SINDBAD: FROM CAD MODEL TO SYNTHETIC RADIOGRAPHS

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INTRODUCTION

X-ray simulation tools are of primary interest during the design stage of radiographic facilities where they can help to choose the device parameters (X-ray tube settings such as voltage and filtration, detector type and thickness, geometry of the bench, etc.) and predict performances of the future device. They can also be helpful, in the evaluation and test of radiation image processing techniques (tomography, tomosynthesis, etc.) and in radiographic non destructive evaluation processes using synthetic images as, for instance, flaw detection, evaluation of object inspectability, assistance to inspection interpretation, inspector training, etc.

The most important part of the simulation deals with interaction of radiation with matter in the examined part or in the detector. This interaction is fully described by the Boltzman transport equation. However, the solution of this equation, usually obtained by a Monte Carlo method is too computer time consuming to be of practical use in the case of complex part geometry. If scattering and internal sources are neglected, an integral solution, the exponential attenuation law, allows to compute the direct flux. This analytical model can be implemented as a possible simplified alternative to the full solution. Several models, more or less sophisticated, are then available to simulate scattered radiation, which can then be added to the direct flux.

This analytical approach has been adopted by several research teams. The German Federal Institute for Materials Research and Testing (BAM) has developed a simulation tool [1] which was later improved by a coupling to a CAD interface. The Italian National Agency for New Technology, Energy and the Environment (ENEA) has included an X-ray simulation in their digital imaging software in order to help design an inspection scenario and assist the operator while detecting flaws [2]. The Center for Non-Destructive Evaluation (CNDE, USA) has built in several stages a sophisticated simulation package XRSIM, which includes an X-ray source model, a CAD description of the inspected object, a scattering model and several kinds of radiation detector models [3-4].

The LETI laboratory (Laboratoire d'Electronique et de Techniques d'Instrumentation, France), is involved in the design of high performance radiographic or tomographic facilities as well as in radiation image processing techniques. As the availability of a computer tool dedicated to the simulation of radiographic devices became necessary, the decision was taken to follow the same approach and to develop Sindbad, a software system whose current state is presented hereafter.

In the first part of the paper, we give a brief description of the models we use and the underlying physics, involving X-ray production, radiation interaction with matter and radiation detection. In the second part, we discuss some validation cases and, in the third part, we present three recent applications of the simulation code.

MODEL DESCRIPTION

γ- and X-ray Source Spectrum

γ- and X-ray sources supply the high energy photons involved in the radiographic imaging process. No model is needed for γ-ray sources as their energy spectrum, composed of one or several characteristic peaks in fixed proportion, is well known.

On the contrary, X-ray sources emit a continuous and complex energy spectrum due to the interaction of accelerated electrons with the material of the anode. Two major physical phenomena, namely bremsstrahlung and characteristic radiation, are involved. Firstly, when an electron passes in the vicinity of a nucleus, it is decelerated and a part or all of its kinetic energy is transformed into bremsstrahlung. This creates a continuous energy spectrum whose upper bound is the kinetic energy of the electron, defined by the high voltage of the tube. Secondly, an accelerated electron or an already created photon can interact with an atom and remove one of its orbital electrons. The void created in the orbit is filled with an outer orbital electron, and a photon, whose energy is the difference between the two orbital energies, is emitted. This produces a characteristic peaks spectrum which is superimposed to the bremsstrahlung spectrum.

The coupled electrons and photons diffusion equations used to model the X-ray source are often computed using the Monte Carlo method. Instead, for the sake of simplicity and computer time saving, and at the expense of a lack of generality, we chose to use semi-empirical models.

In a first stage, we have focused our attention on the simulation of X-ray tube between 30 and 500 kV, and disregarded accelerator devices. The classical and very simple Kramer's model [5] as well as the more recent ones described by Birch and Marshall [6] and Tucker [7] have been implemented. We also added several other models for electron bremsstrahlung cross section, electron absorption and anode stopping power. This gives the user the possibility to mix the models and tailor precisely his simulation.

The parameters the model accounts for are the anode angle and composition, the inherent and additional filtration and the exit angle. It suffers of course from many simplifying assumptions and limits. For example, spectrum variation in the focal spot, anode material aging, voltage ripple and non linearity of the emitted flux with the tube current are not modeled.

If dose measurements are available, we can apply a dose correction (scaling of the spectrum leaving its shape unchanged), thus improving the accuracy of the output spectrum.

X-ray Matter Interaction

Photoelectric effect, Rayleigh and Compton scattering and pair creation are the major phenomena occurring during X-ray interaction with matter. Among others, the Storm Israel tables [8] supply the - photon energy dependent - probability of occurrence of each phenomenon in a tabulated form for every chemical element. We use this table to straightforwardly compute the total and energy absorption attenuation coefficients of pure elements and a mass proportion interpolation of these coefficients is performed to compute the attenuation coefficients of a composed or a mixed material.

The polychromatic source spectrum is split into narrow energy bands on which the attenuation coefficient can be considered constant. The direct flux, transmitted without interaction, through the examined part is then calculated for each energy band, using the exponential attenuation law.

The choice of an analytical model rather than a Monte Carlo method has been driven by simplicity and computer time saving considerations at the expense that photon scattering is not taken into account in the present simulation.

Detector's Model

The detector's model involves two successive steps. The first one is common to all types of detectors. It computes the energy deposition in the sensing part of the detector using the energy absorption attenuation coefficients. The second one, which is specific to each type of detector, simulates the successive physical phenomena involved in the energy to signal transformation. For instance, in the case of a scintillating screen viewed by a CCD camera, it accounts for energy to light photons transformation, light photon absorption in the screen and optical coupling system, and photon to electron conversion in the CCD device.

Poisson noise can be added to the absorbed energy image and a gaussian noise whose standard deviation is computed from the detector's model parameters can be added to the synthetic image. In order to take information spreading into account, a global gaussian blurring of the computed image can also be performed.

Three models of detectors, namely a scintillating screen coupled to a CCD camera model, a scintillating crystal coupled to a photomultiplier model and a general purpose global transfer function model, are implemented.

Inspected Part and System Geometry

The part definition uses the BRL-CAD [9] solid modeling software package. In this system, based on Constructive Solid Geometry, the CAD model of the inspected part is created by boolean combinations (intersection, union or subtraction) of basic solids (boxes, cones, ellipsoids, etc.). Solids boundaries can also be defined with B-spline surfaces. Importation of CAD models from commercially available software is possible by the means of stereo lithography or IGES standard files.

A material name is assigned to each solid and several solids can be grouped to define multi-materials inspected parts.

Once created, the part is translated and rotated in 6 degrees of freedom to its inspection position between the X-ray source and the detector. To determine the attenuation path length, rays are traced through the part between the point source and an array of points located on the detector's plane. This array of points can be placed at the centers of the pixels of the detector or mapped to a refined grid when a better geometrical precision is needed.

One Dimensional Simulation

During the initial design stage, a simplified one dimensional simulation can be performed, in which a single ray is shot through the examined part, defined as a plate of given thickness, to a single pixel detector. This simulation gives the possibility to display the X-ray spectra computed along the beam path (source spectrum, spectrum after object attenuation, spectrum absorbed in the detector) and to access some important figures such as the expected signal and noise values.

Computer Implementation

Sindbad is written in ANSI C language. It uses the raytracing library provided with the BRL-CAD package and some numerical functions from the Numerical Recipes [10]. It runs under UNIX on SUN workstations.

In order to facilitate maintenance and addition of new features, the program is divided into several independent modules, respectively dedicated to X-ray spectra simulation, materials attenuation coefficients management, one and three dimensional pre-processing and one and three dimensional solution. User's interaction with non computing intensive modules is performed through a Motif Graphic User Interface.

On a SUN Ultra Sparc workstation, the production of a 512 x 512 image usually requires a few minutes execution time.

VALIDATION

Comparison of the Source Model with Published Data

As other researchers before us [7], we have not been able to match exactly the spectra computed with our implementation of the Birch and Marshall model and those published in the Birch, Marshall and Ardran catalogue in the 30-140 kV energy range [11]. However, the difference, mostly due to the characteristic peaks model, is always less than 10% and after dose correction, the accuracy of the fit is always better than 2%.

In order to check the validity of the model for higher tube voltages, we have also compared our results to available manufacturer data, and found, for a 420 kV tube voltage with a 3 mm aluminum filtration, a difference of 20% or 5% respectively without or with dose correction.

Source Dosimetry

We have performed a validation of the model based on dose measurements on a X-ray tube (Seifert 225M2) that is available in our experimental facility. The measurement has been made at a distance of 75 cm of the tube focus with a BabyLine hand dosimeter and has been checked with LiF films, for several voltages between 50 kV and 200 kV and several aluminum and copper filtration. The computed dose lies between the measurements made with the hand dosimeter and the films (see Table 1). Additional measurements made for a Pantak MB420/1 tube between 80 kV and 350 kV also show a correct agreement.

Attenuation Through a Step Wedge

To test the validity of the complete simulation, we have compared, computed and measured attenuation for step wedges made of Plexiglas (1 mm to 25 mm), aluminum (1 mm to 25 mm) and steel (3 mm to 12 mm). The difference is most of the time less than 10% and always less than 20%. The model is less accurate for both boundaries of the test domain (small thickness of Plexiglas or aluminum and large thickness of steel).

Simulated and measured noise are in the same order of magnitude. However, the noise measurement that has been made is not accurate enough to allow a definitive conclusion.

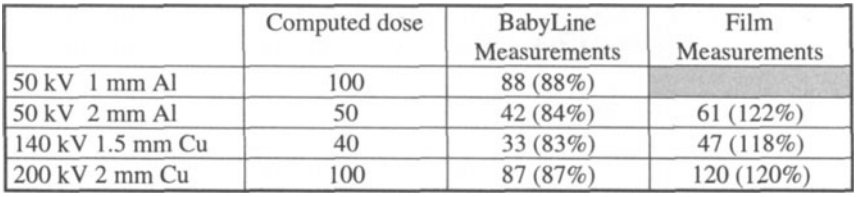
APPLICATIONS

Three examples of application of Sindbad are presented hereafter.

Firstly, the program has been used during the design of a dual-energy tomographic bench dedicated to nuclear waste drums attenuation cartography. In this kind of measurements, the X-ray tube filtration and voltages are chosen in order to obtain two non overlapping spectra, one whose mean energy is located in the photoelectric domain of the examined material and the other in the Compton domain. The photon flux must also remain compatible with the required signal to noise ratio and examination time. The spectrum modeling and the one dimensional simulation led us to choose 80 kV with a 0.5 mm tungsten filtration for the low energy settings and 350 kV with a 5 mm copper and 7 mm lead filtration for the high energy settings (Figure 1). Reconstruction methods without and with noise have then been tested using the three dimensional simulation and a detector modeling a NaI scintillating crystal coupled to a photomultiplier.

Secondly, Sindbad has been helpful during the evaluation of a new method of signal to noise ratio improvement by tomosynthesis processing, applied to NDE of a solid rocket motor. With the help of simulated radiographs, the novel method has been compared to the classical Transfer Delay Integration method and the influence of calibrated defect position and noise level on the defect detectability has been evaluated. The expected improvement must now be confirmed on real data.

Table 1. Comparison of computed and measured (BabyLine hand dosimeter and LiF film) dose (μGy) for a Seifert 225 M2 tube.



	Computed dose	BabyLine Measurements	Film Measurements
50 kV 1 mm Al	100	88 (88%)	
50 kV 2 mm Al	50	42 (84%)	61 (122%)
140 kV 1.5 mm Cu	40	33 (83%)	47 (118%)
200 kV 2 mm Cu	100	87 (87%)	120 (120%)

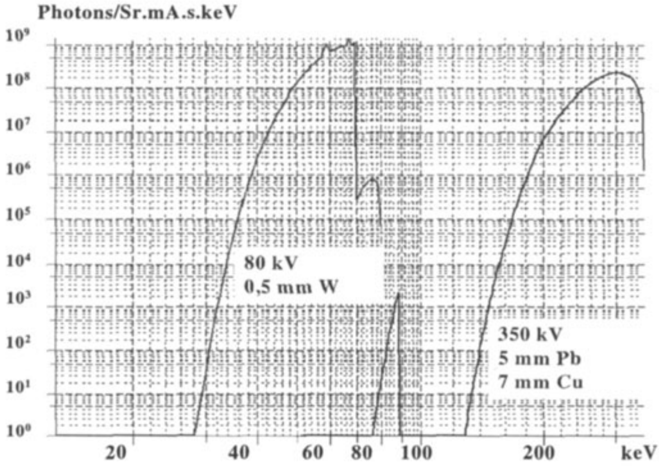


Figure 1. Spectra chosen for dual-energy tomography.

Finally, a slightly different version of the three dimensional solution program performs the simulation task in the RADICAD European project [12] whose aim is to use a few radiographs and the CAD model of a mechanical part to detect and characterize flaws. One of the test parts is made of aluminum alloy in which a hole has been drilled and a copper wire inserted. The synthetic radiograph is accurate enough to meet the requirements of the matching and flaw detection algorithms (Figure 2).

The difference between actual and simulated radiographs is 1 to 10% in aluminum. It is much larger in the drilled hole and in the copper inclusion but can be decreased by blurring the image with a gaussian filter whose standard deviation corresponds to the measured spatial resolution of the detector (Figure 3).

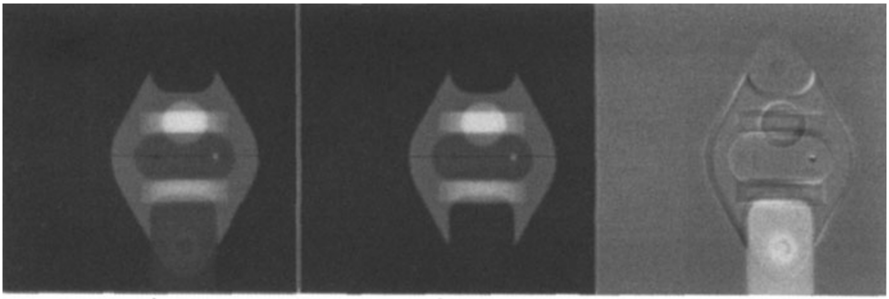

a) b) c)

Figure 2. RADICAD project, a) Actual image, b) simulated image and c) difference image.

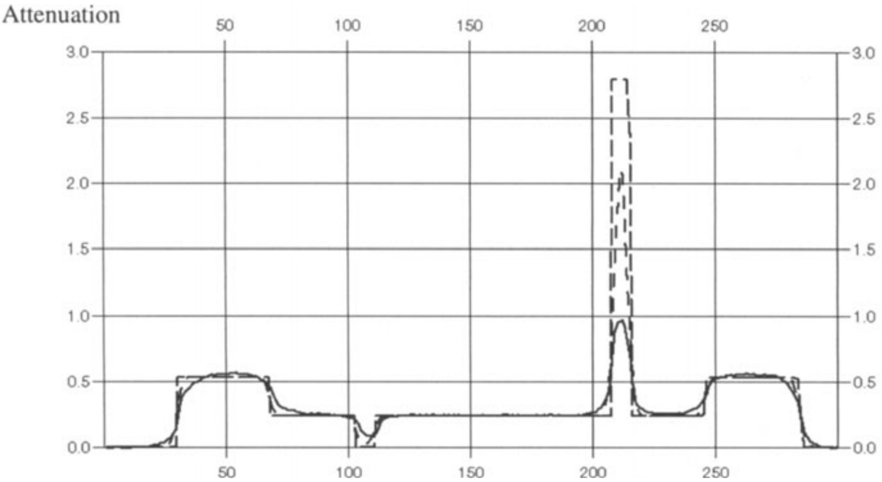


Figure 3. Plot of attenuation along a profile. Measured attenuation (solid line), Simulation without blurring (long dashed line), Simulation with blurring (dashed line).

CONCLUSION

We have presented the initial stage of the development of Sindbad, a simulation software system dedicated to the design of radiographic and tomographic facilities and the computation of synthetic radiographs. Based on semi-empirical and analytical modeling of X-ray physics (radiation production, radiation interaction with matter and radiation detection) and using the CAD model of the examined part, it produces good quality results which have been successfully compared to experimental data.

Now routinely used as a simulation tool at LETI, the program, whose modularity allows easy addition of new capabilities, still requires improvements. Among other features, the implementation and validation of a convolution based scattering model is currently under progress and the addition of new detector models such as semiconductor and film are planned.

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REFERENCES

1. G.R. Tillack, C. Bellon and C. Nockemann, "Computer simulation of radiographic process. A study of complex component and defect geometry.", Review of Progress in Non-destructive Evaluation, Vol. 14, 1995.
2. A.B. Della Rocca, S. Ferriani and L. La Porta, "Computer simulation of the radiographic forming process : implementation and applications.", N.D.T. & E. Intl. 28 (3), 1995.
3. J.N. Gray, "Three dimensional modeling of projection radiography.", Review of Progress in Non-destructive Evaluation, Vol. 7A, 1988

4. T. Jensen and J.N. Gray, "RTSIM: a computer model of real time radiography.", Review of Progress in Non-destructive Evaluation, 14, 1995.
5. H.A. Kramer, "On the theory of X-ray absorption and of the continuous X-ray spectrum", Phil. Mag., 46, pp 836-871, 1923.
6. R. Birch and M. Marshall, "Computation of bremsstrahlung X-ray spectra and comparison with spectra measured with a Ge(Li) detector.", Phys. Med. Biol. 24 (3), 1979.
7. Tucker, G.T. Barnes & D.P. Chakraborty, "Semiempirical model for generating tungsten X-ray spectra.", Med. Phys. 18 (2), 1991.
8. E. Storm and H.I. Israël, "Photon cross sections from 1 keV to 100 MeV for elements Z=1 to Z=100", Nuclear Data Tables, A 7, pp. 565-681, 1969.
9. P.C. Dykstra and M.J. Muus, " The BRL-CAD Package: An overview", USENIX, Proceedings of the Fourth Computer Graphics Workshop, Oct. 1987.
10. W.H. Press, S.A. Teukolsky, W.T. Vetterling, B.P. Flannery, "Numerical Recipes in C", second edition, Cambridge University Press, 1992.
11. R. Birch, M. Marshall and G. Ardran, "Catalogue of spectral data for diagnostic X-ray.", The Hospital Physicists' Associaton, London, 1979.
12. Koenig, A. Glière, P. Rizo, B. Bell, B. Paul, J. Anderson, "Object pose estimation using a set of local radiographs of a part and its CAD model", Review of Progress in Non-destructive Evaluation, Vol. 16A, pp. 829-836, 1997.