SUOMEN GEODEETTISEN LAITOKSEN JULKAISUJA
VERÖFFENTLICHUNGEN DES FINNISCHEN GEODÄTISCHEN INSTITUTES
PUBLICATIONS OF THE FINNISH GEODETIC INSTITUTE

N:o 152

BENCHMARKING OF AIRBORNE LASER SCANNING BASED FEATURE EXTRACTION METHODS AND MOBILE LASER SCANNING SYSTEM PERFORMANCE BASED ON HIGH-QUALITY TEST FIELDS

by

Harri Kaartinen

SUOMEN GEODEETTISEN LAITOKSEN JULKAISUJA
VERÖFFENTLICHUNGEN DES FINNISCHEN GEODÄTISCHEN INSTITUTES
PUBLICATIONS OF THE FINNISH GEODETIC INSTITUTE

N:o 152

Benchmarking of airborne laser scanning based feature extraction methods and mobile laser scanning system performance based on high-quality test fields

by

Harri Kaartinen

Doctoral dissertation for the degree of Doctor of Science in Technology to be presented with due permission of the School of Engineering for public examination and debate in Auditorium E at the Aalto University School of Science (Espoo, Finland) on the 11th of November 2013 at 3 PM.

KIRKKONUMMI 2013

Supervising professor
Professor Henrik Haggrén, Aalto University School of Engineering, Department of Real Estate, Planning and Geoinformatics

Thesis advisor
Professor Juha Hyyppä, Finnish Geodetic Institute, Department of Remote Sensing and Photogrammetry

Preliminary examiners
Professor Dr.-Ing. Norbert Haala, University of Stuttgart, Institute for Photogrammetry, Germany

Associate Professor (Docent) PhD Johan Holmgren, Swedish University of Agricultural Sciences, Department of Forest Resource Management, Sweden

Opponent
Professor Wolfgang Wagner, Vienna University of Technology, Department of Geodesy and Geoinformation, Austria

ISBN (printed): 978-951-711-304-5
ISBN (pdf): 978-951-711-305-2
ISSN: 0085-6932

Tammerprint Oy, 2013

Aalto University
School of Engineering

Abstract

Author
Harri Kaartinen

Title of the doctoral dissertation
Benchmarking of airborne laser scanning based feature extraction methods and mobile laser scanning system performance based on high-quality test fields

Unit Department of Real Estate, Planning and Geoinformatics

Publisher Finnish Geodetic Institute

Series Publications of the Finnish Geodetic Institute

Field of research Remote Sensing

Manuscript submitted 2 April 2013 **Date of the defense** 11 November 2013

Permission to publish granted (date) 26 June 2013 **Language** English

Article dissertation (summary + original articles)

Abstract

Comparing different feature extraction methods based on remote sensing or remote sensing systems is difficult as there are but few common data sets or test fields with reference data of high standard available for analysis. State-of-the-art methods and systems are often in still evolving stage and can be run only by the developers themselves. Establishing a high-quality test field is laborious, but once such a test field has been established, it becomes easier to set up the systems to collect data from the field than to collect reference data from new areas. Comparing either different systems or the same system with different parameters is easier when the number of variables is kept to a minimum; the remotely sensed areas are kept constant and any changes in them can be controlled more easily. The benchmarking results provide valuable information to both developers and users of remote sensing data products.

The benchmarked feature extraction methods studied included extraction of buildings and individual trees using data from common test fields. The performance of the mobile laser scanning systems was benchmarked using data collected from an established urban test field. In all cases, it was concluded that the primary factor affecting the results was the method or the system, and this enabled a high degree of comparability for the results of the given extraction or mapping tasks.

Keywords benchmarking, test field, laser scanning, aerial image, building extraction, tree extraction, mapping, mobile, 3D, accuracy, performance, GNSS/INS, reference data, systems, point cloud, geometric

ISBN (printed) 978-951-711-304-5 **ISBN (pdf)** 978-951-711-305-2

ISSN 0085-6932

Location of publisher Kirkkonummi **Location of printing** Tampere **Year** 2013

Pages 346 **urn** http://urn.fi/URN:ISBN: 978-951-711-305-2

Aalto-yliopisto
Insinööritieteiden
korkeakoulu

Tiivistelmä

Tekijä
Harri Kaartinen

Väitöskirjan nimi
Ilmalaserkeilaukseen perustuvien kohdemallinnusmenetelmien ja liikkuvien laserkeilausjärjestelmien suorituskyvyn vertailu tarkkoja testikenttiä käyttäen

Yksikkö Maankäyttötieteiden laitos
Julkaisija Geodeettinen laitos
Sarja Suomen Geodeettisen laitoksen julkaisuja
Tutkimusala Kaukokartoitus
Käsikirjoituksen pvm 2.4.2013 **Väitöspäivä** 11.11.2013
Julkaisuluvan myöntämispäivä 26.6.2013 **Kieli** Englanti
Yhdistelmäväitöskirja (yhteenveto-osa + erillisartikkelit)

Tiivistelmä

Erilaisten kaukokartoitukseen perustuvien kohdemallinnusmenetelmien tai kaukokartoitus-järjestelmien vertailu on vaikeaa koska yhteisesti käytettävissä olevia aineistoja tai testikenttiä, joista on saatavissa korkealaatuista referenssiaineistoa, on olemassa vain vähän. Uusimmat menetelmät ja järjestelmät ovat usein vielä kehitysvaiheessa ja niiden käyttö onnistuu vain niiden kehittäjiltä. Korkealaatuisen testikentän tekeminen on työlästä, mutta kun testikenttä on perustettu, on helpompaa kerätä aineistoja siltä eri järjestelmillä kuin mitata referenssiaineistoa uusilta alueilta. Eri järjestelmien tai yhden järjestelmän eri asetuksien vertailu on helpompaa kun muuttujien määrä on mahdollisimman pieni; tässä tapauksessa kaukokartoitetut alueet pysyvät vakiona ja mahdolliset muutokset niissä ovat helpommin kontrolloitavissa. Vertailujen tulokset antavat hyödyllistä tietoa sekä kaukokartoitustuotteiden kehittäjille että niiden käyttäjille.

Vertaillut kohdemallinnusmenetelmät olivat rakennusten ja yksittäisten puiden mallinnus yhteisiltä testikentiltä kerättyjä aineistoja käyttäen. Liikkuvien laserkeilausjärjestelmien suorituskykyä vertailtiin käyttäen perustetulta kaupunkitestikentältä kerättyjä aineistoja. Kaikissa tapauksissa todettiin että tärkein tuloksiin vaikuttava tekijä oli menetelmä tai järjestelmä itse, joten annetun mallinnus- tai kartoitustehtävän tulokset ovat hyvin vertailukelpoisia.

Avainsanat vertailu, testikenttä, laserkeilaus, ilmakuva, rakennusmallinnus, puumallinnus, kartoitus, liikkuva, 3D, tarkkuus, suorituskyky, GNSS/INS, referenssiaineisto, järjestelmät, pistepilvi, geometrinen

ISBN (painettu) 978-951-711-304-5 **ISBN (pdf)** 978-951-711-305-2
ISSN 0085-6932
Julkaisupaikka Kirkkonummi **Painopaikka** Tampere **Vuosi** 2013
Sivumäärä 346 **urn** http://urn.fi/URN:ISBN: 978-951-711-305-2

PREFACE

This thesis sums up a large part of my work at the Finnish Geodetic Institute (FGI) during the past ten years. During this time FGI coordinated three international European Spatial Data Research (EuroSDR) projects, the results of which are compiled here. Without the help and support of my advisor, Professor Juha Hyyppä, the head of Remote Sensing and Photogrammetry Department of FGI, probably neither this thesis nor the projects would have ever seen the light of day. I wish to thank Juha for this and for the motivation and understanding also in a larger scale. I'm also grateful for my supervisor, Professor Henrik Haggrén, Aalto University, for his gentle guidance. Working with Henrik and Juha makes me feel that I can work on my own but certainly not alone. I made almost the same statement in my Licentiate's thesis, but it is even more true now after almost six more years of co-operation, which has led to the preparation of this thesis.

I'm also grateful to Norbert Haala and Johan Holmgren, the pre-examiners of this thesis, for their effort, kind words and constructive criticism in pointing out the strong and weak points in the manuscript. I'm sure that their comments have helped to improve this thesis and, hopefully, my future publications as well.

I would also like to thank all partners taking part in the projects of this study, including: George Vosselman, Alexandra Hofmann, Urs Mäder, Åsa Persson, Ulf Söderman, Magnus Elmqvist, Antonio Ruiz, Martina Dragoja, Sylvain Airault, David Flamanc, Gregoire Maillet, Thomas Kersten, Jennifer Carl, Robert Hau, Emil Wild, Lise Lausten Frederiksen, Jane Holmgaard, Kristian Vester, Eberhard Gülch, Iris Lingenfelder, François Gougeon, Aiko Sukdolak, Bernd-Michael Wolf, Christian Heipke, Manuela Hirschmugl, Juho Pitkänen, Svein Solberg, Erik Næsset, Jee-cheng Wu, Sorin Popescu, Felix Morsdorf, Roeland de Kok, Piotr Wezyk, Andrea Barilotti, Francesco Sepic, Gerald Zach, Iain Lorraine, Halvor Holvik, Morten Taraldsten Brunes, Heikki Luukkonen and Jan Biström. All are gratefully acknowledged for their cooperation. Eberhard and François made significant contribution to the planning of the projects. Support of MATIS IGN, Espoo and Helsinki City Survey Divisions, Blom Kartta Oy, Terrasolid Oy, RIEGL Laser Measurement Systems GmbH and 3D Laser Mapping Ltd. in providing data for the projects is gratefully acknowledged.

In addition to the partners of the projects, valuable inputs were needed from other co-authors in analysing and reporting the results. Many experts and colleagues have my gratitude and respect, including Hannu Hyyppä from Aalto University and Helsinki Metropolia University of Applied Sciences, Markus Holopainen and Mikko Vastaranta from Helsinki University, Matti Vaaja from Aalto University and Leena Matikainen, Antero Kukko, Anttoni Jaakkola and Matti Lehtomäki from FGI. Especially, I wish to thank Hannu for his contribution to my studies and Antero, my `brother-in-arms´, for great liaison. Xinlian Liang from FGI also made significant contributions especially in the tree extraction project.

To my friends and colleagues at FGI: thank you for all your help and support during my 17 years at FGI. Risto Kuittinen and Eija Honkavaara employed me originally for four months but it has somewhat prolonged since… With Mika Karjalainen, Jaakko Kähkönen and Eero Ahokas I have had several years of collaboration both personally and professionally. Whenever a question arises, and if has happened often, an answer can usually be found from someone within our four departments or the administration. Most often I have knocked on the door of Pasi Häkli, Hannu Koivula, Juha Oksanen, Petteri Kangas and Pirjo Kivirasi, just to name a few. A full list can be found in the past and present FGI phone directories… I wish I have been or will be able to return the many favours I have received.

The co-operation with the people working for EuroSDR has been fluent, and especially the efforts of Kevin Mooney and Andreas Busch have been priceless in preparing the manuscripts for printing.

Family and friends, I'm truly thankful for your love and support. Always.

Helsinki, October 2013
Harri Kaartinen

The development and research undertakings presented in this thesis have been funded by several different agencies and linked to many projects, such as the following:

- *Academy of Finland through the projects "Novel map updating", "Towards Improved Characterization of Map Objects", "Transportation Data Acquisition by Means of ICT-derived 3D Modelling", "Improving the Forest Supply Chain by means of Advanced Laser Measurements", "Science and Technology Towards Precision Forestry", "Economy and Technology of a Global Peer-produced 3D Geographical Information System in Built Environment - 3DGIS" and "Interaction of Lidar/Radar Beams with Forests Using Mini-UAV and Mobile Forest Tomography".*
- *Finnish Funding Agency for Technology and Innovation (Tekes) through projects "Quality of laser scanning, especially in urban environments" and "Development of Automatic, Detailed 3D Model Algorithms for Forests and Built Environment"*
- *EuroSDR projects "Evaluation of Building Extraction" and "Mobile Mapping - Road Environment Mapping using Mobile Laser Scanning"*
- *EuroSDR/ISPRS project "Tree Extraction"*

CONTENTS

ABSTRACT 3
TIIVISTELMÄ...5
PREFACE..7
CONTENTS 9
LIST OF PUBLICATIONS 10
AUTHOR'S CONTRIBUTION 11
LIST OF ABBREVIATIONS 13
1 INTRODUCTION 15
  1.1 Motivation 15
  1.2 Hypothesis 16
  1.3 Objectives of the study 17
  1.4 Structure of thesis 17
  1.5 Contribution 17
2 REVIEW 19
  2.1 A brief overview of laser scanning and photogrammetry 19
  2.2 State-of-the-art in building extraction 19
  2.3 State-of-the-art in tree extraction 20
  2.4 State-of-the-art in mobile laser scanning system performance 21
3 MATERIALS AND METHODS 23
  3.1 Test fields 23
  3.2 Data sets 23
  3.3 Reference data 25
  3.4 Benchmarked methods and systems 25
  3.5 Methods used for benchmarking methods and systems 30
4 RESULTS 33
  4.1 Building extraction benchmarking results 33
  4.2 Tree extraction benchmarking results 34
  4.3 Mobile laser scanning system benchmarking results 37
5 DISCUSSION 41
  5.1 Building extraction 41
  5.2 Tree extraction 42
  5.3 Mobile laser scanning 45
  5.4 Test fields 46
6 SUMMARY AND CONCLUSIONS 48
REFERENCES 50
ERRATA 58

LIST OF PUBLICATIONS

This thesis is based on the following publications, referred to in the text by their Roman numerals:

I. Kaartinen, H., Hyyppä, J., Gülch, E., Vosselman, G., Hyyppä, H., Matikainen, L., Hofmann, A.D., Mäder, U., Persson, Å., Söderman, U., Elmqvist, M., Ruiz, A., Dragoja, M., Flamanc, D., Maillet, G., Kersten, T., Carl, J., Hau, R., Wild, E., Frederiksen, L., Holmgaard, J. and Vester, K., 2005. Accuracy of 3D city models: EuroSDR comparison. Proceedings of ISPRS Workshop "Laser scanning 2005", September 12-14, 2005, Enschede, The Netherlands, *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXVI(Part 3/W19), 227-232, CD-ROM.

II. Kaartinen, H. and Hyyppä, J., 2006. EuroSDR-Project Commission 3 "Evaluation of Building Extraction", Final Report, In: EuroSDR - European Spatial Data Research, Official Publication No 50, 9-77.

III. Kaartinen, H. and Hyyppä, J., 2008. EuroSDR/ISPRS Project, Commission II "Tree Extraction", Final Report, EuroSDR – European Spatial Data Research, Official Publication No 53, 56 p.

IV. Kaartinen, H., Hyyppä, J., Yu, X., Vastaranta, M., Hyyppä, H., Kukko, A., Holopainen, M., Heipke, C., Hirschmugl, M., Morsdorf, F., Næsset, E., Pitkänen, J., Popescu, S., Solberg, S., Wolf, B.M. and Wu, J.-C., 2012. An International Comparison of Individual Tree Detection and Extraction Using Airborne Laser Scanning. *Remote Sensing*, 4(4), 950-974.

V. Kaartinen, H., Hyyppä, J., Kukko, A., Jaakkola, A. and Hyyppä, H., 2012. Benchmarking the Performance of Mobile Laser Scanning Systems Using a Permanent Test Field. *Sensors* 12(9), 12814-12835.

VI. Kaartinen, H., Hyyppä, J., Kukko, A., Lehtomäki, M., Jaakkola, A., Hyyppä, H., Vosselman,G., Elberink, S.O., Rutzinger; M., Pu, S. and Vaaja, M., 2013. EuroSDR-Project Commission II "Mobile Mapping - Road Environment Mapping using Mobile Laser Scanning", Final Report, In: EuroSDR - European Spatial Data Research, Official Publication No 62, 49-95.

I is peer-reviewed conference article, the other publications are peer-reviewed journal articles.

AUTHOR’S CONTRIBUTION

In **Publication I**, the author’s responsibilities were to select the three Finnish test sites for the project together with Juha Hyyppä, to prepare the test data to be delivered to project participants, to collect the reference data from the Finnish test sites, and to analyse the extracted building models delivered by the project participants. Juha Hyyppä was the advisor in the study and he participated in the planning of the project and analysing the results. Eberhard Gülch, George Vosselman, Hannu Hyyppä and Leena Matikainen contributed on the project planning and analysis. Alexandra Hofmann, Urs Mäder, Åsa Persson, Ulf Söderman, Magnus Elmqvist, Antonio Ruiz, Martina Dragoja, David Flamanc, Gregoire Maillet, Thomas Kersten, Jennifer Carl, Robert Hau, Emil Wild, Lise Lausten Frederiksen, Jane Holmgaard and Kristian Vester delivered the method descriptions for the benchmarked methods.

In **Publication II**, a continuation of the study, whose results were first presented in **Publication I**, the author’s responsibilities included the further analysis of the building extraction results. Juha Hyyppä was the advisor in the study and he participated in analysing the results.

In **Publication III**, the author’s responsibilities were to select the test site for the project, to prepare the test data to be delivered to project participants, to collect the reference data, and to analyse the extracted tree models delivered by the project participants. Juha Hyyppä was the advisor in the study and he participated in the planning of the project and analysing the results.

Publication IV is a continuation of the study, whose results were first presented in **Publication III**. The author’s responsibilities included the further analysis of the tree extraction results based on airborne laser scanning and of four new methods developed at the Finnish Geodetic Institute (FGI). Juha Hyyppä was the advisor in the study and he participated in analysing the results. Xiaowei Yu processed the FGI tree models and wrote the descriptions of the methods. Mikko Vastaranta, Hannu Hyyppä, Antero Kukko and Markus Holopainen participated in analysing the results. Christian Heipke, Manuela Hirschmugl, Felix Morsdorf, Erik Næsset, Juho Pitkänen, Sorin Popescu, Svein Solberg, Bernd-Michael Wolf (né Straub), and Jee-cheng Wu delivered the method descriptions for the benchmarked methods.

In **Publication V**, the author’s responsibilities were to select the location of the test field for mobile laser scanning, to collect the reference data together with Antero Kukko and Anttoni Jaakkola, and to analyse the performance of the mobile laser scanning systems that were used to collect data from the test field. Juha Hyyppä and Hannu Hyyppä were the advisors in the study and they participated in the planning of the project. Juha Hyyppä, Antero Kukko and Anttoni Jaakkola also participated in analysing the results.

Publication VI is a continuation of the study, whose results were first presented in **Publication V**. In addition to **Publication V**, the author's responsibilities included conducting the reference measurements for pole extraction analysis together with Matti Lehtomäki and analysing the results of facade extraction. Matti Lehtomäki developed, documented, and tested the pole extraction algorithm developed at FGI. George Vosselman, Sander Oude Elberink, Martin Rutzinger, and Shi Pu developed and wrote the descriptions of the methods used at the University of Twente, Faculty of Geo-Information Science and Earth Observation, for pole extraction and facade classification using mobile laser scanning data. Matti Vaaja participated in analysing the results.

LIST OF ABBREVIATIONS

ABA	Area-based approach
ALS	Airborne laser scanning
CHM	Canopy height model
CIR	Colour infrared
DEM	Digital elevation model
DSM	Digital surface model
EuroSDR	European Spatial Data Research Organisation
FGI	Finnish Geodetic Institute
FOI	Swedish Defense Research Agency
GCP	Ground control point
GSD	Ground sampling distance
ICC	Institut Cartografic de Catalunya
IGN	Institut Geographique National
IQR	Inter-quartile range
ISPRS	International Society for Photogrammetry and Remote Sensing
ITC	University of Twente, Faculty of Geo-Information Science and Earth Observation
ITD	Individual tree detection
LiDAR	Light Detection and Ranging
MLS	Mobile laser scanning
NIR	Near-infrared
OEEPE	Organisation Européene d'Etudes Photogrammétriques Expérimentales
RGB	Red-green-blue
RMSE	Root mean square error
STD	Standard deviation
SWFI	Standwise field inventory
TLS	Terrestrial laser scanning
2D	2-dimensional
3D	3-dimensional

1 INTRODUCTION

1.1 Motivation

A permanent test field for airborne photogrammetric systems was established by the Finnish Geodetic Institute (FGI) in 1994 (Honkavaara et al., 2008). The Sjökulla, present name Metsähovi, test field includes targets for the calibration of airborne camera geometry and radiometry. It played an important role in the work done to verify the performance of modern digital aerial photogrammetric systems (Honkavaara et al., 2006). Similar benchmarking activity in the field of forestry-related remote sensing was carried out in Kalkkinen, southern Finland. In Hyyppä et al. (2000) and Hyyppä and Hyyppä (2000) it was shown that height-related information from either profiling radar or laser scanner was superior to the information obtained from other remote sensing data sources when extracting standwise forest information. Prior to these studies, it was assumed by foresters that diameter is the primary parameter to be extracted by remote sensing data (Kalliovirta and Tokola, 2005).

In remote sensing, benchmarking is used to measure the performance of a remote sensing data source, process or method using a specific test site and quality indicators resulting in a metric of performance that is then compared to other data sources or methods. Typically, it is difficult to perform good benchmarking of state-of-the-art methods, since only the developer of the method can process the data in full detail. Therefore, many benchmarking studies are international efforts and organized by international organizations such as the International Society for Photogrammetry and Remote Sensing (ISPRS) and the European Spatial Data Research Organisation (EuroSDR, formerly OEEPE, Organisation Européene d'Etudes Photogrammétriques Expérimentales / European Organisation for Experimental Photogrammetric Research). As regards computer vision, some benchmarking platforms have been automated such that the developers of the methods can load the results into a system automatically yielding quality metrics of the method versus other methods, e.g., Arbeláez (2011).

ISPRS conducted an experimental comparison of filtering algorithms for ground extraction using airborne laser scanning data providing a concept of usable filtering techniques in various conditions (Sithole and Vosselman, 2004). The building extraction comparison, initiated in 2004 by EuroSDR and hosted by the FGI, was the first joint study utilizing common airborne image and laser scanning data sets for benchmarking of feature extraction methods (Publications **I** and **II**). This was then followed by, for example, road extraction using airborne and optical satellite images (Mayer et al., 2006), a tree extraction comparison (Publications **III** and **IV**), and automated updating of maps (Champion, 2009). ISPRS has distributed remote sensing data together with reference data for benchmarking and quality analysis of digital elevation models (DEMs) generated from high resolution and very high resolution optical stereo satellite data (Reinartz et al., 2010).

Test site characteristics may dominate in the evaluation of remote sensing data. For example, it is common practise to evaluate new remote sensing methods in a test field and then to compare the results obtainable from other works as reported in scientific literature. Since test site and data analysis characteristics are different, it is possible to draw wrong conclusions. In Hyyppä and Hyyppä (2001), it was shown that stand size in forest inventory can be effectively used to modify the precision of the results. Especially studies, in which stands below a certain threshold size were rejected, the improved performance exaggerated the real output of the method.

Benchmarking activities in the field of remote sensing should be based on high-quality reference data. Modern mapping systems provide data fixed to the global coordinate system and data quality is constantly improving. In the past, reference data were mainly based on good relative accuracy; for example, the positioning of the trees was only tied to the corners of the forest test plots. Experience gained in past research, together with the afore mentioned photogrammetric test field, provided justification for testing and developing high-quality test fields also for other remote sensing applications and to use these test fields for international benchmarking of methods and systems. Empirically, the benefits, and properties, of high-quality test fields were found to be as follows:

- Validated reference data could be more easily measured and updated by using a rigid network of ground control points.
- Once a test field was established, it became easier to make the systems collect data from it than to collect reference data from new areas.
- Comparing either different systems or the same system with different parameters became easier when the number of variables was kept to a minimum; the remotely sensed areas are kept constant and possible changes in them can be controlled more easily.

1.2 Hypothesis

The hypothesis in this thesis is that high-quality test fields and common data sets enhance the comparability and the benchmarking capability of the performance metrics of different remote sensing methods and systems.

1.3 Objectives of the study

The main objective in this thesis was to set up high-quality test fields, perform international benchmarking studies using these test fields, and to contribute new knowledge based on the benchmarking studies. Both the built environment and forests were included as application areas.

The detailed sub-objectives of the study were to use high-quality test field data for the following purposes:

- International benchmarking of building extraction methods using photogrammetry and airborne laser scanning.
- International benchmarking of individual tree extraction methods using photogrammetry and airborne laser scanning.
- International benchmarking of mobile laser scanning system performance in road-side environments.

1.4 Structure of thesis

Section 1 gives the motivation, hypothesis, objectives and contribution of the study. In Section 2 a review of the study subject is given. In Section 3 the used materials and methods are described and Section 4 gives the results achieved in the study. In Section 5 the results are discussed. Section 6 summarises and concludes the study.

1.5 Contribution

Considering the objectives of the study, the contribution of the original publications of the thesis may be summarized as follows:

Publications **I** and **II** present summaries of the EuroSDR Building Extraction comparison, which was initiated as a consequence of the rapid development of sensors and methods in the field of laser scanning and photogrammetry. The objective of the project “Evaluation of Building Extraction” (2004-2006) was to evaluate the quality, accuracy, feasibility, and economic aspects of semi-automatic building extraction based on photogrammetric techniques with the emphasis on commercial and operative systems, semi-automatic and automatic building extraction techniques based on high-density laser scanner data, and semi-automatic and automatic building extraction techniques based on the integration of laser scanner data and aerial images. No studies could be found on testing the performance of different automated building extraction methods using common data sets prior to this study. The author of the thesis acted as the project manager (principal investigator Juha Hyyppä) in the conducting of this international test.

Prior to Publications **III** and **IV**, it was not known how much of the variation in individual tree extraction methods was caused by the methods and how much by the forest conditions. In the EuroSDR/ISPRS project “Tree Extraction” (2005-2008), twelve participants around the world extracted trees in given forest test sites. The objectives included studying the accuracy and feasibility of various methods using the same test data, and finding out how pulse density impacts on individual tree extraction. The author of the thesis acted as the project manager (principal investigator Juha Hyyppä) in the conducting of this international test.

Mobile laser scanning (MLS) systems providing dense point clouds have been commercially available since 2007-2008. Most of the commercially available MLS systems were tested in an established test field in the course of the EuroSDR project “Mobile Mapping - Road Environment Mapping using Mobile Laser Scanning” (2009-2012). Some algorithmic benchmarking was also carried out. Publications **V** and **VI** report the findings of these tests. The author of the thesis acted as the project manager (principal investigator Juha Hyyppä) in the conducting of this international test.

2 REVIEW

2.1 A brief overview of laser scanning and photogrammetry

Laser scanning is a surveying technique used in mapping topography, vegetation, urban areas, and other targets of interest. More precisely, airborne laser scanning (ALS) is a method based on Light Detection and Ranging (LiDAR) measurements made from an aircraft, requiring knowledge of the precise location and orientation of the sensor, and this means that the 3D coordinates of the reflecting objects can be determined. In addition to ALS, there is increasing interest being shown towards terrestrial laser scanning (TLS), a method in which a laser scanner is mounted on a tripod, and MLS, a method in which a laser scanner is mounted on a moving platform. Laser scanning is sometimes referred to as LiDAR because of its central role. The basic principle of LiDAR is to use a laser to illuminate an object and a photodiode to register the backscattered radiation and to measure the range. The output of the laser scanning is then a georeferenced point cloud of LiDAR measurements, i.e. points with x, y and z coordinates in local coordinate system, including the intensity and possibly waveform information of the returned light. More information on laser scanning can be found from, e.g., Shan and Toth, 2009 and Vosselman and Maas, 2010.

Photogrammetry is the practice of determining the geometric properties of objects from images. 3D data from 2D images can be measured using stereo-imagery interpretation or multi-imagery block adjustment. If the topography of the object is known, this measurement can also be done from one image by monoplotting (single-ray back projection). This topography can be obtained by means of laser scanning, for example. Nowadays, photogrammetry is based on digital images. The radiometry of digital imagery is utilised by methods developed in the field of remote sensing. Thus, modern photogrammetric processes, in addition to geometry derivation, include elements of remote sensing techniques. More information on photogrammetry can be found from, e.g., McGlone, 2013.

Digital aerial photogrammetry allows the accurate measurement of single, prominent points and structures, whereas laser scanning is able to provide dense 3D point clouds, which make the integration of automated processes easier. The main drawback of laser scanning is that it samples the target in some fixed pattern, it cannot point to particular objects directly as is the case with photogrammetry. (Brenner, 2005.)

2.2 State-of-the-art in building extraction

Due to the development of scanning systems and improvements in the accuracy of direct georeferencing, ALS became a feasible technology for providing range data in the early 1990s. At that time, ALS was already considered to be a mature technology (Baltsavias, 1999). ALS provides dense point clouds with 3D coordinates, and this makes range data segmentation relatively easy (Brenner, 2005).

The integration of laser point clouds and photogrammetric processes with aerial photos also provides new technological solutions. By combining the good elevation assessment accuracy of a laser scanner and good planimetric accuracy of aerial images, both high accuracy and higher degree of automation can, in theory, be obtained. However, despite the progress made in integrating laser scanning systems and digital images, automated processing of the resulting datasets is still at an early stage of research (Brenner, 2005).

Approaches to building extraction using laser scanner data make use of either laser scanner data as is (point clouds) or regularised data in raster or grid format. Whereas automatic building extraction methods based on aerial imagery typically concentrate on finding edges (Haala, 1996; Henricsson and Baltsavias, 1997; Baillard and Zisserman, 1999; Süveg and Vosselman, 2004), methods based on laser scanner data typically concentrate on finding planes (Vosselman, 1999), and edges are detected either as plane intersections (Brenner, 2000), height jump edges in DSM (Rottersteiner and Briese, 2003) or they are provided as additional data (ground plans) (Brenner and Haala, 1998; Hofmann et al., 2003). Therefore, there is good justification for the development of hybrid systems integrating the power of edge detection of aerial imagery and plane determination accuracy of laser scanner data (TerraSolid, 2003). This is becoming increasingly evident as digital cameras are made integral parts of modern-day laser scanning systems (Brenner, 2005). Aerial images can also be utilised in creating realistic surface textures for modelled buildings and in yielding additional information for laser scanner data interpretation (TerraSolid, 2003).

Prior to Publications **I** and **II** no studies could be found on testing the performance of different automated building extraction methods using common data sets. The present study was also initiated with the purpose of addressing this need.

2.3 State-of-the-art in tree extraction

ALS in the field of forestry was first applied in the estimation of standwise mean height and volume (Næsset, 1997a and 1997b: Hyyppä and Hyyppä, 1999) using the data collected by the means of ranging measurements. Very soon ALS was applied to forest inventorying, focusing on individual trees (Hyyppä and Inkinen, 1999; Brandtberg, 1999; Ziegler et al., 2000; Hyyppä et al., 2001) and then, with the advent of rapid image processing, to tree species classification (Brandtberg, 2003; Holmgren and Persson, 2004) and the measurement of tree growth and detection of harvested trees (Yu et al., 2004) based on bi-temporal data sets. The extraction of forest variables is divided into two categories: area-based inventories and inventories based on individual trees or groups of trees. In addition to being used in forest inventories, ALS data from forested areas is used for purposes such as flight obstacle mapping, power line mapping, virtual city visualisation and mapping, and telecommunication planning.

Hyyppä and Inkinen (1999) presented the basic ALS-based individual tree detection (ITD) approach in which the location, tree height, crown diameter, and species of individual trees are derived using laser technology, possibly in combination with aerial image data, especially in the case of tree species classification, and then other important variables, such as stem diameter, basal area and stem volume, are derived using existing models. The methods were tested in coniferous forests in Finland, Austria, and Germany, with the result that 40% to 50% of the trees could be correctly segmented (Hyyppä et al. 2001). Persson et al. (2002) improved crown delineation and were able to link 71% of the tree heights with the reference trees. Tree detection accuracy results from heterogeneous forests are presented in Pitkänen et al. (2004), who obtained a detection accuracy of only 40% (but 70% for dominant trees). Peuhkurinen et al. (2007) carried out ITD in two marked stands (density ~465 stems per ha). The number of harvestable trees was underestimated by only <3%, but this result was believed to include some commission errors, i.e. a single tree being segmented into several segments, and thus increasing the number of detected trees. Falkowski et al. (2008) tested two different algorithms in stands with varying canopy cover density and showed that across a full range of canopy conditions in a mixed-species, structurally diverse conifer forest in northern Idaho, United States, canopy cover density has significant impact on tree detection accuracy.

Prior to Publications **III** and **IV**, the study conducted by Hyyppä et al. (2001) provided the only reference analysis of the performance of different automated individual tree extraction methods tested using common data sets. Since the topic of forest inventory based on individual tree using laser scanning was reported on for first time by Hyyppä and Inkinen (1999), the need to initiate international testing focusing on state-of-the-art tree extraction methods arose in 2005.

2.4 State-of-the-art in mobile laser scanning system performance

An increasing amount of research is being conducted on mobile laser scanning (MLS) systems (e.g. Geomobil (Institut Cartografic de Catalunya (ICC)), GeoMaster (University of Tokyo), Lara-3D (Ecoles des Mines de Paris), ROAMER and Sensei (FGI)), and commercial and custom-made systems (e.g. Optech Lynx Mobile Mapper, Streetmappers of 3D Laser Mapping based on RIEGL scanners, Mitsubishi using SICK LMS 291 scanners, RIEGL VMX-250 integrating two RIEGL VQ-250 scanners, Topcon's systems for Google IP-S2 having three SICK LMS 291 scanners, Trimble Trident-3D based on SICK and RIEGL scanners (Petrie, 2010), Trimble MX8 and RIEGL VMX-450). Mobile laser scanning systems are being developed both in the field of robotics and surveying. A more complete list of these systems is presented in Petrie (2010) and Narayana (2011).

The accuracy of MLS is limited mainly by the signal degradation of the global navigation satellite system (GNSS) in urban and forest-covered environments. This disadvantage of GNSS can be partly corrected by appropriate data fusion between the GNSS, the inertial measurement unit (IMU), and the odometer. The most common data fusion solution is to use Kalman filter of different flavours (Mohamed and Schwarz, 1999; Mostafa and Hutton, 2001).

Prior to Publications **V** and **VI**, there have been only a few studies that have comprehensively focused on MLS in combination with test fields. System manufacturers have carried out and published their own tests, e.g. Mano et al. (2012), but only a few publications exist addressing system performance using an established high-quality test field and having had the results have analysed by an independent actor. Barber et al. (2008) used RTK-GPS measurements to collect reference data on two test sites to validate the geometric accuracy of the Streetmapper MLS system. The main focus then was on elevation accuracy, and only a few control points, measured on white line markings made on the road surface, were used for analysing planimetric accuracy. Researchers at the University of California at Davis, United States, used total station and static TLS data to analyse the accuracy of MLS systems (Streetmapper 360, Optech Lynx and Ambercore Titan) when producing digital terrain models of pavement surfaces (Yen et al., 2010). Elevation accuracy was then the only subject of concern.

Haala et al. (2008) demonstrated that the StreetMapper system could produce dense 3D measurements with an accuracy of 30 mm in good GNSS conditions. Further, it was possible to correct the remaining differences between the point clouds obtained from different scanners, caused by imperfect boresight calibration of the upward looking scanner, during post processing. Under degraded GNSS conditions, Haala et al. (2008) reported georeferencing errors up to 1 m in the horizontal direction. They also reported that despite limited absolute accuracy, 3D point measurements made under bad GNSS conditions are still useful, especially if their relative position is mainly exploited. As giving an example, they reported the standard deviation of such data as being only 5 cm if points from two scanners are combined and 2.6 cm if the points are separated for each scanner. Thus, such data are useful in the extraction of features of windows or passages, if a certain error regarding their absolute position is acceptable.

3 MATERIALS AND METHODS

3.1 Test fields

The test fields used in compiling data for this thesis for method and system benchmarking are listed in Table 1. Test field description also summarises what requirements were used for selecting the test field.

Table 1. Summary of test fields.

Test field	Publication	Location	Area / Length	Test field description
Senaatti	**I** and **II**	Helsinki, city centre	7.5 ha	City centre. Complex roof shapes, closed city blocks, 3-6 storey buildings and city cathedral. Practically no vegetation.
Hermanni	**I** and **II**	Helsinki, 3 km north-east of city centre	5 ha	Suburban area. Simple shaped roof structures, 4-6 storey houses. Moderate vegetation.
Espoonlahti	**I** and **II**	Espoo, 17 km west of Helsinki	10 ha	Suburban area. Large variety of houses, terraced houses and high-rise buildings. Undulating terrain and a large number of trees.
Amiens	**I** and **II**	Amiens, 140 km north of Paris	0.3 ha	City centre. High density of small buildings, closed city block.
Espoonlahti	**III** and **IV**	Espoo, 18 km west of Helsinki	2.6 ha + 5.8 ha	Boreal forest. Partly flat and partly steep terrain, areas of mixed and more homogenous tree species in various growth stages.
Espoonlahti	**V** and **VI**	Espoo, 16 km west of Helsinki	1700 m	Suburban area. Many types of buildings, large number of other constructions. A lot of vegetation.

3.2 Data sets

The data sets used in this thesis are listed in Table 2.

Table 2. Data sets and reference data.

Test field		Airborne image data	ALS data	Other materials	Reference data
Senaatti	Sensor	Analog RC-30 camera	TopoSys-1	Camera calibration	200 total station points
	Data type	Stereo pair, RGB	First pulse	Image orientation information	
	Resolution	GSD 7.5 cm	1.6 points per m^2	Ground plan for 6 buildings	
Hermanni	Sensor	Analog RC-30 camera	TopEye	Camera calibration	400 total station points
	Data type	Stereo pair, RGB	2 pulses	Image orientation information	
	Resolution	GSD 6 cm	7-9 points per m^2	Ground plan for 9 buildings	
Espoonlahti	Sensor	Analog RC-30 camera	TopoSys Falcon	Camera calibration	980 total station points
	Data type	Stereo pair, RGB	First pulse	Image orientation information	
	Resolution	GSD 5.5 cm	10-20 points per m^2	Ground plan for 11 buildings	
Amiens	Sensor	Digital IGN camera	TopoSys	Camera calibration	32 points from airborne images
	Data type	11 images, RGB	First pulse	Image orientation information	
	Resolution	GSD 25 cm	4 points per m^2	Ground plan for 7 buildings	
Espoonlahti	Sensor	Digital Vexcel UltraCam D	Optech ALTM 2033	Camera calibration	Location and species of 352 trees
	Data type	12 images, CIR and RGB+NIR	First and last pulse	Image orientation information	Height of 254 trees
	Resolution	GSD 20 cm	2 points per m2	DTM, 0.5 m grid spacing	Crown base height of 285 trees
				Training data set of 75 trees	
Espoonlahti	Point clouds collected with five different MLS systems				273 planimetric targets 3283 ground elevation points

3.3 Reference data

The reference data collected in the studies are listed in Table 2.

In each study, the then new technology was utilised in collecting the reference data:

- For building extraction the reference data was mainly collected using a total station with reflectorless distance measurement system.
- For tree extraction the tree parameters were measured from TLS point clouds.
- The MLS test field reference data was mainly acquired from TLS data collected by applying a stop-and-go MLS method.

The procedure in collecting reference data was as follows:

- Ground control point determination. In building extraction project the existing city survey network was utilised, in other cases the ground control point coordinates were measured using real-time differential GPS measurements.
- Control point validation and check point determination using total station measurements.
- Reference data collecting.
- Reference data validating using check points and repeated measurement data.

3.4 Benchmarked methods and systems

The building extraction methods benchmarked in Publications **I** and **II** are listed in Table 3, the tree extraction methods benchmarked in Publications **III** and **IV** are listed in Table 4, and the MLS systems benchmarked in Publications **V** and **VI** are listed in Table 5. The benchmarked methods for feature extraction using MLS data in Publication **VI** are listed in Table 6.

Table 3. The benchmarked building extraction methods.

Method	Used data Laser data	Aerial images	Ground plan	Short description
Cybercity		100		Manual stereoplotting and semi-automatic building reconstruction. (Grün and Wang, 1998 and 1999a,b)
Hamburg		100		Manual stereoplotting and semi-automatic building reconstruction. (BAE Systems, 2000)
Stuttgart		100		Semi-automatic monoplotting. (Gülch and Müller, 2001)
IGN	50	50		DSM creation using laser point data and building outline determination from images. (Flamanc et. al. 2003)
ICC laser+aerial	80	20		Laser point classification and plane matching using TerraScan software. Aerial images used for interpretation purposes. (TerraScan, 2003)
ICC laser	100			Laser point classification and plane matching using TerraScan software. (TerraScan, 2003)
Nebel+Partner	90	10		Laser point classification and plane matching using TerraScan software. Aerial images used for interpretation purposes. (TerraScan, 2003)
FOI	100			Plane finding using cluster analysis of DSM surface normal parameter space. (Söderman et al., 2004)
FOI outlines	100		X	Plane finding within ground plan using cluster analysis of DSM surface normal parameter space. (Söderman et al., 2004)
C+B Technik	100		X	Automatic TIN analysis and interactive check and editing. (Publication **II**)
Delft	100		X	Hough transform, ground plan division and 3D primitive matching. (Vosselman and Dijkman, 2001; Vosselman and Süveg, 2001)
Aalborg	100		X	Automatic selection of points belonging to a roof plane. (Juhl, 1980; Burrough and McDonnell, 1998; Frederiksen et al., 2004)
Dresden	100		X	Detection of planes using clustering of 3D triangle parameter space. (Hofmann et al., 2003; Hofmann, 2004)

Table 4. The benchmarked tree extraction methods.

Method	Used data		Short description
	Laser data	Aerial images	
Definiens AG	X		Canopy height model (CHM) was used to create a forest mask which was split into tree crowns using eCognition software. (Definiens AG, 2006; Bunting and Lucas, 2006)
FOI	X		CHM was filtered using different filters, resulting images were segmented and best segment was selected by fitting a parabolic surface to the CHM. (Persson et al., 2002)
Pacific Forestry Centre aerial		X	Tree crowns were delineated using image analysis, functions used were Individual Tree Crown Valley Following and Individual Tree Crown Isolation. (Gougeon, 2005)
Pacific Forestry Centre hybrid	X	X	Aerial images were used to delineate tree crowns as described above and tree height was obtained from laser data. (Gougeon, 2005)
University of Hannover	X		A wide range of DSM scale levels were segmented using a watershed transformation. The best hypothesis for a crown from the overlapping segments was selected with the help of fuzzy functions for the tree model parameters. (Straub, 2003; Wolf and Heipke, 2007)
Joanneum Research aerial		X	Vegetation height information was derived from adjusted stereo DSM and the provided DTM, orthophoto was used to find seed pixels and delineate tree crowns. (Hirschmugl et al., 2005)
Joanneum Research hybrid	X	X	Tree species were classified and crown areas were segmented from the optical data, and tree height was obtained from the laser data. (Hirschmugl et al., 2005)
Metla	X		Smoothed CHM was segmented using watershed segmentation and trees delineated by masking low pixels. (Pitkänen et al., 2004; Pitkänen, 2005)
Norwegian Forest Research Institute and University of Life Sciences	X		Uppermost laser points were retained and interpolated into a DSM-grid, local maxima was searched and a region-growing algorithm was run. The DSM was adjusted (lifted) using the residuals between the DSM and the first echoes. (Solberg et al., 2006)

National Ilan University	X		Tree locations were found by local maxima filtering of CHM using a 3x3 neighbourhood, height histogram was used for tree species determination and crown width was derived based on tree height and species. (Publication **IV**)
Texas A&M University	X		Local maxima filtering of CHM was applied with a circular moving window of varying sizes. Filter size was based on the relationship between crown size and tree height. This relationship was determined by using manually collected teaching data set. (Kini and Popescu, 2004)
University of Zürich	X		Local maxima were detected in the CHM and a subsequent cluster analysis of the raw data was applied with local maxima as the starting points. (Morsdorf et al., 2004)
ProGea Consulting and Agricultural University of Cracow		X	A beta version of a self developed protocol, tree counting robot, was used in eCognition software to find the centres of single trees within a single image.
University of Udine	X		Filtered triangulation of all laser points was used to create a CHM, trees locations were found based on a morphological analysis of the laser point distribution. Tree crowns were delineated using a region growing algorithm. (Barilotti et al., 2007)
FGI_LOCM	X		Potential tree locations were found by searching the local maxima in a given neighbourhood. Tree crowns were delineated using watershed transformation. (Publication **IV**)
FGI_MLOG	X		Multi-scale Laplacian of Gaussian. (Publication **IV**)
FGI_MCV	X		Minimum curvature-based tree detection. (Yu et al., 2011; Publication **IV**)
FGI_VWS	X		Local maxima finding with varying window size. (Publication **IV**)
Manual	X		Trees were delineated visually by using laser points which were colour-coded based on elevation, and the location and height were measured by finding the highest laser points within the delineated trees. Aerial images were used only for interpretation purposes.

Table 5. The benchmarked MLS systems.

MLS system	Operated by	Short description
ROAMER	Finnish Geodetic Institute	Research system with one TLS scanner. (Kukko et al., 2007)
RIEGL VMX-250	RIEGL Laser Measurement Systems GmbH	Commercial system with two MLS scanners. (RIEGL, 2012)
Sensei	Finnish Geodetic Institute	Low-budget research system with one industrial scanner. (Jaakkola et al., 2010)
Streetmapper 360	3D Laser Mapping	Commercial system with two MLS scanners. (3D Laser Mapping, 2012)
Optech Lynx	TerraTec AS	Commercial system with two MLS scanners. (Optech, 2010)

Table 6. The benchmarked methods for feature extraction using MLS data.

Method	Aim	Short description
FGI	Pole extraction	Data are segmented to find point clusters with narrow and elongated shapes. These clusters are further classified into correct targets (poles and tree trunks) and false targets. In the classification, a mask is used as a model of a pole. Features are extracted from the clusters to improve the classification.
ITC	Pole extraction and facade classification	The point cloud is segmented to detect and label planar regions using a surface growing algorithm with 3D Hough transformation for the detection of seed surfaces. For each segment the size, orientation and connectivity to other segments is investigated in order to roughly classify the ground, vertical walls, and raised features. Features on top of the ground are further classified by extracting all features containing pole-like structures. Ground points are removed and the remaining points are grouped by applying connected component segmentation. Pole-like structures are detected by slicing each component horizontally and fitting an enclosed rectangle to each slice. Then the deviation of the centre point and the length difference of diagonals of neighbouring slices from a stack are compared. The planarity, tilt from vertical and size (height and width) are checked for every façade segment.

3.5 Methods used for benchmarking methods and systems

Table 7 summarises the reference data and methods used for performance analysis in this thesis.

Table 7. The reference data types and analysed properties.

Publication	Reference	Methods / system performance analysed by
I and **II**	Points measured on building, roof and other building part corners, ground points next to building corners. Raster building map.	Planimetric and elevation accuracy of building roof corners, building length and height accuracy and roof inclination accuracy. Accuracy of total delineated building area.
III	Coordinates of tree top and bottom, elevation of crown base, raster map of crown delineation, tree species of measured trees.	Tree location, height, crown height, crown delineation and tree species determination accuracy.
IV	Coordinates of tree top and bottom, elevation of crown base, raster map of crown delineation, tree species of measured trees.	Tree location, height, crown height and crown delineation accuracy and commission and omission errors.
V	Coordinates of building and curb corners and pole centres. Ground points.	Planimetric and elevation accuracy of collected point clouds. Accuracy as a function of distance from the trajectory.
VI	Coordinates of building and curb corners and pole centres. Ground points. Pole locations and diameters. Facade laser point classification.	Planimetric and elevation accuracy of collected point clouds. Accuracy as a function of distance from the trajectory. Pole detection rate and diameter accuracy. Facade classification rate.

The accuracy of each benchmarked method or system was presented using descriptive statistics of the differences between the reference and the measured value. The root mean squared error (RMSE, Equation 1) was calculated for building length and roof inclination (Publications **I** and **II**), for building height (Publication **II**), for tree location, height and crown base height (Publications **III** and **IV**), and for MLS planimetric accuracy (Publications **V** and **VI**).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (e_{1i} - e_{2i})^2}{n}} \qquad \text{(Equation 1)}$$

where e_{1i} is the result obtained with the particular method or system, e_{2i} is the corresponding reference measured value, and n is the number of samples. Additionally, minimum, maximum, medium, mean and standard deviation values of the differences between the reference and the observed value were calculated. If the observed value differed from the reference value by more than 3*std ± mean observation, it was considered to be a gross error, i.e. an outlier, and it was deleted.

The interquartile range (IQR, Equation 2) values were calculated for building location, length and roof inclination (Publications **I** and **II**) and for building height (Publication **II**). Interquartile range values represent the range between the 25th and 75th quartiles.

$$IQR = p_{75th} - p_{25th} \qquad \text{(Equation 2)}$$

where p_{75th} is the value at the 75th quartile and p_{25th} is the value at the 25th quartile. For example, if the IQR is 20 cm and the median value is 0, 50% of the errors are within ±10 cm. The outliers were detected using threshold levels: the lower bound at the 25th quartile minus 1.5*IQR and the upper bound at the 75th quartile plus 1.5*IQR. The IQR is not as sensitive to large deviations as is the standard deviation. Additionally, the coefficient of determination R^2 was calculated to help to separate cases between low variability of the reference data and high estimation accuracy, and high variability of the reference data and low estimation accuracy.

The descriptive statistics were computed before and after the outliers had been deleted.

Reference raster maps of building ground plans were used at the Espoonlahti and Hermanni test sites (Publication **II**), while at the Espoonlahti forest test site use was made of reference tree crown delineations (Publications **III** and **IV**) to compute the total relative building and crown area and total relative shape dissimilarity (Henricsson and Baltsavias, 1997). Total relative shape dissimilarity is the sum of the area difference and the remaining overlap error, i.e. the sum of the missing area and extra area divided by the reference area. Total relative building and crown area gives the difference between the modelled area and the reference area.

When conducting MLS system analysis (Publications **V** and **VI**), the analysed point clouds were first checked by comparing them with the reference data to detect any gross errors either in elevation or plane. If there was a larger systematic shift than a few centimetres, e.g. caused by the differences in GNSS base station coordinates, this was compensated to ensure validity in the comparison. Especially a large systematic shift in plane can lead to distorted elevation accuracy results, and it is a common practice to use some ground control points in laser scanning surveys to eliminate the bias. The values deviating most were checked against the ground truth and removed from the analysis if there was any doubt about the error being caused by the target, not by the system. These errors were mainly detected in the analysis of elevation accuracy and they were caused by parked cars or changes in vegetation. Following this 'gross error filtering', the systematic errors were compensated, in plane separately for easting and northing, and the accuracy values were computed.

The benchmarking of automatic pole extraction methods using MLS data was analysed by using the detection rate (number of reference poles versus number of extracted poles), the number of correct detections, and pole diameter accuracy (Publication **VI**). The automatically classified MLS laser points belonging to a building facade were compared to the original and manually classified laser points to achieve the percentage of correctly classified points (Publication **VI**).

4 RESULTS

4.1 Building extraction benchmarking results

The results for building extraction method benchmarking show that photogrammetric techniques and hybrid techniques provide the highest level of detail and accuracy in the horizontal plane in 3D city reconstruction. The photogrammetric techniques are powerful for visual interpretation of the area, measurement of building outlines, and measurement of small details (e.g. chimneys), whereas laser scanning yield superior elevation, roof planes, and ridge information (Figure 1). When the advantages of both methods are implemented appropriately in a single system, high accuracy and a relatively high level of automation can be achieved. When manual work is considered, also the experience of the operator impacts on accuracy. Point density, shadowing of trees, and complexity of the structure were the major reasons for site-wise variation in the results based on laser scanning. The lowest accuracy was obtained with the lowest pulse density.

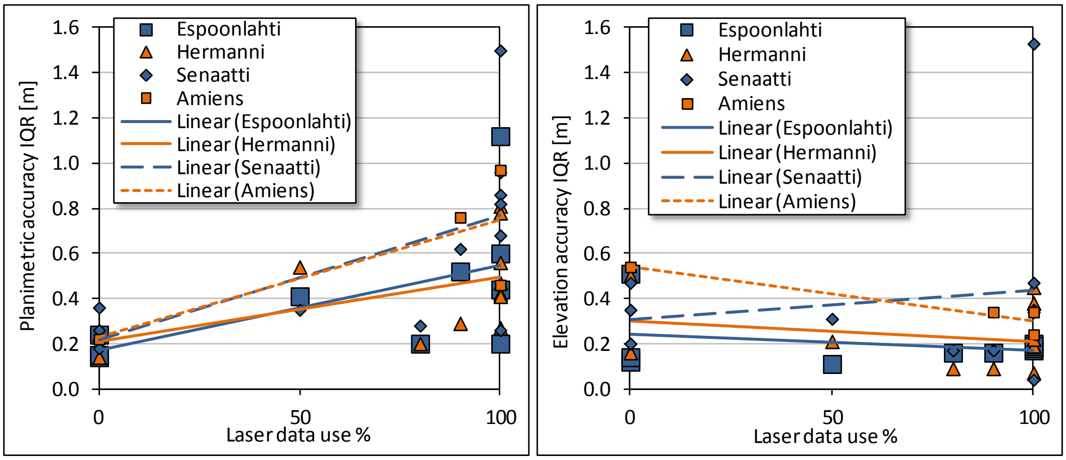

Figure 1. The planimetric and elevation accuracy of the benchmarked building extraction methods as a function of the used data. Laser data use of 0% refers to photogrammetric methods, 100 % to techniques based fully on laser scanning and intermediate values to hybrid techniques.

As was to be expected from these results, laser scanning and photogrammetric methods produced the same accuracy as regards determination of building height. In building length determination laser based methods were not as accurate as photogrammetric methods, as could also be expected from the above. The accuracy (RMSE) of building lengths using photogrammetry varied from 14 cm to 51 cm, using hybrid methods from 19 cm to 108 cm, and using methods based on laser scanning from 13 cm to 292 cm. In laser scanning, the complexity of the buildings rather than the point density was the major cause of site-wise variation.

Determination of roof inclination was more accurate when using laser data than photogrammetry, but there was large variation in quality due to the used methods and the test sites (i.e. complex buildings). When a roof is steeply inclined and short, even small errors in determination of target elevation lead to large errors in inclination angle. In photogrammetry, roof inclination is obtained from two measurements, and consequently the same accuracy was clearly not achieved as that achieved when using laser technology. At the Hermanni test field, which was relatively easy for both methods, the accuracy of determination of roof inclination was about 2.5 degrees for the photogrammetric methods and about 1 degree (RMSE) for the laser methods. When the building size was smaller and/or the pulse density was lower, this difference between photogrammetry and laser scanning was reduced and in some case there was no difference.

Planimetric target accuracy is impacted by the degree of automation and the method (Figure 2). The accuracy of methods characterised by low degree of automation is about 20-30 cm, while for high-automation methods it is about 60-100 cm (IQR). The accuracy of determination of target elevation appears to be almost independent of the degree of automation (20-40 cm IQR).

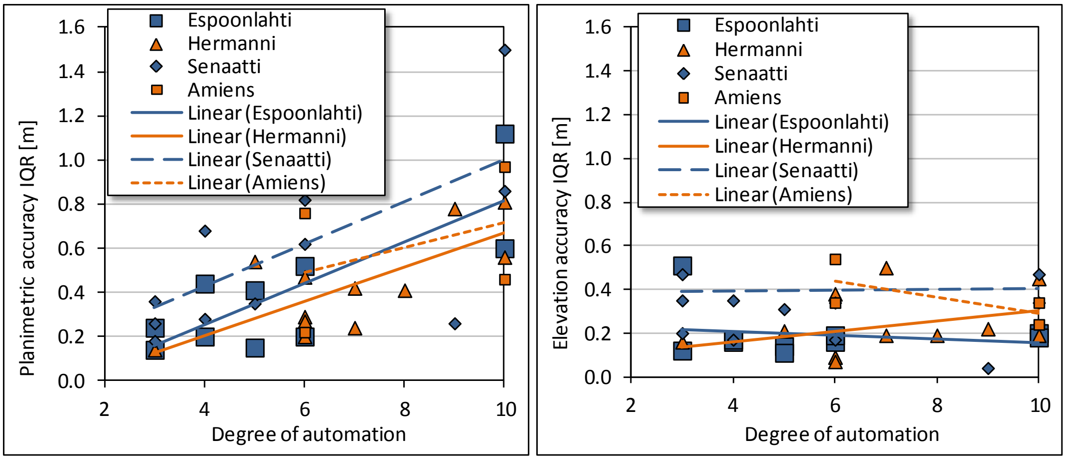

Figure 2. The planimetric and elevation accuracy of the benchmarked building extraction methods as a function of the degree of automation.

4.2 Tree extraction benchmarking results

The results of benchmarking of the tree extraction methods confirmed that the extraction method is the main factor impacting on the accuracy achieved and that laser point density has less impact on the detection of individual trees. The detected tree locations of the best models show RMSEs of less than 1 m (Figure 3). For trees taller than 15 m, a RMSE of 0.5 m was obtained for tree location. In general, and as was to be expected, the taller a tree is, the better is location accuracy. The automated models were as good as the manual processing of the point clouds in determining tree locations.

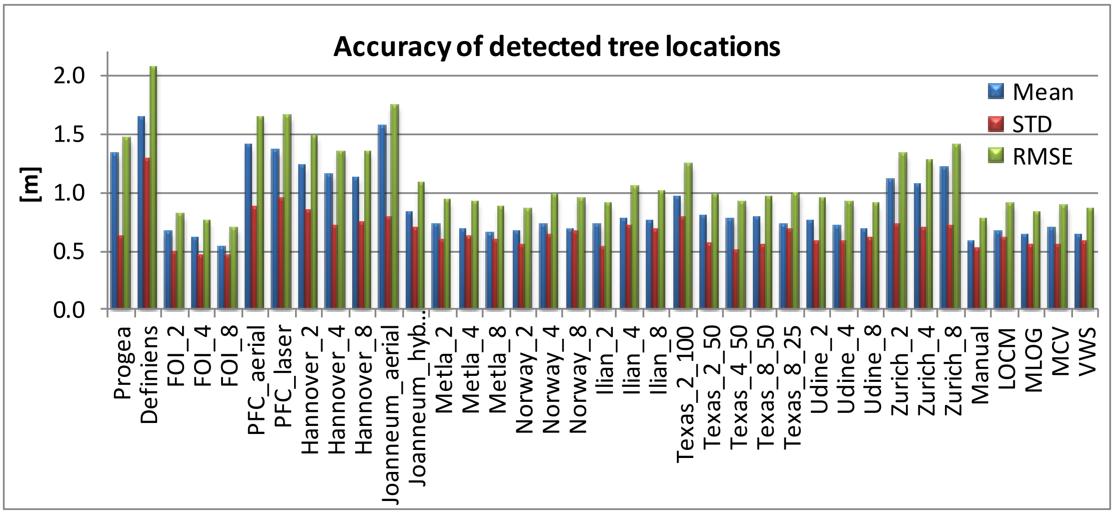

Figure 3. The accuracy of the detected tree locations for all of the benchmarked methods.

The best methods yielded an accuracy level of 0.5 m in the determination of tree height (Figure 4) and this was achieved almost independent of tree height. The impact of the point density was negligible compared to method variability in the accuracy of tree height determination. The results achieved with the best models were significantly better than the results achieved manually. Both the underestimation of tree height and standard deviation diminished in general as point density increased. Crown base height detection proved to be relatively poor when using laser scanning, i.e. 3-5 m (RMSE).

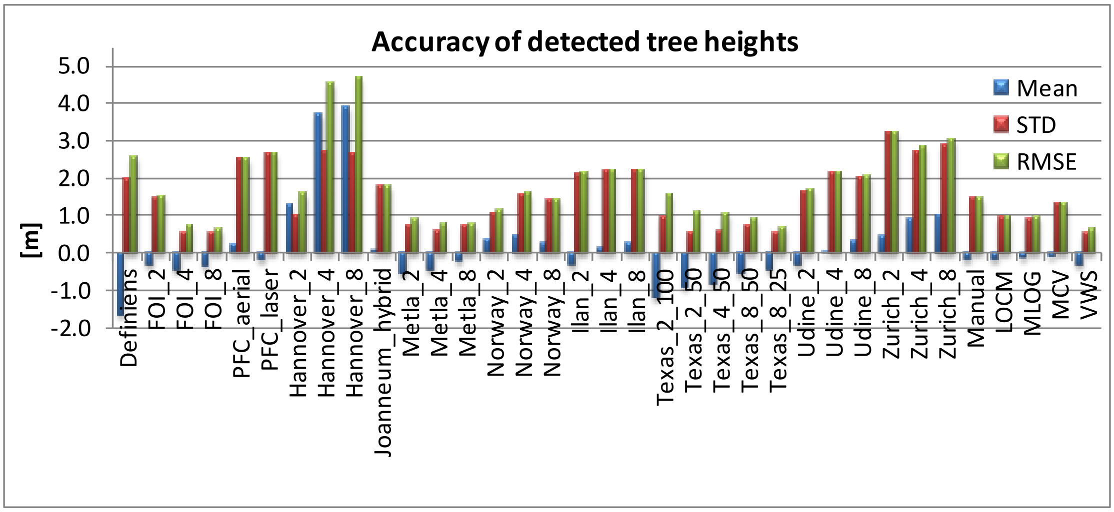

Figure 4. The accuracy of detected tree heights for all of the benchmarked methods.

The results for total crown area proved to vary significantly between the models. The factors leading to false total crown area are as follows: inadequate tree finding capability (small trees missed), inadequate filtering of the raw point cloud data or DSM (leading to too excessive crowns but too few of them), and inadequate calibration of the method with the given reference data.

In order to provide non-biased estimates, e.g. for volume, the correct tree detection rate should be as high as possible without creating too many commission errors. The percentage of detected trees varies from 25% to 102%, which implies different capabilities in detecting dominant and suppressed trees. Manual processing found 70% of the trees. The best models were significantly superior in segregating tree groups into individual trees compared to the manual method. Surprisingly enough, there was no improvement in the detection rate when the pulse density was increased from 2 points to 8 points per m^2. It appeared that the test site was relatively suitable for individual tree detection with a pulse density as low as 2 points per m^2.

In many other applications, manual techniques, as was demonstrated in the above in building extraction, are more accurate than automated techniques. Here it can be seen that several automated methods are superior to manual tree extraction. When analysing the technologies, it was found that method utilising raw laser point cluster analysis yielded the best results in finding the smaller trees. This implied that using the original point clouds would result in finding the smaller trees more accurately than conventional methods, such as filtered CHM.

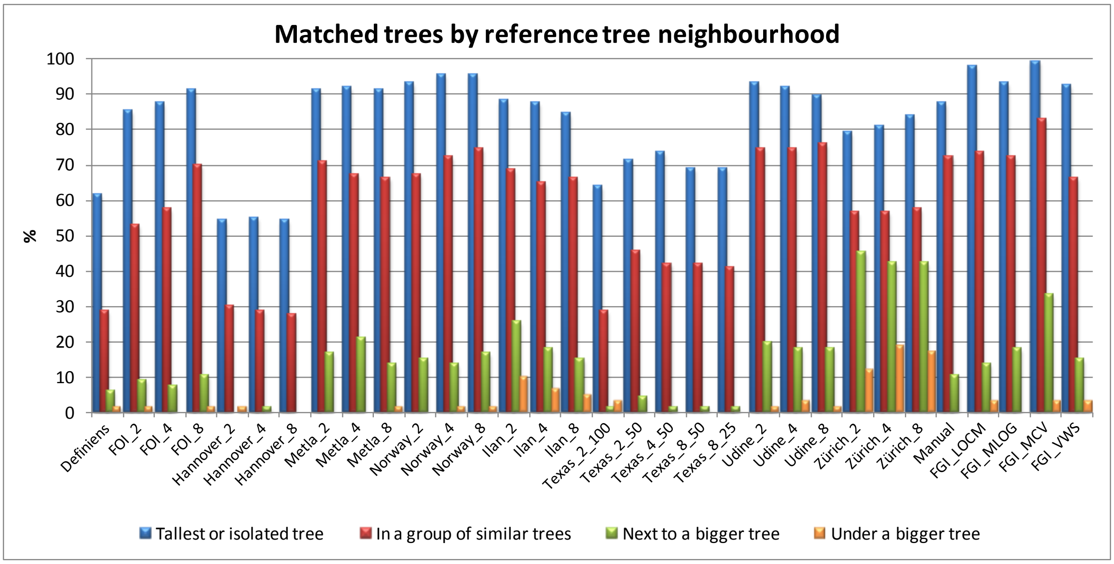

Figure 5. The impact of tree neighbourhood on tree matching.

The impact of tree neighbourhood on tree matching was analysed by computing how many reference trees were matched with the model trees in the four neighbourhood categories. The results of this comparison are shown in Figure 5. Manually extracted trees serve as interesting references for automatically extracted trees. FOI, Ilan and Metla methods are slightly better than the manual method when dealing with the tallest trees and slightly inferior than the manual method when dealing with groups of trees. Norway, Udine, and FGI local maximum finding and multi-scale Laplacian of Gaussian methods are better with the tallest trees, and their performance is about the same with groups of trees as the manual method. The best result was achieved with the FGI_MCV model in these first two categories. When the classes “Next to a bigger tree” or “Under a bigger tree” were considered, Zürich, FGI_MCV and Ilan were the methods that performed the best. When analysing these technologies, it was found that Zürich, utilizing raw laser point cluster analysis, yielded the best results in finding the smaller trees. This implied that smaller trees could be obtained better by means of the original point cloud analysis rather than using conventional methods such as filtered CHM. The automated techniques were superior to manual methods, and especially so with the lowest tree classes.

4.3 Mobile laser scanning system benchmarking results

The benchmarked MLS systems are capable of acquiring accurate point cloud data in conditions of good GNSS coverage (Figure 6). Planimetric errors (Figure 7) and elevation errors (Figure 8) increase as a function of range, but moderately so if the system is properly calibrated.

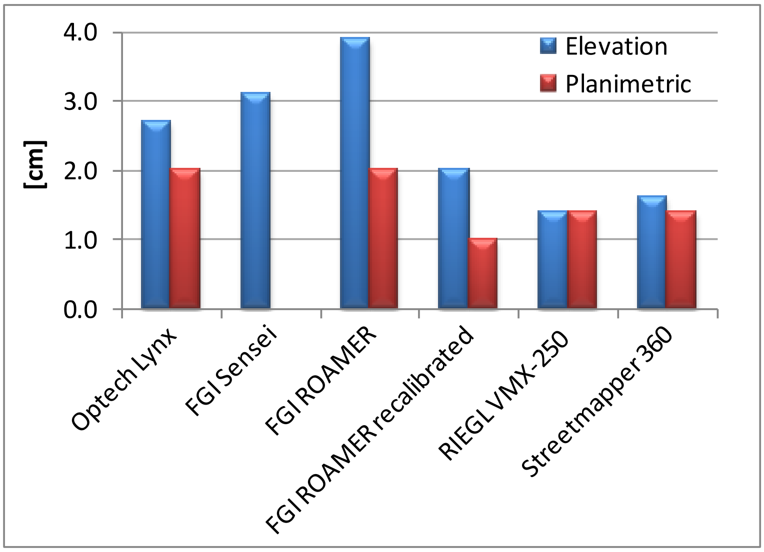

Figure 6. The accuracy (STD) of the benchmarked MLS systems.

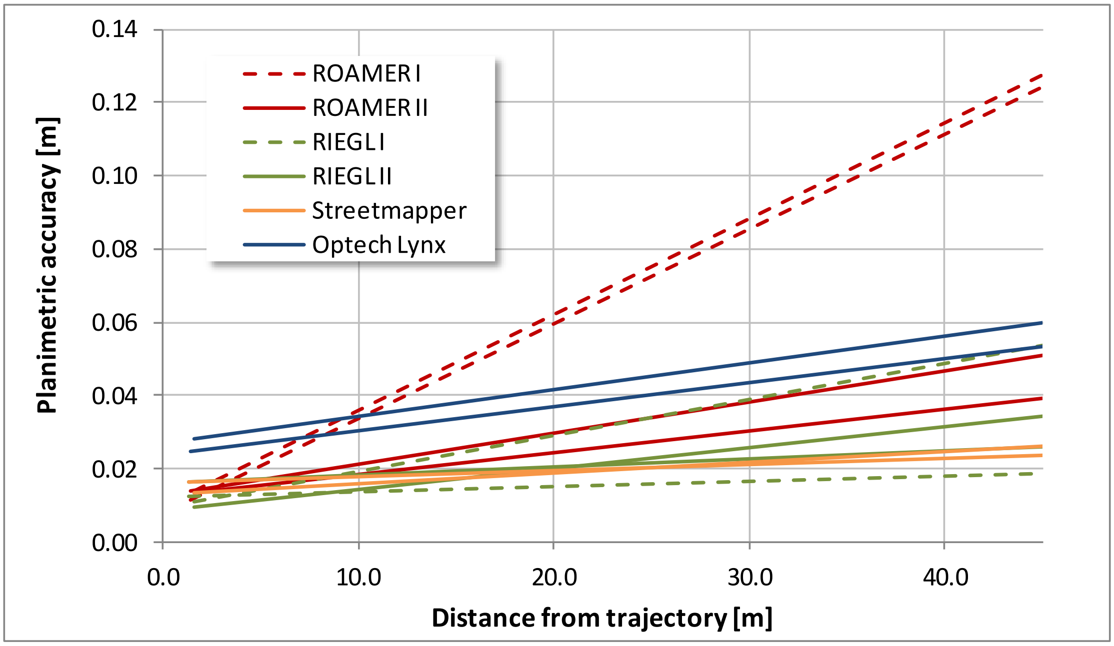

Figure 7. Planimetric accuracy as a function of the distance from the trajectory with linear trend lines fitted to the observed errors in the two driving directions.

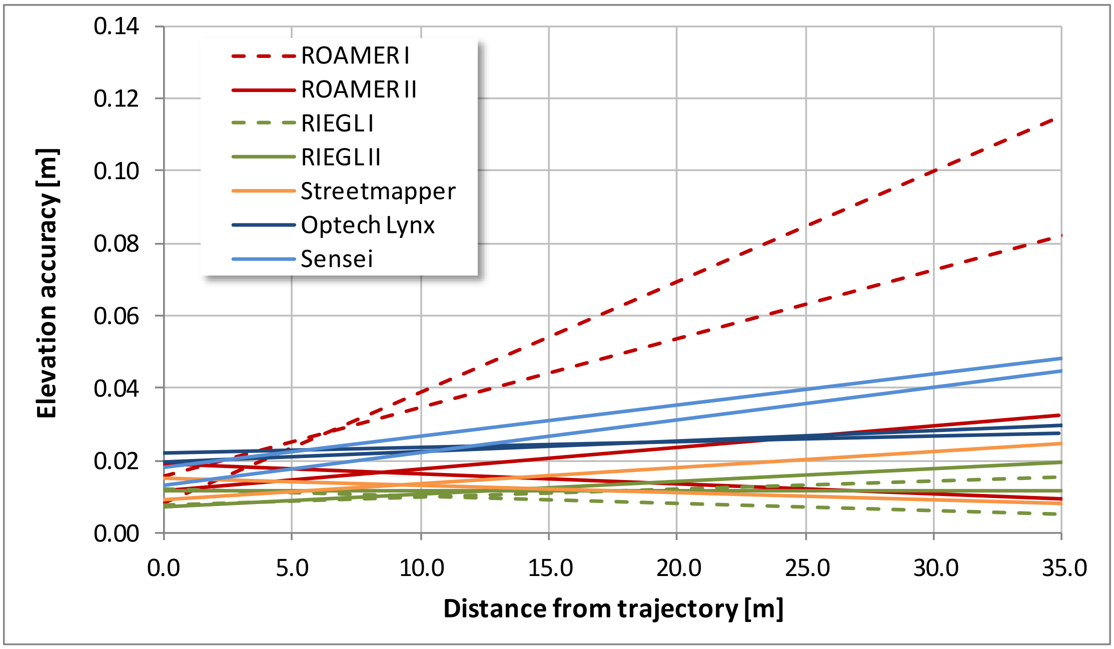

Figure 8. Elevation accuracy as a function of the distance from the trajectory with linear trend lines fitted to the observed errors in the two driving directions.

With all of the systems properly calibrated, elevation accuracy was better than 3.5 cm up to a range of 35 m. The best system had a planimetric accuracy of 2.5 cm even with a range of 45 m. Even though Figure 8 suggests that elevation accuracy improves in some cases when the distance from the trajectory increases, this is unlikely to be so. This phenomenon is most probably caused by the accuracy of the reference data having reached its limits and not being available for analysis of sub-centimetre accuracy. Nonetheless, this proves that the elevation accuracy of the best MLS systems can reach values of 1-2 cm up to a range of 35 m.

The results show very clearly how accuracy is impacted when there are problems with calibration and how recalibration using collected point cloud data can improve the performance. This can be seen in the results of ‘ROAMER’ and ‘ROAMER recalibrated’ (abbreviated as ROAMER I and ROAMER II in Figure 7 and Figure 8). The system calibration was done first by using only the laboratory-type of calibration, which showed the need for further calibration in the field. A significant roll error was found in ROAMER in regard to overlapping point cloud data. This roll error was compensated and the second point cloud was computed. Similar performance improvement can be expected when errors in trajectory, caused by satellite signal outtakes or IMU disturbances, for example, are compensated for using strip adjustments or control targets, for instance.

Imperfect boresight calibration, in addition to the navigation errors, between the scanners on multi-scanner systems leads to multiple reproductions of objects, as is shown in Figure 9.

These kinds of errors in the relative orientation of the instruments lead to errors in the measured point clouds, which in turn can cause problems in the continued processing of the data, such as extraction and modelling of objects.

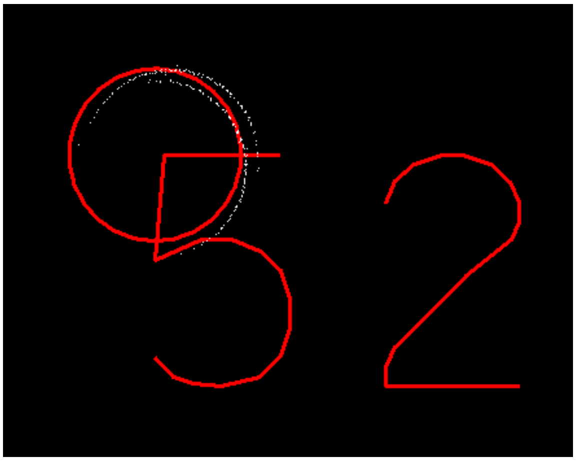

Figure 9. A large pole (reference target no. 52) seen double by a dual-scanner system (white points).

Two methods for pole detection and one method for classifying building facade points were tested as part of the study of road environment mapping using mobile laser scanning systems. MLS data collected with ROAMER was used to for these tests. FGI's pole detection algorithm was implemented based on the knowledge of the used MLS system measurement principle and it had been developed originally only for pole type objects. Therefore, it yielded better accuracies than the general classification concept of the ITC. The pole detection rate for FGI was 69.7% (ITC 51.9%) and 86.5% (ITC 86.2%) of the detections were correct. Targets that were visible in the MLS data and closer than 30 m (ITC 15 m) to the trajectory and taller than 1 m were included in the analysis. The facade classification result shows that 87.4 % of the points that ITC classified as facades were correct.

5 DISCUSSION

5.1 Building extraction

Despite the great amount of research conducted during the past decade, the level of automation in feature extraction is still relatively low. Improvement in automation can be achieved most significantly by utilising the synergy between laser scanning and photogrammetry. Currently, most systems do actually acquire image and laser data simultaneously.

ISPRS has an ongoing project for benchmarking of urban object extraction. A modern data set consisting of digital aerial image and ALS data was made available to the research community via the ISPRS web site (ISPRS, 2012). Also, reference data including 2D outlines of multiple object types are being distributed. Researchers have access to the sensor data and are encouraged to carry out one or more of several urban object extraction tasks. The goal of urban object detection is to determine the 2D outlines of urban objects in the input data. The focus in evaluation is on the thematic and geometrical accuracy of the results. The goal in 3D building reconstruction is to reconstruct detailed 3D roof structures in the test areas. The focus of evaluation here is on the quality of the roof plane segmentation and on the geometrical accuracy of the roof polygons. Test participants evaluate their own results, which are then submitted to the organisers. As far as object detection is concerned, the object classes most frequently submitted by the participants have been buildings and trees. The first results of this project were presented at the ISPRS Congress in Melbourne, Australia, in August 2012. (Rottensteiner et al., 2012.)

Surprisingly, the results obtained so far in this new study indicate that the accuracy of and conclusions drawn from building reconstruction have not changed much in comparison to the studies addressed in this thesis with data sets dating back some 8-12 years. As is shown in Publications **I** and **II**, the mean accuracies (IQR) for automatic and semi-automatic building extraction methods were 0.56 m (max 1.50 m) in plane and 0.29 m (max 1.53 m) in elevation. The results of the ISPRS study gave RMSE values 0.96 m (max 1.68) in plane and 0.96 (max 3.33 m) in elevation. One method, which produced extreme errors in elevation, was left out of the ISPRS results. It should be noted that the systematic errors are included in the RMSE values, but in IQR they are excluded. The conclusions drawn by Rottensteiner et al. (2012) for the building reconstruction are as follows:

- Building reconstruction works well for buildings simple in shape.
- The accuracy potential of the sensors has not yet been fully exploited.
- The results obtained are generally sufficient for 'nice' visualisations.

- The fully automatic generation of topologically and geometrically correct models in complex environments is still a challenge.

Thus, the conclusions drawn continue to reflect the situation in 2006 and that depicted in Publication **II**. The efficiency of the available algorithms to reliably extract a suitable percentage of objects from large areas is also important. In this respect the progress gained since the study described in this thesis is significant.

Based on the results and developments of the past ten years, the following conclusions can be drawn:

- There is still a need to integrate laser scanning and photogrammetric techniques in a more advanced way to increase the degree of automation.
- The quality improvement of digital camera data will enhance the quality of photogrammetric techniques and it will also enable higher degree of automation through the use of remote sensing methods, e.g., calibration of image radiometry, in image processing.
- The technological development in laser scanning will enable higher degree of accuracy to be obtained by techniques relying only on laser scanning.
- Laser scanning will enable the higher degree of automation needed in the feature extraction process.
- New algorithmic innovations will emerge in all areas thanks to digital camera data and laser scanning developments that will enhance the degree of automation.

In practice, the availability of the material (aerial image or laser point clouds) determines significantly what kind of techniques can be used. In future, the challenge is to find out how existing models should be upgraded and updated, how changes will be verified, and how existing information can be used optimally in more automated processes. The state of the art in the updating of building maps can be seen in Matikainen et al. (2010).

5.2 Tree extraction

The Nordic countries are currently in the process of replacing the retrieval of stand characteristics (e.g. mean tree height, dominant height, mean diameter, stem number, basal area, and timber volume), which are needed in forest management planning, by applying ALS-based inventory methodologies. As regards operational forest inventories, the two-stage procedure using ALS data and field plots, i.e. area-based approach (ABA, (Næsset, 2002)), has become common and it serves as a reference for other inventory methodologies. The foremost advantages of the state-of-the-art ABA, when compared to traditional standwise field inventory (SWFI), are its greater precision in the prediction of forest variables (Holopainen et al., 2010a), sampling-based estimation of forest variables with the possibility to calculate accuracy statistics, and (at least in principle) the feature that ALS-based inventory is not dependent on stand boundaries. Moreover, current ALS data acquisition and processing costs are less than those of traditional SWFI methods.

The ALS-based forest inventory methodology based on ITD has been widely studied in recent years. Yu et al. (2011) reported an accuracy of 69% for tree detection under various forest conditions (different forest densities, ages, site types and tree species). Heinzel et al. (2011) introduced an approach that classifies crown size in advance and uses this information as prior knowledge for single-tree extraction. Crown size is classified from aerial colour infrared image texture with an improved grey-scale granulometry followed by a crown-size-adapted watershed segmentation of single trees. The accuracy achieved varies between 64% and 88%.

A broader in scope comparison of individual tree extraction was presented by Vauhkonen et al. (2011), who tested several algorithms using ALS data under different types of forests; a Eucalyptus plantation in Brazil (point density 1.6 per m^2), coniferous and deciduous forest plots in Germany (point densities 16 per m^2 and 7 per m^2) and mainly coniferous forest plots in Norway (point density 7.4 per m^2) and in Sweden (point density 30 per m^2). The average tree detection rate between the test sites varied between 54% and 86%. Vastaranta et al. (2012) combined automated ITD and visual interpretation to acquire reference data for ABA. They assumed that, in contrast to mere automated ITD, additional visual interpretation would significantly enhance the accuracy of the derived plot-level forest variables and provide superior results when used to train the ABA. Visual interpretation improved the accuracy of ITD validated at plot-level as the RMSE of stem volume decreased from 32.1% to 28.6%. However, there was no improvement in ABA prediction.

Vastaranta et al. (2011a) investigated ITD error sources, and their effects on forest management planning calculations. The investigated error sources were detection of trees, errors in tree height prediction, and errors in tree diameter prediction. The effects of these errors were analyzed with Monte Carlo simulations. The results showed that the foremost error source in ITD is in tree detection.

Even though ALS-based ITD has been widely studied, it is not widely used in practice due to assumed problems related to tree detection under various forest conditions (Falkowski et al., 2008; Vastaranta et al., 2011b). Other problems related to the practical use of ITD include the need for higher ALS point density, which adds to the costs and the amount of data that would need to be stored, as well as inadequate accuracy of tree species identification. The assumed main advantage of ITD would be that it provides true stem distribution series, enabling better predictions of timber assortments. Stem distributions are predicted in the ABA, causing inaccuracy in timber assortment estimates and forest value (Holopainen et al., 2010b). Another advantage of ITD is the reduced amount of expensive fieldwork compared to that needed when applying the ABA approach.

As the results obtained in this study show, there should be more focus on finding smaller trees from underneath the dominant storey. Full waveform technology is expected to improve individual tree detection, especially in the case of suppressed trees, as waveform analysis can be used to produce denser point clouds within the crowns (Wagner et al., 2004 and 2008; Litkey et al., 2007). In principle, higher pulse densities should result in a better capability to find trees, but this also depends on the forest type. Hyyppä et al. (2012) showed that using penetrated hits instead of highest hits (first pulse), the individual tree detection accuracy improved by 6% points.

The extracted data, acquired from detected trees, need to be calibrated with the ground truth, but it is vital for the method to reveal as correctly as possible the number of dominant and suppressed trees with a small number of commission errors. The extracted individual trees can also be used in a simple way for improving area-based estimates with significantly improved accuracy and without using any calibrations (Hyyppä et al., 2012). Hyyppä et al. (2012) used features based on individual trees in addition to the statistical point height metrics in area-based prediction of forest variables. By using features based on individual trees as the input in non-parametric estimation, the RMSEs in stem volume estimation, when compared to solely point height metrics (i.e. ABA), were reduced from about 25% to 20% at plot level. Point height metrics and features based on individual trees complemented each other, especially in basal area estimation. Thus, individual tree extraction techniques are currently also important from the practical forestry point of view. Non-parametric estimation methods used in area-based ALS inventories are currently becoming more common also in ITD (Maltamo et al., 2009). Yu et al. (2011) showed that non-parametric estimation can provide a stable and reliable solution for predicting tree height, diameter at breast height, and volume of individual trees based on both the physical and statistical features derived from ALS data.

Several of the methods in this study were superior to manual processing in dealing with dominant, co-dominant, and suppressed tree storeys. This also means that manually processed tree maps based on airborne laser surveys cannot be used as reference for developing automatic algorithms for tree detection, although this has been done previously. Inventories based on individual trees require reference data on individual trees collected in the field by some other means. Calibration is needed to reduce the underestimation of tree height and calibration of the basal area and stem volume (e.g. Vastaranta et al., 2011b).

This study demonstrated that the quality of one method versus other methods cannot be verified without testing the methods under the same forest conditions since the effect of variability of forest conditions is believed to have a high impact on the achieved accuracy. This is evident when the results achieved in this study are compared to those reported in existing literature. Also the results obtained by Vauhkonen et al. (2011) support this; even though they had fewer methods tested than in this study, they had a larger variety in forest types and point densities to work with. The aim in the ongoing ISPRS benchmarking of urban object extraction is to detect urban trees. The geometrical accuracy of the reference for tree detection was estimated to be about 0.5-1.5 m (Rottensteiner et al., 2012), and consequently the results are not comparable with the results obtained in the studies of this thesis.

5.3 Mobile laser scanning

Given good GNSS coverage conditions, the benchmarked MLS systems are capable of acquiring accurate point cloud data. Often buildings, trees and other structures cause disturbances in satellite visibility. Moreover, the performance of other navigation instruments, such as IMUs and odometers as well as post-processing algorithms, defines the achievable accuracy. Tools for trajectory accuracy improvement are being developed and new satellites are being launched, all of which should improve accuracy in areas where the current systems run into problems.

Even though the computation of the sensor's driving path and orientation results in observation (GNSS, IMU) errors being minimized, there are still the errors in laser distance measurement, in scanning mirrors, in position (GNSS), and in orientation (IMU). Consequently, there are systematic offsets and random variations both in plane and height (Pfeifer et al., 2005). These errors can be minimized by means of strip adjustment, which is familiar from ALS (e.g. TerraMatch), and which requires repeated measurements of the same surfaces and objects. With MLS, the possible objects and surfaces, which can be used in the correction process, include elevation model, painted patterns in the pavement, vertical poles and building corners. The main focus in mobile laser scanning development in the near future should be on the improvement of the trajectory solution, especially under non-ideal conditions, using both improvements in hardware and computational solutions.

Imperfect boresight calibration, in addition to the navigation errors, between the scanners on a multi-scanner systems leads to multiple reproductions of objects. These kinds of errors in the relative orientation of the instruments lead to errors in the measured point clouds, which can cause problems in the continued processing of the data, such as extraction and modelling of objects. Systematic offset errors between the sensors (ΔX, ΔY, ΔZ) can be detected using observations of common objects close to them. For example, painted patterns on the road surface are feasible for such analysis. The Δroll error can be detected using the elevation model acquired with multiple surveys; Δpitch and Δheading errors can be detected with vertical objects such as poles and building corners. These systematic errors can be corrected appropriately by even manual processing of the data. The time-dependent variation of these data (random part) needs larger numbers of observations for corrections, and this calls for development and use of more automated techniques.

5.4 Test fields

The experiences obtained by utilizing high-quality test fields prove that they are well suited for verifying and comparing the performance of different methods and systems. They can also be utilised in data processing development and testing, e.g. when compiling new algorithms for automatic feature extraction. The FGI's test fields have aroused both domestic and international interest. Requests for data sets for building and tree extraction are still being received from the scientific community, and data from the MLS test field have been collected so far by means of seven different systems.

When planning a test field, several aspects have to be considered; e.g. usability, homogeneity versus heterogeneity of the test field features and surroundings, stability, and reference data collection methods and the required accuracies. As an example, when selecting the test field for MLS system benchmarking, the following properties were sought after:

- Areas with varying GNSS visibility.
- Large number of different structures and objects along the route.
- Flat and undulating terrain.
- Easily accessible for reference measurements and operation.
- Spacious public parking spaces for measurement preparations and special tasks, such as laser intensity research.

The geometric accuracy of modern remote sensing systems is high, for example the accuracy of a MLS derived point cloud under good GNSS conditions can be within 1-2 cm. The relative accuracy can be even higher, when considering individual scanning lines, for example. The commonly applied requirement for reference data is that the accuracy should be at least one order of magnitude better than the property due to be evaluated. It is clear that this requirement is difficult, if not impossible, to fulfil in practice. Robust test field data can still be used to validate the performance of remote sensing systems and feature extraction methods under varying measurement conditions.

In order to be able to separate methodological development from development due to improvement of the data, it is recommended that the same test fields be used with old and new data for future verifications. As test field environments and structures are subject to change, and do change, regular updating is required to ensure that the reference data and test data are comparable.

6 SUMMARY AND CONCLUSIONS

The basic hypothesis in this study was that high-quality test fields and common data sets increase the comparability and the benchmarking capability of the performance metrics of different remote sensing methods and systems. To test the hypothesis, the objectives of the study were to use high-quality test field data to

- International benchmarking of building extraction methods using photogrammetry and airborne laser scanning.
- International benchmarking of individual tree extraction methods using photogrammetry and airborne laser scanning.
- International benchmarking of mobile laser scanning system performance.

Various approaches using common datasets collected at common test fields were tested against high-quality references when benchmarking feature extraction methods. Factors affecting the achieved results that were analysed included several parameters, e.g. the data used, laser point density, level of automation and test site. It was concluded that:

- The principal factor affecting the results is the method used for the datasets used in the studies.
- When applied to building extraction, photogrammetric and hybrid methods produce better planimetric accuracy and enable higher level of detail than methods based solely on laser scanning; however, laser data produce superior results in elevation determination.
- In tree extraction, automated methods based on laser scanning are spatially superior to individual tree detection; tree location and height determination is more accurate than what can be achieved when using photogrammetric methods.
- Airborne image data can be used as aids to the interpretation of the extracted features, e.g. tree species classification or to enhance the created models by providing texture.
- When the laser point density increases, the results of feature extraction improve, but this is highly dependent on site-specific properties, e.g. building complexity and forest type.
- Highly automated systems can produce models that look ‘nice’, but high-quality models still require operator involvement.
- Laser scanning enables the higher degree of automation in the feature extraction process.

When benchmarking the performance of the MLS systems, several systems were used to collect data from a common test field and the geometric accuracy of the acquired point clouds was tested against high-quality reference values. The area selected for system performance was characterised by good GNSS conditions and this meant that the MLS system remained the principal factor affecting the results.

The results achieved confirmed the hypothesis.

REFERENCES

3D Laser Mapping, 2012. Streetmapper 360 brochure. http://www.3dlasermapping.com/ downloads/brochures/StreetMapperBrochure_v2.pdf

Arbeláez, P., Maire, M., Fowlkes, C. and Malik, J., 2011. Contour Detection and Hierarchical Image Segmentation. IEEE TPAMI, 33(5), 898-916. University of California at Berkeley, Computer Vision Group, Contour Detection and Image Segmentation Resources at http://www.eecs.berkeley.edu/Research/ Projects/CS/vision/grouping/resources.html.

BAE Systems, 2000. SOCET Set – User's Manual Version 4.3.

Baillard, C. and Zisserman, A., 1999. Automatic reconstruction of piecewise planar models from multiple views. In: Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition, 559-565.

Baltsavias, E.P., 1999. Airborne laser scanning: existing systems and firms and other resources. *ISPRS Journal of Photogrammetry and Remote Sensing,* 54, 164-198.

Barber, D., Mills, J. and Smith-Voysey, S., 2008. Geometric validation of a ground-based mobile laser scanning system. *ISPRS Journal of Photogrammetry and Remote Sensing*, 63, 128–141.

Barilotti, A., Sepic, F., Abramo, E. and Crosilla, F., 2007. Assessing the 3d structure of the single crowns in mixed alpine forests. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 36 (3/W49A).

Brandtberg, T., 1999. Automatic Individual Tree-Based Analysis of High Spatial Resolution Remotely Sensed Data. Ph.D. Thesis, Acta Universitatis Agriculturae Sueciae, Silvestria 118, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Brandtberg, T., Warner, T., Landenberger, R. and McGraw, J., 2003. Detection and analysis of individual leaf-off tree crowns in small footprint, high sampling density lidar data from the eastern deciduous forest in North America. *Remote Sensing of Environment*, 85, 290-303.

Brenner, C. and Haala, N., 1998. Rapid acquisition of virtual reality city models from multiple data sources. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. 32 Part 5, 323-330.

Brenner, C., 2000. Towards fully automatic generation of city models. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. 32 part 3, 85-92.

Brenner, C., 2005. Building reconstruction from images and laser scanning. *International Journal of Applied Earth Observation and Geoinformation,* 6(3-4), 186-198.

Bunting, P. and Lucas, R., 2006. The delineation of tree crowns in Australian mixed species forests using hyperspectral Compact Airborne Spectrographic Imager (CASI) data. *Remote Sensing of Environment*, 101(2), 230-248.

Burrough, P. and McDonnell, R., 1998. Principles of Geographical Information Systems. Oxford University Press, ISBN: 0-19-823366-3.

Champion, N., 2009. EuroSDR Project, Commission 2 ” Detection of Unregistered Buildings for Updating 2D Databases.”, Final Report, EuroSDR – European Spatial Data Research, Official Publication No 56, 7-54.

Definiens AG, 2006. eCognition Version 5 User Guide.

Falkowski, M.J., Smith, A.M.S., Gessler, P.E., Hudak, A.T., Vierling, L.A. and Evans, J.S., 2008. The influence of conifer forest canopy cover on the accuracy of two individual tree measurement algorithms using lidar data. *Canadian Journal of Forest Research*, 34, 338-350.

Flamanc, D., Maillet, G. and Jibrini, H., 2003. 3D city models: an operational approach using aerialimages and cadastral maps. *ISPRS archives*, Vol XXXIV, Part 3/W8.

Frederiksen, L., Holmgaard, J. and Vester, K., 2004. Automatiseret 3D-bygningsmodellering – fran laserscanning til bygningsmodel. University of Aalborg (in Danish).

Gougeon, F., 2005. The Individual Tree Crown (ITC) Suite Manual. Pacific Forestry Centre, Canadian Forest Service, Natural Resources Canada.Victoria. B.C. Canada.

Grün, A. and Wang, X., 1998. CC-Modeler: a topology generator for 3-D city models. *ISPRS Journal of Photogrammetry and Remote Sensing*, 53(5), 286-295.

Grün, A. and Wang, X., 1999a. CyberCity Modeller, a tool for interactive 3-D city model generation. Photogrammetric Week’99, 317-327.

Grün, A. and Wang, X., 1999b. CyberCity Spatial Information System (CC-SIS): a new concept for the management of 3-D city models in a hybrid GIS. The 20th Asian Conference on Remote Sensing, Nov. 22-25, 1999, Hong Kong, China, 8 p.

Gülch, E. and Müller, H., 2001. New applications of semi-automatic building extraction. In: Proceedings Third International Workshop on Automatic Extraction of Man-Made Objects from Aerial and Space Images. Ascona, Switzerland, 10-15 June 2001. Swets & Zeitlinger Publishers/Balkema, The Netherlands.

Haala, N., 1996. Gebäuderekonstruktion durch Kombination von Bild- und Höhendaten. PhD thesis, Universität Stuttgart, Institut für Photogrammetrie, Deutsche Geodätische Kommission,C 460.

Haala, N., Peter, M., Kremer, J. and Hunter, G., 2008. Mobile LiDAR mapping for 3D point cloud collection in urban areas—A performance test. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 37, 1119–1127.

Heinzel, J.N., Weinacker, H. and Koch, B., 2011. Prior-knowledge-based single-tree extraction. *International Journal of Remote Sensing*, 32, 4999-5020.

Henricsson, O. and Baltsavias, E., 1997. 3-D building reconstruction with ARUBA : a qualitative and quantitative evaluation. International Workshop "Automatic Extraction of Man-Made Objects from Aerial and Space Images (II), 5.-9. May [1997], Ascona, Switzerland. http://e-collection.ethbib.ethz.ch/show?type=inkonf&nr=96

Hirschmugl,M., Franke, M., Ofner,M., Schardt, M. and Raggam, H., 2005. Single tree detection in very high resolution remote sensing data. Proceedings of ForestSat, May 31-June 3, Borås, Sweden. ISSN 1100-0295.

Hofmann, A.D., 2004. Analysis of tin-structure parameter spaces in airborne laser scanner data for 3-D building model generation. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXV(B3/III), 6 p.

Hofmann, A., Maas, H.-G. and Streilein, A., 2003. Derivation of Roof Types by Cluster Analysis in Parameter Spaces of Airborne Laser Scanner Point Clouds. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXIV-3/W13.

Holmgren, J. and Persson, Å., 2004. Identifying species of individual trees using airborne laser scanning. *Remote Sensing of Environment*, 90, 415-423.

Holopainen, M., Mäkinen, A., Rasinmäki, J., Hyyppä, J., Hyyppä, H., Kaartinen, H., Viitala, R., Vastaranta, M. and Kangas, A., 2010a. Effect of tree level airborne laser scanning accuracy on the timing and expected value of harvest decisions. *European Journal of Forest Research*, 29, 899-910.

Holopainen, M., Vastaranta, M., Rasinmäki, J., Kalliovirta, J., Mäkinen, A., Haapanen, R., Melkas, T., Yu, X. and Hyyppä, J., 2010b. Uncertainty in timber assortment estimates predicted from forest inventory data. *European Journal of Forest Research*, 129, 1131-1142.

Honkavaara, E., Ahokas, E., Hyyppä, J., Jaakkola, J., Kaartinen, H., Kuittinen, R., Markelin, L. and Nurminen, K., 2006. Geometric test field calibration of digital photogrammetric sensors. *ISPRS Journal of Photogrammetry and Remote Sensing*, Special Issue on Digital Photogrammetric Cameras, 60(6), 387–399.

Honkavaara, E., Peltoniemi, J., Ahokas, E., Kuittinen, R., Hyyppä, J., Jaakkola, J., Kaartinen, H., Markelin, L., Nurminen, K. and Suomalainen, J., 2008. A permanent test field for digital photogrammetric systems. *Photogrammetric Engineering & Remote Sensing*, 74(1), 95-106.

Hyyppä, H. and Hyyppä, J., 1999. Comparing the accuracy of laser scanner with other optical remote sensing data sources for stand attributes retrieval. *The Photogrammetric Journal of Finland*, 16, 5-15.

Hyyppä, J. and Inkinen, M., 1999. Detecting and estimating attributes for single trees using laser scanner. *The Photogrammetric Journal of Finland*, 16, 27-42.

Hyyppä, J., Hyyppä, H., Inkinen, M., Engdahl, M., Linko, S., and Zhu, Y.H., 2000. Accuracy comparison of various remote sensing data sources in the retrieval of forest stand attributes. *Forest Ecology and Management*, 128, 109-120.

Hyyppä, H., and Hyyppä, J., 2000. Comparing the accuracy of laser scanner with other optical remote sensing data sources for stand attribute retrieval. *The Photogrammetric Journal of Finland*, 16(2), 5-15.

Hyyppä, H. and Hyyppä, J., 2001. Effects of stand size on the accuracy of remote sensing-based forest inventory. *IEEE Transactions on Geoscience and Remote Sensing*, 13, 2613-2621.

Hyyppä, J., Schardt, M., Haggrén, H., Koch, B., Lohr, U., Scherrer, H.U., Paananen, R., Luukkonen, H., Ziegler, M., Hyyppä, H., Pyysalo, U., Friedländer, H., Uuttera, J., Wagner, S., Inkinen, M., Wimmer, A., Kukko, A., Ahokas, A. and Karjalainen, M., 2001. HIGH-SCAN: The first European-wide attempt to derive single-tree information from laserscanner data. *The Photogrammetric Journal of Finland*, 17 (2), 58-68.

Hyyppä, J., Yu, X., Hyyppä, H., Vastaranta, M., Holopainen, M., Kukko, A., Kaartinen, H., Jaakkola, A., Vaaja, M., Koskinen, J. and Alho, A., 2012. Improved forest inventory using penetrated hits and data fusion at feature level. *Remote Sensing*, submitted.

Jaakkola, A., Hyyppä, J., Kukko, A., Yu, X., Kaartinen, M., Lehtomäki, M., and Lin, Y., 2010, A low-cost multi-sensoral mobile mapping system and its feasibility for tree measurements. *ISPRS journal of Photogrammetry and Remote Sensing*, 65 (6), 514-522.

Juhl, J., 1980. Det analytiske stråleudjævningsprogram sANA. Laboratoriet for fotogrammetri og landmåling, University of Aalborg (in Danish).

Kalliovirta, J. and Tokola, T., 2005. Functions for estimating stem diameter and tree age using tree height, crown width and existing stand database information. *Silva Fennica*, 39(2), 227–248.

Kini, A. and Popescu, S.C. , 2004. TreeVaW: a versatile tool for analyzing forest canopy LIDAR data: A preview with an eye towards future. In Proceedings of ASPRS 2004 Fall Conference, Kansas City , Missouri , Sept. 12-16.

Kukko, A., Andrei, C.-O., Salminen, V.-M., Kaartinen, H., Chen, Y., Rönnholm, P., Hyyppä, H., Hyyppä, J., Chen, R., Haggrén, H., Kosonen, I. and Čapek, K., 2007. Road Environment

Mapping System of the Finnish Geodetic Institute—FGI Roamer. In Proceedings of the ISPRS Workshop “Laser Scanning 2007 and SilviLaser 2007”, Espoo, Finland, 12–14 September, 241–247.

Litkey, P., Rönnholm, P., Lumme, J. and Liang, X., 2007. Waveform features for tree identification. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. XXXVI, Part 3/W52, 258-263.

Maltamo, M., Peuhkurinen, J., Malinen, J., Vauhkonen, J., Packalén, P. and Tokola, T., 2009. Predicting tree attributes and quality characteristics of Scots pine using airborne laser scanning data. *Silva Fennica*, 43 (3), 507–521.

Mano, K., Ishii, K., Hirao, M., Tachibana, K., Yoshimura, M., Akca, D. and Gruen, A., 2012. Empirical Accuracy Assessment of MMS Laser Point Clouds. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXIX-B5, 495-498.

Matikainen L., Hyyppä, J., Ahokas, E., Markelin, L., and Kaartinen, H., 2010. Automatic Detection of Buildings and Changes in Buildings for Updating of Maps. *Remote Sensing*, 2(5), 1217-1248.

Mayer, H., Hinz, S., Bacher, U. and Baltsavias, E., 2006. A test of automatic road extraction approaches. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXVI-3, 209–214.

McGlone, C. (Ed.), 2013. Manual of Photogrammetry, Sixth Edition. American Society for Photogrammetry and Remote Sensing, 1372 p.

Mohamed, A. H. and Schwarz, K. P., 1999. Adaptive Kalman Filtering for INS/GPS. *Journal of Geodesy*, 73, 193-203.

Morsdorf, F., Meier, E., Kötz, B., Itten, K. I., Dobbertin, M. and Allgöwer, B., 2004. Lidar-based geometric reconstruction of boreal type forest stands at single tree level for forest and wildland fire management. *Remote Sensing of Environment*, 3(92), 353–362.

Mostafa, M. M. R. and Hutton, J., 2001. Direct positioning and orientation systems - how do they work? What is the attainable accuracy? American Society of Photogrammetry and Remote Sensing Annual Meeting Proceedings, St. Louis, MO, USA, April 24-27, 2001.

Narayana, K., 2011. Solutions for the localization of Mobile Mapping Systems in structured environments. Doctoral thesis, MINES ParisTech, 267 p.

Næsset, E., 1997a. Determination of mean tree height of forest stands using airborne laser scanner data. *ISPRS Journal of Photogrammetry and Remote Sensing*, 52, 49-56.

Næsset, E., 1997b Estimating timber volume of forest stands using airborne laser scanner data. *Remote Sensing of Environment*, 61, 246-253.

Næsset, E., 2002. Predicting forest stand characteristics with airborne scanning laser using a practical two-stage procedure and field data. *Remote Sensing of Environment*, 80, 88-99.

Optech, 2010. Optech Lynx data sheet. http://www.optech.ca/pdf/LynxDataSheet.pdf

Persson, Å., Holmgren, J. and Söderman, U., 2002. Detecting and measuring individual trees using an airborne laser scanner. *Photogrammetric Engineering and Remote Sensing* , 68, 925-932.

Petrie, G., 2010. An introduction to the technology, mobile mapping systems. *Geoinformatics*, 13 (1), 32–43.

Peuhkurinen, J., Maltamo, M., Malinen, J., Pitkänen, J. and Packalén, P., 2007. Preharvest Measurement of Marked Stands Using Airborne Laser Scanning. *Forest Science*, 53, 653-661.

Pfeifer, N., Oude Elberink, S. and Filin, S., 2005. Automatic tie elements detection for laser scanner strip adjustment. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. 36, Part 3/W19, 174-179.

Pitkänen, J. 2005. A multi-scale method for segmentation of trees in aerial images. Forest Inventory and Planning in Nordic Countries, Proceedings of the SNS-meeting at Sjusjøen, Norway, September 6-8, 2004. Norwegian Institute of Land Inventory, NIJOS-report 09/05, 207-216.

Pitkänen, J., Maltamo, M., Hyyppä, J. and Yu, X., 2004. Adaptive Methods for Individual Tree Detection on Airborne Laser Based Canopy Height Model. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. XXXVI, Part 8/W2, 187-191.

Reinartz, P., d'Angelo, P., Krauß, T., Poli, D., Jacobsen, K., Buyuksalih, G., 2010. Benchmarking and quality analysis of DEM generated from high and very high resolution optical stereo satellite data. *The International Archives of Photogrammetry and Remote Sensing and Spatial Information Sciences*, Vol. XXXVIII, Part 1, 6 p.

RIEGL, 2012. http://www.riegl.com/uploads/tx_pxpriegldownloads/10_DataSheet_VMX-250_20-09-2012.pdf

Rottensteiner, F. and Briese, Ch., 2003. Automatic generation of building models from LIDAR data and the integration of aerial images. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. XXXIV, Part 3/W13, 174-180.

Rottensteiner, F., Sohn, G., Jung, J., Gerke, M., Baillard, C., Benitez, S. and Breitkopf, U., 2012. The ISPRS Benchmark on Urban Object Classification and 3D Building Reconstruction. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, I-3, 293-298.

Shan, J. and Toth, C. (Eds.), 2009. Topographic Laser Ranging and Scanning: principles and processing. CRC Press, Taylor & Francis London, 590 p.

Sithole, G. and Vosselman, G., 2004. Experimental comparison of filter algorithms for bare-Earth extraction from airborne laser scanning point clouds. *ISPRS Journal of Photogrammetry and Remote Sensing*, 59, 85-101.

Solberg, S., Næsset, E. and Bollandsas, O.M, 2006. Single Tree Segmentation Using Airborne Laser Scanner Data in a Structurally Heterogeneous Spruce Forest. Photogrammetric *Engineering & Remote Sensing*, 72(12), 1369–1378.

Straub, B., 2003. Automatische Extraktion von Bäumen aus Fernerkundungsdaten. Reihe C, Deutsche Geodätische Kommission, München, Vol. 572, 99 p.

Süveg, I. and Vosselman, G., 2004. Reconstruction of 3D building models from aerial images and maps. *ISPRS Journal of Photogrammetry and Remote Sensing*, 58(3-4), 202-224.

Söderman, U., Ahlberg, S., ÅPersson, Å. and Elmqvist, M., 2004. Towards rapid 3D modelling of urban areas. In Proceeding of the Second Swedish-American Workshop on Modeling and Simulation (SAWMAS-2004), Cocoa Beach, FL, USA, February 2004.

TerraSolid, 2003. TerraScan User's Guide.

Vastaranta, M., Holopainen, M., Yu, X., Hyyppä, J., Mäkinen, A., Rasinmäki, J., Melkas, T., Kaartinen, H. and Hyyppä, H., 2011a. Effects of ALS individual tree detection error sources on forest management planning calculations. *Remote Sensing*, 3, 1614-1626.

Vastaranta, M., Holopainen, M., Yu, X., Haapanen, R., Melkas, T., Hyyppä, J. and Hyyppä. H., 2011b. Individual tree detection and area-based approach in retrieval of forest inventory characteristics from low-pulse airborne laser scanning data. *The Photogrammetric Journal of Finland*, 22, 1-13.

Vastaranta, M., Kankare, V., Holopainen, M., Yu, X., Hyyppä, J. and Hyyppä, H., 2012. Combination of individual tree detection and area-based approach in imputation of forest variables using airborne laser data. *ISPRS Journal of Photogrammetry and Remote Sensing*, 67, 73-79.

Vauhkonen, J., Ene, L., Gupta, S., Heinzel, J., Holmgren, J., Pitkänen, J., Solberg, S., Wang, Y., Weinacker, H., Hauglin, K.M., Lien, V., Packalén, P., Gobakken, T., Koch, B., Næsset, E., Tokola, T. and Maltamo, M., 2011. Comparative testing of single-tree detection algorithms under different types of forest. *Forestry*, 18(1), 27-40.

Vosselman, G., 1999. Building reconstruction using planar faces in very high density height data. *The International Archives of Photogrammetry and Remote Sensing and Spatial Information Sciences*, Vol. 32(3-2W5), 87-92.

Vosselman, G. and Dijkman, S., 2001. 3D building model reconstruction from point clouds and ground plans. *The International Archives of Photogrammetry and Remote Sensing and Spatial Information Sciences,* 34(3W4), 37-43.

Vosselman, G. and Maas, H.-G. (Eds.), 2010. Airborne and Terrestrial Laser Scanning. Whittles Publishing, 336 p.

Vosselman, G. and Süveg, I., 2001. Map based building reconstruction from laser data and images. Automatic Extraction of Man-Made Objects from Aerial and Space Images (III), Ascona, Switzerland, June 11-15, Balkema Publishers, 231-239.

Wagner, W., Ullrich, A., Melzer, T., Briese, C. and Kraus, K., 2004. From Single-pulse to Full-waveform Airborne Laser Scanners: Potential and Practical Challenges. *The International Archives of Photogrammetry and Remote Sensing and Spatial Information Sciences*, Vol. XXXV, Part B3 , 201-206.

Wagner, W., Hollaus, M., Briese, C. and Ducic, V., 2008. 3D vegetation mapping using small-footprint full-waveform airborne laser scanners. *International Journal of Remote Sensing*, 29(5), 1433-1452.

Wolf (né Straub), B.-M. and Heipke, C., 20075. Automatic extraction and delineation of single trees from remote sensing data. *Machine Vision and Applications*, 18, 317-330.

Yen, K.S., Akin, K., Lofton, A., Ravani, B. and Lasky, T.A., 2010. Using Mobile Laser Scanning to Produce Digital Terrain Models of Pavement Surfaces. Final report of the Advanced Highway Maintenance and Construction Technology Research Center research project, University of California at Davies, USA, http://ahmct.ucdavis.edu/pdf/UCD-ARR-10-11-30-01.pdf

Yu, X., Hyyppä, J., Kaartinen, H. and Maltamo, M., 2004. Automatic detection of harvested trees and determination of forest growth using airborne laser scanning. *Remote Sensing of Environment*, 90, 451-462.

Yu, X., Hyyppä, J., Vastaranta, M., Holopainen, M. and Viitala, R., 2011. Predicting individual tree attributes from airborne laser point clouds based on random forests technique. *ISPRS Journal of Photogrammetry and Remote Sensing*, 66, 28-37.

Ziegler, M., Konrad, H., Hofrichter, J., Wimmer, A., Ruppert, G., Schardt, M.and Hyyppä, J., 2000. Assessment of forest attributes and single-tree segmentation by means of laser scanning. *Proceedings of SPIE*, 4035, 73-84.

ERRATA

In Publication **I**, page 229.

is: Mean squared error (abbreviated to MSE), was calculated.

$$MSE = \sum_{i=1}^{n} (e_{1i} - e_{2i})^2 / (n-1)$$

where e_{1i} is the result obtained with the described retrieved model, e_{2i} is the corresponding reference measured value, and n is the number of samples. MSE was...

should be: Root mean squared error (abbreviated to RMSE), was calculated.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (e_{1i} - e_{2i})^2}{n}}$$

where e_{1i} is the result obtained with the described retrieved model, e_{2i} is the corresponding reference measured value, and n is the number of samples. RMSE was...

In Publication **III**, page 9.

is: Figure 2-1: Espoonlahti test site A (left) and B (right) as color coded digital surface model (TopoSys Falcon).

should be: Figure 2-1: Espoonlahti test site A (left) and B (right) as colour coded digital surface model (Optech ALTM 2033).

In Publication **III**, page 16.

is: ...(abbreviated as PFC_hybrid in Chapter 4).

should be: ...(abbreviated as PFC_laser in Chapter 4).

In Publication **III**, page 32.

is: ...are shown in Figures Figure 3-10 and **Fehler! Verweisquelle konnte nicht gefunden werden.**.

should be: ...are shown in Figures 3-10 and 3-11.

PUBLICATIONS

I. Kaartinen, H., Hyyppä, J., Gülch, E., Vosselman, G., Hyyppä, H., Matikainen, L., Hofmann, A.D., Mäder, U., Persson, Å., Söderman, U., Elmqvist, M., Ruiz, A., Dragoja, M., Flamanc, D., Maillet, G., Kersten, T., Carl, J., Hau, R., Wild, E., Frederiksen, L., Holmgaard, J. and Vester, K., 2005. Accuracy of 3D city models: EuroSDR comparison. Proceedings of ISPRS Workshop "Laser scanning 2005", September 12-14, 2005, Enschede, The Netherlands, The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXVI(Part 3/W19), 227-232, CD-ROM.

http://www.isprs.org/proceedings/XXXVI/3-W19/papers/227.pdf

II. Kaartinen, H. and Hyyppä, J., 2006. EuroSDR-Project Commission 3 "Evaluation of Building Extraction", Final Report, In: EuroSDR - European Spatial Data Research, Official Publication No 50, 9-77.

http://bono.hostireland.com/~eurosdr/publications/50.pdf

III. Kaartinen, H. and Hyyppä, J., 2008. EuroSDR/ISPRS Project, Commission II "Tree Extraction", Final Report, EuroSDR – European Spatial Data Research, Official Publication No 53, 56 p.

http://bono.hostireland.com/~eurosdr/publications/53.pdf

IV. Kaartinen, H., Hyyppä, J., Yu, X., Vastaranta, M., Hyyppä, H., Kukko, A., Holopainen, M., Heipke, C., Hirschmugl, M., Morsdorf, F., Næsset, E., Pitkänen, J., Popescu, S., Solberg, S., Wolf, B.M. and Wu, J.-C., 2012. An International Comparison of Individual Tree Detection and Extraction Using Airborne Laser Scanning. Remote Sensing, 4(4), 950-974.

http://www.mdpi.com/2072-4292/4/4/950

V. Kaartinen, H., Hyyppä, J., Kukko, A., Jaakkola, A. and Hyyppä, H., 2012. Benchmarking the Performance of Mobile Laser Scanning Systems Using a Permanent Test Field. Sensors 12(9), 12814-12835.

http://www.mdpi.com/1424-8220/12/9/12814

VI. Kaartinen, H., Hyyppä, J., Kukko, A., Lehtomäki, M., Jaakkola, A., Hyyppä, H., Vosselman,G., Elberink, S.O., Rutzinger; M., Pu, S. and Vaaja, M., 2013. EuroSDR-Project Commission II "Mobile Mapping - Road Environment Mapping using Mobile Laser Scanning", Final Report, In: EuroSDR - European Spatial Data Research, Official Publication No 62, 49-95.

http://www.eurosdr.net/publications/62.pdf