Scattered and Stray Light as Scene Encoding

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Abstract: Stray light entering the lens system, uncontrolled illumination variations and scattering by participating media are often considered as image degradations. We show that such effects can be useful, yielding 3D structure, camera and lighting calibration.

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1. Introduction

Scattered and stray light can cause significant spatial and temporal image variations unrelated to the background object reflectance. Hence, they are usually treated as nuisance. However, these effects are affected by the scene and camera, specifically their geometry. In a sense, the effects encode scene information. To extract it, these effects are modulated relative to the background reflectance, and then decoupled. Modulation can be created simply by changes of viewpoint or angle (camera motion or stereo), polarization, illumination settings or other means.

2. Stray light in the imaging system

Stray light reflected by lens surfaces creates *lens flare*. A common and salient form of this flare is *aperture ghosting:* bright spots that resemble the shape of the lens aperture are overlaid on the image. It occurs when a bright narrow source (usually the Sun) is in the vicinity of the field of view, though often the source may be outside the actual viewed field. Aperture ghosting is often labeled as an image degradation. As analyzed in [1], lens flare typically condenses around a straight line (Fig.1), that passes through two anchor points: (1) the projected location of the (often unseen) illumination source (Sun), and (2) the projected optical center of the camera, i.e. the intersection of the optical axis and the detector plane.

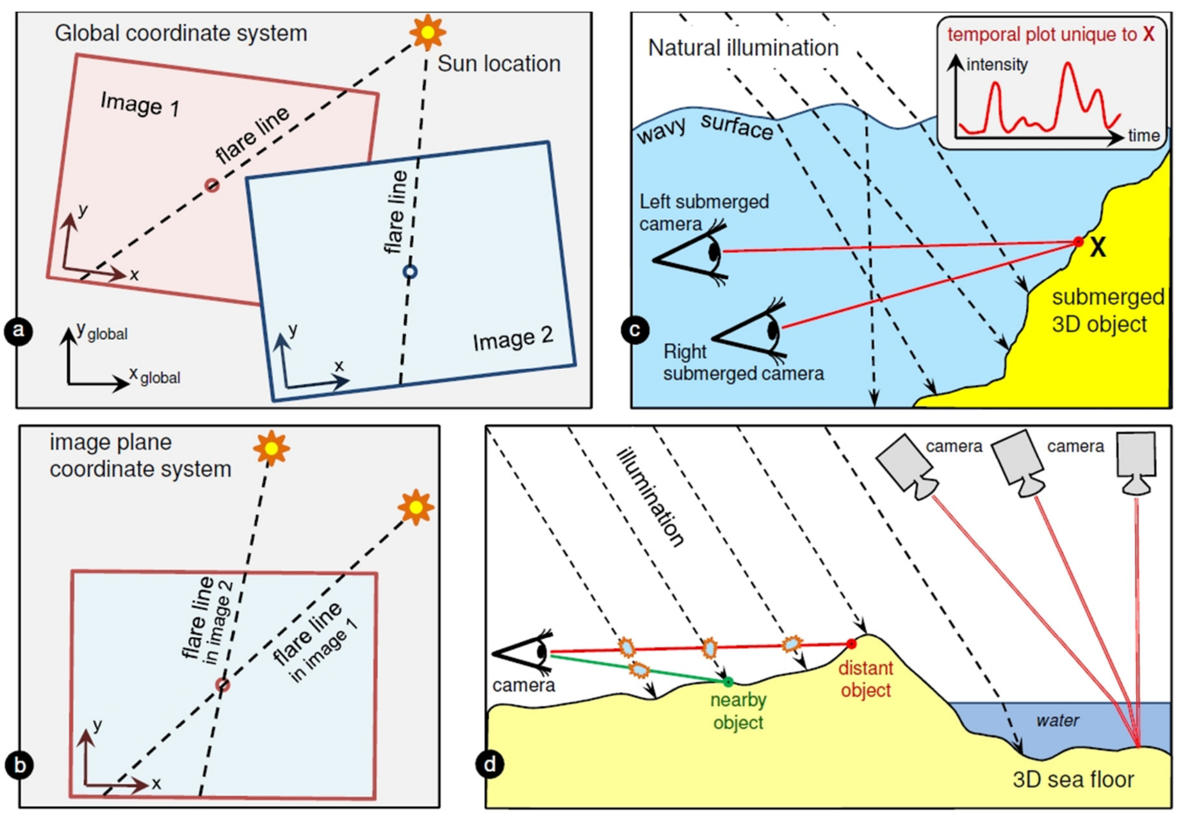

Fig.1 Lens flare can localize the light source (a) and camera center (b); Dynamic caustics give unique temporal signature per 3D point (c), easing triangulation. Scattering affects more strongly farther or deeper objects (d). Structure can be extracted by multiangular or polarimetric imaging.

These anchor points are useful. Based on the light source location, computer vision methods derive three dimensional (3D) scene structure from shadows, and information about camera location and orientation [2]. The optical center is an internal parameter, needed for back projecting objects based on images, in geometric measurements. Hence, it should be useful to find a way of extracting these anchor points, based on lens flare. Separating aperture-ghosts from the underlying scene is easily achievable [1] using as few as two frames taken when the camera moves. Simple image alignment reveals the flare pattern as a component distinct from the background. Then, the extracted flare components are triangulated [1], decoding the sought anchor points (Fig.1a,b).

3. Uncontrolled spatiotemporal illumination variations

Outdoors, light often strays from its idealized path. Consider imaging underwater in shallow areas. Had the water surface been flat, illumination would have been spatially uniform, and temporally quasi-static. However, waves on the water surface refract downwelling light in significant angular variations, creating a *caustic network:* an illumination pattern that is strongly spatiotemporally varying, random, irreproducible and uncontrolled. This has generally been considered as a disturbance that makes image analysis very difficult. However, Ref. [3] shows that this pattern encodes 3D scene information into video sequences. Analysis yields 3D structure very accurately and simply, *because* of these spatiotemporal variations (See Fig.1c).

Let the scene be viewed stereoscopically, by left and right cameras. Pixel $\mathbf{x}_{\mathrm{L}}$ in the left camera is a projection of 3D object point $\mathbf{X}$. Point $\mathbf{X}$ is projected to pixel $\mathbf{x}_{\mathrm{R}}$ in the right camera. Thus $\mathbf{x}_{\mathrm{L}}$ and $\mathbf{x}_{\mathrm{R}}$ correspond to the same object point in 3D. Automated determination of correspondence between image points in different viewpoints is a necessity for range triangulation by stereoscopic vision. This step, known as the *correspondence problem,* is often difficult. However, the spatiotemporal caustic pattern establishes stereo correspondences [3] very effectively. Thus, we term the use of this effect as *CauStereo.* The principle (Fig.1c) is that temporal radiance variations of the pattern are unique to each object point, disambiguating the correspondence using simple temporal correlation.

Moreover, the stereoscopic system can move in an unknown trajectory during acquisition. Hence, the 3D structure, camera motion and illumination variations are all unknown. Nevertheless, the varying caustic patterns enable a solution [4]: they enable easier stereoscopic ranging, which is insensitive to temporal variations of illumination and viewpoint. The stereoscopic range maps constrain the determination of the unknown trajectory, which is also constrained to 6-degrees of freedom per frame, being rigid body motion.

4. Scattering by participating media

Light strays in scenes also due to scattering, e.g., by atmospheric haze or underwater hydrosols. Object radiance is attenuated. Moreover, light is scattered into the line of sight from other directions, creating path radiance. These effects reduce contrast and object signal, while often increasing photon-noise. Hence, scattering is usually regarded as an imaging degradation. However, it encodes useful information both about the particles and the 3D scene structure. Images of objects that reside farther (or deeper) in a scattering medium are affected more strongly [5] by scattering than nearby objects (Fig.1d). The 3D scene structure and scatterer characteristics can thus be extracted, if they can be decoupled from the background object radiance in the images. Decoupling is enabled by modulating scattering components relative to the background. In haze and underwater, polarization filtering modulates the sensed path radiance. Polarization-picture post processing (P^4) derives the desired fields [6,7].

In remote sensing of submerged objects, views are affected both by the water (as a function of depth) and atmospheric scatter. Modulation of components is achievable [8] using multiple views: as the view angle from the nadir increases, light takes a longer trajectory in the media, varying their effect on the images (Fig.1d). Analysis of multi-angular data decouples the image components, enabling remote recovery of underwater topography.

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5. References

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