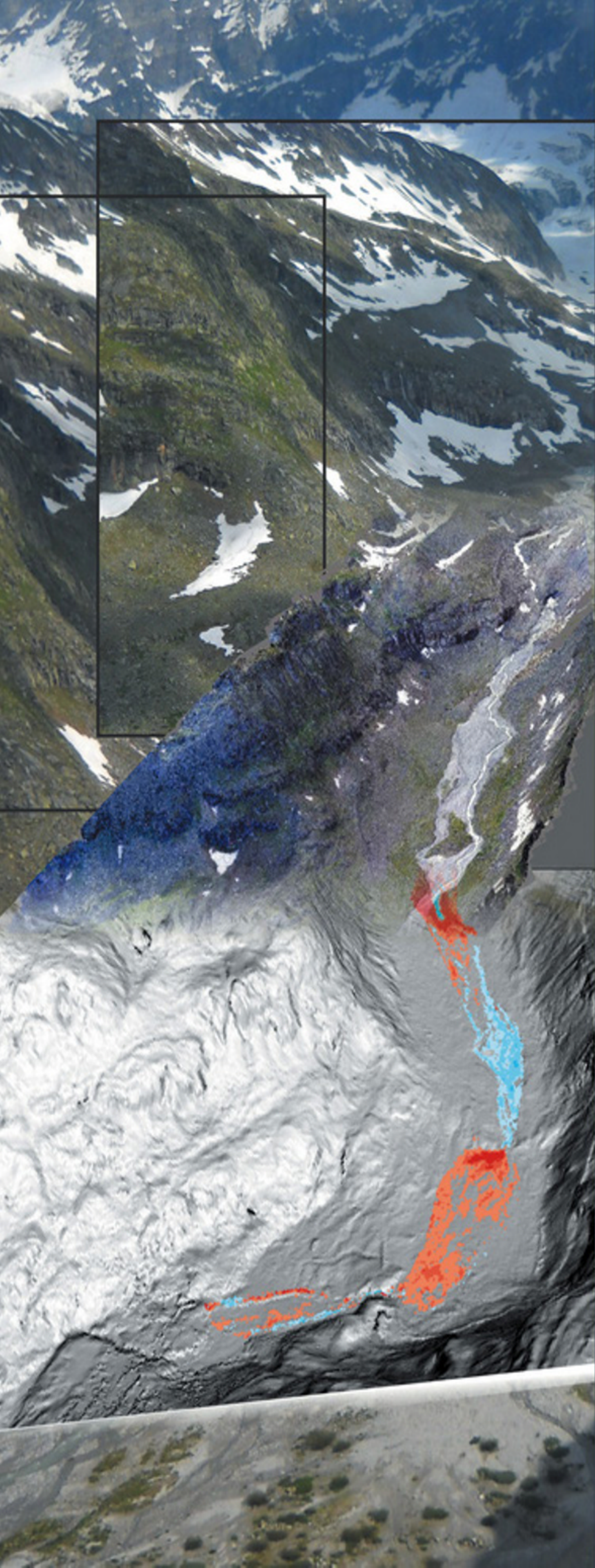

New Analytical Methods in Earth and Environmental Science

STRUCTURE FROM MOTION IN THE GEOSCIENCES

Jonathan L. Carrivick
Mark W. Smith
Duncan J. Quincey

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Cover image: Illustration of SfM -MVS workflow which progresses from multiple overlapping images to point cloud generation and usually then to differenced elevation model: in this case for detecting and analysing erosion and deposition in an alpine river © Jonathan Carrivick

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Contents

Abbreviations

ALS	airborne laser scanning
DEM	digital elevation model
dGPS	differential Global Positioning System
DoD	DEM of difference
DSLR	digital single-lens reflex camera
EXIF	exchangeable image file format
Gb	gigabyte
LiDAR	light detection and ranging
MAE	mean absolute error
Mb	megabyte
NRSfM	non-rigid Structure from Motion
PMVS	patch-based multi-view stereo
RAM	random access memory
RANSAC	random sample consensus
RGB	red–green–blue
RMSE	root-mean-square error
SfM-MVS	Structure from Motion–Multi-View Stereo
Tb	terrabyte
TLS	terrestrial laser scanning
TS	total station
UAV	unmanned aerial vehicle

About the Companion Website

This book is accompanied by a companion website:

www.wiley.com/go/carrivick/structuremotiongeosciences

The website includes the following:

- Videos
- Figures and tables from the book for downloading
- Interactive figures

1 Introduction to Structure from Motion in the Geosciences

Abstract
Structure from Motion (SfM) is a topographic survey technique that has emerged from advances in computer vision and traditional photogrammetry. It can produce high-quality, dense, three-dimensional (3D) point clouds of a landform for minimal financial cost. As a topographic survey technique, SfM has only been applied to the geosciences relatively recently. Its flexibility, particularly in terms of the range of scales it can be applied to, makes it well suited to a field as diverse as the geosciences. This book is designed to act as a primer for scientists and environmental consultants working within the geosciences who are interested in using SfM or are seeking to understand more about the technique and its limitations. The early chapters consider SfM as a method within the context of other digital surveying techniques, and detail the SfM workflow, from both theoretical and practical standpoints. Later chapters focus on data quality and how to measure it using independent validation before looking in depth at the range of studies that have used SfM for geoscience applications to date. This book concludes with an outward look towards where the greatest areas of potential development are for SfM, summarising the main outstanding areas of research.

Keywords
geosciences; Structure from Motion; multi view stereo; GIS; landform

1.1 The Geosciences and Related Disciplines

Geoscience is a term that encompasses many disciplines of research and industry, particularly environmental consultancy. It is an umbrella term for climate, water and biogeochemical cycles, and planetary tectonics, which are the three basic processes that shape the Earth's surface. These are complex natural

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Figure 1.1 A word cloud of geoscience sub-disciplines. The font size of each word does not indicate anything.

systems in space and time. For example, process responses and interactions occur on spatial scales spanning hundreds of kilometres to microns, such as river catchments and abrasion marks on fluvially-transported grains, respectively. Process responses and interactions occur on timescales ranging from picoseconds for chemical reactions to millions of years for plate tectonics and biological evolution, respectively.

Whether academic or applied, whether large scale or small scale, the geosciences seek to understand the forces and factors that shape our world and the environments in which we live. Reasons for requiring understanding of these forces and factors span many remits: exploitation for the hydrocarbon and renewable energy sectors, managing natural hazards, managing a resource-consuming and dynamic society, mitigating effects of climate change, and academic interest and enquiry, for example.

In seeking ever-refined understanding for application to real-world problems, the geosciences now transcend "traditional" earth science disciplines (Fig. 1.1). The multidisciplinary nature of the geosciences is partly due to it having become particularly adept at pursuing interactions between the biological, chemical, and physical sciences. Analysis across these traditional boundaries is critical to understanding systems in an integrated and holistic manner.

Furthermore, the geosciences are now established as being notable for embracing emerging and novel technologies and innovations. Indeed the revolution brought about by spatial analysis software such as geographical information systems (GIS) has been argued as a new paradigm in the discipline. Many technologies in the geosciences have been adapted from the military, from the petroleum industries, and more recently from computer science.

No matter what particular specialism to which they affiliate themselves, many geoscience disciplines will generally recognise three key tasks:

1. Recognition of spatial patterns
2. Documentation of transient landforms
3. Linking processes to products

Here it is important to note that in this book we use the term **landform** independent of any scale; the term as used in this book is considered to encompass landscape, terrain, feature, surface, and texture, for example.

A common requirement for each of these three key tasks is for the geosciences to have topographic information. The primary function of topographic information in digital format is to quantify landform variability and more specifically three-dimensional (3D) structure.

Topographic information can be used to identify landforms and landform properties. Landforms can include natural and artificial features and thus form part of the description of a specific place. When landforms are observed to change, the processes causing those changes are often inferred conceptually, and perhaps also tested by numerical models. New methods of acquiring topographic data with a fine spatial resolution are to be welcomed because they expose greater detail about landform morphology. They also provide an opportunity to match the scale of topographic data with the spatiotemporal scale of the landform or processes under investigation.

On the basis of the multidisciplinary nature of the geosciences and of the widespread academic and applied need for topographic survey data, we consider that this book, which will focus specifically on one specific method for generating topographic data, has relevance for all the geosciences (Fig. 1.1) and for related disciplines. Related disciplines requiring topographic information include architecture, archaeology, civil engineering and subdisciplines associated with built structures, objects, and artefacts, and biology and medicine where concerns range from vegetation to anatomical surveys.

1.2 Aim and Scope of this Book

The aim of this book is to describe an emerging survey method and workflow that is better established in related disciplines such as archaeology (e.g. De Reu et al. 2013) and cultural heritage (Koutsoudis et al. 2014) and is now finding widespread uptake in the geosciences, namely, "Structure from Motion" (SfM). This book is designed to act as a primer for geoscientists who are interested in using SfM or are seeking to understand more about the technique and its limitations.

This book is designed to appeal to students, professional academics, and industry practitioners, particularly environmental consultants. Whilst existing texts dealing with SfM are often heavily mathematical, originating commonly from computer vision literature, this book is designed to be fully accessible by an interested geoscience audience that may not necessarily be fully conversant in complex mathematical operations involved in SfM. Thus, the workflow of SfM is described in a predominantly qualitative manner, and the reader is referred elsewhere for further technical details. Important terms are in bold at first use, a list of abbreviations is provided, and emphases of particularly important properties are in italics. This book is designed to balance the conceptual discussion of application, theory, and technical details of analytical methods. Thereby this book serves as a synoptic reference to both inform and educate. In educating, we emphasise the discussion and development of a critical understanding of the application of SfM in the geosciences to date. In terms of informing, we build on this critical understanding to stimulate ideas for carefully considered future developments of the SfM workflow by the geosciences.

1.3 The Time and the Place

This book is timely and of immediate relevance because of (i) the emergence of an affordable, user-friendly software; (ii) rapid developments in unmanned aerial vehicles (UAVs) or drones and other potential SfM survey platforms; and (iii) a dearth of textbooks on SfM in the geosciences. Notwithstanding that, of course, the pace of technological change in hardware and software is incredibly rapid, and for that reason the forward-looking chapters of this book do not dwell on specific hypothetical applications but rather on major themes and concepts.

At present, the use of SfM can only really be evaluated in academic literature since technical and industry reports tend not to be listed on public databases. A search in the academic publications database *Web of Knowledge* for *Structure from Motion* (made in April 2015) delivered approximately 1000 records since the early 1980s (Fig. 1.2). Computer science was the category with the most counts of that phrase. Engineering was ranked 2nd and geosciences was ranked 9th. Notably, the geosciences have only started producing publications incorporating SfM in the past decade (Fig. 1.2).

The impact of SfM is arguably going to be greater than that associated with the advent of airborne laser scanning (ALS) or airborne light detection and ranging (LiDAR), not least because SfM workflows democratise data collection and the development of fine-resolution 3D models at all scales of landscapes, landforms, surfaces, and textures. Moreover, to produce such advanced data products, very little input data are required: as little as a photograph set from an uncalibrated, compact (and therefore often cheap) camera. In a similar vein to airborne LiDAR surveys and terrestrial laser scanning (TLS) 15 and 10 years ago, respectively, the past couple of years have seen a raft of sessions at major international conferences describing work using SfM. This book places these developments in context, outlines the analytical framework and key issues, and presents 10 detailed case studies contributed by SfM practitioners.

This book fills a niche where there is a current dearth of textbooks on SfM for the geosciences. Although existing photogrammetry-orientated and

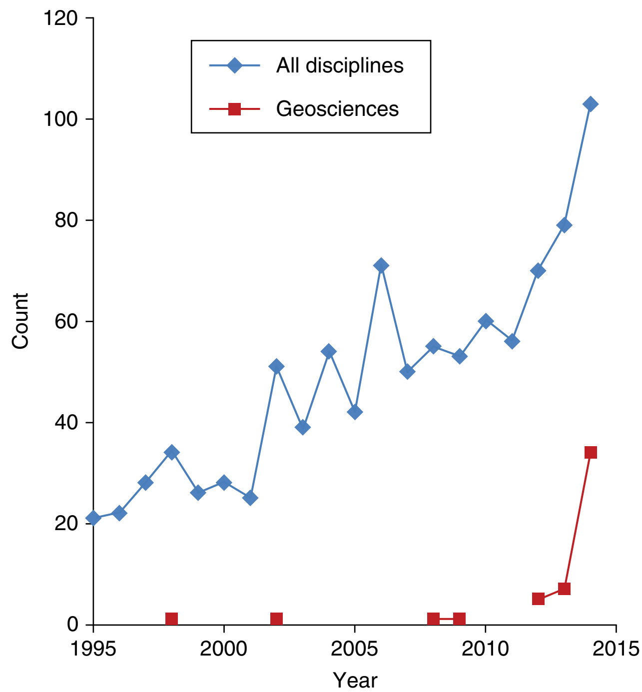

Figure 1.2 Count of citations to "Structure from Motion" in the academic literature.

computer vision-oriented texts will describe in depth many of the algorithms and procedures that SfM utilises, albeit in a modified or improved form to handle the input of dozens or hundreds of images, these texts are often extremely technical and may be largely inaccessible to the "average" geoscientist. The Wiley-published book series "New Analytical Methods in Earth and Environmental Science" has two other titles in that series that may be complementary to this book: *Techniques for Virtual Palaeontology* (Sutton et al. 2014) and a proposed *Digital Outcrop Modelling*. Both of these certainly fall within the geosciences domain and illustrate that geoscience usage of SfM is not just about terrain models.

1.4 What Is Structure from Motion?

Structure from Motion (also known as Structure-and-Motion) has developed since the 1980s into a valuable tool for generating 3D models from 2D imagery, not least with the development of software with graphical user interfaces (GUIs). Full details of the SfM workflow are provided in Chapter 3 but are summarised briefly here. In contrast to traditional photogrammetry, SfM uses algorithms to identify matching features in a collection of overlapping digital images and calculates camera location and orientation from the differential positions of multiple matched features. Based on these calculations overlapping imagery can be used to reconstruct a "sparse" or "coarse" 3D point cloud model of the photographed object or surface or scene. This 3D model from the SfM method is usually refined to a much finer resolution using Multi-View Stereo (MVS) methods, thereby completing the full SfM-MVS workflow. Whilst there is prevailing practice in the geosciences literature to abbreviate this workflow simply to **SfM**, we herein use the SfM-MVS acronym to give clarity and precision to the workflow, and thus to champion rigorous practice in reflecting the different aspects of the full workflow. More details on the distinction between SfM and MVS are provided in Chapter 3.

In brief, the exciting and attractive properties of SfM-MVS are that it is cheap in both hardware and software requirements, is fast in comparison to other digital surveying in the field, and is a workflow that is virtually independent of spatial scale. Furthermore, SfM-MVS can produce a spatial density/resolution of survey points and 3D point accuracy that in some circumstances is comparable to that from modern terrestrial laser scanners. However, SfM-MVS is still in its infancy, especially in the geosciences, and as is explored in this book, more technical research needs to be done to understand the quality of data produced.

1.5 Structure of this Book

This book broadly comprises a critical commentary on the present usage of SfM-MVS alongside other digital surveying methods in the geosciences, an appraisal of the SfM-MVS workflow and data products, and a consideration of future developments of SfM-MVS that the geosciences could exploit.

All of the main chapters have boxes detailing **case studies**, and these have been contributed either by researchers invited for their particularly interesting and novel use of SfM-MVS in the geosciences, or else case studies have been provided by the authors of this book as examples of innovative use of SfM-MVS. All of the main chapters have hyperlinked text to relevant websites and online material. Some figures contain links to an interactive or animated version of that figure, or to an equivalent example online. All chapters have suggestions for further reading.

Specifically, Chapter 2 outlines the place of SfM-MVS in the geosciences in the context of other existing digital surveying methods via qualitative and graphical comparisons of advantages and disadvantages. The properties of the resulting data are compared quantitatively with those produced by other methods.

Chapter 3 presents a thorough outline of the SfM-MVS workflow. Technical details of each step in the SfM-MVS workflow are outlined to provide the reader with a greater understanding of how exactly the SfM-MVS method works. As such, Chapter 3 provides a useful stand-alone reference for geoscientists who wish to know more about SfM-MVS, without needing to delve into the computer vision literature. Steps in the described workflow include detection of corresponding features in multiple images, reconstruction of camera position, and derivation of a sparse point cloud, MVS to derive a dense point cloud, scaling and georeferencing, and optimisation.

Chapter 4 presents practical and logistical details that a practitioner would need to know before undertaking an SfM-MVS survey. As a flexible survey method, there are many choices to be made when designing a survey, with advantages and disadvantages to each choice. These decisions include, and thus this chapter compares, different cameras, platforms, processing software, point cloud viewers, and methods of constructing 2.5d terrain models (or digital elevation models (DEMs)) from point clouds, specifically filtering, decimation, surface interpolation/reconstruction, and surface rendering.

Whilst Chapter 2 focuses on a qualitative comparison with other digital survey methods, Chapter 5 presents a more quantitative analysis by summarising existing validation studies of SfM-MVS for the first time. Many SfM-MVS validation studies have emerged in the geosciences in recent years; however, each deploys a slightly different method, and there is little standardisation of such validation. This reflects that the use of SfM-MVS in the geosciences is still in its infancy. Synthesis of existing data provides useful indication of the achievable data quality given any particular SfM-MVS survey design and thus the potential of SfM-MVS in the geosciences.

Chapter 6 summarises the way in which SfM-MVS is being used in the geosciences today. A wide variety of applications have been found for this technique over a wide range of spatial and temporal scales and in many different environments. Current applications are reviewed, and key science questions being asked are examined. Several case studies have been chosen to emphasise the breadth and depth of contrasting applications of SfM-MVS in the geosciences.

Chapter 7 offers suggestions as to the potential development of SfM-MVS for the geosciences not only in terms of hardware and software but also in terms of whole avenues and themes of study yet to be explored. Chapter 7 discusses major project types that have yet to be exploited by the geosciences; namely, automatic detection, augmented reality, real-time mapping, and non-rigid SfM-MVS. The deliberate aim of Chapter 7 is not to look for incremental developments or simply for different applications. Rather, it is more ambitious, firstly examining developments in SfM-MVS in other disciplines and secondly using this information to suggest where the geosciences should look to develop itself.

Chapter 8 summarises the main outstanding areas of research identified in this book. Gaps in knowledge and potential future directions are indicated. Given the rapid development of SfM-MVS in the geosciences and the potential revolution it could bring to our discipline, these are exciting times indeed.

References

De Reu, J., Plets, G., Verhoeven, G. et al. (2013) Towards a three-dimensional cost-effective registration of the archaeological heritage. *Journal of Archaeological Science*, **40** (**2**), 1108–1121.

Koutsoudis, A., Vidmar, B., Ioannakis, G., Arnaoutoglou, F., Pavlidis, G. & Chamzas, C. (2014) Multi-image 3D reconstruction data evaluation. *Journal of Cultural Heritage*, **15** (**1**), 73–79.

Sutton, M., Rahman, I. & Garwood, R. (2014) *Techniques for Virtual Palaeontology*, p. 208. John Wiley & Sons, Inc., Hoboken, NJ.

2 The Place of Structure from Motion

A New Paradigm in Topographic Surveying?

Abstract

Three-dimensional (3D) spatial data on the form of the earth's surface are of paramount importance to geoscientists seeking to document the shape of landforms and to understand land-forming and natural hazard processes. Commonly, spatiotemporal information on landform changes is required. Therefore, advances in digital survey and sensor technology that address spatial and temporal constraints have created new opportunities to investigate the structure and dynamics of landform systems. Structure from Motion (SfM) represents the latest and a very significant advance in digital surveying. This chapter places SfM in the context of existing techniques, namely, total stations (TS), differential Global Positioning Systems (dGPS), photogrammetry, airborne laser scanning (ALS), and terrestrial laser scanning (TLS). TS points are surveyor determined and thus whilst slow to gather, they can be carefully selected to produce the most efficient representation of topography and are unlikely to include artefacts. GPS survey equipment can be cumbersome to transport by hand, it but does deliver spatial data in real-world coordinates and can gather thousands of points per hour. ALS is very expensive and only achieved on a campaign basis but does offer broader spatial coverage than ground-based methods, typically at 1–2 m point spacing. TLS can offer point spacing at millimetre scale and can include truly 3D information such as within cliff undercuts resulting in multiple surface levels at a single 2D coordinate. In comparison, Structure from Motion (SfM) is very cheap and fast, can offer truly 3D information, and with careful use of ground control points (GCPs) can rival other digital survey methods for spatial accuracy.

Keywords

topography; topographic survey; photogrammetry; global positioning system; LiDAR; laser scanning; total station; digital elevation model; point cloud

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