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Applications of optical principles in clinical X-ray visualization

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ABSTRACT

Clinical X-ray imaging uses optical engineering principles. This includes principles of quantum optics, laws of geometric optics and virtual optics in 3-D visualization. Quantum optics plays a major role in describing X-ray photon distribution and selection of this distribution for specific clinical protocols. Geometric optics explains parallax in image stitching. Mitigating parallax requires application of optical engineering principles in imaging system design. Virtual optics used in 3-D image visualization applies laws of geometric optics in surface rendering and maximum intensity projection. Application of optical engineering in clinical X-ray system design is pervasive, even though it may not have been recognized as such.

1. Introduction

Optical principles describe properties and behavior of visual, ultraviolet and infrared radiations. However, since these radiations are electromagnetic radiations, most of the optical principles are also applicable to other electromagnetic radiations [1]. One of the notable examples is radio waves. Engineering theory of radio wave antenna design uses laws of optics.

Physical optics – the field describing wave, particle and quantum nature of light – has found significant role in X-ray theory and applications compared to geometric optics. This is because refractive index of X-ray for all material is closer to 1, and all materials absorb X-ray [2]. Another area of optical engineering used in all modalities of medical imaging is virtual optics. In virtual optics, optical simulation and modeling are used for generating output image of a scene [3]. Using virtual optics, realistic and meaningful visuals of internal anatomical structures are generated.

Medical imaging technologies enable physicians to see internal anatomy and physiological functions without surgical interference. X-ray imaging, Computed Tomography (CT), radioisotope scanning, Magnetic Resonance Imaging (MRI) and ultrasound imaging are commonly used modalities in medical imaging. Digital X-ray is a 2-dimensional (2-D) technology. CT and MRI acquire 3-dimensional (3-D) volume data. Radioisotope scanning can be used for planar 2-D data acquisition or 3-D volume data acquisition. Single Photon Emission Computed Tomography (SPECT) and Positron Emission Tomography (PET) are most commonly used 3-D radioisotope scanning technologies. X-ray imaging is the most common modality among all these.

Raw data acquired in all these modalities are just numbers that do not provide any direct clinical information. Image processing and visualization techniques are used for extracting and presenting clinical information from raw data. Quantum optics of X-ray photons and image processing techniques are considered together for clinical image acquisition. Voltage applied to X-ray source determines energy range of photons while current controls number of photons emitted from X-ray target. Statistical distribution of photons depends on target material and beam hardening filters. Image processing techniques remove unwanted information and enhance information sought for clinical diagnosis. Unwanted information is called noise while sought after information is called signal. In Planar X-ray imaging statistical distribution of X-ray photon quanta plays a significant role in deciding the information presented in image. Techniques used for image visualization are customized to the X-ray photon distribution.

Virtual optics is used in many fields, including computer games, flight simulators, warfare, cryptography and medical imaging. Data acquired in medical imaging should be presented in a form that doctors could visualize. Therefore 3-D human body data are placed in a virtual studio with virtual lights, and image projections are reconstructed using virtual camera acquisition. Ray casting in virtual optics is used in 3-D imaging [4]. Ray-casting is also important for managing projection artifacts in planar X-ray imaging.

One of the primary benefits of medical imaging is segmenting and visualizing human tissue volumes interactively but without physically segmenting the actual human body. In order to present

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the virtual tissue volume as a visual object, voxels in the virtual tissue volume would be assigned certain optical properties such as opacity, reflectance, color and translucency. These properties would have been true if the physical tissue volume was physically segmented and placed in a studio with similar lighting conditions. We introduced a virtual scalpel in MRI and CT scanner console software, and doctors use this scalpel to segment irregular shapes from 3-D image data [18].

In early 1990s, at Cedara Software Corporation we developed medical imaging console software for Hitachi Medical Systems and Philips Medical Systems. Processing Server in this software used virtual optics for presenting tissue volumes [4]. At InfiMed Inc. we used physical optics in X-ray imaging consoles for reducing noise and enhancing image information [10]. In projection X-ray image stitching we used geometric optics in stitching algorithms [19]. In this paper important image processing techniques used in 2-D and 3-D X-ray imaging are discussed in order to describe applications of optical engineering in clinical X-ray visualization.

2. Grayscale display

X-ray images are viewed in grayscale displays because historically physicians are trained to understand human anatomy in grayscale. In grayscale display, gradually varying levels of grays represent monotonically varying characteristic such as tissue opacity to X-ray. Grayscale Standard Display Function (GSDF) provided in Part 14 of Digital Imaging and Communication in Medicine (DICOM) standard is supported by all major equipment manufacturers [5]. GSDF maps Digital Driving Levels (DDL) to luminance levels that provide Just Noticeable Differences (JND) in gray levels an average human observer can perceive (Fig. 1).

When an X-ray photon interacts with soft tissues and bones it could be scattered, absorbed or it could penetrate through and impinge the detector. Energy of the photon determines the type of interaction. At diagnostic energy range, Compton scattering is the dominant form of interaction; photoelectric effect is the primary means of absorption [6]. Gray levels represent number of photons that were able to penetrate through tissues along the path of the X-ray beam. Photons with less energy are scattered or absorbed while higher energy photons penetrate through tissues. In clinical protocols combination of X-ray tube voltage in killovoltage, current in milliamperes and exposure time in seconds are specified for a given diagnosis. For example, a chest X-ray on which soft tissues in lungs should be visible is taken with lower X-ray voltage compared to a rib X-ray (Fig. 2). While high-energy photons penetrate through lungs, low energy photons are scattered and absorbed by lung tissues thus producing statistical lung distribution on an X-ray image. In rib X-ray, ribs scatter and absorb all low energy photons, hence producing a rib image.

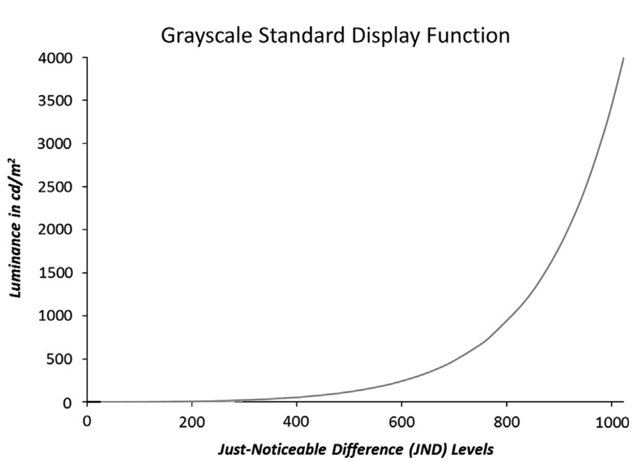

Fig. 1. Grayscale standard display function.

3. Quantum noise

Any unwanted information in an image is noise that degrades the signal. X-ray images are degraded by both high-frequency and low-frequency noise. One important source of high-frequency noise is statistical distribution of X-ray photons – an inherent property of electromagnetic radiation. During image acquisition X-ray is turned on for a few seconds. This duration is known as exposure time. Photons emitted within this duration are statistically distributed, and this distribution follows Poisson statistics. This statistical noise interferes with high resolution detail of fine structures in human anatomy. This noise is sometimes called quantum noise, shot noise or salt and pepper noise because of its origin in photon quanta statistics, small size and wide-spread distribution.

Another source of noise is photon scatter. Scattering is necessary for forming X-ray image, but scattered photons may be scattered multiple times along their way towards the X-ray detector and impinge on the detector surface at some location. These photons degrade image because they do not represent structures along the path of X-rays.

4. Low-frequency degradation

Low-frequency noise blurs an image. Primary contribution for low-frequency noise is the limitation of system response to a point object. Because of limitations in geometric optics, a point object is not represented by a point in an image; instead it is represented by a blurred circular distribution (Fig. 3) of the point [7]. This distribution is called point spread function (PSF). Frequency distribution of a PSF is called Modulation Transfer Function (MTF), which describes low-frequency blurring introduced in the image by spatial detail transfer characteristics of the system [8].

Physical mechanisms such as shields, grids and patient-restraints are used for minimizing noise and artifacts. These mechanisms are not sufficient for acquiring acceptable image quality [9]. Noise introduced because of statistical photon distribution cannot be mitigated by physical mechanisms. Blurring of image because of MTF also cannot be mitigated using physical structures. Image processing filters that allow low-frequency information to pass through while suppressing high frequency content are used for reducing the impact of statistical photon noise. Inverse recovery filters designed using an MTF of a system are used for recovering image sharpness.

5. Nonlinear corrections

Clinical X-ray images are transmission images. Tissues in human body attenuate X-ray along its path. Amount of X-ray photons are reduced exponentially along the path of X-ray. Characteristic attenuation coefficient of tissue determines the amount of photon attenuation. From this nonlinear data, linear representation of tissue opacity is obtained using logarithmic transformation of photon counts [10]. Distribution of transmitted X-ray photons represents tissue volume distribution [11].

Image detectors and displays do not represent values linearly. A nonlinear correction known as gamma correction is necessary [5]. Gamma correction for monitors and detectors are provided by manufacturers. Human vision is also nonlinear. Human observers are limited in their ability to distinguish number of just noticeable