INFRARED SENSOR MODELING FOR REALISTIC THERMAL IMAGE SYNTHESIS

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ABSTRACT

To generate realistic synthetic IR images, image acquisition by IR sensors must be reproduced. In this paper, we propose an IR sensor model[*] based on physical laws governing effects involved in the IR imagery formation process. Our approach consists in a combination and an extension of current camera models used in visible and infrared image synthesis, and thus merges ray tracing and post-processing techniques. Our model represents the geometric and radiometric relationship between the points in the 3D observed scene and the corresponding pixels of the IR sensor output image. It offers the capability of simulating each IR sensor component in accordance with any given system technology and to any desired degree of precision. Moreover, it can also account for variations in many physical quantities through spatial, spectral, and temporal dimensions.

1. INTRODUCTION

IR sensors are currently widely used on aircraft for navigation at night, passive remote detection, etc... Therefore synthetic image generators in flight simulators must be able to produce high-fidelity thermal image. Realistic thermal image generation requires modeling of three main physical effects: thermal radiation emission from the scene, radiation propagation through the atmosphere and image acquisition by the IR sensor, which is the subject of this paper.

Our IR sensor model allows computing of the pixel values of the output image produced by an IR sensor given the incoming radiance from the observed scene. It accounts for each component of the IR image chain (optics, scanner, detectors, and electronics) and can match the IR imaging system technology and the desired precision. This model is meant to be included in an overall modeling tool called SYTHER (Synthesis of THERmal images) developed by SOGITEC, a subsidiary of DASSAULT AVIATION which designs training simulators in Rennes, France. SYTHER's purpose is to generate realistic synthetic images of scenes made of landscapes and targets observed by a wide range of sensors in any IR waveband and in any environmental condition.

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This paper begins with a presentation of current camera models used in image synthesis in both visible and infrared range. Then our approach is described: it is based on the combination and the extension of these existing models, and thus merges ray tracing and post-processing techniques. At last, we specify how IR sensor effects are accounted for in our IR sensor model.

2. STATE-OF-THE-ART

Camera modeling is the subject of little research in image synthesis. Even if existing models are incomplete and not quite correct from the physical viewpoint, they are usually sufficient to add the desired effects to a synthetic image. Thus an accurate physically-based sensor model is required to simulate physical phenomena involved in the image acquisition process. Three approaches can be distinguished from works carried out in visible image synthesis. The first approach consists in applying the camera model as a post-processing [1]: a 2D image is computed from the 3D scene by a pinhole camera model, then the final degraded image is obtained by passing this 2D image through a series of sensor effect modules. This method has the advantage of simplicity and speed in proportion to image size, but is restricted by the 2D image resolution. The second approach consists in integrating the camera model into a ray tracing algorithm [2]: the deviation of rays passing through the optical system is directly calculated by Snell's law. This method is more in accordance with sensor physics, but has high computational cost depending on the scene complexity and the number of traced rays. The third approach combines the two previous ones [3] and represents a compromise solution. All these models focus on accurately modeling optical effects: in particular depth of field limitation and motion blur.

In the IR range, sensor models are used as a part of an overall simulation chain in IR image generators or as an independent tool for analyzing existing IR sensor performance and designing novel IR sensors. All the current IR sensor models have architecture based on post-processing. They account for each sensor component, and radiometric effects in a more detailed way than visible camera models [4][5]. Existing models provide computations for many phenomena modeling [6], including spatial effects, noise, and other effects, such as non-uniformity and non-linearity of the detector responsivity, AC coupling,

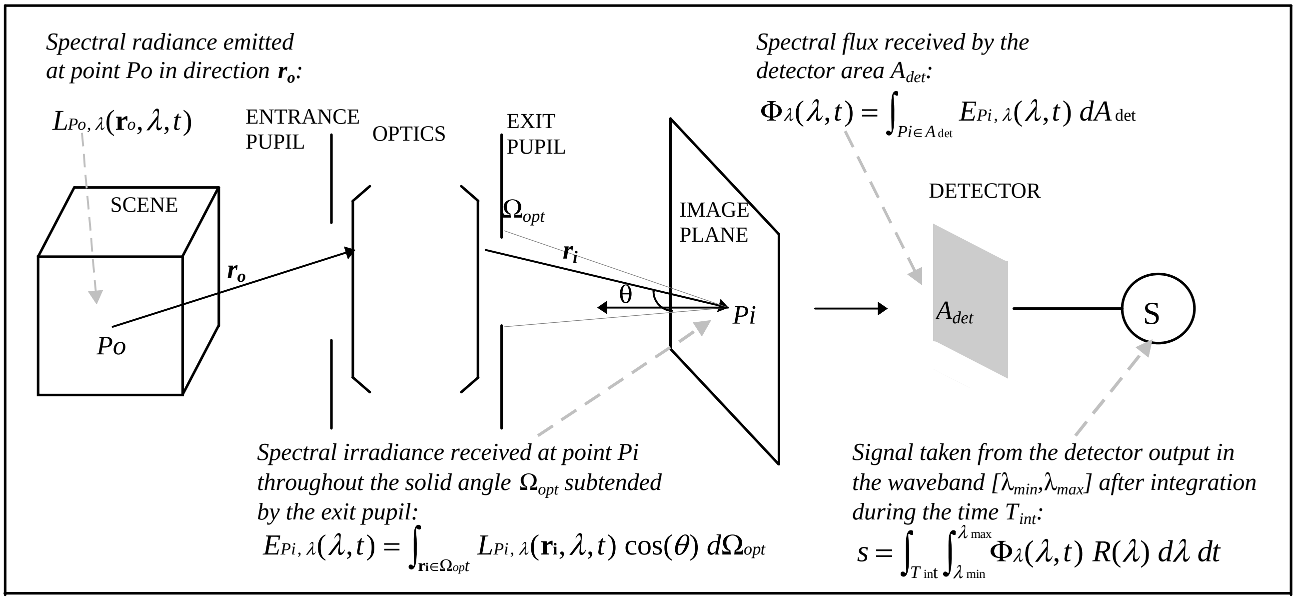


Figure 1. Main stages in conversion of thermal radiation into electrical signal by an IR sensor.

automatic gain control (AGC), etc... Spatial effects producing image blurring are modeled by an overall sensor point spread function (PSF) or a transfer function (PSF Fourier transform), which are meant to be constant on the entire sensor field of view (FOV). Effects are usually much approximated. A few models [7] are more in accordance with physics and notably take into account PSF variations across the sensor FOV. However, some effects are today still not simulated: modification of the distance between optics and detector plane during focusing, geometric distortion and depth of field. Other phenomena are not accurately simulated: spatio-temporal relationship between detectors and the observed scene, wavelength dependent effects, in particular in optical transmittance and detector responsivity, and image plane location dependent effects, such as aberrations, and irradiance received on the image plane which produces image edge darkening. At last, we can add that existing models are not precise enough with regard to the definition of used physical quantities.

3. MODELING APPROACH

To design and develop our IR sensor model, we take up and combine existing modeling approaches and computations in the visible and the IR waveband. However we modify and extend them so that the modeling solution is in accordance with sensor physics, takes into account each of the IR sensor components, resorts to a minimum of simplifying assumptions, and keeps the specific strength of ray tracing, which is high sampling capability. The following sections describe our modeling principles.

3.1 Accordance with physical laws

Figure 1 shows the main stages in conversion of thermal radiation into electrical signal by an IR sensor. Equations governing this process involve several physical quantities [8]:

- *Spectral radiance* $L_{P,\lambda}(\mathbf{r},\lambda,t)$ defined at a point P on a transmitting or receiving surface in a direction $\mathbf{r}$ and measured in $W.m^{-2}.sr^{-1}.m^{-1}$.
- *Spectral irradiance* $E_{P,\lambda}(\lambda,t)$ defined at a point P on a receiving surface through a solid angle Ω and measured in $W.m^{-2}.m^{-1}$.
- *Spectral flux* $\Phi_\lambda(\lambda,t)$ defined over a whole transmitting or receiving surface A through a solid angle Ω and measured in $W.m^{-1}$.
- *Detector spectral responsivity* $R(\lambda)$, which is the ratio of the detector output electrical signal $ds_\lambda(\lambda)$ to the incident spectral flux $d\Phi_\lambda(\lambda)$ and has units of V(Volts).W^{-1} or A (Amperes).W^{-1}.

The equations in Figure 1, established from definition of these quantities, sum up basic IR sensor effects and constitute a physical basis for IR sensor modeling.

3.2 Model decomposition

Our IR sensor model is split up into several modules. Each module corresponds to one of the IR sensor components. Only the interfaces (input and output data) between these modules are fixed, no assumption is made on the computations which are implemented within. Dividing the model in this way results in a general, open, and highly adjustable framework [9]. This framework can support the development of modeling algorithms for each component of the IR image chain (optics, scanner, detector, and electronics) to match the system technology and the desired precision. The IR sensor model allows simulation of a wide range of technologies including staring and scanning systems based on thermal and photon detectors [8]. For each module, the framework uses two types of parameter files. One is called description file and includes physical sensor parameters. The other is called configuration file and contains application parameters defining calculation methods, sampling precision, and simulated phenomena.

3.3 Spatial, temporal and spectral sampling

According to basic equations stated in Figure 1, the value V of an output image pixel is proportional to the following expression:

$$V \propto \int_{T\,\mathrm{int}} \int_{\lambda\,\min}^{\lambda\,\max} \int_{Pi \in A\,\det} \int_{\mathbf{ri} \in \Omega_{opt}} L_{Pi,\,\lambda}(\mathbf{r_i}, \lambda, t).R(\lambda).$$
$$\cos(\theta).d\Omega_{opt}.dA_{\det}.d\lambda.dt$$

This expression involves several integrals: over the integration time T_{int}, over the sensitive spectral range [λ_{min},λ_{max}], over the detector area A_{det} and over the solid angle subtended by the exit pupil Ω_{opt}. In existing IR sensor models, sampling precision is inherently restricted by the temporal, spatial, and spectral resolution of the input image. Consequently, the equation is most often simplified like this:

$$V \propto \sum_{Pi \in A\,\det} L_{Pi}(\mathbf{r_{opt}}, t_{ima}).\overline{R}.\cos(\theta_{opt}).\Omega_{opt}.T_{\,\mathrm{int}}.A_{pixel}$$

where $\mathbf{r_{opt}}$ is the ray passing through the optical center, t_{ima} is the moment when the sensor begins to scan the scene, $L_{Pi}(\mathbf{r_{opt}},t_{ima})$ is the radiance received by point Pi in direction $\mathbf{r_{opt}}$ and at time t_{ima} in the sensitive waveband [λ_{min},λ_{max}], $\overline{R}$ is the mean responsivity in the range [λ_{min},λ_{max}], θ_{opt} is the angle of the ray $\mathbf{r_{opt}}$ to the optical axis, and A_{pixel} is the pixel area of the input image containing Pi.

Our model can perform precise sampling along the four integration dimensions by resorting to the ray tracing technique. This method interest lies in the fact that rays sample physical quantities, which produces several sensor effects. Sampling in the temporal dimension simulates motion blur. Sampling in the spatial dimension (detector area and exit pupil) simulates detector sampling and depth of field. Sampling in the spectral dimension takes into account variations in physical magnitudes (optical transmittance, detector responsivity, etc...) according to wavelength. The model offers the possibility of choosing between several sampling patterns.

3.4 Input and output data

Input data are physical quantities that feature the 3D scene points observed by the IR sensor during a specific temporal interval. They consist of:

- *Spectral radiance* emitted during the detector dwell time (time required for the detector to scan over a point) for wavelengths within the sensitive waveband and in directions included in the solid angle subtended by the entrance pupil.
- *Depth* from the optical center along the optical axis.

To get these data, the IR sensor model conveys a request to an interface module that controls the rendering process [9]. This one can be executed by ray tracing or z-buffer that can construct full or partial images of the observed scene. In extreme cases, requests are made for an elementary solid angle, that is, restricted to one ray (use of ray tracing) or for a solid angle corresponding to the whole sensor FOV (use of z-buffer). Middle solutions also exist: input data can be transmitted for a solid angle corresponding to the FOV of the detector array. The advantage is that it can be done at the exact time when this solid angle is covered by the detector array. Thus input data are precise and optimized. Output data are images which have the same resolution as the simulated infrared sensor.

4. IR SENSOR EFFECTS MODELING

This section presents the IR sensor model developed in accordance with the specific principles described before. It reviews the effects taken into account within each module of the model, as well as the implemented computations to simulate them. Notations are the same as in Figure 1.

4.1 Scanner

The scanner module accurately simulates the movement of the detector array FOV in the IR sensor FOV in time. In reality, the scanner moves an elementary area of the scene over a detector array whose position is fixed. To simplify scanner modeling, we can consider conceptually that the scanner moves the detector array across the image of the entire scene.

Thus, for each pixel on the output image, the scanner module determines the detector from which the electrical signal is taken, the image plane area scanned by this detector, and the time at which the detector begins to scan this area. The module allows the simulation of a wide variety of scanning systems: scanning with a single detector, parallel or serial scanning (TDI systems) with a linear array, and serial-parallel scanning with a bidimensional array. The module can also be used to model staring systems. In this case, the image plane area "scanned" by the detector simply corresponds to the detector FOV.

4.2 Optics

The optics module includes:

• *A geometric function,* which simulates image formation in the presence of geometric distortion. According to Seidel aberration classification [8], the position of an image point Pi corresponding to an object point Po in the observed scene is :

$$P_i = G.P_o + C_d.(P_i - GP_o)^3$$

where C_d is the Seidel distortion coefficient and G is the optical system magnification.

• *A radiometric function,* which simulates optics radiometric effects. It accounts for wavelength dependent variations in optical transmittance $\tau_{opt}(\lambda)$, image edge darkening due to collection of incident radiance through the entrance pupil, and vignetting due to radiation stopping by optical components different from the entrance pupil. This function also enables addition of radiance emitted by the optical system to radiance received from the scene. The spectral irradiance received by a point Pi on the image plane is:

$$E_{Pi,\,\lambda}(\lambda, t) = \tau_{opt}(\lambda).\int_{\mathbf{ri} \in \Omega_{opt}} (L^{scene}_{Pi,\lambda}(\mathbf{r_i}, \lambda, t) +$$
$$L^{optics}_{Pi,\lambda}(\mathbf{r_i}, \lambda, t)).\cos(\theta).d\Omega_{opt}$$

• *A blurring function,* which simulates optical effects which make an image point look larger, as a blur, on the detector plane. It considers variations of blurring effects across the IR sensor FOV: they are more important in the edges than in the center. This function accounts for aberration blur, diffraction blur, focus blur, and also IR sensor line of sight vibrations due to the platform movements. The irradiance distribution function around a point Pi on the image plane is obtained by convolving several point spread functions (PSF):

$$h_{Pi}^{distribution}(P,\lambda,t) = h_{Pi}^{aberrations}(P,\lambda,t) * h^{diffraction}(P,\lambda,t)$$
$$* h_{Pi}^{focus}(P,\lambda,t) * h^{vibrations}(P,\lambda,t)$$

where $h_{Pi}^{aberrations}(P,\lambda,t)$ and $h^{vibrations}(P,\lambda,t)$ are Gaussian functions, $h^{diffraction}(P,\lambda,t)$ is the Airy disk and $h_{Pi}^{focus}(P,\lambda,t)$ is regularly distributed on a disk.

4.3 Detectors

The detector module includes:

- *A geometric function,* which simulates detector action on irradiance reaching the image plane. Detectors perform spatial and temporal sampling of the received thermal radiation, because they have finite dimensions and also collect radiation during a finite time. This function takes into account detector temporal response and FOV limitation by the cooled aperture in front of the detector array. In the case of a scanning system, it also models effects due to detector area A_{det} movements across the image plane in time. The spectral energy quantity collected by the detector area during the integration time T_{int} is:

$$Q_{\lambda}(\lambda) = \int_{T_{\text{int}}} \int_{Pi \in A_{\text{det}}(t)} \left[E_{Pi,\lambda}(\lambda,t) * h_{Pi}^{distribution}(P_i,\lambda,t) \right]$$
$$dA_{\text{det}}(t).dt$$

- *A radiometric function,* which simulates conversion of the thermal radiation into electrical signal by a detector. It computes the electrical signal generated by a detector which receives incident thermal radiation, the electrical additive noise s_n, and the dark signal s_{dark} delivered by the detector in the absence of incident radiation. This function takes into account wavelength dependent variations in the detector responsivity $R(\lambda)$. It also accounts for detector responsivity non-uniformity, which is a multiplicative noise source, and non-linearity. Non-uniformity is modeled by assigning different random values ΔR and Δs_{dark} to each detector. These values are used to define a deviation from the mean responsivity $R(\lambda)$ and the mean dark signal s_{dark}. Non-linearity is modeled by providing several values which characterize the detector input-output function describing an S-shaped curve. Noise is assumed to be governed by a Gaussian distribution. The electrical signal s taken from a detector output is:

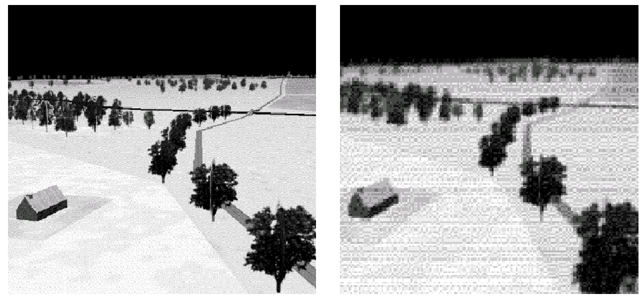
$$s = \int_{\lambda \min}^{\lambda \max} Q_{\lambda}(\lambda).\, R(\lambda).\,(1+\Delta R).\, d\lambda$$
$$+ s_{dark}.\,(1+\Delta s_{dark}) + s_n$$

4.4 Electronics

The electronics module groups all the electrical and numerical processing applied to the electrical signal and then to the produced image. It includes the following processing: amplification (modeled by a low-pass filter), electrical signal quantification, AC coupling in the case of scanning systems (modeled by a high-pass filter because it removes the signal direct component), automatic gain control (AGC), offset control, and corrections of specific output image defaults.

5. SUMMARY

This paper describes an IR sensor model developed from study of physical effects involved in IR image acquisition process. This model is capable of modeling each component of the IR image chain in accordance with any given system technology and to any desired degree of precision. For example, Figure 2 illustrates the simulation of a parallel scanning system. Moreover, variations in many physical quantities through spatial, spectral, and temporal dimensions can be accounted for.



(a) Without sensor effects. (b) With sensor effects.

Figure 2. Example of thermal synthetic image.

This work has led to a software that is currently in validation. It consists in comparing quantities which characterize IR sensor image quality (SiTF, LSF, NEDT...) [8]: on the one hand quantities measured on a real IR sensor in accordance with standard test methodology, on the other hand quantities obtained by simulation of this IR sensor and simulation of laboratory measurement techniques.

6. REFERENCES

[1] Potsemil M. and Chakravarty I. "A lens and aperture camera model for synthetic image generation". *Computer Graphics*, vol. 15, no. 3, pp. 297-305, Aug. 81.

[2] Kolb C., Mitchell D., Hanrahan P. "A realistic camera model for computer graphics". *Computer Graphics Proceedings*, Annual Conference Series, pp. 317-324, 1995.

[3] Haeberli P. and Akeley K. "The Accumulation Buffer: hardware support for high-quality rendering". *Computer Graphics*, vol. 24, no. 4, pp. 309-318, Aug. 90.

[4] Cathcart J.M., Sheffer A.D. and Faust N.L. "High-fidelity infrared scene simulation at Georgia Tech". *Proceedings of SPIE*, vol. 2740, pp. 142-152, Apr. 96.

[5] Donn M., Yanni P. and Bernstein U. "Realistic approach to an IR mission rehearsal simulator". *Proceedings of SPIE*, vol. 2743, pp. 290-301, Apr. 96.

[6] Akiyama T., Tamagawa Y., Yanagisawa T. "Simulation of visible/infrared sensor images". *Proceedings of SPIE*, vol. 2744, pp. 61-67, Apr. 96.

[7] Horger J.D. "NVSIM: UNIX-based thermal imaging system simulator". *Proceedings of SPIE*, vol. 1969, pp. 27-40, Apr. 93.

[8] Accetta J. S., Shumaker D. L., editors. *The infrared and electro-optical systems handbook*. Environmental Research Institute of Michigan (ERIM), 1993.

[9] Garnier C., Collorec R., Flifla J. and Rousée F. "General framework for IR sensor modeling". *Proceedings of SPIE*, vol. 3377, pp. 59-70, Apr. 98.