

The definitive version is available at <http://http://online.medphys.org/>.

F.P. Vidal, P.-F. Villard, M. Garnier, N. Freud, J.M. Létang, N. John, and F. Bello: Joint Simulation of Transmission X-ray Imaging on GPU and Patient's Respiration on CPU. In *Medical Physics*, 37(6):3129, July 2010, American Association of Physicists in Medicine

DOI: 10.1118/1.3468154

```
@article{Vidal2010MedPhys-B,
  author = {F. P. Vidal and P. F. Villard and M. Garnier and N. Freud and J. M. L\`etang and N. W. John and
  title = {Joint Simulation of Transmission X-ray Imaging on {GPU} and Patient's Respiration on {CPU}},
  journal = {Medical Physics},
  year = 2010,
  volume = 37,
  pages = {3129},
  number = 6,
  month = jul,
  address = {Philadelphia, Pensilvania, USA},
  annotation = {AAPM Annual Meeting, Jul-18--22, 2010},
  abstract = {Purpose: We previously proposed to compute the X-ray attenuation
from polygons directly on the GPU, using OpenGL, to significantly
increase performance without loss of accuracy. The method has been
deployed into a training simulator for percutaneous transhepatic
cholangiography. The simulations were however restricted to
monochromatic X-rays using a point source. They now take into account
both the geometrical blur and polychromatic X-rays.
Method and Materials: To implement the Beer-Lambert law with a
polychromatic beam, additional loops have been included in the
simulation pipeline. It is split into rendering passes and uses frame
buffer objects to store intermediate results. The source shape is
modeled using a variable number of point sources and the incident beam
is split into discrete energy channels. The respiration model is composed
of ribs, spine, lungs, liver, diaphragm and the external skin. The organ
motion simulation is based on anatomical and physiological studies:
the model is monitored by two independent active components:
the ribs with a kinematics law and the diaphragm tendon with an up and
down translation. Other soft-tissue components are passively deformed
using a 3D extension of the ChainMail algorithm. The respiration rate
is also tunable to modify the respiratory profile.
Results: We have extended the simulation pipeline to take into account
focal spots that cause geometric unsharpness and polychromatic X-rays,
and dynamic polygon meshes of a breathing patient can be used as input data.
Conclusions: X-ray transmission images can be fully simulated on the GPU,
by using the Beer-Lambert law with polychromatism and taking into account
the shape of the source. The respiration of the patient can be
modeled to produce dynamic meshes. This is a useful development to improve
the level of realism in simulations, when it is needed to retain both speed
and accuracy.},
  doi = {10.1118/1.3468154},
  publisher = {American Association of Physicists in Medicine}
}
```

Joint Simulation of Transmission X-ray Imaging on GPU and Patient's Respiration on CPU

F. P. VIDAL¹, P.-F. VILLARD², M. GARNIER³, N. FREUD⁴, J. M. LÉTANG⁴, N. W. JOHN⁵, and F. BELLO⁶

¹ University of California, San Diego, La Jolla, CA

² LORIA, Nancy University, FR

³ BRGM, Orleans, FR

⁴ INSA de Lyon, FR

⁵ Bangor University, GB

⁶ Imperial College London, GB

Purpose

We previously proposed to compute the X-ray attenuation from polygons directly on the GPU, using OpenGL, to significantly increase performance without loss of accuracy. The method has been deployed into a training simulator for percutaneous transhepatic cholangiography. The simulations were however restricted to monochromatic X-rays using a point source. They now take into account both the geometrical blur and polychromatic X-rays.

Method and Materials

To implement the Beer-Lambert law with a polychromatic beam, additional loops have been included in the simulation pipeline. It is split into rendering passes and uses frame buffer objects to store intermediate results. The source shape is modeled using a variable number of point sources and the incident beam is split into discrete energy channels. The respiration model is composed of ribs, spine, lungs, liver, diaphragm and the external skin. The organ motion simulation is based on anatomical and physiological studies: the model is monitored by two independent active components: the ribs with a kinematics law and the diaphragm tendon with an up and down translation. Other soft-tissue components are passively deformed using a 3D extension of the ChainMail algorithm. The respiration rate is also tunable to modify the respiratory profile.

Results

We have extended the simulation pipeline to take into account focal spots that cause geometric unsharpness and polychromatic X-rays, and dynamic polygon meshes of a breathing patient can be used as input data.

Conclusions

X-ray transmission images can be fully simulated on the GPU, by using the Beer-Lambert law with polychromatism and taking into account the shape of the source. The respiration of the patient can be modeled to produce dynamic meshes. This is a useful development to improve the level of realism in simulations, when it is needed to retain both speed and accuracy.

Joint Simulation of Transmission X-ray Imaging on GPU and Patient's Respiration on CPU

F.P. Vidal^{a,b}, P.-F. Villard^{c,d}, M. Garnier^{a,e}, M. Jacob^b, N.W. John^f, F. Bello^g, N. Freud^h, J.M. Letang^h, D.A. Gould^g

^a Bangor University, UK
^b University of California, San Diego, CA
^c LORIA, Nancy University, France
^d Imperial College, London, UK
^e BRGM, Orléans, France
^f INSA Lyon, France

^g Royal Liverpool University and Broadgreen Hospitals NHS Trust, UK

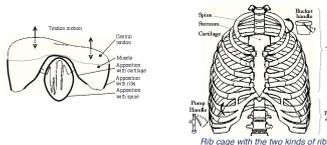
We present a simulation framework that combines respiratory motion and X-ray imaging. Our aim is to provide a validated training tool for interventional radiology to perform percutaneous transhepatic cholangiography (PTC). A CPU-based set of algorithms is presented to model the organ behaviour during breathing. Soft tissue deformation is computed with an extension of the ChainMail method and rigid elements move according to kinematic laws. A GPU-based surface rendering method is proposed to compute the X-ray image using the Beer-Lambert law. We demonstrate the efficiency of this approach by combining both visual and haptic cues and showing that interactive frame rates can be achieved.

Introduction

PTC consists in injecting a contrast agent into a bile duct within the liver to visualize the biliary tract using fluoroscopy (real-time X-ray images). The training of PTC is still performed as an apprenticeship within patients, and we have developed a virtual reality simulator to provide an alternative¹. We present here the implementation of the two main software components of our simulator: i) the respiration modeling (inc. soft tissue deformation), and ii) the simulation of X-ray imaging.

Respiration Modelling

Our respiration model consists of a combination of i) rib motion following a kinematic law, and ii) a translation of the diaphragm.



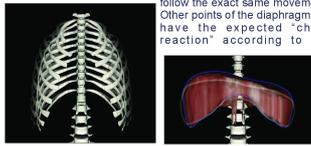
Diaphragm heterogeneous composition.

tendon. They are respectively defined here by the angles α and β . Wilson *et al.*² measured these angles for five subjects at Functional Residual Capacity (FRC) and Total Lung Capacity (TLC). The rib rotation was thus decomposed into two distinct rotations. We consider here that the rest position is at FRC. In our model, the rotation angles are given by the following equations:

$$\alpha^t = ((\beta_{TLC} - \beta_{FRC}) \times \frac{1}{3} \times (1 + \sin(2\pi f t)))$$

where: α^t is the reduced "bump handle" angle, α (FRC) = 0 and α (TLC) = $\alpha_{TLC} - \alpha_{FRC}$, β^t is the reduced "bucket handle" angle β (FRC) = 0 and β (TLC) = $\beta_{TLC} - \beta_{FRC}$, f is the respiration frequency and t is the time.

The central tendon is forced to have a sinusoidal movement along the vertical axis similarly to the previous Equations. During inhalation, the central tendon has a downward movement, which is synchronous with the expanding rib cage. As the links for the central tendon are rigid, the points corresponding to this tendon will follow the exact same movement. Other points of the diaphragm will have the expected "chain reaction" according to the



Rib cage. Diaphragm. Respiration simulation: expiration to inspiration (transparent rendering).

Acknowledgements

This work has been partially funded by the UK Department of Health under the Health Technology Devices programme and commissioned by the National Institute for Health Research (NIHR). This is independent research and the views expressed are those of the authors and not necessarily those of the NIHR, the NIHR or the Department of Health.

ChainMail rules. However, the diaphragm is also supposed to follow the movement of the ribs. To do this, the idea is to "fix" some points of the diaphragm to some points of the ribs. Finally, the movement of the diaphragm will be a combination of the downward movement of the central tendon and the movement induced by the contact points with the ribs.

Soft Tissue Deformation

Ribs and bones are modeled using rigid bodies. Other anatomical structures are modeled as soft tissues. Their deformation is performed using the 3D ChainMail algorithm extension proposed by Li and Brodlie³. Mesh elements are

interconnected as links in a chain. So, within a certain limit, each point can move freely without influencing its neighbours. When one element of the object is moved and reaches this limit, the neighbours are forced to move in a chain reaction that is governed by the stiffness of the links in the mesh. The ChainMail parameters to simulate the deformation behaviour include the compression, the stretching and the shearing. The ChainMail parameters are set for each kind of tissue independently.

X-ray Imaging Simulation

This dynamic data is used as input for our X-ray imaging simulation using the Beer-Lambert law. It relates the absorption of light to the properties of the material through which the light is traveling. For a monochromatic incident X-ray beam, it is:

$$N_{out}(E) = N_{in}(E) \exp\left(-\sum_{i=1}^{obj} \mu(E, i) L_p(i)\right)$$

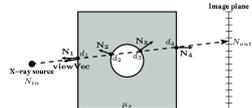
with $N_{in}(E)$ the number of incident photons at energy E , $N_{out}(E)$ the number of transmitted photons at energy E , obj is the total number of objects in the 3D scene, μ is the linear attenuation coefficient (in cm^{-1}), which depends on: i) E , the energy of incident photons, and ii) the material properties of the object. $L_p(i)$ is the path length (in cm) of the ray in the i^{th} object.

$L_p(i)$ is computed for each polygon mesh using the method proposed by Freud *et al.*⁴. Normal vectors at the surface of objects are outward. The path length of the ray in a given object can be written as follows:

$$L_p = \sum_i -(\text{sgn}(\text{viewVec} \cdot \mathbf{N}_i) \times d_i)$$

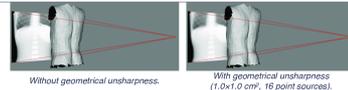
where i refers to the i^{th} intersection found in an arbitrary order, d_i is the distance from the X-ray source to the intersection point of the ray with the triangle, $\text{sgn}(\text{viewVec} \cdot \mathbf{N}_i)$ stands for the sign of the dot product between viewVec and \mathbf{N}_i .

We showed that these operations can be efficiently achieved on the GPU using OpenGL and the OpenGL Shading Language (GLSL)⁵.



References

- (1)VILLARD P, F. VIDAL, F. P. HUNT, G. GILLOU, N. W. JOHNSON, S. GOULD D. A.: Simulation of percutaneous transhepatic cholangiography training simulator with real-time breathing motion. *Int J Comput Assist Radiol Surg* 4 (9) (2009), 577-579.
- (2)LI Y, BRODLIE K.: Soft object modeling with generalised ChainMail - extending the boundaries of web-based graphics. *Comput Graph Forum* 22, 4 (2003), 717-727.
- (3)WILSON T.A, et al.: Respiratory effects of the external and internal intercostal muscles in humans. *J Physiol* 530, 2 (2001), 319 - 330.

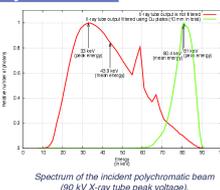


Geometric unsharpness

The shape of the source is modeled using a variable number of point sources⁶. Each point is assigned a fraction of the total number of photons in the system.

Polychromatism

The incident beam is split into discrete energy channels⁶. To produce the final image, the total amount of energy received by each pixel is computed.

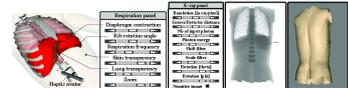


Simulated X-ray images are presented as "energy fluence" (F) maps (total energy received by the detector):

$$F = \sum_j E(j) \times N_{out}(E(j))$$

Results

The application is written in C++ and Python using the H3D API for haptics, and OpenGL and GLSL for the graphics (inc. the simulation of X-ray imaging). The complete patient model contains the ribs, spine, sternum, diaphragm, lungs, cartilage, liver and the skin, and is integrated into a visu-haptic environment capable of 70 frames per second (FPS) for the graphics to enable stereovision, and 1 kHz for the haptic rendering.



Conclusion

The respiration of the patient can be modeled to produce dynamic meshes in real-time. This data is then used to simulate X-ray transmission imaging on the GPU, by using the Beer-Lambert law with polychromatism and taking into account the shape of the source. This is a useful development to improve the level of realism in simulations, when it is needed to retain both speed and accuracy.

- (4)FREUD N, DUVAUCHELLE P, LETANG J, M, BABOT D.: Fast and robust ray casting algorithms for virtual X-ray imaging. *Nucl Instrum Methods Phys Res B* 248, 1 (2006), 175-180.
- (5)VIDAL F, P, GARNIER M, FREUD N, LETANG J, M, JOHN N, W.: Simulation of X-ray attenuation on the GPU. In *Proc Theory Pract Comput Graph* (2009), pp. 25-32.
- (6)VIDAL F, P, GARNIER M, FREUD N, LETANG J, M, JOHN N, W.: Accelerated Deterministic Simulation of X-ray Attenuation Using Graphics Hardware. In *EG 2010 - Posters* (2010), poster5011.

Figure 1: Poster presented at AAPM Annual Meeting, Philadelphia, Pennsylvania, USA, Jul 18-22, 2010.