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Editorial

Shaping the future through innovations: From medical imaging to precision medicine

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ABSTRACT

Medical images constitute a source of information essential for disease diagnosis, treatment and follow-up. In addition, due to its patient-specific nature, imaging information represents a critical component required for advancing precision medicine into clinical practice. This manuscript describes recently developed technologies for better handling of image information: photorealistic visualization of medical images with Cinematic Rendering, artificial agents for in-depth image understanding, support for minimally invasive procedures, and patient-specific computational models with enhanced predictive power. Throughout the manuscript we will analyze the capabilities of such technologies and extrapolate on their potential impact to advance the quality of medical care, while reducing its cost.

1. Introduction

Medical imaging has impacted the practice of medicine during the recent decades, contributing to greatly improved disease diagnosis, treatment and follow-up. Image-guided, minimally invasive procedures are becoming more and more common in hospitals, replacing conventional surgery and allowing faster recoveries with fewer post-procedure complications. We anticipate that this trend will continue, medical imaging playing an increasingly important role towards moving precision medicine into clinical practice. By being able to characterize anatomy, physiology and metabolism of the patient, medical imaging enables precise, personalized procedures and predictive, patient-specific therapy selection and delivery.

In this paper we highlight a number of technologies that will most likely contribute to the success of medical imaging for the years to come, helping medical care to advance, while reducing its cost. In Section 2 we discuss Cinematic Rendering, a 3D visualization technology that is capable of producing superb photorealistic images from traditional Computer Tomography (CT) or Magnetic Resonance (MR) volumes, thus potentially enhancing the conspicuity of pathologies. Section 3 addresses the topic of next generation image understanding, which contributes to faster and more reproducible image reading, benefiting from the recent advances in machine learning and artificial intelligence. Furthermore, in Section 4 we discuss the real-time imaging needs in the operating room and focus on heart valve procedures, addressing both their planning and guidance. Finally, in Section 5 we present patient-specific computational models that contribute to advances in diagnosis, patient stratification, therapy selection and therapy optimization. All images shown in the paper are images of real, living patients.

2. Cinematic rendering: photorealistic visualization of medical images

Efficient clinical decisions and procedures require the rapid appreciation of the relevant information contained within medical images. Even though medical image viewing based on multi-planar reconstruction (MPR) is still dominant in diagnostic imaging, the significance of three-dimensional visualization of medical data is rising. This is due to the fact that these methods allow much faster understanding of spatial anatomical structures and have the potential to increase the sensitivity and specificity of medical images. Especially medical professionals who are not trained in planar image viewing as well as patients benefit from such visualizations.

Recent advances in computer graphics have made interactive physically-based volume visualization techniques possible. Such techniques reproduce complex illumination effects in computer-generated images by mimicking the real-world interaction of light with matter. The results are physically plausible images that are often easier for the human brain to interpret, since the brain is trained to interpret the slightest shading cues to reconstruct shape and depth information. Such shading cues are often missing from

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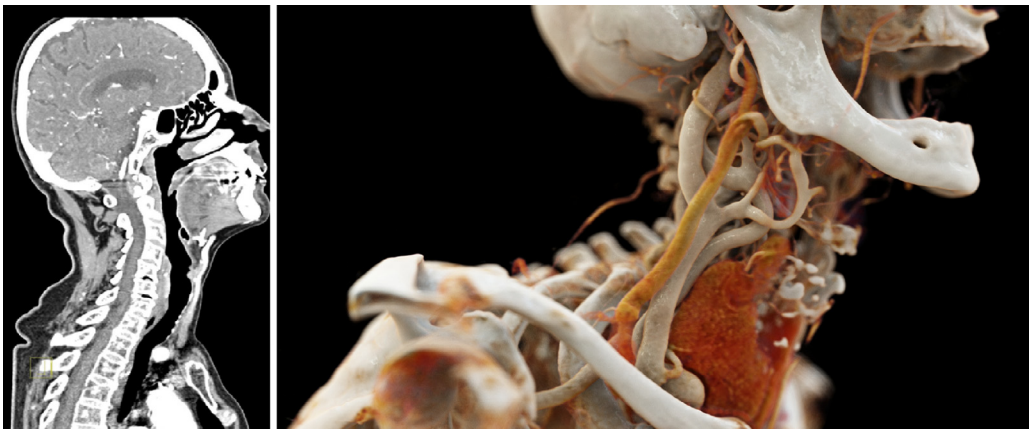

Fig. 1. Cinematic Rendering. Left: Original computed tomography (CT) data; Right: Cinematic rendering of the same dataset. Data courtesy of Israelitisches Krankenhaus, Hamburg, Germany.

computer generated images based on more simple geometric calculations such as ray casting.

We developed a physically-based volume rendering method called Cinematic Rendering (Engel 2016; Paladini 2015) which computes in real-time the interaction of visible photons with the scanned patient anatomy. The algorithm uses a Monte Carlo path tracing method to generate photorealistic or even hyper-realistic images by light transport simulation along hundreds or thousands of photons paths per pixel through the anatomy using a stochastic process (Fig. 1)

In traditional volume ray casting, only emission and absorption of radiant energy along a straight ray is considered. Radiant energy q_e is emitted at each point x' along the ray up to a maximum distance D.

$$L(x, \boldsymbol{\omega}) = \int_0^D e^{-\tau(x,x')} q_e(x') dx' \tag{1}$$

The emitted radiant energy at each point is absorbed according to the Beer-Lambert law along the ray to the observer location with absorption coefficients σ_a.

$$\tau(x, x') = \int_x^{x'} \sigma_a(t) dt \tag{2}$$

Single scattering is usually modelled in traditional volume rendering using a surface shading model that considers local gradient information of the volume data (local illumination). While this integral can be easily solved numerically using a Riemann integral, the method neglects complex light paths with multiple scattering events and extinction of light (global illumination).

In contrast, the Monte Carlo path tracing integration method solves the following multi-dimensional and non-continuous rendering equation:

$$L(x, \boldsymbol{\omega}) = \int_0^D e^{-\tau(x,x')} \sigma_S(x') \left[\int_{\Omega_{4\pi}} p(\boldsymbol{\omega}, \boldsymbol{\omega}') L_i(x', \boldsymbol{\omega}') d\boldsymbol{\omega}' \right] dx' \tag{3}$$

Eq. (3) determines the radiant flux (radiance) L at distance x received from the direction $\boldsymbol{\omega}$ along a ray. We have to integrate the radiance scattered into that direction from all possible directions $\boldsymbol{\omega}'$ at all points along the ray up to a maximum distance D. The optical properties of a relevant tissue are defined using the phase function $p(\boldsymbol{\omega}, \boldsymbol{\omega}')$, which describes the fraction of light travelling along a direction $\boldsymbol{\omega}'$ being scattering into the direction $\boldsymbol{\omega}$. $L_i(x', \boldsymbol{\omega}')$ is the radiance arriving a distance x' from direction $\boldsymbol{\omega}'$. In practice, we model scattering in different tissue types using a Henyey-Greenstein phase function and compute shading of implicit surfaces using a BRDF (bidirectional reflectance distribution function).

Radiance scattering into the direction $\boldsymbol{\omega}$ is also absorbed and scattered out of the direction $\boldsymbol{\omega}$. This is modelled using the optical depth τ, with extinction coefficient $\sigma_t = \sigma_s + \sigma_a$, defined as the sum of scattering (σ_s) and absorption (σ_a) coefficients:

$$\tau(x, x') = \int_x^{x'} \sigma_t(t) dt \tag{4}$$

Note that, in contrast to out-scattering, absorption and in-scattering, emission was omitted in the rendering equation for simplicity. Since the rendering equation cannot be computed analytically, solving the integral numerically would involve sampling the function at many distances, each with many directions. Additionally, L_i must be computed with the same rendering equation to allow multiple scatter events. Since this would be computationally too complex, the Monte Carlo method allows us to compute the radiance at random positions along the ray with light being in-scattered from random directions. By averaging many of such Monte Carlo samples into a single image we can progressively generate a smooth final result. By means of multiple sampling, the convergence of the method can be accelerated considerably.

The medical data is illuminated using image-based lighting by high-dynamic range lighting environments, which can either be captured photographically or generated synthetically. Photographically captured lighting leads to a very natural appearance of the data when compared to images created using the traditional ray casting method. Such natural lighting in combination with the accurate simulation of photon scattering and absorption, leads to photorealistic images (see Fig. 1) that resemble many shading effects that can be observed in nature, such as soft shadows, ambient occlusion, volumetric scattering and subsurface photon interaction. By modelling a virtual camera with variable aperture, focal length and exposure, additional effects such as depth-of-field and motion blur can be produced. Motion blur allows movies generated using our key frame animation engine to be smoother during fast camera movements while, similar to photography, depth-of-field effects allow to focus the attention of a viewer on a particular structures.

Beyond photorealism the algorithm also permits to visualize invisible or hidden processes such as the propagation of electrical activation on the heart surface or metabolic processes in the body. Such hyper-realistic images are created by modelling visible light photon emission from voxels affected by electrical activation, increased metabolism indicated by Positron Emission Tomography (PET) or the detection of chemical compounds such as monosodium urate from a dual-energy CT scan (Fig. 2).

The combination of different imaging modalities in a single picture, such as PET, MR and CT as well as simulated and computed