

Lecture 6: Imaging by Visible Light IV

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Dual Photography (1)

Dual Photography

- ◆ Standard 2-D photographic imaging:
 - Light sources emit light homogeneously into a wide angular range, i.e. *illumination has no spatial resolution.*
 - Detectors are designed to distinguish between light from different directions, i.e. *detectors have high spatial resolution.*
- ◆ *Dual Photography* inverts this relation.
 - The light source has high spatial resolution.
 - The detector has no spatial resolution.

How can this be achieved?

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Dual Photography Procedure

- ◆ We use as a light source a data projector and project a single light beam into a scene without other illumination.
- ◆ As sensor, a simple photodiode is sufficient that detects the diffuse reflected light in the room.
- ◆ By moving the light point over the scene, the scene is scanned in two dimensions. From the recorded intensities, an image is synthesised.

Helmholtz Reciprocity

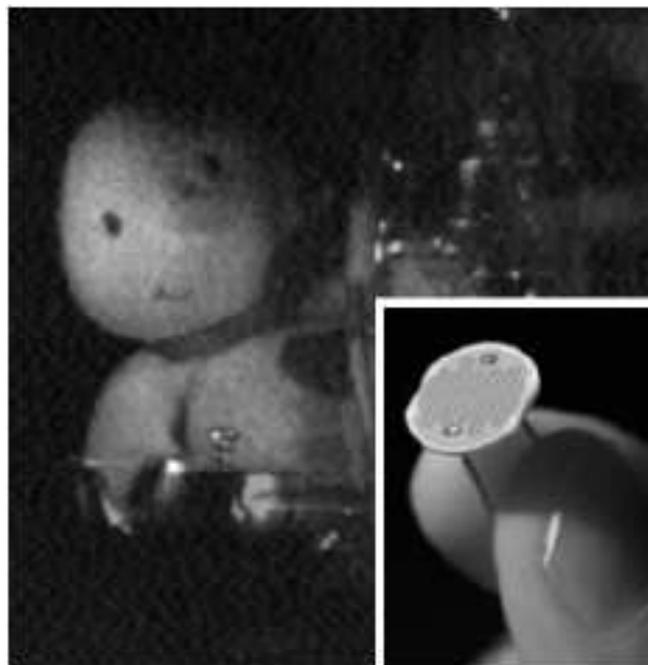
The direction of light beams can be completely reverted without changing the transfer properties.

This principle formulated by Hermann von Helmholtz (see Lecture 5) underlies the dual photography method.

Dual images represent the scene *as seen from the light source location and illuminated from the detector position.*

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Dual Photography Examples



Main image: Dual photographic image generated with a data projector as illumination source and photo-resistors as detectors. **Inserted image:** photo-resistor as detector. (P. Sen et al., 2005)

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Dual Photography Examples



Comparison of primal and dual images. A data projector was used as light source, and a camera as detector. **Top:** Primal images, using the spatial resolution of the camera and a homogeneous illumination by a white image from the data projector. **Bottom:** Dual images, using the spatial resolution of the data projector and integrating intensity over the camera image. (P. Sen et al., 2005)

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Complete Transfer Matrix Recording

If a data projector and a camera are used, in fact a 4-D array of data is collected that measures the full *transport matrix* T point-to-point between the 2-D illumination source and the 2-D detector.

This can be exploited to generate a posteriori images with different virtual illumination (within the camera array).

Moreover, this instrumentary can be used to speed up image acquisition by an adaptive procedure which measures more than one illumination pixel at the same time.



Left two frames: Synthetic re-illumination of scene computed from 4-D transport matrix T . **Right two frames:** Adaptive algorithm for faster measurement of T by parallelising pixels. In regions with complex reflections, the density of illuminating pixels has to be reduced. Acquisition time for T (ca. $600 \times 600 \times 600 \times 600$) is thereby reduced from approx. 11 days to two hours. (P. Sen et al., 2005)

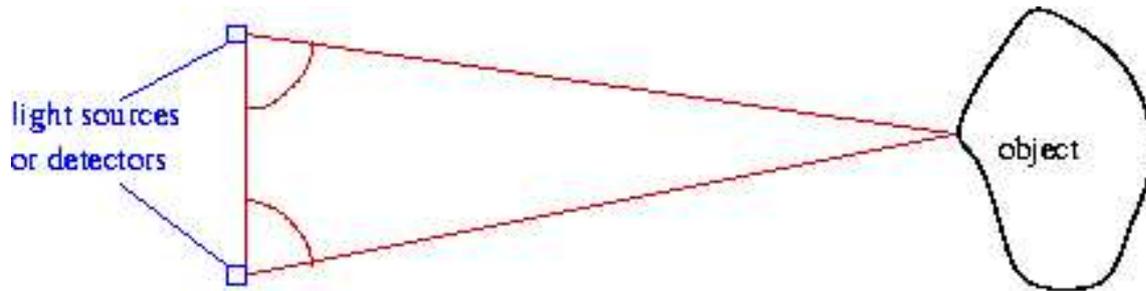
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Stereo Vision

Triangulation

Triangulation techniques in general rely on triangles formed by an object point with two points (base points) of the imaging equipment (either illumination sources or detectors).

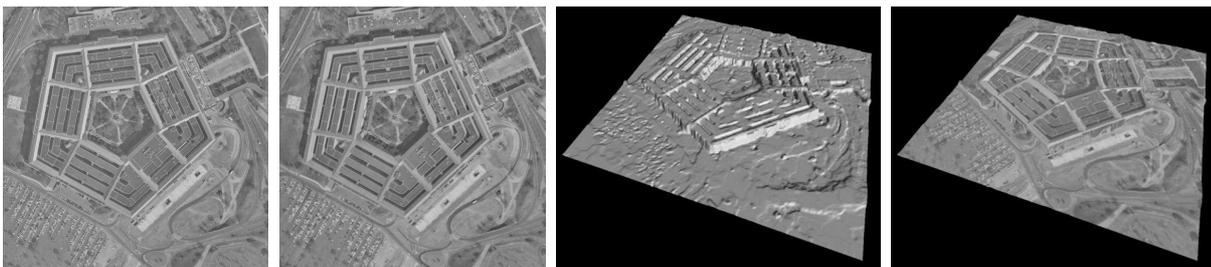
Knowing the base line and angles between base line and lines to the object point, the spatial position of the object point can be calculated.



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Stereo Vision

- ◆ Two or more cameras are used to take 2-D images of the same 3-D scene.
- ◆ Illumination is not prepared specially w.r.t. spatial information.
- ◆ Computation of depth information from the 2-D images is a task of computer vision. You can learn more about this in *Image Processing and Computer Vision* (winter term), and our group also does research in this field.



Left two images: Pentagon stereo image pair. (<http://vasc.ri.cmu.edu/idb/html/stereo/>)

Right two images: Stereo reconstruction without and with texture. (Slesareva et al. 2005)

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Time-of-Flight of Modulated Light

Another way to acquire depth information for a 3-D image consists of measuring the *time-of-flight (TOF)* τ of a light signal from the illumination source to the object and back to the sensor. The depth z is then calculated via

$$z = \frac{1}{2} c\tau$$

Two important techniques to achieve this:

- ◆ *Pulse Modulation*: pulses from a laser diode pulsed at high frequency are directly counted electronically to measure the TOF. This is extremely demanding w.r.t. the electronic components used.
- ◆ *Continuous-Wave Modulation* uses amplitude-modulated or frequency-modulated pulses. Superposition of the returning echoes with the pulses yields signals whose parameters depend on the TOF.

Holography (1)

Holography

- ◆ Technique that allows to image full 3-dimensional scenes.
- ◆ Relies on capturing not only intensity but also phase information of light.
- ◆ Depends on coherent light sources, like lasers, and is highly sensitive to smallest position changes of objects and imaging equipment.
- ◆ In its simplest form, it does not need lenses for imaging.



Object and holographic image.

(Tony Brock-Fisher 2004, <http://www.dragonseye.com/holography/guests/tonybrockfisher/>)

Holography (2)

History



Left: Dennis Gábor (1900–1979). **Middle:** Emmett Leith and Juris Upatnieks. **Right:** Yuri Denisyuk. (Images: Ostrovskiy 1987)

- ◆ Dennis Gábor invented holography in 1947, and made first experiments using mercury arc lamps as light sources.
- ◆ Emmeth Leith and Juris Upatnieks were the first to use a laser to capture holograms in 1963.
- ◆ Yuri Denisyuk proposed in 1962 volume holograms, i.e. such registered in “thick” emulsions.

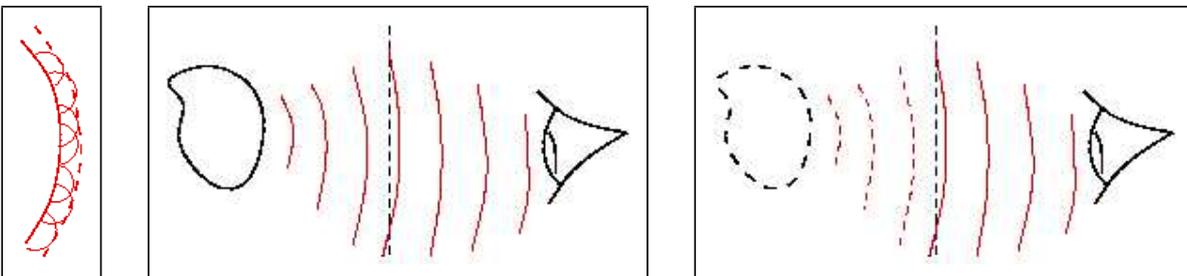
Holography (3)

Principle of Holography

- ◆ Remember *Huygens' principle* (compare Lecture 3): *Each point of a wave front is the centre of spherical waves which superpose to give the propagating wave front.*
- ◆ Assume we have an observer, and an object, and a window between them. If we could properly image the entire light waves passing through the window area, and reproduce those, the light waves coming from the window were indistinguishable from the true object wave.
- ◆ Unfortunately, any detector that measures only intensities loses the *phase information* and therefore cannot image the full information of the wave.



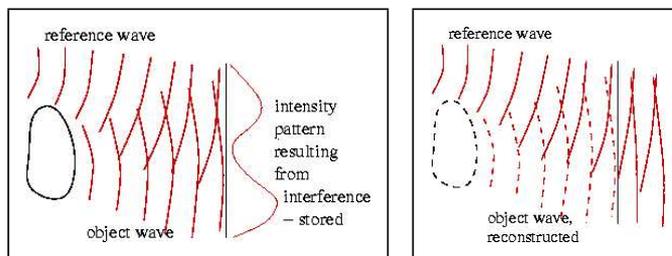
Christiaan Huygens (1629–1695) (Image: Wikipedia)



Holography (4)

Basic Idea Behind Holography

- ◆ Let the light wave from the object interfere with a wave of *known* phase (reference wave). Assume both waves are coherent, i.e. their phases have a temporally constant relation.
- ◆ Then a stationary pattern of locations with constructive and destructive interference emerges (stationary waves).
- ◆ Recording the intensity distribution of this stationary wave pattern, we have stored the *full* information on the superposed wave since we know that the phase of the wave equals the phase of the reference wave.
- ◆ Illuminating the recorded pattern with (a copy of) the reference wave leads, by Huygens' principle, to a reconstruction of the interference wave. In particular, the wave pattern of the object is reproduced.
- ◆ Typically, reference and object waves are generated by beam-splitting from a single laser beam.



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Holography (5)

A Simple Example

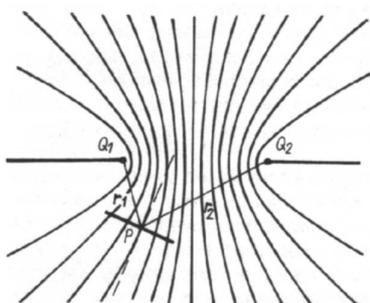
Consider two point-shaped light sources emitting coherent light of equal wavelength. The maxima and minima of the superposed wave lie on surfaces characterised by

$$d_1 - d_2 = \pm \frac{N}{2} \lambda$$

where d_1 , d_2 are the distances from a given point to the light sources, N is an even integer for constructive interference, an odd integer for destructive interference, and λ the wavelength.

These surfaces are rotation hyperboloids with the light sources as focal points.

Intersection with a plane leads either to a series of concentric circles, or to a series of hyperbolae.



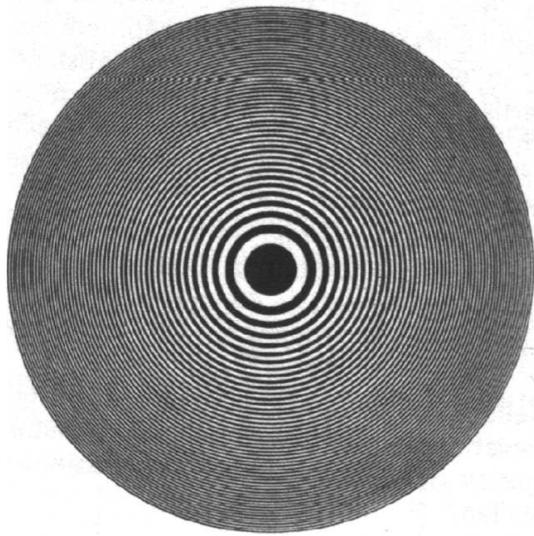
Hyperboloid-shaped interference maxima between two point-shaped light sources. (Ostrovskiy 1987)

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Hologram of a Point Source

Sending one point source to infinity – thus making one light wave planar – , the hyperboloids become paraboloids.

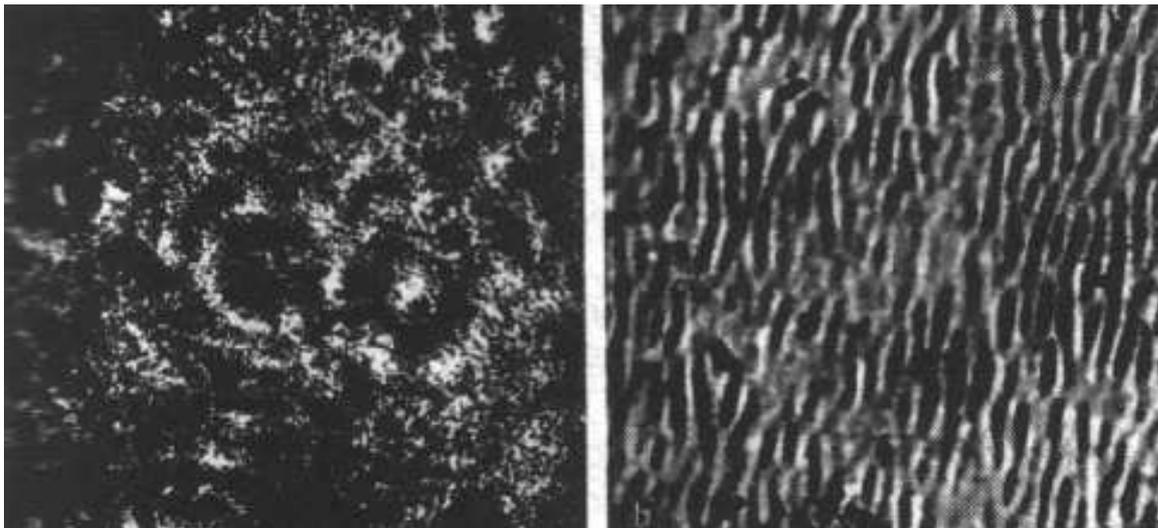
In the special case that the intersecting plane is perpendicular to the planar wave propagation, the interference pattern in that plane consists of concentric circles: a *Fresnel zone plate*.



Fresnel zone plate (schematic). (*Ostrovskiy 1987*)

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Example



Macroscopic (left) and microscopic (right) aspect of a hologram. (*Ostrovskiy 1987*)

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Holography (8)

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Other Types of Holograms

- ◆ By so far, we have spoken of *transmission holograms*. Completely analogous are *reflection holograms*, with the only difference that reference light source and observer now are located on the same side of the hologram.
- ◆ *Volume holograms* record the interference pattern also in depth direction (at least a few interference surfaces deep). Such a hologram has a high selectivity for wavelength and can be reconstructed reasonable well even with white light.

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Holography (9)

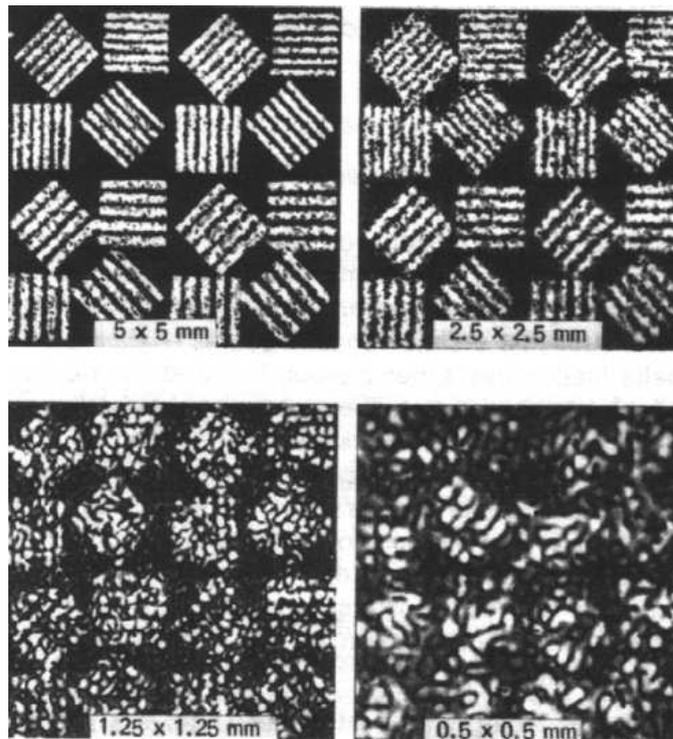
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Further Properties of Holograms

- ◆ A hologram and its negative reconstruct the same object wave.
- ◆ The reference wave in reconstruction needs only to be an approximative copy of the reference wave used to record the hologram. That's why many holograms can be viewed without laser illumination (at the expense of some distortions).
- ◆ Provided that all parts of the hologram have been exposed to the object wave, even a part of the hologram reproduces an image of the whole object. However, resolution and view angles are reduced.
- ◆ The previous property indicates that holography is in some aspects analog to Fourier transform. Indeed, the holographic image formation is described by a "holographic transform" which is similar to the Fourier transform.

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Example



Reconstruction of a test image with varying effective size of the hologram. (*Ostrovskiy 1987*)

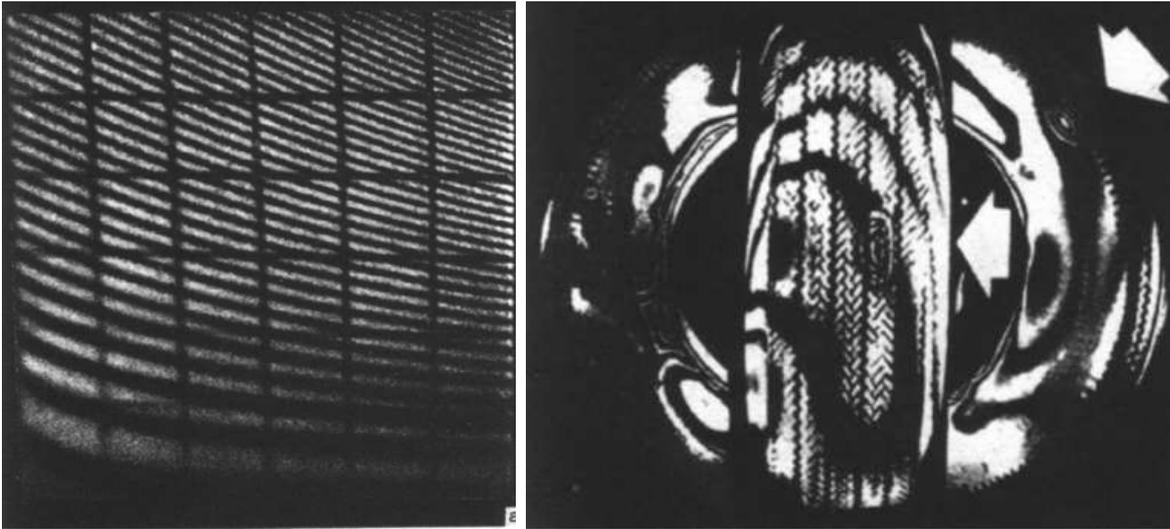
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Holographic Interferometry

- ◆ By superposing two holographic reconstructions of the same object, small displacements between the two exposures (down to less than a wavelength) can be detected: The resulting phase shifts induce an interference stripe pattern. This allows to measure microscopic deformations.
- ◆ A variant of this method is to reconstruct directly the first holographic image onto the object. Then the reconstructed first object wave interferes with an authentic second object wave.
- ◆ By the interference patterns, the phase shifts are detected modulo the wavelength. Therefore the most interesting information is in the density and direction of stripes.
- ◆ This technique has been in use for material testing for decades. Interference patterns are often digitally processed.
- ◆ For vibrating objects, a time averaging occurs in this process which reduces the contrast; sometimes this can be overcome by using a stroboscope.

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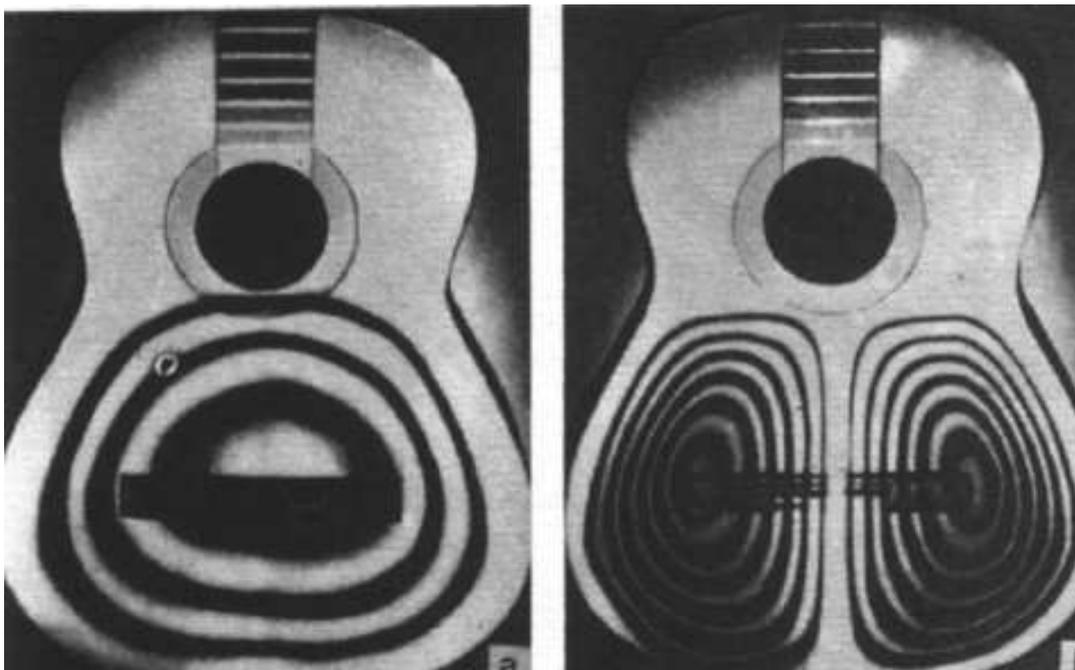
Examples



Left: Holographic interferogram of a stressed elastic plate. The interference pattern gives information about the deformation caused by the stress. **Right:** Holographic interferogram of a tyre. Pressure has been varied slightly between the two exposures. High density of stripes indicates regions with weakness or defects in the material. (Ostrovskiy, 1987)

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Examples



Holographic interferograms of a guitar at two different vibration frequencies, with time averaging. (Ostrovskiy, 1987)

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Extensions and Remarks

- ◆ Sometimes also configurations with lenses are used.
- ◆ Many holographic images are still processed in analog form. So far, digital image processing concentrates on derived images, like those from holographic interferometry. Besides this, digital synthesis of holograms is common.
- ◆ Holography is also used in other wavelength ranges than visible light, and there are also acoustic variants.

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Summary

Summary

- ◆ Dual photography inverts the role of light source and detectors: light source with high resolution, detector with low resolution.
- ◆ Stereo vision uses the displacements between two images to reconstruct the depth information of the scene.
- ◆ Using time-of-flight of modulated light is another technique for obtaining 3D information.
- ◆ Holography captures not only the intensity, but also the phase information of light. It allows to image full 3-D scenes.
- ◆ The spatial information of the 3D scene is scattered over the entire hologram. This transformation is similar to a Fourier transformation.
- ◆ Using only a part of the hologram still allows to reconstruct the scene, but with less accuracy.
- ◆ Also nonoptimal illumination conditions (different wavelengths or non-monochromatic light for reconstruction) may create distortions.
- ◆ Holographic interferometry allows highly precise deformation measurements.

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(links to research on holography)

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