Non-Line-of-Sight MoCap

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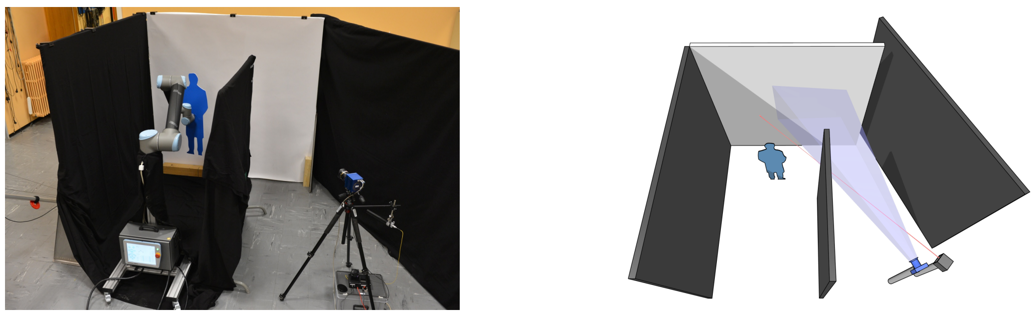

Figure 1: Hidden scene containing a shape of a man that is not in the direct line of sight of the camera (left) and visualization of the object position reconstructed from diffuse reflections in real time (right).

ABSTRACT

The sensing of objects hidden behind an occluder is a fascinating emerging area of research and expected to have an impact in numerous application fields such as automobile safety, remote observation or endoscopy. In the past, this problem has consistently been solved with the use of expensive time-of-flight technology and often required a long reconstruction time. Our system is the first one that only relies on off-the-shelf intensity cameras and lasers. To achieve this, we developed a novel analysis-by-synthesis scheme which utilizes the output of a specialized renderer as input to an optimizer to perform the reconstruction. In the exhibition, visitors can freely move the object around in the hidden scene, while our camera setup on the other side of the wall reconstructs the object position and orientation in real time. We hope that this first hand experience will spread excitement about possible future applications of this new technology.

CCS CONCEPTS

•**Computing methodologies** →**Tracking;** *Ray tracing;* •**Theory of computation** →*Nonconvex optimization;*

KEYWORDS

non-line-of-sight vision, intensity based, analysis by synthesis, active imaging, real time

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1 MOTIVATION

Cameras can be used to quickly reconstruct properties of distant objects such as shape, position and movement. They have however the major drawback, that they require a direct line of sight to the object and thus objects hidden behind occluders cannot be sensed. The emerging field of non-line-of-sight sensing tries to tackle this problem by using diffuse reflections from other parts of the scene for the reconstruction. In the future, this could become a useful technology to prevent collisions in narrow streets, to locate and rescue persons in dangerous places such as burning buildings or to advance or replace endoscopic equipment.

In the basic scenario, an object is hidden from the camera by an occluder, prohibiting any form of direct sensing. If however a large, planar object, e.g. the back wall of the setup, is visible from both, the camera and the object it can act as a diffuse mirror. A laser pointer located next to the camera is focused onto this wall and the light reflected from the laser spot on the wall illuminates the hidden scene. The object reflects the incoming light back to the wall, where it then can be sensed by the camera. In this so called three-bounce-setup [Velten et al. 2012] the wall and object are usually diffuse, which means that all angular information is destroyed by the reflections, making the reconstruction a challenging problem.

2 STATE OF THE ART

The idea of non-line-of-sight sensing was introduced in 2009 [Kirmani et al. 2009] and was quickly adopted by various research

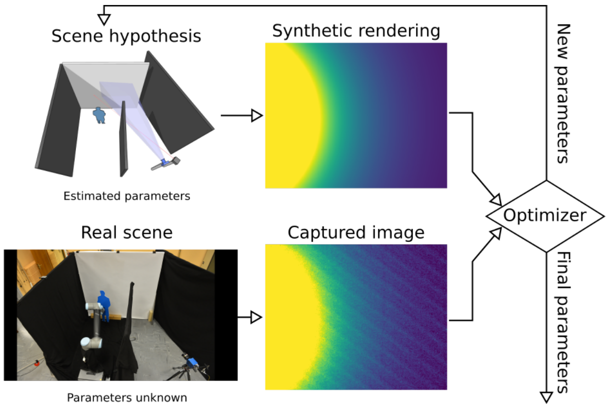

Figure 2: The analysis-by-synthesis scheme used in our algorithm.

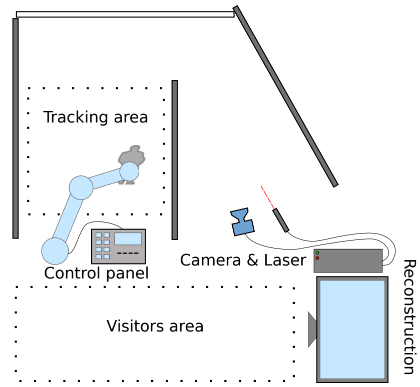

Figure 3: Floor plan of our setup.

groups. Over the past years, there have been numerous publications that tackle various aspects of the problem including geometry reconstruction [Heide et al. 2014; Velten et al. 2012], material reconstruction [Naik et al. 2011] and object tracking [Gariepy et al. 2016]. Outside the scientific community, many of them have also been well received by mass media [Gray 2015].

Except for some approaches that use alternative wavelength ranges for which the occluding medium is transparent [Adib and Katabi 2013], all existing approaches rely on diffuse reflections and use time-of-flight measurements as an additional source of information. They require specialized hardware such as high-end streak detectors or single-photon imagers, and most of them are not capable of real-time operation. By measuring the time delay of the incoming light for each pixel, the length of the light paths can be determined. With a back projection method borrowed from computer tomography, the possible origins of reflections inside the scene can then be determined.

3 OUR METHOD

Our main contribution is the introduction of the analysis-by-synthesis scheme to the field of non-line-of-sight sensing (see Figure 2). The reconstruction of a hidden scene from camera data is a challenging inverse problem, whereas the forward problem, the computation of synthetic camera images from a given scene, is readily solved by means of established rendering techniques.

To reconstruct the object position the algorithm starts with an initial guess and renders a synthetic camera image. If the shape of the object is known, it can be used for rendering directly. Otherwise, a proxy can be used, resulting in a decreased accuracy. At the same time, the real camera in the scene takes a picture of the wall and both pictures are compared using the root-mean-square error. This error depends on the estimated object position and becomes the target function of a numerical optimization algorithm, which adapts the object position until the minimum is found.

Besides not requiring any temporal information, this approach offers great flexibility: Arbitrary scene parameters such as position, orientation and material of the object or even more complex scenes consisting of multiple objects that occlude each other can be simulated and in principal be reconstructed. However, with the number of scene parameters, the dimensionality of the optimization problem grows and the optimization becomes less stable and more time consuming. So far, we have been able to reconstruct the position and orientation of a known object concurrently in real time and are confident, that more scene parameters such as material and shape will be reconstructable in the future.

For a more in-depth description of the algorithm and an evaluation of its accuracy and limitations, we refer to our technical paper [Klein et al. 2016].

4 EXHIBIT AND USER EXPERIENCE

In our setup (see Figure 3), the hidden object is mounted to a robotic arm, which offers precise control over its movement in all six dimensions. We will offer visitors to directly control the object and watch how our system reconstructs their movement in real time despite being on the other side of the wall. As we use infrared light, there is no visible evidence inside the hidden scene, that the object is being tracked. Since there are no front walls, visitors are free to explore every detail directly. This offers an unprecedented hands-on experience of this exciting new technology.

REFERENCES

Fadel Adib and Dina Katabi. 2013. See Through Walls with WiFi! *SIGCOMM Comput. Commun. Rev.* 43, 4 (Aug. 2013), 75–86. DOI:http://dx.doi.org/10.1145/2534169.2486039

Genevieve Gariepy, Francesco Tonolini, Robert Henderson, Jonathan Leach, and Daniele Faccio. 2016. Detection and tracking of moving objects hidden from view. *Nature Photonics* 10, 1 (2016).

Richard Gray. 2015. MailOnline. http://www.dailymail.co.uk/sciencetech/article-3349556/Spy-camera-CORNERS-Technology-track-people-sight-spot-cars-blind-junctions.html. (2015).

Felix Heide, Lei Xiao, Wolfgang Heidrich, and Matthias B. Hullin. 2014. Diffuse Mirrors: 3D Reconstruction from Diffuse Indirect Illumination Using Inexpensive Time-of-Flight Sensors. *IEEE Conf. on Computer Vision and Pattern Recognition (CVPR)* (2014).

A. Kirmani, T. Hutchison, J. Davis, and R. Raskar. 2009. Looking around the corner using transient imaging. In *Proc. ICCV.* 159–166.

Jonathan Klein, Christoph Peters, Jaime Martn, Martin Laurenzis, and Matthias B. Hullin. 2016. Tracking objects outside the line of sight using 2D intensity images. *Scientific Reports* 6 (08 2016). http://www.nature.com/articles/srep32491

Nikhil Naik, Shuang Zhao, Andreas Velten, Ramesh Raskar, and Kavita Bala. 2011. Single View Reflectance Capture Using Multiplexed Scattering and Time-of-flight Imaging. *ACM Trans. Graph.* 30, 6, Article 171 (Dec. 2011), 10 pages. DOI:http://dx.doi.org/10.1145/2070781.2024205

A. Velten, T. Willwacher, O. Gupta, A. Veeraraghavan, M.G. Bawendi, and R. Raskar. 2012. Recovering three-dimensional shape around a corner using ultrafast time-of-flight imaging. *Nature Communications* 3 (2012), 745.