this equation is only valid for incompressible bodies and not for participating media as plume or smoke). While Q_{cond} usually occurs within a body, between bodies or via a participating medium, Q_{conv} involves a moving medium, e. g. air rising due to heating or wind cooling an object (natural and forced convection). Q_{rad} includes all incoming and outgoing sources of heat radiation, clarifying the necessity to model solar irradiance, sky irradiance and atmospheric transmittance as non-negligible factors. A physically accurate temperature distribution models all contributing terms of the full heat transfer equation (Eq. 1), utilizing all three dimensions of the object (within in the object and on its surface). An alleviating 1D heat transfer only applies for one direction within the object's interior, excluding heat exchange between individual surface elements, and either totally excluding heat conduction or only allowing heat conduction in bulk.

Radiance In the infrared spectrum, each object emits heat radiation and reflects the incoming radiation from the sun and its environment, namely other radiating objects or the sky. Also, the path between the sensor and the observed point in the scene adds a non-negligible amount of radiance which is usually referred to as path radiance. With this, radiance reaching the sensor at wavelength λ is given by

$$L_\lambda(\theta,\phi) = \left[L_{\lambda,e}(\theta,\phi) + L_{\lambda,r,\Omega}(\theta,\phi) + L_{\lambda,r,s}(\theta,\phi)\right]\tau_\lambda(\vec{l}) + L_{\lambda,p}(\vec{l})\,, \tag{2}$$

with the object's spectral emitted radiance $L_{\lambda,e}$, the spectral reflected environmental radiance $L_{\lambda,r,\Omega}$ from the hemisphere Ω of the object surface and the spectral reflected solar radiance $L_{\lambda,r,s}$, damped by the spectral atmospheric transmittance $\tau_\lambda(\vec{l})$ on the path $\vec{l}$ between the sensor and the object and the spectral path radiance $L_{\lambda,p}(\vec{l})$ [HZZW14]. θ is the sensor's zenith angle and ϕ the corresponding azimuth angle. Note that in order to finally generate the sensor view of a scene, the spectral radiance has to be multiplied by the normalized spectral sensor response and integrated over the sensed wavelength band. The spectral emitted radiance of a blackbody $L_{\lambda,bb}(T)$, absorbing all incoming radiation and emitting all absorbed radiation at each wavelength, links temperature and radiance by Planck's law. In reality, an object only partially absorbes incoming radiation, its spectral emitted radiance is thus described by $L_{\lambda,e}(\theta,\phi) = \varepsilon_\lambda(\theta,\phi,T)L_{\lambda,bb}(T)$, with emissivity ε as the ratio of the actual radiance of an object and the radiance of a blackbody at the same temperature. For opaque materials the simplification $\varepsilon = 1-\rho$ holds, relating this spectral-directional emissivity to the spectral-directional reflectivity ρ. The reflected radiance from hemisphere in Eq. 2 can be expressed as

$$L_{\lambda,r,\Omega}(\theta,\phi) = \int_\Omega f_\lambda(\theta_i,\phi_i,\theta,\phi)L_{\lambda,i}(\theta_i,\phi_i)\cos\theta_i d\omega_i\,, \tag{3}$$

with the well-known bi-directional reflectance distribution function (BRDF) $f_\lambda(\theta_i,\phi_i,\theta,\phi)$ and $L_{\lambda,i}(\theta_i,\phi_i)$ as incoming radiance from incident direction $\omega_i = (\theta_i,\phi_i)$. The connection to the radiance for the visible spectrum modeled by Kajiya's rendering equation becomes obvious:

$$L_\lambda(\theta,\phi) = L_{\lambda,e}(\theta,\phi) + L_{\lambda,r,\Omega}(\theta,\phi)\,, \tag{4}$$

with $L_{\lambda,e}(\theta,\phi)$ as emitted radiance at an observed point and $L_{\lambda,r,\Omega}(\theta,\phi)$ as the reflected radiance from its hemisphere. Referring to the simplification $\varepsilon = 1-\rho$ for opaque materials, the emissivity can be expressed using the BRDF by definition:

$$\varepsilon_\lambda(\theta,\phi) = 1 - \int_\Omega f_\lambda(\theta_i,\phi_i,\theta,\phi)\cos\theta_i d\omega_i\,. \tag{5}$$

The reflected radiance $L_{\lambda,r,s}(\theta,\phi)$ from direct solar irradiation does not include all incident directions. Solar radiation is assumed to be parallel and thus represents one unique incidence direction. However, an additional occlusion factor ensures that only direct illumination is taken into account [HZZW14]. The rendering equation only considers the reflectance as energy scattering by materials. Refraction of light at a translucent material (transmissivity) may be described by a bi-directional transmission distribution function (BTDF), but is usually neglected. In TI it depends on the material's temperature.

3. Related Work

Methods for predicting temperature distributions and the overall radiance in a 3D scene already evolved from approaches few decades earlier.

The TAITherm software uses the 3D heat transfer model and is well established in automotive industry due to its high-presicional results [TAI]. Contrary to these time-consuming calculations, the 1D heat transfer equation is proven to be sufficient for many applications and is therefore applied i. a. in DIRSIG [GB17] and SE-Workbench [LC16]. The radiance estimation often requires the spectral directional emissivity or transmissivity of a material as manual input parameters - an elaborating process since corresponding databases are rare. The model developed by Bartos and Stein [BS15] attempts to overcome this issue in a semi-empirically manner: required material parameters are fitted to measured temperature data, while the subsequent radiance determination is not considered. Assuming those parameters by averaging over their hemispherical values or wavebands allows for real-time rendering, although a validation of this approach by Duong and Wegener [DW01] demonstrates that this accuracy loss can be a non-negligible source of error. The necessity of band-averaging the emissivity only in the considered wavelength band is highlightened, even though a precise setting of band limits for averaging is non-trivial.

The emissivity of an opaque material is deducible by determining its BRDF according to Eq. 5. The BRDF itself is either collected through accurate measurements or is analytically determined and may be used predictively. In general, only physically or aesthetically significant parameters are taken into account in terms of a simplified function, e. g. by modeling a Lambertian radiator. Early works measure reflectance models in multispectral IR ranges in context of land-cover classification and land surface temperature algorithms, e. g. to predict the refletance and emissivity of a canopy of leaves and soils ([CSWZF97], [CSW98]), or to reasonably evaluate the quality of black painted materials and to compare thermal cyclings and damages [LM04]. Several reflectance models base on empirical or rather phenomenological surveys; one example is the Phong reflection model used for direct illumination, portioning the reflection term into a diffuse and specular one. A simplified material model in mid-wavelength infrared is given by [LBM*09]. It extends the Phong model by adding a Lambertian self-emission term according to $L_{\lambda,e}(\theta,\phi,T)$, which is then approximated by a 4th order polynomial. The fitting parameters are obtained empirically. Common BRDFs used for infrared signatures of aircrafts and ships base on the Sandford-Robertson reflectance model [San85]. It sums the wavelength dependent diffuse and specular portions to get the total reflectance using four parameters: the emissivity and diffuse spectral reflectivity of a surface are determined from hemispherical-directional reflectance measurements.

Concerning rendering, most of the available software tools either use rasterization particularly for real-time implementations or ray tracing [LC16]. TAITherm uses of a photorealistic rendering technique with multi-bounced, voxel-based ray tracing. DIRSIG applies a hierarchical ray tracing for imaging, its currently available version renders with Monte Carlo path tracing. This is motivated by the inclusion of diffuse lightning, increasing not only the physical accuracy in the simulation, but also the rendering performance in contrast to prior ray tracing method. Being however inefficient for discrete light sources such as the sun, these light sources are directly sampled and explicitly calculated [GB17]. To the best of our knowledge, path tracing remains a rather uncommon method for thermal rendering. An alternative solution for solving the rendering equation is with radiosity as described in [XZBY13].

4. Discussion

A realistic TI simulation demands a well determined distribution of temperature. In remote sensing, physical precision is only needed to same degree as resolved by the used thermal sensor itself. Most of the existing heat transfer solvers therefore rely on a 1D approach, ignoring only marginal contributing transfer rates: Since only certain material classes are actually good heat conductors such as electric conductors, the conduction term becomes insignificant; on the other hand, those heat conductors are usually rather poor heat radiators so that sensed radiation is restrictable to reflection of the environmental radiation from the sky or the sun. Nevertheless, heat conduction may be crucial for accurate temperature prediction. A heat conductor painted with a well radiating coat changes the material's surface properties and thereby its visible radiation. Resultant differences between a simulation and measurements are reconsidered by Lapierre et al. [LAB*09], indicating that lateral heat conduction impacts thermal shadows. Object parts lying in a shadow heat up by conduction from adjacent surface parts that are directly exposed to sunlight. [BS15] allow surface heat transfer without using the full heat transfer equation, providing satisfactory results compared to experimental data. However, a detailed analysis of simulation improvement due to inclusion of surface heat transfer has not been carried out.

The reliability of the measured BRDF used for estimating an unknown emissivity according to Eq. 5 depends on the employed TI sensor. The BRDF for thermal simulation is likewise used for sensor development itself. This discloses a chicken-egg-problem due to the difficulty in precisely discriminating the emitted and reflected radiance of an unkown source. Infrared sensors hence might not include material-dependent emissivity. Additionally, sensor algorithms for transforming the measured radiance into temperature are often poorly documented. Implying reflection models such as the empirically derived Phong model inherently results in absence of physical plausibility and just complies with isotropic materials. Concepts for modeling BTDFs are not known to the authors so far, but might be a first step for modeling thermal transmission.

Photorealistic material models may struggle with real-time issues and are already physically idealized or approximated; their expansion to handle thermodynamic characteristics seems to amplify these factors. Assuming to simulate a dynamic 3D scene with altering viewpoints and sun positions, many thermal effects need to be taken into account. For instance, not only occlusions have a thermal impact, also cast shadows fundamentally differ from those in visible spectrum: A shadowed region heats up less over time and the shape of the thermal shadow may be influenced by lateral heat conduction. If the illumination changes or objects are moving, the cooler temperature of the previously shadowed region is preserved and a thermal footprint is visible. Current TI simulations tend to rely on well-established rendering methods to guarantee best perfomance. Although their applications might differ a lot, the chosen rendering techniques resemble as outlined by Willers et al. [WWL11]; to the best of our knowledge, no outstanding or novel approaches in thermal rendering are involved.

At first glance, sophisticated concepts from photorealistic rendering seem to be promising for adopting in thermal imaging. Particularly for real-time rendering many-lights methods for instance are able to approximate a complex multi-bounce light transport by using a multitude of virtual point lights. With that, all types of illumination such from large area lights, environmental light and sun light can be captured [DKH*14]. Given the key assumption that any object in TI is a radiating source, a large amount of such sources within a 3D scene need to be handled. An improved generation of virtual "point lights" only on those objects might be an approach for TI - since an object usually emits more radiance as it reflects, they might then be used to compute direct radiation. Still, this method might be adjusted for a setting at night without any external light source like sun (specifically appealing for TI applications), given that at least one real light source is needed to distribute the virtual ones. Another method that meets the challenge of optimized rendering with several light sources is deferred shading. It decouples the illumination process from identifying visible scene geometry and avoids a multiple excution of tasks as in forward rendering. Material information like BRDF parameters can be stored in a separated texture as frame buffer object. Bounding volumes might then be used to represent radiating sources that have only influence on local environment within a certain distance, excluding again the sun. This method would insofar oblige TI rendering, that deferred shading is de facto not handling transparent materials. More notably, approaches that take time dependence and full visible wavelength range into account resemble the goal to render in TI wavelengths. Fluorescent materials are examples for re-emitting photons in another energy state and thus in another wavelength (leading to wavelength shifts). A spectral path tracer using a bi-spectral bidirectional reflectance and re-radiation (bi-spectral BRRDF) is given in [MFW18]. However, this method is not capable to be used interactively.

Learning light transport paths by a neural network has been introduced by Dahm [DK17]. These trained neural networks allow efficient importance sampling in a path tracing algorithm and are able to learn the full radiance distribution in a scene, therefore replacing the need for solving the rendering equation by ray tracing or other techniques. A different approach for thermal imagery tries to overcome the complex scene generation outlined in this survey by using the ability of creating high-quality images in RGB and mapping them into the infrared domain, e. g. [LBK17], [KGM17]. This requires already rendered RGB images and eliminates a transfer of common rendering methods for visible spectrum into thermal rendering.

5. Conclusion

In this paper we gave an introduction to synthetic thermal infrared imagery in terms of a short survey on current implementations of temperature prediction and rendering. A temperature distribution is determined with help of the heat transfer equation. A 1D approximation or the negligence of lateral heat conduction leads to a performance optimization but at the same time to a loss of physical accuracy. Thermal shadows may be crucial within certain scenarios but would not be reproduced. A rendering is mostly handled by rasterization or physics-based ray tracing to solve the adapted rendering equation. Self-emission in TI is essential for correct rendering, however parameters as the emissivity or the related BRDF are difficult to obtain. Refined rendering methods as multi-light, deferred or wavelength shifted shading have not yet been used in thermal rendering and therefore state a promising field for future work.

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