Rendering wave effects



15-468, 15-668, 15-868 Physics-based Rendering Spring 2022, Lecture 16

http://graphics.cs.cmu.edu/courses/15-468

Course announcements

- How many of you attended Thomas Mueller's talk?
- Take-home quiz 9-10 posted, due 4/26.
- Nobody was around for yesterday's recitation :-(.
- Will try to go over final project proposals tonight.

Coherent Scattering and Memory Effect



Applications and Related Work

LETTER

invasive imaging through opaque scattering

Ælbert G, van Putten¹)*, Christian Blum¹, Ad Lagendijk^{1,4}, Willem L, Vos¹ & Allard P, Mosk¹

ues, such as optical coherare case tial diagnostic tools in many disci-

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TT G. VAN PUTTEN,^{3,2} JACOPO BERTOLOTTI,^{1,3} AD LAGENDUK, ALLARD P. MOSK S), MESA+ Institute fo vch 2015; accepted 21 March 2015 (Doc. ID 226377); published 27 Ap 0 nm. Here, we intre

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stical microscope.

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Non-invasive single-shot imaging through

scattering layers and around corners via ined in the signal and s have shown that star effects', allow for diffraction access to) the source or scatte e static during the m speckle correlations st time single-shot video Ori Katz^{1,2}*, Pierre Heidmann¹, Mathias Fink¹ and Sylvain Gigan^{1,2}

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Single-sh

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Physica A 108 (1990) 49-65 North-Holland

LOOKING THROUGH WALLS AND AROUND CORNEL

Received: 26 April 2016 Eitan Edrei & Giuliano

Accepted: 30 August 2016

Department of Physics, Bar-Ilan University, Ramat-Gan, Israel

SCIENTIFIC REPORTS

OPEN Memory-effect based deconvolution

microscopy for super-resolution imaging through scattering media

s shown theoretically that under appropriate conditions a visu ring optical barrier can be made to serve as a thin lens which pre a image of objects lying behind the barrier. Preliminary e described which verify the validity of the underlying assumptions. to serve as various other types of optical instru al Fourier analyzers, theodolites, etc. Thus it is now clear that m should no longer be considered barriers to optical propagation. s potential high-precision optical inst

1. Introduction

With the advent of radar half a century ago, detection visually opaque barriers, such as dense cloud cover, be randomness in size and position of water droplets which n leads to substantial scattering of the coherent electromag prising a radar beam. Thus, the study of coherent tion through random media became an impor British Admiralty. Some of the earliest theoretical studies were carried out by Cyril Domb while seconded to the were to form later on the basis of his very first publishe As always, the problems attacked early on by Dom fields of study down to this day, and, indeed, over the la been an enormous upsurge of interest in the propagat waves in highly random media [2-53]. Here, we const rich reservoir of new knowledge may be applied to t imaging through highly random, multiply scattering mee

ARTICLES

Translation correlations in anisotropica scattering media

Benjamin Judkewitz^{1,2*†}, Roarke Horstmeyer^{2†}, Ivo M. Vellekoop³, Ioannis N. Pa and Changhuei Yang²

cation. Long considered ent advances in the field of wavefront shaping¹² -as long as the correct input thick scatt ont is used. With direct optical access to the target plane, the

sever, there is no direct access to the target ould enable high-speed imaging. One of the most widely ons is the so-called 'memory will be gene which describes the following phenon enon: when an its discrete nature, the tra g a diffusing sample is tilted within a certain to experim f the far-field speckle pattern at a distance behind the

ample (see Fig. 1). 1). ion distance within which this effect holds (that plete mea

nory effect should be minimal"

perfectly correct low-order aberrations using using but require the presence of a bright point-source 'guide star' or a high initial image contrast⁶. Recent exciting advances in controlled wavefront shaping' have allowed focusing and imaging through highly scattering samples⁸⁻²⁶. However, these techniques either require initial access to both sides of the scattering medium⁸⁻¹⁵, the presence of a guide-star or a known object¹⁶⁻¹⁹, or a long acquisition sequence that involves the projection of a large number of optical patterns²⁰⁻²⁶. A recent breakthrough approach reported by plasti et al. has removed the requirement for a guide-star or a

S

Scattering

medium

Optical imaging through and inside complex samples is a difficult challenge with important applications in many fields. The fundamental problem is that inhomogeneous samples us a different chanenge with important applications in many neids. The fundamental problem is that inhomogeneous samples such as biological tissue randomly scatter and diffuse light, uncamental problem is that inflomogeneous samples such as biological ussue randomly scatter and unruse light, bling the formation of diffraction-limited images. Despite many recent advances, no current method can perform

Camera image

I = O * S

A schematic of the experim medium, as well as a numerical example, are pre-An object is hidden at a distance u behind a highly scattering medium of thickness L. The object is illuminated by a spatially incoherent, narrowband source, and a high-resolution camera that is placed at a distance v on the other side of the medium records the pattern of the scattered light that has diffused through the scattering medium. Although the raw recorded camera image is a low-contrast, random and seemingly information-less image (Fig. 1b), its autocorrelation (Fig. 1c) is essentially identical to the object's autocorrehad been imaged by an aberration-free diffraction-

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attered light, captured with a standard camera, encodes sufficient ound cor

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Object

Illing light propagation across scattering media by wavefront shaping hold unications and imaging applications. But, finding the right shape for the wavef an input and output scattered wavefronts (that is, the transmission matrix) is no ally the so-called memory effect, have been exploited to address this inner applies to thin scattering layers at a distance from the target, which pre such as fog and biological tissue. Here, we theoretically predict and experimen



Monte Carlo (MC) Simulation of Speckles



Wave Solution v.s. Monte Carlo



MC requires the scatterers density – no need for exact positions



2nd Moment - Covariance



Cross –illumination statistics



Memory Effect:

tilting illumination results in highly correlated shifted speckles

Next: Cross Illumination Covariance

Cross –illumination statistics



Monte Carlo Rendering 101





Covariance Rendering































Computing ME extent as a function of θ :







 θ



Summary



Seeing Through Scattering Layers

Cool Application by Ori Katz et al 2014



 $C(\theta)$

Coherent scattering and memory effect (ME)



32

Coherent scattering and memory effect (ME)

Hidden illuminators



Microscope

Objective

Speckle image

33

Correlation

Problems with classical see-through approach

- Limited range: Only illuminators within the ME range can be recovered.
- Limited density: Only a small number of illuminators can be recovered.
- Unrealistic setup: Far-field imaging conditions do not apply to tissue imaging.



Our contributions

(i) Theoretical and rendering based analysis of ME in **near** and **far**-field settings

(ii) Develop a better algorithm for imaging thoughscattering: 1. higher density 2. wider range 3. near sources

(iii) Real Lab experiments in near and far fields



10

Δ, [μm]

Theory and simulation analysis

Problem setting and memory effect



Change **illumination** plane

ME correlation in near-field vs. far-field



Aligning ME correlation in the near and far fields





For-field

scattering

tissue

Imaging plane

- Theorem: ME range depends only on angular displacement.

- Moving the illumination plane farther away, scales the ME range to cover larger patterns.

- Imaging-through-scattering is easier in farfield than near-field Near-field



ME correlation in the near-field

0



- As the thickness increases, ME correlation decreases.

50[μm], OD=1 200[μm], OD=4 500[μm], OD=10 1[mm], OD=20

10

[µm]

40

Speckle Local Support



Summary of theoretical contributions

(i) Theoretical and rendering based analysis of ME in **near** and **far**-field settings



Our algorithm

Seeing though scattering using ME

i¹ i² i³ •) Scattering layer





Reconstruction using local speckle correlation

Correlation(Δ) = $\sum I_x \cdot I_{x+\Delta}$ What illuminators Just produce this image? noise **Previously**: **Noisy** sum over full frame **Theorem:** Ours: order of sum over magnitude local window increase in SNR

45

Optimization with local support



Local vs. global correlation



Local correlation: less noisy and reveals some information about the desired shape

Lab Results

Lab setup







Lab results: far-field



Chicken breast thickness 170 µm

Lab results: far-field





Chicken breast thickness 140 µm

Lab results: near-field





Chicken breast thickness 200 μm

Lab results: near-field





Lab results: near-field





Thanks to **Dr. Lucien Weiss** from Schechtman lab for preparing the fluorescent samples