MAS.963 Special Topics: Computational Camera and Photography
Fall 2008

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Underwater Photography and Theory of Multiplex Illumination

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Lecture 7

1 Underwater Photography

This part of the lecture covered acoustic sensing techniques and camouflage of underwater animals presented by Hanumant Singh, an associate scientist from Woods Hole Oceanographic Institution (WHOI).

1.1 Acoustic

An underwater exploration typically uses a sonar system for navigation and studing seafloor geography. A way to capture an "image" using acoustic waves is different from capturing an image using light and a camera. A traveling acoustic wave is governed by the wave equation that is very different from the light equation. A typical sonar receive level can be summarized by

$$RL = SL - 2TL + BP_R + BP_T + TS, \tag{1}$$

where

- RL represents a received level of the signal at the receiver,
- SL represents a transmitted level of the source signal,
- TL represents a transmission loss. The factor of two reflects the forward path and the backward (reflected) path,
- BP_R represents a beam pattern on the receiver side,
- BP_T represents a beam pattern on the transmitter side,
- TS represents a target strength that depends on material, shape, incident angle, and other factors. This factor is similar to a bidirectional reflectance distribution function (BRDF) in the imaging application using light.

Equation (1) is written in an algebraic form because it is written in the log domain. The log domain allows high dynamic range representation, which is more suitable for sonar applications.

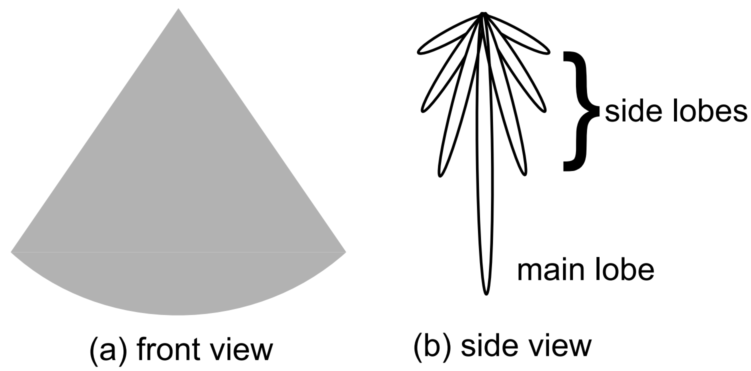

Figure 1: Fan-shaped beam example

1.2 Side-scan sonar

A side-scan sonar system is an exploring device that can progressively scan a small region at a time, like a line scanner. A final result is just a stitch of all line scans together. The output signal has a fan-shaped beam with a narrow width as shown in Figure 1. Other explanations can be found here [1].

The fan-shaped beam is generated by a linear array of transmitters sending pulses of coherent signal. The system can computed the depth by measuring time of flight of the transmitted signal. A typical frequency used in this system is the order of hundreds of kilo-hertz range. The resolution of the image depends on the wavelength of the signal. For example, the speed of sound in water is approximately 1,500 m/sec. Using the 100 kHz frequency, the wavelength of the sound is

$$\begin{aligned} \lambda &= \frac{v}{f} \qquad (2) \\ &= \frac{1500\,\mathrm{m/sec}}{100\,\mathrm{kHz}} \\ &= 1.5\,\mathrm{cm}. \end{aligned}$$

The wavelength indicates the resolution of the system. Higher frequency has a smaller wavelength and higher resolution; however, the scanning range is shorter. A typical array of transducers (transmitters) is separated by a half wavelength apart ($\lambda/2$). As a result, we can approximate the wavelength from the array configuration.

1.2.1 Beam pattern effect

Because the transponder is not perfect, the beam pattern includes side lobes as well as shown in Figure 1. The side lobe has less power and spread out over different tilted angle. Beams from the side lobes have oblique angles; therefore the received signal appear smaller. This beam pattern effect can be seen in the image by the variation of the brightness in the picture.

1.2.2 Received singal pattern

A typical sonar received pattern can be displayed as a received signal strength vesus time. Using these time and signal strength, various parameters such as depth and approximate shape may be recovered and constructed. The wave pulse transmission and sample of received signal are shown in Figure 2.

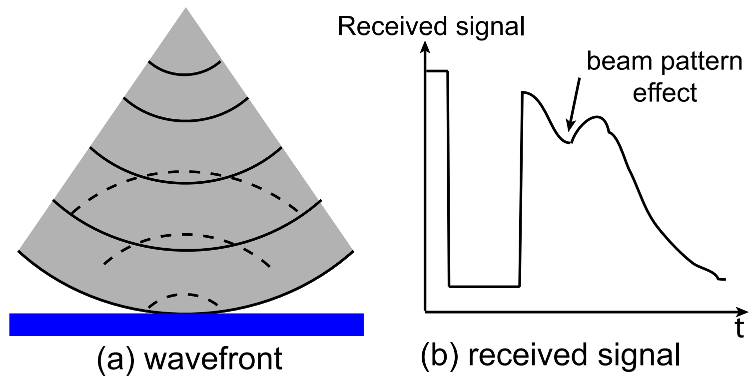

Figure 2: Beam transmission and sampled received signal

The first peak near the beginning of the beginning is the transmitted time. The receiver is almosted co-located with the transmitter; hence, the feedthough can be observed. The low signal region (region II) indicates small or no signal, which corresponds to the water. The next peak corresponds to the first return of the signal (echo). The first dip in the signal indicates the beam pattern effect as described above.

The received signal is mapped and displayed in a warp image with color coded. The result is hard to described because of 3-D geometry.

1.3 Multibeam sonar

This sonar system is similar to the side-scan sonar with different optimization. The objective of this type of sonar is to explore the sea floor only. The resolution of this system can be about 1 m. The system has to be calibrated and compensated for the position of the vessel. GPS and more sophisticated devices are needed to compenstate for heading and roll of the vessel. One other difficulty is the sensor offset. Calibration can be done by scanning back-and-forth and perform photometric stereo to compenstate for the row-offset.

1.4 Issues of underwater optical imaging

Optical imaging underwater can be challenging because of the property of the water media. Major issues can be listed below

Illumination: Light is attenuated non-linearly across the spectrum. A rapid attenuation is observed. Normally the underwater image looks either bluish or greenish with just a sunlight or a regular flash because the red color gets attenuated more than other colors. The compensation can be done using a custom flash that compensate for the wavelength-dependent attenuation.

Back scattering: This effect describes the volumetric overlap between the light source and the camera field-of-view. Larger volume intersection means more scattering. The improvedment can be done by separating the illuminating source and the camera further. See Figure 3

Wide baseline: Subsequent pictures are far apart.

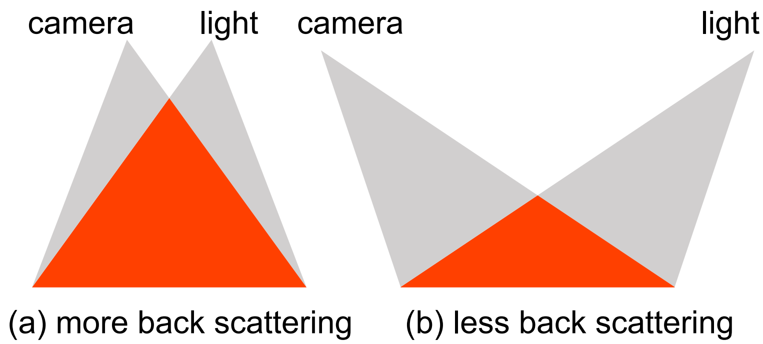

Figure 3: Back scattering

Given many the underwater optical imaging issues, interesting projects to be included in the "next generation" underwater photography could be

- Improve range of object to be taken
- Color correction – want the result image to look asif the subjects are illuminated by a sunlight – a sunlight filter
- Compensate flash system
- Shear reflector
- LED lighting – currently Zenon strobe has no spectral control and slow response
- White balance correction at pixel level
- image registration

1.5 Camouflage

Undersea animals such as cuttle fish and octopus have interesting mechanisms to disguise themselves from predators and preys. These creatures can change the skin color within a few sections. Basic camouflage techinques are

- general resemblance – the animal tries to match the background
- become an element in the texture
- break the pattern – make the pattern more standout. This technique is also called "disruptive camouflage."

If the predator uses edge-based detection, the camouflage pattern can include the edge with is lined-up with the environment. Psychologically, the line is created from the eye by filling the gap. Interestingly, how does the animal know what is it looked like from the third person perspective? In addition, the cuttle fish is also color blind. It can only see the contrast not the actual color. Furthermore, the fish can only produce the color in the natural environment only. Examples can be found at

- Invisible octopus
  http://www.youtube.com/watch?v=ckP8msIgMYE&feature=related
- Coconut octopus
  http://www.youtube.com/watch?v=7WPvqQZ4B9Y
- National Geographic
  http://www.youtube.com/watch?v=zC0zOLqYnRg
- PBS
  http://www.youtube.com/watch?v=2x-8v1mxpR0

1.6 Ligth field camouflage

To make object invisible, we cannot just project the image from the back of the object to the projector screen because it will not work for different view points. However, one idea is to use a light field camera capturing the scene from the back and reproject to the light field display on the front. In this case, the object will be come "invisible." A conceptual example is shown in Figure 4.

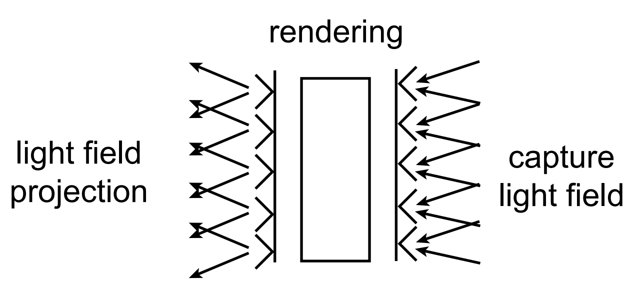

Figure 4: Light field camouflage

2 Multiplex illumination

Multiplex illumination technique uses the linearity of amount of light received to capture the scene from different combinations of light sources and recompute the contribution of each individual light source. This technique can then render an image with any combination of light sources. See the lecture slide on Oct 17, 2008 for the actual procedure.

Benefits of multiplex illumination include

- higher signal-to-noise ratio (SNR) because more light means less noise in general. The exception can be the saturation of the sensor.

- less acquisition time compared to a standard single light source illumination.

The question becomes what are the optimal combinations of light sources to be turn on. The solution is to use a modified Hadamard code. This code has a roughly equal number of ones and zeros in each row and column. As a result, half of the light sources will be on and half of the light source will be off. Using this coding algorithm, SNR is improved by $\sqrt{N}/2$, where N is a number of light source.

3 Coded aperture imaging

In astronomy imaging, we could not focus the x-ray source using optics. The system can be implemented using a pinhole camera but the exposure time would be long. Multiple-pinholes camera with a single sensor can be used and the system will produce multiple of shifted pictures on the single sensor. The challenge becomes the recovery of the original image. Different coded aperture imaging systems are shown in Figure 5.

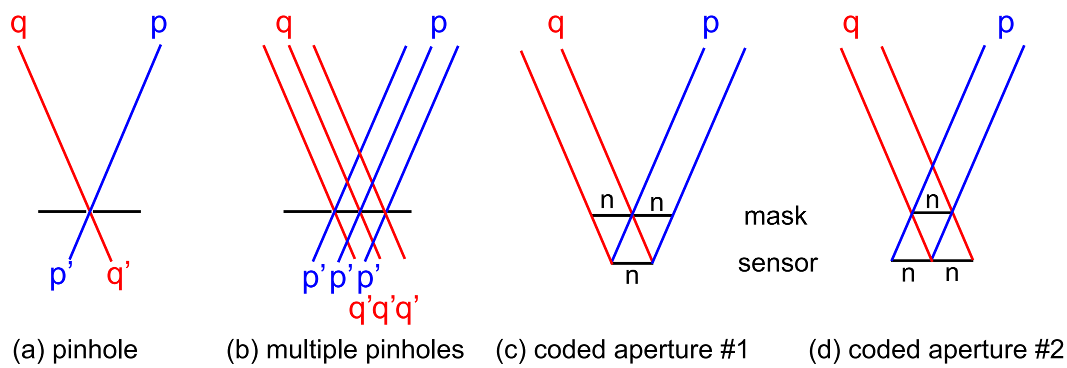

Figure 5: Coded aperture imaging systems

An example of a coded aperture is the modified uniformly redundant array (MURA). This code has 50% opening area, and the correlation function is a dirac delta. The issue of the image reconstruction is a noise in the system. Prof. B.K. Horn has simulated the reconstruction image with different noise levels. The result indicates that the reconstruction result is only good when there is no noise in the system. Only 1% of noise, the original image could not be reconstructed. Reconstruction noise is directly correlated to the condition number of the matrix, indicating the inverse may not be numerically stable and the noise can be amplified.

If we plot the SNR improvement of the multiple pinhole system as a function of the sparsity of the scene, we can clearly see the diminishing return of the coded aperture as the scene get denser, i.e. paintings. See Figure 6. As a result, we have to be careful using the coded aperture system.

Other coded aperture include the lens-based, 7x7 mask coded aperture which we have seen in the lecture on September 19 [2].

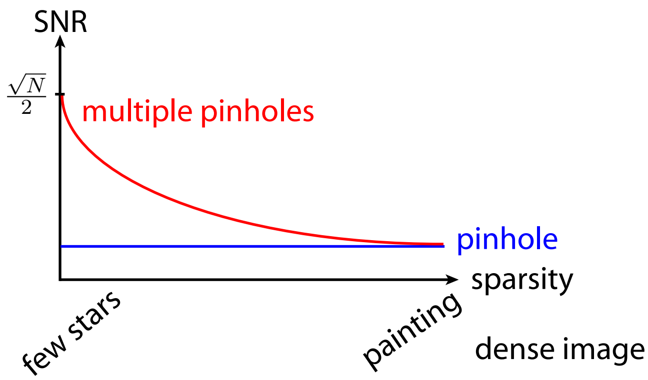

Figure 6: SNR improvement as a function of scene sparsity

4 Final project

Additional ideas for final projects from people in the class

- Removing the static portion and tracking the moving portion instead.
- Playing with a moiré effect. Projecting a stripe pattern onto a moving object and capture a sequence of photos from the camera. The moire pattern should manifest itself along the shape of the object as its moving. Interesting pattern should be observed.
- Dual projector – calibrating the projector using dual-photography technique.
- Thermal sensing by other method such as the thermal expansion of different metal fingers
- Using laser sheet to capture the flow of fluid or particles

Acknowledgement

I would like to thank Rise Riyo for her lecture note and recorded file that helping me compile this scribe.

References

[1] http://en.wikipedia.org/wiki/Side-scan_sonar

[2] Veeraraghavan, Raskar, Agrawal, Mohan, and Tumblin, *Dappled photography: Mask enhanced cameras for heterodyned light fields and coded aperture refocusing*, ACM Trans. on Graphics, July 2007.