

Real-time ultrasound simulation on GPU

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1. Introduction

Despite the increasing adoption of other imaging modalities, ultrasound (US) guidance is widely used for surgical procedures and clinical imaging due to its low cost, non-invasiveness, real-time visual feedback. Many US-guided procedures require extensive training and where possible training on simulations should be preferred over patients.

Computational resources for existing approaches to US simulation are usually limited by real-time requirements. Unlike previous approaches we simulate freehand US images from CT data on the Graphics Processing Unit (GPU). We build upon the method proposed by Wein et al. [1] for estimating US reflection properties of tissue and modify it to a computationally more efficient form. In addition to previous approaches, we also estimate US absorption properties from CT data. Using NVIDIA's Compute Unified Device Architecture (CUDA), we provide a physically plausible simulation of US reflection, shadowing artifacts, speckle noise and radial blurring. All parameters of the simulated probe are interactively configurable at run-time, including US frequency and intensity as well as field geometry.

2. Methods

Our complete simulation pipeline is shown in figure 1. First, given the position and orientation of the probe, a 2-D reformatted image is extracted from the 3-D volume. Then, the physical phenomena involved in US image generation are simulated from the data, i.e. acoustic impedance, reflection, and absorption. Finally, speckle noise and blurring are added in a post-processing step, and the image can be updated in real time according to the user-defined parameters.

Reflection: The intensity reflected at a specular interface can be computed as

$$\frac{I_r}{I_i} = \left(\frac{Z_2 \cdot \cos \theta_i - Z_1 \cdot \cos \theta_t}{Z_2 \cdot \cos \theta_i + Z_1 \cdot \cos \theta_t} \right)^2 \stackrel{\theta \approx 0}{\approx} \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2$$

where Z_1 and Z_2 are the acoustic impedances of the two types of tissue and θ_i and θ_t are the angles of incidence and transmission, respectively. Usually, a combination of diffuse and specular reflection is approximated by using $I_r/I_i = \cos(\alpha)^n$ with $n=1$ for a perfect diffuse reflection and $n>1$ for a combination of specular and diffuse reflection. We may choose $n=2$, as it further simplifies the equations. We substitute the cosine with the dot product of a unit vector d in ray direction and the normalised gradient vector. In the following formula, $d^T \nabla Z(x)$ equals the gradient magnitude along the ray, which can be easily computed in the simulated 2-D US scan plane:

$$\frac{I_r}{I_i}(x) \stackrel{est.}{=} \left(d^T \cdot \frac{\nabla Z(x)}{\|\nabla Z(x)\|} \right)^2 \left(\frac{\|\nabla Z(x)\|}{2 \cdot Z(x)} \right)^2 = \left(\frac{d^T \cdot \nabla Z(x)}{2 \cdot Z(x)} \right)^2$$

Absorption: Absorption, i.e. energy transfer into a localised heating of the tissue, accounts for nearly all US attenuation in soft tissue. It can be characterised by an exponential law $I/I_0 = e^{-\beta x}$, similar to X-ray attenuation. Typical absorption coefficients for various media are known, so we estimate absorption coefficients for each pixel by an interpolation from the values of air, water, and bone.

Transmission: To simulate the image, track the amount of intensity transmitted along each column of the image. Initially, the US intensity at the location of the probe is set, and for every pixel in the column we compute the amount of intensity that is transmitted to that pixel, and how much intensity is reflected or absorbed.

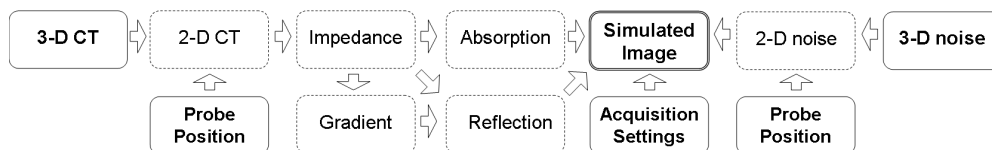


Figure 1: Simulation of US image from 3-D CT data, 3-D noise, probe position, and acquisition settings.



Figure 2: Timing overview (left) and a breakdown of the “Computation” step on GPU (right).

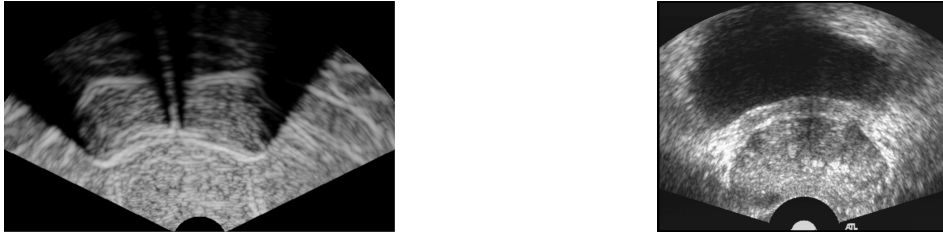


Figure 3: Screen shot of our ultrasound simulation (left), configured like a transrectal ultrasound probe, with a similar image from a real transrectal ultrasound examination of a different patient (right).

Speckle noise and blurring: A “fully developed speckle pattern”, i.e. pure diffuse scattering with many (i.e. >10) scatterers per resolution cell, can be well characterised by a Rayleigh distribution. We use GLSL to extract a 2-D slice from a 3-D Rayleigh noise texture and CUDA for blending. Radial blurring (in lateral and axial direction) is added using CUDA again.

3. Results and Conclusion

We simulated an ultrasound image of size 512×384 pixels from a raw CT volume of size $512 \times 512 \times 148$ voxels on a work station equipped with a GeForce 8800 GTX, Dual Intel Xeon 3 GHz, and 2 GB RAM. For detailed timing information cf. figure 2.

One possible application is simulating a transrectal ultrasound examination, as needed for e.g. US-guided needle biopsy of the prostate. For a visual comparison of our simulation with a typical image from a real examination cf. figure 3. As visible in the image, we provide a realistic simulation of US reflection and artifacts like shadows, attenuation, speckle noise, and radial blurring.

We modified an existing physically plausible approach to simulate US images so that computation is entirely feasible within the virtual US scan plane and with only one slice from the original 3-D CT image. No manual annotation or adjustment of the input data is necessary. Ultrasound reflection, attenuation, shadowing artifacts, speckle noise, and radial blurring are reproduced. Like a real probe, all acquisition parameters can be interactively changed during the simulation, including US frequency, US intensity, time-gain compensation, and field geometry, as well as speckle size and radial blurring. A wide range of different probe types can be simulated and our simulation framework is generally applicable to training of different US examinations or US-guided procedures.

4. References

- [1] W. Wein, S. Brunke, A. Khamene, M. Callstrom, and N. Navab, “Automatic CT-ultrasound registration for diagnostic imaging and image-guided intervention”, *Medical Image Analysis* 12, September 2008. In Press.

5. Photographs of authors

