Towards X-ray Plenoptic Imaging: Emulation with a Laboratory X-ray Scanner

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Abstract: X-ray plenoptic apparatuses acquire multi-view single-shot radiographs, but their development is challenging. We present a physical emulation setup for rapidly and inexpensively exploring their design parameter-space, that only uses a flexible laboratory X-ray scanner.

1. Introduction and Motivation

X-ray imaging is ubiquitous as a tool for medicine, industry, and science. Conventional radiography is commonly used for simple medical examinations and high-throughput industrial quality inspection, but it lacks the three-dimensional (3D) information. Computerized tomography (CT) delivers a 3D volumetric representation of the object by combining a series of X-ray images computationally, but it comes with relatively long scanning times and high dose levels.

Plenoptic imaging is a technique that produces a single-shot multi-view photograph and that is demonstrated in the visible regime. This special photograph (light-field) allows for computational refocusing after acquisition [1], and depth estimation of the photographed scene. In [2], it was shown that a light-field image is geometrically equivalent to a limited-angle cone-beam CT (CBCT) acquisition, establishing a bridge between the geometrical concepts of plenoptic visible-light photography and CT imaging. An X-ray plenoptic camera allows for bringing several superimposed 3D structures into focus at their respective depth planes, instead of only the object surface, as in visible-light imaging. If the structures are located at a particular depth and have sharp features, focusing on them enables determining their depth and segmenting their shape. This effectively enables fast depth-resolved 3D imaging that is only limited by the flux of the X-ray source (XRS) and framerate of the detector.

Despite its appealing features, X-ray plenoptic imaging has only seen limited development so far. Only two X-ray plenoptic apparatuses have currently been developed: one uses a relatively large crystalline object and a monochromatic parallel-beam [3], and the other one uses poly-capillary optics and a poly-chromatic cone-beam [4]. Unfortunately, these ingenious solutions suffer from a few key limitations: fixed fabrication configuration, impossibility to adjust the field-of-view (FoV), angular sampling, or angular range on the experimental conditions, a significantly small plenoptic region around the focal plane, and for the latter very long exposure times (3 min. per image). These aspects render those setups not competitive against traditional CT setup, which has hindered the development of the field, and made it difficult (if not impossible) to get hold of X-ray light-fields. Thus, no algorithm has been developed so far to deal with its limitations and challenges (e.g., semi-transparency).

2. Method and Results

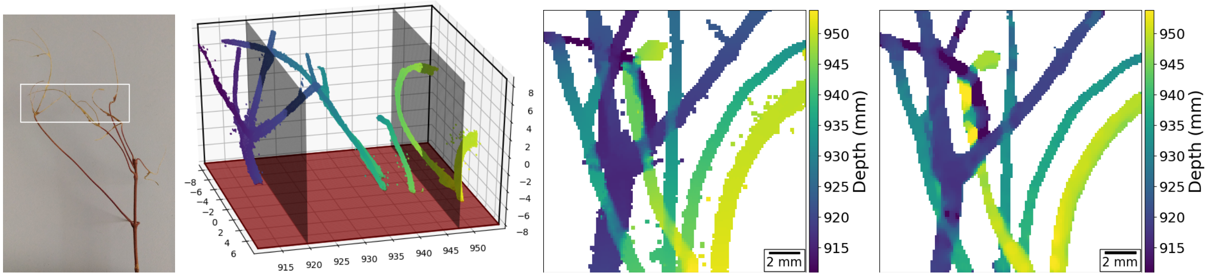
In [5], we first presented an emulation scheme that allows reproducing the X-ray light-field acquired by a hypothetical X-ray plenoptic camera, before even purchasing the optics. The single-shot acquisition is mechanically emulated with a flexible X-ray laboratory scanner [6], by moving the source to sequential positions without the need for X-ray lenses.

Our emulation scheme requires movements of the XRS and detector (a flat panel sensor, FPS) with respect to the sample in both the horizontal and vertical directions. The position of the XRS and FPX are mapped in the (u,v) space, where u and v are the horizontal and vertical transverse coordinates to the optical axis of the system. A pin-hole image (PHI), also known as sub-aperture image (SAI), is taken at specific points in the (u,v) coordinates, which are identified as $S(u,v)$ and $D(u,v)$ for the XRS and the center of the FPS, respectively. If we trace lines from all of the points in the $S(u,v)$ to the corresponding points in the $D(u,v)$ set, then they cross in one specific point along the optical axis, which corresponds to the position of the focal plane of the imaging system. The XRS-to-focus distance is called z_0, while the XRS-to-FPS distance is called z_{sd}. The lattices $S(u,v)$ and $D(u,v)$ are computed as follows:

$$S(u,v) = p_u \, \delta u \, \hat{u} + p_v \, \delta v \hat{v} \,, \tag{1}$$

$$D(u,v) = -\frac{z_{sd} - z_0}{z_0} \, S(u,v) \,, \tag{2}$$

where $\hat{u}$ and $\hat{v}$ are the unit vectors of the u and v axes, respectively, $(\delta u, \delta v)$ is the angular resolution of the emulated setup, and p_u and p_v are integers. For more extensive details, we refer to [5].



(**a**) Sample (**b**) Tomographic reconstruction (**c**) Depth map tomography (**d**) Depth map light-field

Fig. 1. X-ray light-field imaging of a tree branch to demonstrate the ability to capture the three-dimensional (3D) structure of vessel-like objects. The sample is shown in (**a**), where the white box identifies the analyzed region. The traditional CBCT reconstruction is rendered in (**b**). (**c**,**d**) present the depth maps extracted from the tomographic reconstruction and the light-field acquisition, respectively.

In Fig. 1 we present results obtained with our emulation scheme on a tree branch. They show that depth and 3D position of sharp substructures can be computed from light-field data. When combined with the single-shot aspect of X-ray plenoptic apparatuses, this will allow for depth-resolved 3D imaging at high framerates, which is competitive against both tomographic and stereo imaging approaches.

3. Conclusions and Outlook

The presented emulation scheme provides a way to quantify the potential of a camera design and guide its development, even before the actual prototype implementation: It will assist and markedly accelerate the design and development of new X-ray plenoptic imaging solutions, in a cost efficient manner. Moreover, it will provide access to unlimited X-ray light-field data, as the X-ray equivalent to the light-field acquisition gantry setups from the Stanford light-field archive (`http://lightfield.stanford.edu/acq.html`), which allowed for acquiring iconic visible light datasets, that are still used nowadays as reference benchmarks.

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