Transmissive Structured Illumination Reveals Target Depth and Cast Shadow Details Obscured by Scattering Media

Avinash Kumar,[1,2] Patrick R. Gill,[1] Thomas Vogelsang,[1] and David G. Stork[1]

[1] *Rambus Labs, 1050 Enterprise Way Suite 700, Sunnyvale, California 94089 USA*
[2] *Department of Electrical and Computer Engineering, University of Illinois, Urbana-Champaign, Illinois 61801 USA*
dstork@rambus.com

Abstract: We describe novel methods of computing sharp shadows and depth estimates of objects immersed in highly scattering media using multi-scale structured transmissive illumination, such as modified Hadamard tiles.

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1. Background and problem

The problem of computing separate images of a scene based on direct illumination and on indirect (scattered) illumination has been addressed by means of structured illumination photography. [1, 2] Such work has concentrated on imaging surfaces under *reflective* illumination, and only recently has also included conditions of highly scattering interposed media, such as milky water. [3] We address a related but separate problem—that of recovering high fidelity images of the *shadows* cast by opaque occluders immersed in highly scattering media, where *transmissive* structured illumination is required. Our computational methods also allow the estimation of a depth map of the obscured occluder. Applications for such methods include biometrics of finger vasculature, automated inspection and others.

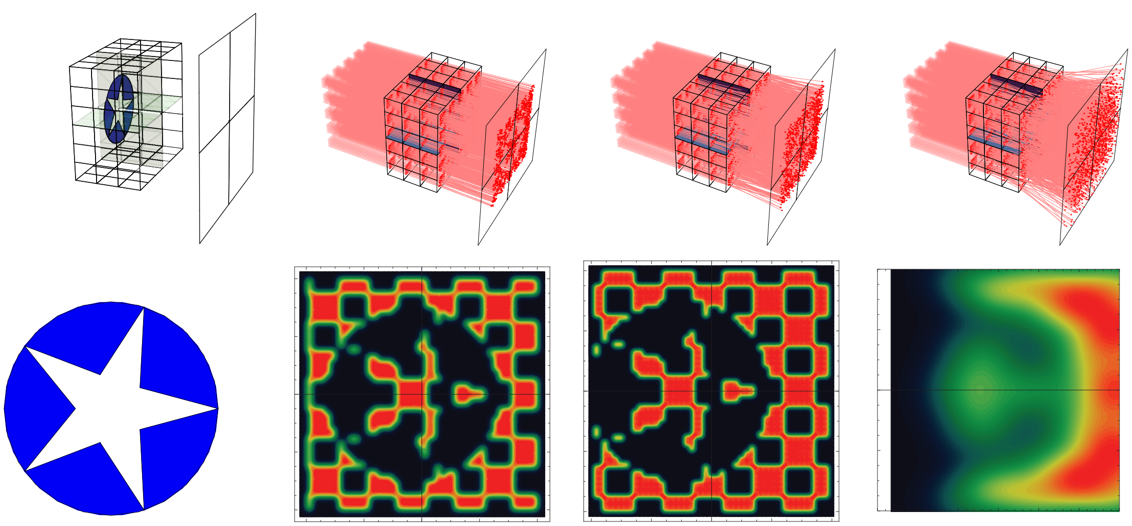

Fig. 1. The top-left panel shows our setup, in which an occluding star target sits within a tank of fluid. The other top panels show ray-tracing diagrams for checkerboard illumination through low-, medium-, and high-scattering fluid; the figures beneath show the corresponding light intensity patterns on the screen. In the high-scattering case, the target shadow details are lost but can be recovered through computation on images captured under multiple illumination patterns.

2. Theory

The measured luminance $L[x,y]$ on the screen is the sum of the direct (unscattered) and global (scattered) contributions, $L_d[x,y]$ and $L_g[x,y]$. In a non-scattering medium such as pure water, the captured image on the screen is due solely to L_d, which reveals the cast shadow in high fidelity; in a highly scattering medium such as milky water, the captured image is due primarily to L_g and the shadows are obscured. Our unique structured illumination was a set of either 32 or 128 binary patterns which are repeated to tile the entire scene. These patterns were generated as follows. Let $\mathbf{H}$ denote a 16×16 or 64×64 Hadamard matrix with a random subset of its rows flipped in sign—and with its `-1`s replaced by `0`s. We construct the matrix $\mathbf{D} = [\mathbf{H}, \mathbf{1} - \mathbf{H}]$ and assign each element of the 32 or 128 columns of $\mathbf{D}$ by lexicographic ordering onto a 4×4 or 8×8 tile of illumination pixels (Fig. 2), and cover the entire scene with repetitions of this tile. We photographed the blurred shadow of the object under each of such 32 or 128 illumination conditions.

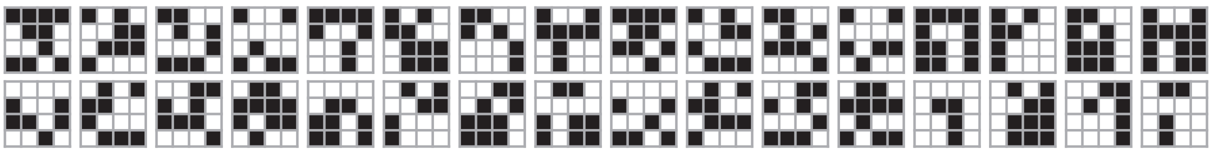

Fig. 2. The structured illumination was based on binary luminance tiles derived from columns of Hadamard matrices. Such non-regular tiles eliminated aliasing artifacts in the reconstructed images.

To find L_d and L_g, consider the set S_j of all the tiles which directly illuminate a particular pixel j in the tiles. Due to the properties of the Hadamard matrix, all pixels other than j on S_j are illuminated precisely in half of S_j, as they are in S_j's complement S_j^C. Therefore, regardless of which pixels within a tile happen to contribute to L_g at a certain point, the L_g contribution to L caused by illumination with S_j is the same as the L_g contribution caused by S_j^C. This insensitivity to potentially directional contributions of global scatterers is not afforded by previous techniques. [1] The direct image L_d can be found by subtraction, i.e., $L_{d,j} = L_{S_j} - L_{S_j^C}$, where $L_{d,j}$ is the direct component of illumination directly illuminated by pixel j and L_{S_j} and $L_{S_j^C}$ are the mean L over illumination conditions S_j and S_j^C.

To compute the direct image, it is necessary to know which j applies for each location in the images scene. Let $\mathbf{M}$ be the map of the j at every location in the image for which L_{S_j} is maximal. Under the assumption that $\mathbf{M}$ indicates the js that directly illuminate the screen, $\mathbf{M}$ can be used to indicate which j to use at each image location. (This assumption would be violated under certain conditions, for instance if substantial specular reflection exists in the image.) In the event that illumination is not normal to the screen but incident at an angle θ, $\mathbf{M}$ will encode depth information of the occluders in the scene. Let $\mathbf{M}_0$ be the $\mathbf{M}$ expected in the absence of any occluders; a simple geometric construction show the the value of $M(x,y)$ for occluded objects some distance d from the screen will be $M_0(x + d\tan(\theta), y)$.

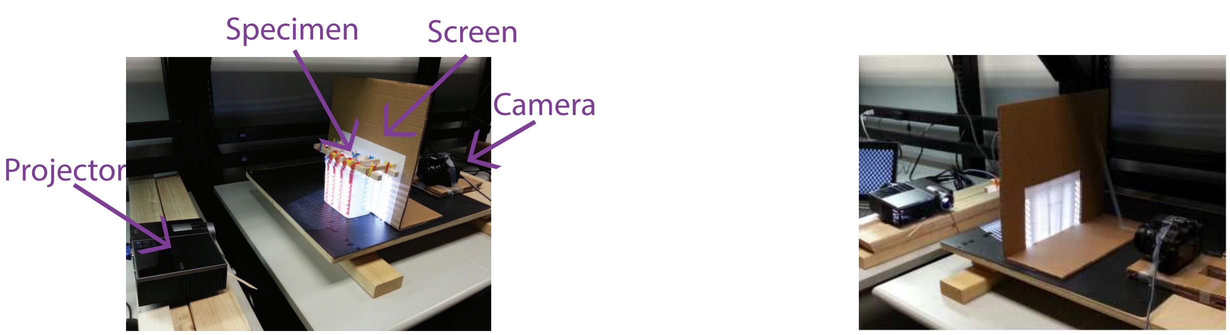

Fig. 3. Experimental setup. (Left) The illumination side, where a video projector projects the Hadamard-based structured illumination into the tank of milky water. (Right) The image on the projection screen is captured by a Canon 550D (Rebel T2i) with an 18.0Mp APS-C sensor. Projector, camera and data collection operate under PC control.

3. Experimental setup and results

Figure 1 shows a schematic of our setup, where structured illumination is projected through the tank of highly scattering medium (milky water) and the immersed target or specimen (wire mesh) to the transmissive projection screen (which abuts the water tank), where it is photographed (Fig. 3). In the case of highly scattering media, the images captured appear featureless and the target cast shadows are completely obscured, invisible to the human eye (Fig. 4, left). Nevertheless, computation based on 128 Hadamard-based illumination patterns yields crisp, high-contrast, highly accurate cast shadows (Fig. 4, right), even when the of target-screen distances differ by a ratio of more than 3:1. Moreover, some depth information can be extracted from the scene by considering deviations of $\mathbf{M}$ from $\mathbf{M}_0$. Depth information is available at transitions in $\mathbf{M}$, where the lateral shift between $\mathbf{M}$ and $\mathbf{M}_0$ is known precisely (Fig. 5).

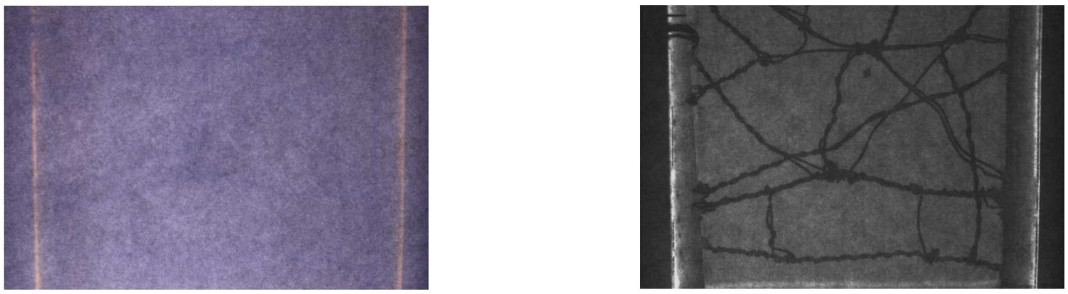

Fig. 4. (Left) A broad wire mesh in a highly scattering medium under full-field illumination leads to a structureless image on the screen. Illumination by any single structured pattern similarly does not reveal shadow details. (Right) The direct illumination computed from 128 Hadamard patterns reveals crisp details of the shadow cast by a broad wire mesh.

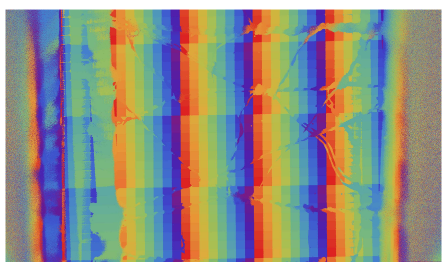

Fig. 5. Color-coded representation of $\mathbf{M}$ for a wire mesh target. For most of the screen, $\mathbf{M} = \mathbf{M}_0$ (regular colored columns), indicating the wire is not present there. However, at locations of the wire, $\mathbf{M}$ takes the value of $\mathbf{M}_0$ a distance to the right proportional to $d\tan(\theta)$ (thin colored displacements).

4. Conclusions

We have extended structured lighting methods to the case of cast shadow recovery in extremely challenging optical situations, where shadows are essentially lost and invisible. Our method also provides 3D information about targets.

References

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