

Matthias Ehrhart

**Applications of image-assisted  
total stations: Concepts, experiments,  
results and calibration**

# Applications of image-assisted total stations: Concepts, experiments, results and calibration

Matthias Ehrhart

Dissertation

Graz University of Technology

Graz, October 2017

Series Editor

Werner Lienhart

Engineering Geodesy and Measurement Systems  
Graz University of Technology  
Steyrergasse 30, A-8010 Graz, Austria  
<http://www.igms.tugraz.at>

Previously published:

H. Hartinger, *Development of a Continuous Deformation Monitoring System using GPS*, 2001

A. Wieser, *Robust and fuzzy techniques for parameter estimation and quality assessment in GPS*, 2002

E. Grillmayer, *Untersuchungen systematischer Fehlereinflüsse bei Messungen mit dem Kreisel DMT Gyromat 2000*, 2002

H. Woschitz, *System Calibration of Digital Levels: Calibration Facility, Procedures and Results*, 2003

W. Lienhart, *Analysis of Inhomogeneous Structural Monitoring Data*, 2007

A. Lippitsch, *A Deformation Analysis Method for the Metrological ATLAS Cavern Network at CERN*, 2007

A. Wieser, *GPS based velocity estimation and its application to an odometer*, 2007

D. Wijaya, *Atmospheric correction formulae for space geodetic techniques*, 2010

K. Macheiner, *Development of a fiber optic tiltmeter for static and kinematic applications*, 2010

Engineering Geodesy – TU Graz

Matthias Ehrhart

**Applications of image-assisted total  
stations: Concepts, experiments,  
results and calibration**

Shaker Verlag  
Aachen 2017

**Bibliographic information published by the Deutsche Nationalbibliothek**

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <http://dnb.d-nb.de>.

Zugl.: Graz, Techn. Univ., Diss., 2017

This doctoral thesis was submitted to the Faculty of Mathematics, Physics and Geodesy at Graz University of Technology for achieving the academic degree of a Doctor of Technical Sciences (Dr.techn.).

Examination Committee:

First Examiner: Univ.-Prof. Dr.techn. Werner Lienhart  
Second Examiner: Prof. Dr.-Ing. habil. Thomas Wunderlich

Day of oral examination: December 18, 2017

Copyright Shaker Verlag 2017

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8440-5636-5  
ISSN 1864-2462

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen  
Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9  
Internet: [www.shaker.de](http://www.shaker.de) • e-mail: [info@shaker.de](mailto:info@shaker.de)

# *Abstract*

Today, different manufacturers of total stations equip their instruments with additional cameras which results in image-assisted total stations (IATSS). In contrast to the fully operational hardware of these instruments, the number of available applications which use the additional cameras for image-based measurements is still very limited.

To exploit the potential of these new instruments, different applications of IATSS are presented in this thesis. Along with the preparation of the required theory and the description of the used image processing algorithms, the individual applications are evaluated by experimental measurements with commercially available state-of-the-art IATSS under realistic environmental conditions.

The presented applications include static and dynamic deformation monitoring of civil engineering structures in which an IATSS serves as a contactless measurement system that does not require access to the monitored structure at any time. The image-based

measurements of an IATS are also used to tackle the correction of the vertical refraction angle which biases the vertical angle measurement of every total station. By measurements in a small-scale geodetic network, it is demonstrated that an IATS allows the determination of the coordinates of passive targets, such as simple printouts of a circle, with an accuracy of a few 0.01 mm. Furthermore, the image data of an IATS is used for the improvement of the conventional prism tracking with total stations in terms of robustness and seamless operation.

Besides these applications, also concepts for relating the image-based measurements to theodolite angles and for a thorough but fast and simple calibration of an IATS are presented.

# Zusammenfassung

Die Totalstationen verschiedener Hersteller sind heutzutage vielfach mit zusätzlichen Kameras ausgestattet und werden folglich als Video-Totalstationen (engl.: *image-assisted total station*, IATS) bezeichnet. Im Gegensatz zu den voll funktionsfähigen Kameras dieser Instrumente sind die verfügbaren Anwendungen für bildbasierte Messungen noch sehr limitiert.

Um das Potential dieser neuartigen Instrumente ausschöpfen zu können, werden in dieser Arbeit verschiedene Anwendungen von IATS vorgestellt. Neben der Aufbereitung der notwendigen theoretischen Grundlagen und der Beschreibung der verwendeten Algorithmen für die Bildverarbeitung, werden die Anwendungen durch experimentelle Messungen unter realistischen Bedingungen evaluiert. Dabei werden ausschließlich kommerziell erhältliche Standard-Instrumente verwendet.

Die vorgestellten Anwendungen beinhalten statische und dynamische Deformationsmessungen an Bauwerken wobei eine IATS

als kontaktloses Messsystem dient. Daraus folgt, dass Zugang zum überwachten Bauwerk zu keiner Zeit notwendig ist. Mithilfe der Messdaten einer IATS wird der Versuch unternommen, den Einfluss des vertikalen Refraktionswinkels, welcher die Ableitung genauer Höhenunterschiede aus Vertikalwinkelmessungen von Totalstationen beeinträchtigt, zu korrigieren. Durch Messungen in einem kleinräumigen geodätischen Netz wird gezeigt, dass eine IATS die Bestimmung der Koordinaten von passiven Zielen, wie z.B. Ausdrucken von Kreisen, mit einer Genauigkeit von wenigen 0.01 mm ermöglicht. Weiteres werden die Bilddaten einer IATS zur Verbesserung von Robustheit und Unterbrechungsfreiheit der automatischen Zielverfolgung mit Totalstationen verwendet.

Neben den genannten Anwendungen werden zudem Konzepte für die Berechnung von bildbasierten Theodolit-Richtungen sowie für die vollständige aber zugleich auch einfache und schnelle Kalibrierung einer IATS vorgestellt.

# *Acknowledgments*

I would like to thank Prof. Werner Lienhart for offering me the opportunity to write a doctoral thesis at his institute. I truly appreciate the trust he placed in me so that I could perform my research activities independently and focus on areas of my personal interest. Nevertheless, I also acknowledge the possibility to receive his input and feedback whenever needed.

I would further like to thank Prof. Thomas Wunderlich from TU Munich for the reviewing of this thesis as an external expert and also for his valuable comments.

Finally I express my gratitude to my colleagues at IGMS for the pleasant collaboration during the last years. Dr. Helmut Woschitz deserves special thanks for his input in different discussions and Prof. Fritz K. Brunner is mentioned for his indispensable help in the *Refraction* chapter of this thesis.

# Contents

<i>Abstract</i>	v
<i>Zusammenfassung</i>	vii
<i>Acknowledgments</i>	ix
<i>Symbols</i>	xv
<i>Acronyms</i>	xvii
<i>1 Introduction</i>	<i>1</i>
<i>1.1 Motivation</i>	<i>1</i>
<i>1.2 Outline of the thesis</i>	<i>3</i>
<i>1.3 State-of-the-art</i>	<i>4</i>
<i>1.3.1 Hardware and system specifications</i>	<i>4</i>
<i>1.3.2 Applications</i>	<i>11</i>
	<b>xi</b>

1.4	<i>Used instruments</i>	15
2	<i>Static and dynamic deformation monitoring</i>	19
2.1	<i>Introduction</i>	19
2.2	<i>Measurement concepts</i>	21
2.2.1	<i>Polar measurements</i>	21
2.2.2	<i>Stereo photogrammetry</i>	23
2.2.3	<i>Surface texturing</i>	24
2.3	<i>In-plane and out-of-plane measurements</i>	26
2.3.1	<i>Measurement geometries</i>	27
2.3.2	<i>Proposed measurement concept</i>	28
2.3.3	<i>Accuracy considerations</i>	34
2.4	<i>Measuring natural targets by feature matching</i>	38
2.4.1	<i>Feature matching</i>	39
2.4.2	<i>Sub-pixel refinement</i>	41
2.4.3	<i>Summary and relation to theodolite angles</i>	43
2.5	<i>Static deformation monitoring</i>	44
2.5.1	<i>Experiment description</i>	44
2.5.2	<i>Stability control</i>	48
2.5.3	<i>Results</i>	50
2.6	<i>Dynamic deformation monitoring</i>	55
2.6.1	<i>With favorable measurement geometry</i>	57
2.6.2	<i>With unfavorable measurement geometry</i>	62
2.7	<i>Conclusions</i>	72
3	<i>Refraction</i>	75
3.1	<i>Acknowledgments</i>	75
3.2	<i>Introduction</i>	76
3.2.1	<i>Related research</i>	78
3.3	<i>Measurement concept and theory</i>	81
3.3.1	<i>Basic considerations</i>	81
3.3.2	<i>Estimation of the vertical refraction angle</i>	82
3.4	<i>Experimental measurements</i>	85
3.4.1	<i>Experimental setup</i>	85

3.4.2	<i>Stability control</i>	85
3.4.3	<i>Measurement program</i>	88
3.4.4	<i>Preparation of measurement data</i>	91
3.4.5	<i>Experimental results</i>	92
3.5	<i>Conclusions and outlook</i>	95
4	<i>High-precision measurements</i>	99
4.1	<i>Introduction</i>	99
4.2	<i>Error sources</i>	100
4.2.1	<i>Insufficient calibration</i>	101
4.2.2	<i>Warm-up effects</i>	105
4.2.3	<i>Target specific errors</i>	110
4.3	<i>Experimental measurements</i>	119
4.3.1	<i>Experimental setup</i>	120
4.3.2	<i>Results</i>	122
4.4	<i>Conclusions</i>	129
5	<i>Object tracking</i>	133
5.1	<i>Introduction</i>	133
5.1.1	<i>State-of-the-art tracking techniques</i>	134
5.1.2	<i>Patents for visual tracking with total stations</i>	136
5.2	<i>Coarse search and target identification</i>	138
5.2.1	<i>Visual tracking</i>	139
5.2.2	<i>Theodolite angles to prism</i>	143
5.2.3	<i>Coarse search</i>	146
5.2.4	<i>Robust target tracking</i>	150
5.3	<i>Experimental measurements</i>	151
5.3.1	<i>Coarse search</i>	151
5.3.2	<i>Robust target tracking</i>	153
5.4	<i>Conclusions</i>	155
6	<i>Mapping relations</i>	159
6.1	<i>Introduction</i>	159
6.2	<i>Generic mapping relation</i>	160
6.2.1	<i>Involved coordinate systems</i>	160

6.2.2	<i>Image sensor and image system</i>	162
6.2.3	<i>Image and camera system</i>	165
6.2.4	<i>Camera and telescope system</i>	166
6.2.5	<i>Telescope and theodolite system</i>	168
6.2.6	<i>Summary of required parameters</i>	170
6.3	<i>Mapping relation for telescope camera</i>	170
6.3.1	<i>Alternative relation by gnomonic projection</i>	173
6.3.2	<i>Notes for practical use</i>	175
6.3.3	<i>Measurements in different telescope faces</i>	176
6.4	<i>Conclusions</i>	179
7	<i>Calibration</i>	181
7.1	<i>Introduction</i>	181
7.2	<i>Reported calibration approaches</i>	182
7.3	<i>Proposed calibration approach</i>	184
7.3.1	<i>Principal point</i>	185
7.3.2	<i>Camera constant, image rotation, distortion</i>	186
7.3.3	<i>Focus-dependent calibration</i>	191
7.3.4	<i>Rotation between different collimation axes</i>	192
7.3.5	<i>Fast recalibration</i>	195
7.3.6	<i>Notes for practical use</i>	196
7.4	<i>Calibration results</i>	198
7.5	<i>Verification of the calibration</i>	204
7.6	<i>Temporal stability</i>	208
7.7	<i>Conclusions</i>	212
8	<i>Summary and outlook</i>	213
	<i>References</i>	219