Dual Photography

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Pradeep Sen, Billy Chen, Gaurav Garg, Stephen R. Marschner, Mark Horowitz, Marc Levoy, and Hendrik P. A. Lensch. Dual photography. In *SIGGRAPH '05: ACM SIGGRAPH 2005 Papers*, pages 745–755, New York, NY, USA, 2005. ACM

Sen et al.'s Dual Photography consists mostly of ways to speed up the capture of light fields. The authors accomplish this in two ways: taking advantage of Helmholtz reciprocity, they are able to use a physical setup that inherently allows for faster capture; taking advantage of localized light source influence, they are able to use an algorithm that shows logarithmic speed-up. Given a projector with resolution $p \times q$ and a camera with resolution $m \times n$, we can describe their states with vectors $\mathbf{p}' = [p'_1 p'_2 \ldots p'_{pq}]^T$ and $\mathbf{c}' = [c'_1 c'_2 \ldots c'_{mn}]^T$ respectively. Each element of $\mathbf{p}'$ is the output of a particular projector pixel, and each element of $\mathbf{c}'$ is the input at a particular camera pixel. The transport matrix, $\mathbf{T} = [\mathbf{c'^1 c'^2} \ldots \mathbf{c'^{pq}}]$, of size $mn \times pq$, relates the two states: $\mathbf{c}' = \mathbf{T}\mathbf{p}'$. Each column of $\mathbf{T}$ is the camera image resulting from the corresponding projector pixel lighting up with value 1. The goal is to populate the matrix $\mathbf{T}$ so that we can relight a scene using any $\mathbf{p}'$ we desire, without having to measure the physical scene for each $\mathbf{p}'$.

Helmholtz reciprocity says that the reflectance of light from ω_i to ω_o is equivalent to the reflectance from ω_o to ω_i. Let $\mathbf{c}''$ be the state of a virtual projector with the camera's position, orientation, and resolution, and $\mathbf{p}''$ be the state of a virtual camera with the projector's position, orientation, and resolution, resulting from illumination from the virtual projector. Helmholtz reciprocity implies that $\mathbf{p}'' = \mathbf{T}^{\mathrm{T}}\mathbf{c}''$. The capture of a 6D light field requires multiple projectors. Projectors can not operate simultaneously (two projector pixels conflict with each other if they activate the same camera pixel), but cameras can. This means that using a single projector (or virtual camera) and multiple cameras (or virtual projectors) gives almost the same results, but in a much shorter time. Helmholtz reciprocity thus speeds up the capture process in any setup requiring multiple projectors.

Now $\mathbf{T}$ is very large. If we capture each column of $\mathbf{T}$ separately (meaning sequentially illuminating each projector pixel), it will take a very long time. Instead, we can illuminate multiple projector pixels at the same time, but determine how to separate contributions from different projector pixels. This is easy if, for any given projection, each illuminated projector pixel activates a non-intersecting set of camera pixels. Sen et al. introduce an adaptive subdivision algorithm that takes advantage of the sparseness of $\mathbf{T}$ by grouping projector pixels into blocks. They try to capture as many projector pixels as possible at a time. At each subdivision level, they divide each block into four sub-blocks. The previous set of block conflicts determines an illumination order for the new sub-blocks. This series of projections then determines the conflicts among the new sub-blocks. Subdivision stops when a sub-block no longer activates any pixels, or can not be divided anymore. The illumination history of each projector pixel determines which camera pixels were activated by which projector pixels, allowing us to build $\mathbf{T}$. This algorithm speeds up the capture process in any setup, assuming the scene is well-behaved (the worst case would be that every projector pixel needs to be illuminated separately).

The two main ideas in this paper are each interesting, but they are completely independent of each other. Helmholtz reciprocity and input/output device duality are not new, but the the authors apply them to computational photography in a novel way. Dual photography and its applications are new and interesting[1] enough that they could be presented in a paper by themselves. The authors appear to have relegated the core of dual photography to an appendix. They also spent very little space discussing the capture of 6D and 8D light fields, which seem to be the most important application of dual photography.

The paper also contains a set of other algorithms and techniques devoted to efficiently and effectively capturing light fields. These in no way contribute to dual photography, and seem extraneous. The adaptive subdivision algorithm is simple and neat, but not explored very thoroughly. It would have been interesting to see more performance evaluations for this algorithm (the performance graph was not very convincing), and the hierarchical signal conservation algorithm.

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[1] I was especially impressed by the detection of doubly-bounced (diffuse) light to reveal a surface that was facing away from the physical camera.