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Laser interactive 3D computer graphics

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Introduction

A non-conventional three-dimensional optical imaging technique with laser system or LADAR (LAsER Detection And Ranging) has emerged [Berginc and Jouffroy, 2009a, Berginc and Jouffroy, 2009b, Berginc and Jouffroy, 2010, Berginc and Jouffroy, 2011, Berginc, 2014]. A scene is illuminated by a laser source, in the visible or near-infrared band (500-2200 nm). At the same time, a high pixel density detector collects the backscattered radiation. Such a record provides a high-resolution image with a large dynamic range, and can be obtained in various experimental conditions: day, night, sun, fog,... Even better, combining a set of laser images provides a 3D reconstruction of the scene with ability to detect and recognize occluded objects. Such a laser system could be applied in many areas, such as surveillance or robotic vision. New scientific and industrial challenges have arisen from laser imagery, including the need of mathematical algorithms and dedicated visualization tools.

Concerning the algorithm, Computerized Tomography has been extended to 3D laser imaging in [Berginc and Jouffroy, 2009b]: the FDK algorithm maps a set of 2D laser images to a 3D volume which represents the scene. Numerical results show that the highest values in such a computed volume are features from the scene. Let us illustrate this method by the means of real laser images of a complex scene: car under branches (courtesy of Thales). The scanning provides a laser sinogram of the scene over 180 degrees: see Figure 1. It contains 181 laser images of size 342×421 . Some images of the sequence are depicted on Figure 2. Orthogonal slices of the resulting FDK volume are represented in Figure 3.

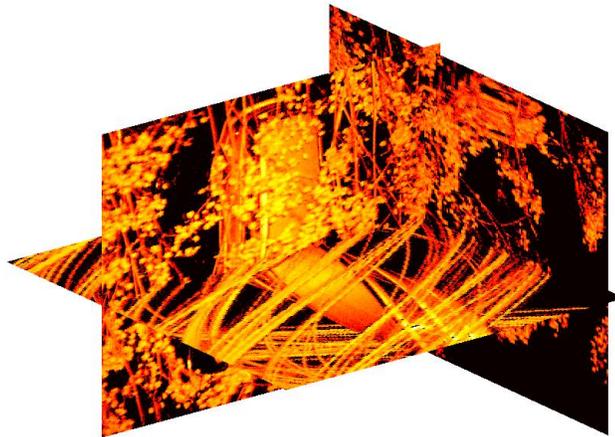


Figure 1: Slices through a real laser sinogram.

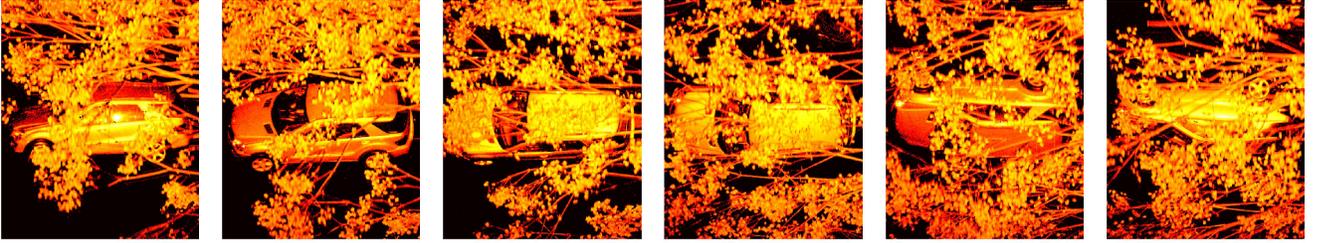


Figure 2: A few laser images of the sequence : 20, 50, 80, 110, 140, 170 degrees.

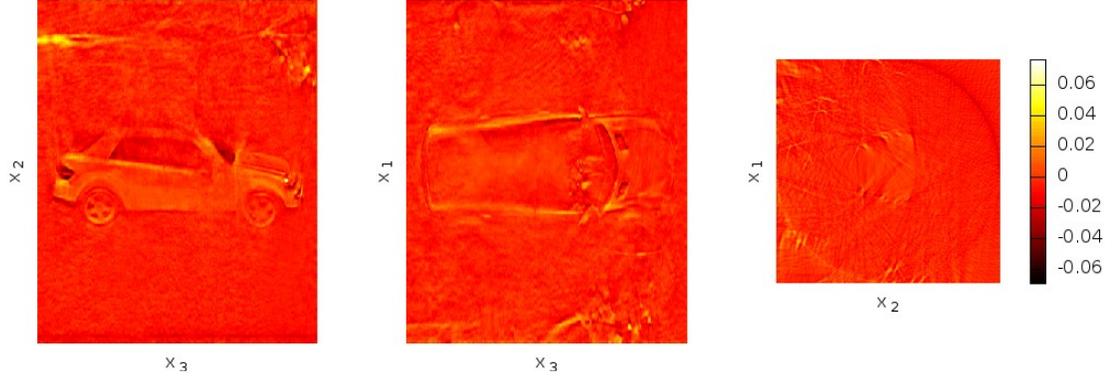


Figure 3: Slices through the computed laser FDK volume.

This paper tackles two issues in laser imaging. The first one concerns an upstream mathematical question. We provide some link between transmission tomography and reflective tomography [Knight et al., 1989] on a canonical case. It reinforces the credibility of transmission algorithms in reflective imaging. The second one concerns a downstream visualization issue. The Maximum Intensity Projection (MIP) [Wallis and Miller, 1991] is shown to be well suited; the FDK algorithm and the MIP are combined in a home-made software whose functionalities include real-time displacements in the virtualized scene. The relevancy of this approach is shown on the considered laser imagery example.

From transmission to reflection

Laser imaging using the FDK algorithm introduces a mathematical upstream challenge. Filtered BackProjections (FBP), such as the FDK algorithm, are designed to invert Radon-kind transforms from transmission tomography. Since laser measurements result mainly from backscattering by opaque surfaces, laser imaging extends the validity of FBP from transmission to reflection. Is there a mathematical proof? One of the first papers about the use of transmission algorithms for reflective data is [Knight et al., 1989]; in particular the authors notice that the sum of data from opposite angles yields transmission kind data. This idea has been used later in [Jin et al., 2011] to design a method which is based on this sum. In this paper we use Radon inversion without using explicitly this sum. We prove here that without any pre-processing, FBP of reflective data coincides exactly with FBP of the built transmission data, and thus the FBP already contains the building of transmission-kind data.

So we assume that for each angle β , for each $s \in \mathbb{R}$, we know reflective data $R(\beta, s)$ on the line $L(\beta, s) : x \cdot \theta(\beta) = s$, with $\theta(\beta) = (\cos \beta, \sin \beta)$. Of course, R is 2π -periodic in β . Reflective data on the opposite side is $R(\beta + \pi, -s)$, on $L(\beta, s) = L(\beta + \pi, -s) : x \cdot \theta(\beta + \pi) = -s$. Then we define the sum $T(\beta, s) = R(\beta, s) + R(\beta + \pi, -s)$. For a convex object, $T(\beta, s)$ looks like transmission data which are generated by the boundary of the object: see Figure 4.

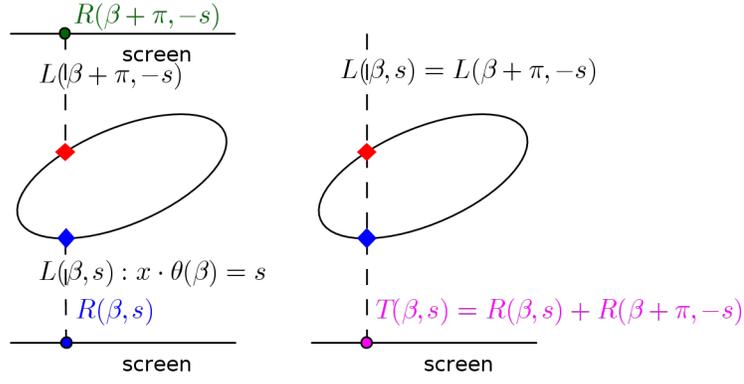


Figure 4: Transmission data $T(\beta, s)$ deduced from reflection data $R(\beta, s)$.

Definition. Let $v(s)$ be an even filter and $f(\beta, s)$ be a 2π -periodic function in β . The FBP (over 360 degrees) of f is:

$$\mathcal{R}^*[v \star f](x) = \int_0^{2\pi} \int_{\mathbb{R}} v(x \cdot \theta - t) f(\beta, t) dt d\beta.$$

Theorem. The FBP of the transmission-kind data T is twice the FBP of the reflection data R :

$$\mathcal{R}^*[v \star T(\beta, s)] = 2\mathcal{R}^*[v \star R(\beta, s)].$$

Proof. The proof relies on basic properties of the integral. By linearity, FBP of T is $\mathcal{R}^*[v \star T(\beta, s)] = \mathcal{R}^*[v \star R(\beta, s)] + \mathcal{R}^*[v \star R(\beta + \pi, -s)]$. FBP of $R(\beta, s)$ is by definition $\mathcal{R}^*[v \star R](x) = \int_0^{2\pi} \int_{\mathbb{R}} v(x \cdot \theta - t) R(\beta, t) dt d\beta$ and FBP of $R(\beta + \pi, -s)$ is $\mathcal{R}^*[v \star R(\beta + \pi, -s)](x) = \int_0^{2\pi} \int_{\mathbb{R}} v(x \cdot \theta - t) R(\beta + \pi, -t) dt d\beta$. The change of variable $(\beta, t) \leftarrow (\beta + \pi, -t)$ yields $\mathcal{R}^*[v \star R(\beta + \pi, -s)](x) = \int_{\pi}^{3\pi} \int_{\mathbb{R}} v(-x \cdot \theta + t) R(\beta, t) dt d\beta$. But the integrand is 2π -periodic and v is even so $\mathcal{R}^*[v \star R(\beta + \pi, -s)](x) = \int_0^{2\pi} \int_{\mathbb{R}} v(x \cdot \theta - t) R(\beta, t) dt d\beta$. \square

Corollary. The FBP (over 360 degrees) of the reflection data is exactly the FBP over 180 degrees of the transmission-kind data:

$$\mathcal{R}^*[v \star R(\beta, s)] = \int_0^{\pi} \int_{\mathbb{R}} v(x \cdot \theta - t) T(\beta, t) dt d\beta.$$

Proof. It comes from the fact that T satisfies: $T(\beta, s) = T(\beta + \pi, -s)$, and so its FBP between 0 and π is equal to its FBP between π and 2π . \square

This elementary result gives a partial answer to the mathematical question: applying FBP on reflective data generated by an opaque convex object looks like applying FBP on transmission data which are generated by the surface of the object. As a result, reflective FBP tends to reconstruct a function which is supported by this surface. More general extensions such as FBP for several arbitrary occluded objects are still under study.

From 2D laser images to interactive 3D computer graphics

A sequence of 2D laser images is fastly converted into a 3D volume. The FDK algorithm has indeed been implemented in CUDA C to be executed on a GPU. Using one Nvidia Tesla C2075 for the considered example, the current version of the code computes the weighted filtering by cuFFT in 0.4 second and computes the massively parallelized backprojection in 3.6 seconds. The result is a laser FDK volume which is stored on the GPU.

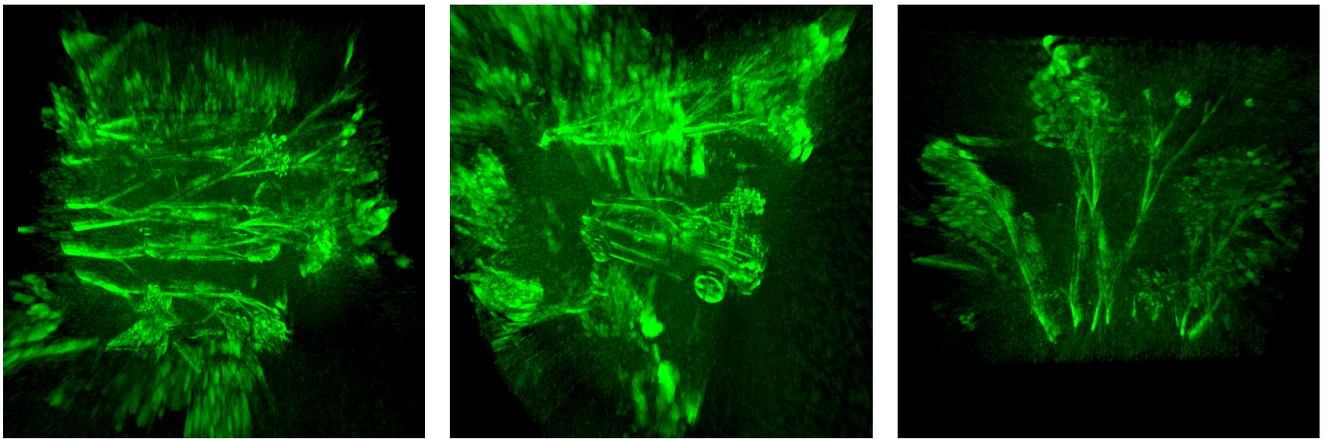


Figure 5: MIP through the laser FDK volume: full scene and interactively extracted branches.

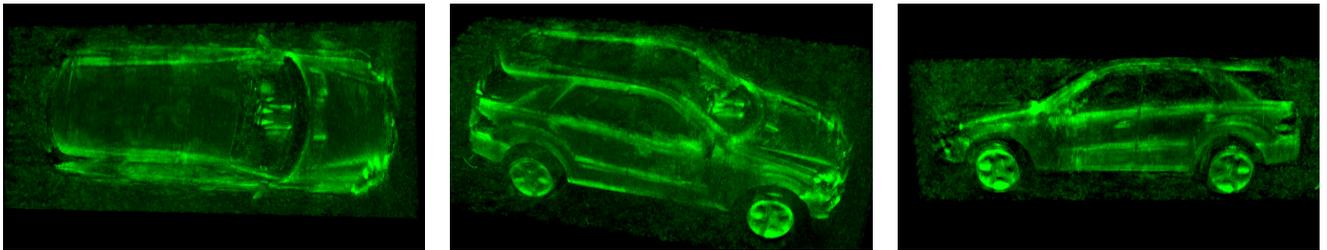


Figure 6: MIP of interactively extracted sub-volumes.

The next step of the process deals with visualization of a laser FDK volume. Several ways will be investigated [Wallis and Miller, 1991]. The easiest one is slicing the volume as above (Figure 3). But it is difficult to appreciate structures in that way. The second way is surface rendering. This has already been done in [Berechet and Berginc, 2011, Berechet et al., 2013], where extraction of incomplete surfaces by thresholding is combined with a completion algorithm. Another way that needs to be investigated is volume rendering, which consists in projecting the volume into a plane, along a set of rays. We have mentioned before that the voxels of interest in a laser FDK volume are the most intense ones. So we choose in this paper to focus on the Maximum Intensity Projection (MIP) which takes advantage of this fact [Wallis and Miller, 1991]: it selects the most intense voxel along each ray of projection. MIP has numerous advantages. It is fast and efficient. It provides high contrasted images. Its easiest version is free of parameters, which is very comfortable to get automatic visualization. Some easy improvements are available: thresholding can delete unexpected voxels, an attenuation coefficient can improve the perception of distance; also the first local maximum above a threshold can be used instead of the maximum to increase spatial localities [Sato et al., 1998].

In this paper we propose to use the MIP as the visual field of a virtual observer (or the field of view of a camera). A MIP view is computed directly on the GPU, in real time. Then it is displayed on the computer screen using OpenGL. Changing the set of rays provides several points of view. Using the GLUT library to manage interactions with mouse/keyboard, we get at the end a software that enables to move as a virtual observer inside the laser FDK scene. Displacements are managed by the mouse, whereas some other parameters such as attenuation coefficient are managed by the keyboard. Last but not least, every thing works in real time.

Two different views of the whole scene using MIP have been represented on Figure 5. Another interesting point is interactive extraction of zones of interest. This is another option of the software; it is useful for object identification [Berechet et al., 2014]. Here it is used to get separate views of the car and the branches: see views of Figure 6 for the car and Figure 5 (on the right) for some branches and foliage. High contrasted images of the objects are observed; they include features and details.

Conclusion

This paper starts with a short mathematical consideration that reinforces the extension of Computerized Tomography to reflective imaging, including 3D laser imaging. The second part combines on a GPU the laser FDK algorithm with an interactive 3D computer graphics approach which is based on the MIP. The quality of the real-time results demonstrates the power of this laser FDK-MIP approach.

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