A Survey of Photometric Stereo Techniques

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Contents

Abstract

Reconstructing the shape of an object from images is an important problem in computer vision that has led to a variety of solution strategies. This survey covers photometric stereo, *i.e.*, techniques that exploit the observed intensity variations caused by illumination changes to recover the orientation of the surface. In the most basic setting, a diffuse surface is illuminated from at least three directions and captured with a static camera. Under some conditions, this allows to recover per-pixel surface normals. Modern approaches generalize photometric stereo in various ways, *e.g.*, relaxing constraints on lighting, surface reflectance and camera placement or creating different types of local surface estimates.

Starting with an introduction for readers unfamiliar with the subject, we discuss the foundations of this field of research. We then summarize important trends and developments that emerged in the last three decades. We put a focus on approaches with the potential to be applied in a broad range of scenarios. This implies, *e.g.*, simple capture setups, relaxed model assumptions, and increased robustness requirements. The goal of this review is to provide an overview of the diverse concepts and ideas on the way towards more general techniques than traditional photometric stereo.

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Notation

n	normal	R	reflectance map or albedo matrix
X	a 3D point	P	number of pixels/patches
$\mathcal{P}$	set of 3D points (*i.e.* a patch or mesh)	S, T	factorization of the radiance matrix
L	radiance	A	transformation matrix
L_s	incoming (source) radiance	B	arbitrary matrix
ω	direction vector	$B^\dagger$	pseudoinverse of B
D	light matrix/vector	α, μ, ν	parameters
$\omega_{\text{in/out}}$	incoming/outgoing direction vector	λ, γ	parameters
Ω	solid angle	r	inner matrix dimension
$\mathrm{d}\omega$	differential solid angle	D_R	reflection vector
ρ	BRDF or diffuse constant	φ	angle
c, C	arbitrary constant (scalar or matrix)	$\mathcal{D}, \mathcal{K}$	factorization of L
M	number of images	Φ	lobe function
I	image intensity	$\mathcal{M}$	general model
f	camera response	W	reciprocal pair matrix
θ, ϕ	angles (typically zenith and azimuth)	o	general observation
p, q	coordinates of the gradient	K	error free radiance matrix
σ	standard deviation	H	indicator matrix
$\mathcal{N}$	normal distribution	v	viewing direction
Z	depth map/height field	W	intensity profile matrix
(u, v)	2D coordinates	w	intensity profile
N	normal map/normal field (possibly in matrix notation)	m	mixing coefficients
E	error (matrix, measure, *etc.*)	$\mathcal{S}$	the unit sphere in $\mathbb{R}^3$
		$\mathcal{M}$	manifold
		Φ	embedding
		d	distance score
		τ	projection operator
		Ψ	Haar-Wavelet
		h_i	EMOR basis function
		ξ	shadow function

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Introduction

The shape of an object, its reflectance, and the incoming illumination define the image that the object forms in our eyes or on a camera sensor. Even for a uniformly colored, diffuse object, the shading typically changes depending on the local orientation of the surface and the properties of the incoming light. Highlights form on glossy or specular surfaces, providing additional cues about the surface shape and reflectance as well as the illumination. Humans are remarkably good at deducing such information from images even under very general conditions (Thompson et al. [2011]). In contrast, recovering one or several of these individual components is a much more difficult task for a computer system.

To solve such inverse problems, different techniques exist such as shape from defocus (Pentland [1987]), shape from texture (Blostein and Ahuja [1989]), or (multi-view) stereo (Seitz et al. [2006]). In this survey, we direct our attention to photometric approaches. These exploit the intensity variations caused by illumination changes. Typically, the input is a set of images of an object or scene under a varying set of lighting conditions, and the output is the 3D shape, *e.g.* encoded as a field of surface normals.

The goal of classic photometric stereo is to recover the surface orientation from a known combination of reflectance and lighting in multiple images. Starting from this, a rich body of literature was developed that generalizes the problem and its solution in various directions. Many of these approaches assume a controlled capture setup because well-behaved input data is crucial for inverse problems. These requirements constrain the application mostly to the research community and production settings. In this survey, we put a focus on approaches with a potential to broaden this applicability, *e.g.*, through simple capture setups or relaxed requirements.

1.1 Scope of this survey

Shape and appearance reconstruction have connections to different fields in computer vision, computer graphics, optimization theory, statistics, optics, *etc.* We will only cover those areas that are most relevant for this survey. These are approaches that rely on varying illumination in multiple images to recover at least the surface orientation and possibly even reflectance and illumination.

That excludes for example the large area of shape from shading approaches that operate on single images (Zhang et al. [1999], Johnson and Adelson [2011], Oxholm and Nishino [2012], Han et al. [2013]) and the related works on intrinsic image decomposition (*e.g.* Barron and Malik [2012, 2013]). These are highly ill-posed problems and their solution requires strong regularization. Using multiple images provides more information and better constrains the result space. Some works (*e.g.* Magda et al. [2001], Koppal and Narasimhan [2007], Liao et al. [2007]) exploit the fall-off in radiance with the distance from a near point light or more general changes in the apparent source intensity (*e.g.* Davis et al. [2005]). Our focus will be on illumination variations caused by directional changes in the incident light. We also do not consider purely specular surfaces (Healey and Binford [1986], Bonfort and Sturm [2003], Tarini et al. [2005], Chen et al. [2006], Nehab et al. [2008], Weinmann et al. [2013]) or the specialized approaches for face (Debevec et al. [2000], Zhou et al. [2007], Ghosh et al. [2011]) and dynamic performance (Ahmed et al. [2008], Vlasic et al. [2009], Wu et al. [2012]) capturing. Similarly, we will mention only a few approaches that require highly complex capture setups because they have less potential to be adapted for unconstrained environments

In many modern works ideas from different disciplines get combined, *e.g.* when silhouette constraints are merged with photometric cues in certain multi-view approaches. This makes a clear distinction to other fields difficult at times. We include such cases in our discussion if it suits the overall perspective.

1.2 Overview

We begin this survey with an introduction for readers unfamiliar with photometric stereo methods in Chapter 2. It serves as a tutorial and to promote awareness for the challenges present in practical applications of such techniques. Before proceeding to the main part, we briefly discuss some early works in Chapter 3 that laid the foundations for present-day research.

Finding an optimal categorization of photometric approaches to structure this survey is not trivial. We decide for a selection scheme based on common challenges among the algorithms such as unknown lighting in Chapter 4, complex reflectance in Chapter 5, or extremely uncontrolled conditions in Chapter 9. Within each category we aim at presenting relevant representatives instead of cluttering the exposition with lists of similar approaches.

Finally, we conclude the survey in Chapter 10 with a summary of the most important concepts and our views on future developments.

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