Aktuelle Forschung Medizintechnik

RESEARCH

Yulia Levakhina

Three-Dimensional Digital Tomosynthesis

Iterative Reconstruction, Artifact Reduction and Alternative Acquisition Geometry

Springer Vieweg

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Unter den Zukunftstechnologien mit hohem Innovationspotenzial ist die Medizintechnik in Wissenschaft und Wirtschaft hervorragend aufgestellt, erzielt überdurchschnittliche Wachstumsraten und gilt als krisensichere Branche. Wesentliche Trends der Medizintechnik sind die Computerisierung, Miniaturisierung und Molekularisierung. Die Computerisierung stellt beispielsweise die Grundlage für die medizinische Bildgebung, Bildverarbeitung und bildgeführte Chirurgie dar. Die Miniaturisierung spielt bei intelligenten Implantaten, der minimalinvasiven Chirurgie, aber auch bei der Entwicklung von neuen nanostrukturierten Materialien eine wichtige Rolle in der Medizin. Die Molekularisierung ist unter anderem in der regenerativen Medizin, aber auch im Rahmen der sogenannten molekularen Bildgebung ein entscheidender Aspekt. Disziplinen übergreifend sind daher Querschnittstechnologien wie die Nano- und Mikrosystemtechnik, optische Technologien und Softwaresysteme von großem Interesse.

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Preface by the Series Editor

The book *Three-Dimensional Digital Tomosynthesis: Iterative Reconstruction, Artifact Reduction and Alternative Acquisition Geometry* by Dr. Yulia M. Levakhina is the 14th volume of the Springer-Vieweg series of excellent theses in medical engineering. The thesis of Dr. Levakhina has been selected by an editorial board of highly recognized scientists working in that field.

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Foreword

Conventional X-ray imaging suffers from the drawback that it only produces two-dimensional projections of a three-dimensional object. This results in a reduction in spatial information (although an experienced radiologist might be able to compensate for this). In any case, a projection represents an averaging. The result of the averaging can be imagined if one were to overlay several radiographic sections at the light box for diagnosis. It would be difficult for even an expert to interpret the results, as averaging comes along with a considerable reduction in contrast, compared with the contrast present in one slice.

In the 1920s, the desire to undo the averaging process that characterizes conventional X-ray radiography led to the first tomographic concept. The word tomography was considerably influenced by the Berlin physician Grossmann, whose Grossmann tomograph was able to image one single slice of the body. The principle of the conventional or analog geometric tomography method is very simple. During image acquisition, the X-ray tube is linearly moved in one direction, while the X-ray film is synchronously moved in the opposite direction. For this reason, only points in the plane of the rotation center are imaged sharply. All points above and below this region are blurred, more so at greater distances from the center of rotation. However, blurred information above and below the center of rotation does not disappear, but is superimposed on the sharp image as a kind of gray veil or haze. Therefore, a substantial reduction in contrast is noticeable.

This book on *Three-Dimensional Digital Tomosynthesis: Iterative Reconstruction, Artifact Reduction and Alternative Acquisition Geometry* summarizes the research work of Dr. Yulia Levakhina. The work has been carried out at the Institute of Medical Engineering at the University of Lübeck. It focuses on image-improvement methods for a tomosynthesis device working with insufficient and inconsistent projection data.

If the raw projection data to be used for 3D reconstruction in X-ray imaging are insufficient and/or inconsistent, artifacts cover the reconstructed objects that reduce the diagnostic value of the images significantly. However, digital tomosynthesis is a concept that is based on the reconstruction of three-dimensional volumes from a few projections.

This book concludes the results of a number of original papers and innovations Dr. Yulia Levakhina has achieved in the discipline of digital tomosynthesis. A new method for the reduction of out-of-focus artifacts and an innovative acquisition geometry are spotlights that significantly exceed the current state-of-the-art.

November 2013, Lübeck

Prof. Dr. Thorsten M. Buzug
Institute of Medical Engineering
University of Lübeck

It has been said that something as small as the flutter of a butterfly's wing can ultimately cause a typhoon halfway around the world - Chaos Theory

"The Butterfly Effect" (film)

Acknowledgments

When four and a half years ago I arrived from Moscow to Lübeck with a suitcase with some clothes and a "fresh" diploma, I could have not even imagined what wonderful and challenging journey is awaiting for me. During this time I have collected a lot of stuff which now can fill a half of an LKW-car and I have gained a valuable experience which is unmeasurable. But what is the most important, is that I met a lot of incredible people without whom I would probably have never reached my goals.

I am very lucky person, because I had such a great supervisor as Prof. Thorsten M. Buzug. I thank him for his help throughout the years in moments when I needed help. A the same time he gave me a chance to try everything on my own and to find my own way: it was hard but very important on the long run. Thank him, I learned how to do research and how *to think*. This helped me a lot to grow professionally and personally. While being quite busy person, he always found a time for a scientific discussion or for proofreading of a paper even if it was finished a few hours before the deadline. Yes, *every* student including myself start to write at the last moment and I am thankful for his understanding. He believed that I can find a solution to any problem and that I can accomplish any task. Indeed, with his support, optimism and enthusiasm, each time I succeed.

I must say a special thank to you the Graduate School for Computing in Medicine and Life Sciences and DFG for funding this project and for my scholarship. And again thanks Prof. Buzug for admitting me to this program. Based on my motivation letter and on the list of my grades he invited me to a personal interview (from Moscow) and organized a very exciting day at the Institute of Medical Engineering (IMT) with a pizza in the evening. Few weeks after the interview I got an acceptance and with no doubts started to pack my luggage. The last six monthes of my study were supported by the company YXLON International GmbH, Hamburg.

During my PhD time I traveled as much as I never done in my life before. I had an opportunity to visit a number of conferences and summer schools and to presented my research to the CT community. In such events I meet many interesting people (including Prof. J. Fessler, Prof. E. Todd Quinto and Dr. B. de Man), I learned a lot from their talks and I was inspired by exchanging ideas.

But of course, the main refreshing insight and idea generation came from my colleagues at IMT (listed in a random order): Alex Opp, Andreas Mang, Sven Biederer, Kerstin Ludtke-Buzug, Matthias Kleine, Maik Stille, Gael Bringout, Matthias Graeser, Alina Toma, Tina Anne Schuetz, Stefan Becker, Maren Bobek, Mandy Grüttner, Tomas Weidinger. Thank you for all nice moments (also listed in a random order): discussing, talking, chatting (also at nights), drinking coffee, reading papers, doing science, learning, teaching, going out, shopping, proofreading, writing, solving IT-problems, going to partys, doing sport, having fun at conferences. I had a great time with my office-mate Bärbel Kratz who shared an office with me. Many thanks goes also to all undergraduate students at IMT and especially to my bachelor student Aileen Cordes and my master student Sylvia Kiencke. While supervising your thesis I learned quite a lot of new things. I wish both of you great success with your PhD study.

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Without Sergey Tarassenko I would have never ended up with an idea of doing PhD in Germany. Thank you for this and for your support during the first two years of my study.

This list is definitely not complete without my friends from Moscow and my family. Thanks for not forgetting me and always looking forward when I am coming back for a vacation. Thanks to all of you for remaining my friends even if there are almost 2000 km between us, thanks for all the support you gave me, thanks for believing in me. I miss all of you: Tatjana and Max Kurganskiy, Mischa Kruchkov, Konstantin Barsukov, Alex Asmodeev, Larisa Levakhina and Konstantin Mozgov.

Last but not least, my deep appropriation goes to Jan Müller. Thank you for being my science-mate and soul-mate, for your your love, support and unwavering belief in me.

November 2013, Lübeck Yulia Levakhina

Abstract

Digital tomosynthesis (DT) is an X-ray based limited angle imaging technique. It is a non-invasive and non-destructive method for three-dimensional visualization of the inner structures of an object. Tomosynthesis is historically the first X-ray based tomographic technique. However, it has been forgotten with the development of computed tomography (CT). Only recently, developments in the field of digital X-ray detectors and computer technologies have led to a renewed interest in this technique. A high in-plane resolution, three-dimensionality and a low radiation dose make DT an attractive alternative to CT in many imaging applications. The most widely used DT application in medical imaging is breast imaging. In this thesis an alternative application of tomosynthesis for imaging of hands is considered.

In contrast to CT, the DT projection dataset is incomplete, because the X-ray source and the detector do not completely rotate around the patient. The incompleteness of the dataset violates the tomographic sufficiency conditions and results in limited angle artifacts in the reconstructed images. Although DT is a volumetric imaging technique and provides dimensional information about the location of structures, the complete three-dimensional information about the object cannot be reconstructed. Therefore, one of the major issues is the improvement of the tomosynthesis image quality.

This thesis addresses the connection of the reconstruction problem and the incompleteness of the DT dataset. The main aim is to understand the factors, which cause the formation of limited angle artifacts and, thus, to account for them in order to improve the image quality and the axial resolution.

A thorough literature review on the tomosynthesis topic is presented in each chapter. A three-dimensional tomosynthesis reconstruction framework including fast and accurate forward- and backprojectors and flexible geometry, has been developed to study several aspects of DT. All experimental studies presented in this thesis use simulated data and real clinical data of hands.

Two conceptually different strategies for improving the image quality are investigated. The first strategy deals with reconstruction algorithms. Within this strategy a non-linear backprojection is used in the simultaneous algebraic reconstruction technique (SART). The non-linear backprojection is based on a spatially-adaptive weighting scheme which is designed to reduce out-of-focus artifacts caused by high-absorption structures. The novel concepts of the backprojected space representation and a dissimilarity degree are proposed to construct this weighting scheme. It will be shown that the weighted SART reduces contribution of high-absorption structures to the formation of artifacts on out-of-focus slices while preserving these features in the in-focus slices.

The second strategy is based on the assumption that the incompleteness degree of the dataset can be reduced by using more appropriate acquisition geometry. The impact of several acquisition parameters to the tomosynthesis image quality for the standard geometry used in clinics is studied. In the presented study the limitations of the standard geometry will be demonstrated. Although the image quality can be improved by acquiring data over a wider angular range, above a certain threshold this becomes infeasible. Therefore, the results motivate to search for an alternative acquisition geometry. A novel dual-axis acquisition geometry with a tiltable platform will be proposed. The data in the original direction are acquired using the X-ray tube movement and the data in the additional perpendicular direction are acquired by tilting the object. The projection data acquired along two axes have less incompleteness. Based on a simulation study it will be shown that such acquisition geometry results in less artifacts and improves the axial resolution.

The findings and conclusions of this work have a number of important implications for future research, therefore, the suggestions for further work are given for each addressed topic.

Contents

Chapter 1

Introduction

Contents

1.1 X-ray imaging and tomosynthesis

X-ray based imaging techniques are already the subject of active research for almost 130 years starting right after the discovery of X-rays by Wilhelm Conrad Röntgen in 1895 (Roentgen 1895a, Roentgen 1895b) up to the present. The nature of X-rays to penetrate the object which has been used to visualize the inner structures of opaque objects have changed the world in medical and non-medical application fields. It opened new opportunities in recognition and understanding of human diseases without surgical intervention and in non-destructive material testing (NDT). Although the human body is "transparent" for X-rays and can be visualized using X-rays, a single X-ray image contains only the projective overlap of all structures in the body. The three-dimensional information about the structure locations can be recovered only by using the principle of tomography. For this, a set of X-ray images from different sides must be measured and the inverse problem of image reconstruction must be solved.

Historically, the first X-ray imaging modality which aims to visualize an object in three-dimensions was tomosynthesis. In tomosynthesis projection images are acquired over a limited angular range. In general, this is not enough to reconstruct the object

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exactly. However, some three-dimensional information can still be recovered but the image quality is degraded by blurring out-of-focus artifacts. Back in the 1930s to 1970s, tomosynthesis was a promising imaging modality and a lot of effort was given to improve its performance in terms of speed and to obtain images with less artifacts. A lack of digital X-ray detector technology was the main stopping factor in the development of tomosynthesis. With the development of the true tomographic principle in 1972 (Hounsfield 1973, Ambrose 1973), in which the data is obtained over the 360^o angular range, tomosynthesis was abandoned because of the clear advantages of CT to produce slices of an object without typical tomosynthesis blurring artifacts. Tomosynthesis has regained scientific interest in the beginning of the 21st century because of technological advances. The combination of fast digital flat-panel X-ray detectors and improved computer technologies offered a solution to the problem of long examination time and long processing time. It made tomosynthesis practically feasible. Nowadays, tomosynthesis is one of the "hot topics" in the field of X-ray based tomographic imaging (Sechopoulos 2013a, Sechopoulos 2013b). The main field of tomosynthesis application is breast imaging. Alternative applications also exist. The focus of this thesis is tomosynthesis with application to the imaging of human hands. Tomosynthesis is an attractive alternative to CT and computed radiography (CR) for imaging of hands because DT combines the simplicity, high resolution and low dose of CR and the three-dimensionality of CT.

1.2 Contribution of this work

With the development of advanced detectors and PC, digital tomosynthesis is again of great interest among scientists. However, the problem of data incompleteness of the projection dataset does not disappear. The incompleteness of the data violates tomographic sufficiency conditions and results in images with artifacts and limits the in-depth resolution. This makes an accurate image reconstruction a very challenging task.

The main goals of this work are to understand what influences the tomosynthesis performance in terms of image quality and artifacts and to propose methods to improve the tomosynthesis performance. An understanding of the tomosynthesis topic in general is important, therefore an intensive literature review on tomosynthesis history, existing methodology, the state of the art and open problems will be presented. Additionally, the study of the related CT subjects and the adaptation of several CT algorithms for tomosynthesis will be given.

Two different approaches to improve tomosynthesis performance will be proposed in this work. The first approach is based on the optimization of the reconstruction strategy for the given limited data. Given the measured tomosynthesis data, a suitable reconstruction algorithm is required to provide images with less artifacts and better quality. This includes the choice of the reconstruction algorithm and its parameters as well as an accurate implementation. The second approach is based on the acquisition of more reliable data using an adapted acquisition geometry. It can improve the image quality and resolution because the acquisition parameters and geometry influence the incompleteness degree of the obtained data. If the data incompleteness is reduced, the image quality and resolution will be improved. As such geometry, a novel dual-axis acquisition geometry will be proposed.

The contributions of this work are following

- **A topical review** which includes a thorough literature review on tomosynthesis and a comparison of the state of the art tomosynthesis device with CT and micro-CT devices. Since tomosynthesis and CT are closely related, also the review of CT literature is necessary for several topics. The obtained knowledge, then, is adapted and applied for tomosynthesis.
- **A short summary of limited angle tomography** which explains where the limited angle artifacts come from.
- **Implementation the reconstruction toolbox** for three-dimensional tomosynthesis from the scratch using the knowledge from CT. Each chapter of this thesis (if applicable) contains corresponding consideration regarding practical implementation of algorithms in MATLAB® and C++ (mex). The toolbox includes
  - fast and accurate forward- and backprojector (FB and BP) for two- and three-dimensions [2 - 4], [15];
  - several standard iterative algebraic (SART) and statistical reconstruction algorithms with the possibility to vary parameters (number of iterations, initial guess, projection access order) [1], [4], [5];
  - a weighted version of simple backprojection (ωBP) and a weighted algebraic reconstruction (ωSART) with an adaptive weighting scheme and a flexible control of the weighting parameters for tomosynthesis and CT [6 - 8], [11];
  - a flexible geometry with the possibility to change the acquisition parameters (number of projections, the angular range and the angular step size), distances (source-to-object, source-to-detector, source-to-isocenter) and the X-ray tube trajectory [9], [10];

  - methods to construct the backprojected space representation in two- and three-dimensions [6 - 8], [11].

- **Finding an optimal implementation** of every single component of the reconstruction toolbox. It includes

  - a study of the advantages and drawbacks, accuracy, complexity and possibility of fast implementation of FB and BP methods for CT [3];
  - fast and accurate implementation of the distance-driven projector for CT and tomosynthesis with only one loop for all angular cases [3], [4];
  - a method for an optimal memory handling for processing large tomosynthesis datasets [3], [4];
  - a method to address a large number of variables from different datasets (reconstruction and projections) [3], [4].

- **A parameter optimization analysis** which includes

  - a discussion of basis functions for image representation and interpolation strategy for FP and BP [2], [3];
  - a parameter optimization for SART on the example of the projection access order [5], [14];
  - a study on parameters for the dissimilarity-based weighting scheme for tomosynthesis and additionally for metal artifact reduction in CT;
  - a study in the impact of the geometry acquisition parameters on tomosynthesis performance [10], [12], [13].

- **Novel ideas** which include

  - a usage of the distance-driven FP and BP algorithm for tomosynthesis and benefit from the fixed detector geometry [3], [4];
  - a novel data-based projection access order for SART based on the minimum correlation [5], [14];
  - the backprojected space representation as a generalization of the stackgram approach [6 - 8], [11];
  - data dissimilarity coefficients in BP-space [6 - 8], [11];
  - a weighing scheme for tomosynthesis based on the dissimilarity in BP space for simple backprojection and for SART [6 - 8], [11];
  - BP-space for metal artifact reduction in CT;
  - a novel dual-axis acquisition geometry for tomosynthesis [9], [10].