Recording lightspace so shadows and highlights vary with varying viewing illumination

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Methods are proposed to record the way in which objects respond to varying illumination—to capture and reproduce varying shadows and highlights and thus give the illusion that absent objects are present behind a "window" into which people may shine arbitrary lights of their choice. When the recording is viewed under two separate point sources, one sees a reproduction of the original scene with double shadows. When it is viewed outdoors, on an overcast day, one sees a reproduction of soft or almost nonexistent shadows, whereas the reproduction of the objects themselves remains sharply defined, regardless of the viewing illumination.

What information can we obtain by probing objects with rays of light from all possible directions while measuring the response from every possible direction (see Fig. 1)? Hypothetically, this entire measurement space ("lightspace") completely characterizes the appearance of the scene under arbitrary lighting conditions.

Traditional holography captures the part of lightspace that corresponds to fixed lighting and varying viewpoint. I propose the recording and viewing of new dimensions; the goal depicted in Fig. 1 is to record *both* changes in viewpoint and changes in lighting. The lightspace recording may be thought of as a collection of many holograms of the same object, one for each object beam position.

The Denisyuk hologram has the property that the illumination during viewing coincides exactly with the object beam during recording, so the reproduced objects appear to derive their shadows from the viewing illumination. Combining multiple Denisyuk exposures, differing only in object beam placement, on a single plate gave rise to a crude recording of lightspace. I imaged a plaster model of a human head, making a plate that could be viewed with one or more white lights. I found that the result was visually compelling: I could illuminate the plate from above to obtain the pleasant appearance of how a human face appears when lit from above or from below to obtain the appearance of a face resembling a scene from a horror movie (face lit from underneath). By the superposition of incoherent light, I found, as expected, that if I simultaneously lit the plate from both below and above, in a particular ratio, I could obtain the likeness of a face lit in that same ratio.

The major practical limitations were (1) reduced diffraction efficiency of each exposure as I increased the total number of exposures and (2) limited localization of the reproduction of each one (each hologram exposure becomes distorted rather than turning dark when the light is moved from its proper location, giving rise to overlapping of the multiple exposures). Thus successful recordings of this sort were limited to those that captured the response of objects to a few discrete light source locations, although they did show that both parallax and the new dimensions of lightspace could coexist on the same plate.

I then explored recordings of lightspace that captured only the way in which the scene responds to light, and not to changes in viewpoint. These recordings surprised people: the new dimensions of lightspace alone provided a compelling sense of three-dimensional structure despite the lack of parallax.

People first held the plates steady with respect to the light source, moving their heads from side to side as though expecting to see parallax, until I put the plates in boxes (open at the top, sides, or back to accept varying lighting) fitted with peepholes to force them to adopt the new viewing paradigm. (I also made some recordings in pairs to be viewed in standard and familiar stereo viewers.)

The elimination of parallax made it possible to use an emulsion of moderate thickness (such as Agfa 8E75) to record the response to a continuously varying light

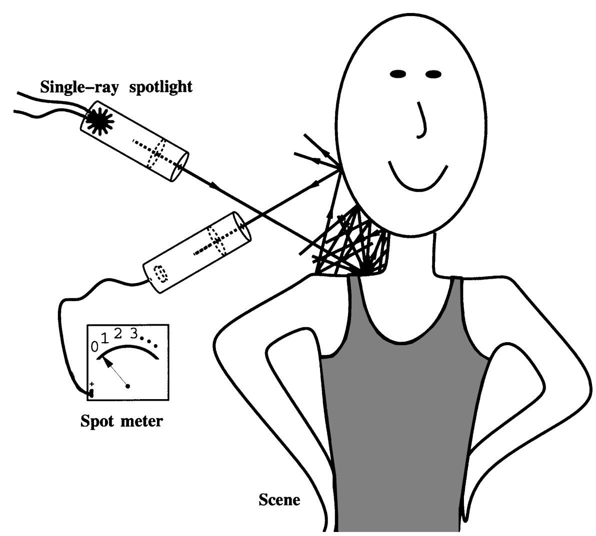

Fig. 1. Hypothetical measurement of the response of a scene to light, using a spot meter and an idealized spotlight (producing a single ray). The entire measurement space provides all information necessary to reconstruct the scene from any viewpoint under any illumination.

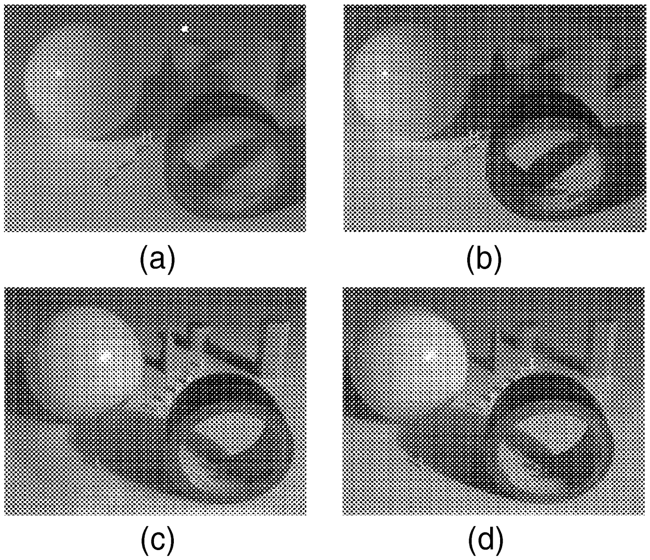

Fig. 2. Two of the 615 image pairs I acquired by moving a white light over a planar lattice 41 source widths across and 15 source widths high: (a) frame 163 left, (b) frame 163 right, (c) frame 203 left, (d) frame 203 right.

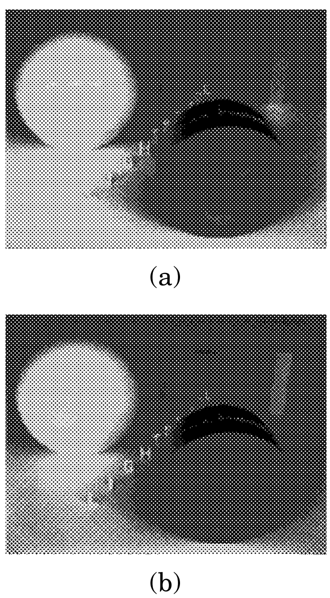

Fig. 3. In a fixed-viewpoint recording of lightspace, all the objects remain sharp regardless of illumination during reconstruction: (a) When objects are viewed under a fluorescent lamp, at close range, the viewer experiences a superposition of images that reconstructs shadows that appear sharp perpendicular to the line of the lamp but soft across it. Notice also the slender linelike highlight in the specular sphere. (b) When objects are viewed under diffuse illumination (e.g., outside on an overcast day), a superposition of all 615 images produces shadows that are soft both horizontally and vertically.

source. I made one such recording by taking 615 pairs of pictures (Fig. 2) of a static scene, where I varied the lighting in small increments in accordance with the geometry designed for the final plate. I moved an approximately Gaussian-distributed light source to each of 41 different horizontal and 15 different vertical positions. I chose light source size to be large enough that there would be a smooth transition from one location to the next but small enough that there would be sharply defined shadows whenever the plate was viewed under sharply defined illumination.

Two 8 in. × 10 in. (20.3 cm × 25.4 cm) transmission masters were made by sequential He–Ne projection of each image onto 4 in. × 5 in. (10.15 cm × 12.7 cm) of ground-glass screen. The recording process was the same as that commonly used to make traditional holographic stereograms.[1,2] (For a good review of holographic stereograms see Refs. 3 and 4.) I transferred the master to a 4 in. × 5 in. plate using a large collimator for the object beam and another (smaller) lens (set to converge slightly so viewing with a hand-held light bulb close to the plate would produce an approximately phase-conjugated beam) for the reference beam on the opposite side of the plate.

When a conventional reflection hologram is viewed under fluorescent light, or outdoors on a cloudy day, the different perspective views are blurred together, making objects imaged far from the plate difficult or impossible to discern. A recording of lightspace where parallax is omitted, however, differs in that all objects

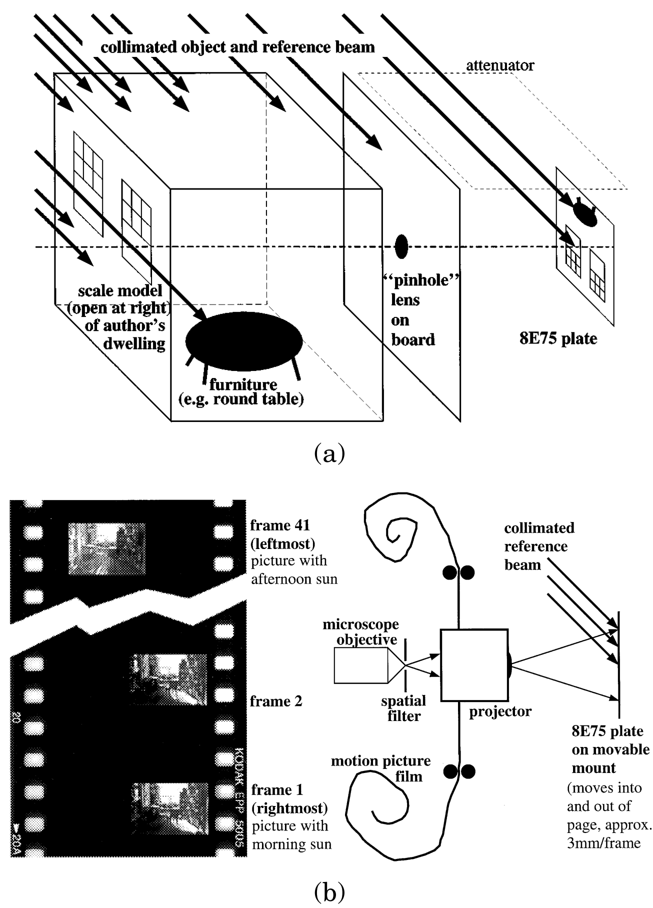

Fig. 4. Making the recording of the way the author's dwelling responds to light: (a) With a scale model. (b) With a sequence of 41 pictures taken at different times of day, using the sun shining in the windows as the sole source of illumination; the sequence of images was later multiplexed onto a holographic plate with a 35-mm motion picture projector illuminated with laser light.

in the scene are just as easy to see under diffuse light as under a point source (Fig. 3).

I also made some transmissive lightspace recordings. The most compelling example was a recording of my dwelling that gave people the illusion of being inside a scale model of the dwelling while holding the sun (actually a light bulb), moving it around outside and shining moving beams of sunlight into the windows.

The first attempt at recording the dwelling consisted of making a backward scale model [Fig. 4(a)]. The geometry is such that the collimated beam appropriately illuminates the scene while providing the correct reference beam so phase-conjugated viewing will reconstruct correct shadows. Multiple exposures made while the angle of a collimated beam is varied record the way the model responds to light. In principle, the beam angle could be varied continuously (in at least the horizontal direction) with a laser shining through a cylindrical lens, projected onto a ground glass behind a moving slit (approximating a collimated beam sweeping through a continuum of different angles), although results were not very successful.

I made a successful recording by setting up a time-lapse camera in the dwelling itself and recording images at different times of day, with the Sun shining into the south-facing windows. The pictures were scanned to PhotoCD, and then I recorded them back onto film but in a slightly different place in each frame [Fig. 4(b)], starting at the right edge of the film and moving across (approximately 0.35 mm/frame), so that an 8E75 plate could also be moved between exposures while maintaining registration. (See Refs. 5 and 6 for background reading.) The motion of the plate provided a moving image of the node of the lens through which one could then see moving shadows and highlights of the dwelling when it was backlit with the moving phase-conjugated illumination. Although the recording captured the way the scene responded to changes in lighting only along a horizontal path, the image was very clear and bright, and the illusion proved to be visually compelling.

Although overmodulation was frequently encountered, I found that for lightspace recordings containing no depth information it was not distracting to the viewer. I found registration of images to be the most troublesome of all problems and therefore used electronic acquisition instead of film in more recent work.

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