An Error Analysis of Structured Light Scanning of Biological Tissue

This paper presents an error analysis and correction model for four structured light methods applied to three common types of biological tissue: skin, fat and muscle. Despite its many advantages, structured light is based on the assumption of direct reflection at the object surface only. This assumption is violated by most biological material e.g. human skin, which exhibits subsurface scattering. In this study, we find that in general, structured light scans of biological tissue deviate significantly from the ground truth. We show that a large portion of this error can be predicted with a simple, statistical linear model based on the scan geometry. As such, scans can be corrected without introducing any specially designed pattern strategy or hardware. We can effectively reduce the error in a structured light scanner applied to biological tissue by as much as factor of two or three.

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A performance assessment of a 2 axis scanning mirror galvanometer for powder bed fusion
Additive Manufacturing by powder bed fusion allows production of high strength parts with complex features, not possible through conventional manufacturing. To experiment and test current theory within laser processing of metal powder, an
open and customizable laser scanner platform is developed and constructed. The platform seeks to fully support and enable the laser driven process of selective consolidation metal powder, as most industrially available powder bed fusion machine tools are closed and proprietary systems. This allows the machine tool manufacturer to strictly control how the system is used and therefore maintain stability through limiting the operator to use proprietary software hardware and process materials but unfortunately limits to an equally wide extent how such machine tools can be applied for research purposes as it renders the scientist to become a mere operator of the machine tool. A galvanometer based laser scanning system is here presented. The system was designed to meet a theoretical resolution of 0.009 mm. From inspiration of the use of optomechanical hole plates as reference artefacts for coordinate metrology a test was conducted to verify the accuracy of the laser scanning system. The system was found to perform excellent for relative positioning. Absolute positioning of the laser beam did not conform with design specifications, as the test deviated by 0.12 mm with respect to the nominal test value, yet this is expected in the future to be met from the implementation of a better galvanometer control system.

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**In-line 3D print failure detection using computer vision**

Here we present our findings on a novel real-time vision system that allows for automatic detection of failure conditions that are considered outside of nominal operation. These failure modes include warping, build plate delamination and extrusion failure. Our system consists of a calibrated camera whose position and orientation is known in the machine coordinate system. We simulate what the object under print should look like for any given moment in time. This is compared to a segmentation of the current print, and statistical detection of significant deviation. We demonstrate that this methodology precisely and unambiguously detects the time point of print failure.

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**Photogrammetry for Repositioning in Additive Manufacturing**

In this preliminary work, we present our current status on how to use single camera photogrammetry to determine the orientation of an additively manufactured partly finished object that has been repositioned in the printing chamber from a single image taken with a calibrated camera, and comparing this to the CAD model of the object. We describe how knowledge can be used to update the machine code of the printer such that printing of the object can be resumed. This opens possibilities for embedding and assembling foreign parts into the additive manufacturing pipeline, adding another layer of flexibility to the process.
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Scene reassembly after multimodal digitization and pipeline evaluation using photorealistic rendering
Transparent objects require acquisition modalities that are very different from the ones used for objects with more diffuse reflectance properties. Digitizing a scene where objects must be acquired with different modalities requires scene reassembly after reconstruction of the object surfaces. This reassembly of a scene that was picked apart for scanning seems unexplored. We contribute with a multimodal digitization pipeline for scenes that require this step of reassembly. Our pipeline includes measurement of bidirectional reflectance distribution functions and high dynamic range imaging of the lighting environment. This enables pixelwise comparison of photographs of the real scene with renderings of the digital version of the scene. Such quantitative evaluation is useful for verifying acquired material appearance and reconstructed surface geometry, which is an important aspect of digital content creation. It is also useful for identifying and improving issues in the different steps of the pipeline. In this work, we use it to improve reconstruction, apply analysis by synthesis to estimate optical properties, and to develop our method for scene reassembly.

General information
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Organisations: Department of Applied Mathematics and Computer Science, Image Analysis & Computer Graphics, Department of Physics, Neutrons and X-rays for Materials Physics
Precision and Accuracy Parameters in Structured Light 3-D Scanning

Structured light systems are popular in part because they can be constructed from off-the-shelf low cost components. In this paper we quantitatively show how common design parameters affect precision and accuracy in such systems, supplying a much needed guide for practitioners. Our quantitative measure is the established VDI/VDE 2634 (Part 2) guideline using precision made calibration artifacts. Experiments are performed on our own structured light setup, consisting of two cameras and a projector. We place our focus on the influence of calibration design parameters, the calibration procedure and encoding strategy and present our findings. Finally, we compare our setup to a state of the art metrology grade commercial scanner. Our results show that comparable, and in some cases better, results can be obtained using the parameter settings determined in this study.

Real Time Structured Light and Applications

Structured light scanning is a versatile method for 3D shape acquisition. While much faster than most competing measurement techniques, most high-end structured light scans still take in the order of seconds to complete.
Low-cost sensors such as Microsoft Kinect and time of flight cameras have made 3D sensor ubiquitous and have resulted in a vast amount of new applications and methods. However, such low-cost sensors are generally limited in their accuracy and precision, making them unsuitable for e.g. accurate tracking and pose estimation.

With recent improvements in projector technology, increased processing power, and methods presented in this thesis, it is possible to perform structured light scans in real time with 20 depth measurements per second. This offers new opportunities for studying dynamic scenes, quality control, human-computer interaction and more.

This thesis discusses several aspects of real time structured light systems and presents contributions within calibration, scene coding and motion correction aspects. The problem of reliable and fast calibration of such systems is addressed with a novel calibration scheme utilising radial basis functions [Contribution B]. A high performance flexible open source software toolkit is presented [Contribution C], which makes real time scanning possible on commodity hardware. Further, an approach is presented to correct for motion artifacts in dynamic scenes [Contribution E].

An application for such systems is presented with a head tracking approach for medical motion correction [Contribution A, F]. This aims to solve the important problem of motion artifacts, which occur due to head movement during long acquisition times in MRI and PET scans. In contrast to existing methods, the one presented here is MRI compatible [Contribution D], not dependent on fiducial markers, and suitable for prospective correction.

Factors contributing to accuracy and precision of structured light systems are investigated with a study of performance factors [Contribution G]. This is also done in the context of biological tissue, which exhibit subsurface effects and other undesirable effects [Contribution H], and it is shown that this error is to a large extent deterministic and can be corrected.

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Method for Surface Scanning in Medical Imaging and Related Apparatus
A method and apparatus for surface scanning in medical imaging is provided. The surface scanning apparatus comprises an image source, a first optical fiber bundle comprising first optical fibers having proximal ends and distal ends, and a first optical coupler for coupling an image from the image source into the proximal ends of the first optical fibers, wherein the first optical coupler comprises a plurality of lens elements including a first lens element and a second lens element, each of the plurality of lens elements comprising a primary surface facing a distal end of the first optical coupler, and a secondary surface facing a proximal end of the first optical coupler.

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An MRI Compatible Surface Scanner

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Correction of Motion Artifacts for Real-Time Structured Light

While the problem of motion is often mentioned in conjunction with structured light imaging, few solutions have thus far been proposed. A method is demonstrated to correct for object or camera motion during structured light 3D scene acquisition. The method is based on the combination of a suitable pattern strategy with fast phase correlation image registration. The effectiveness of this approach is demonstrated on motion corrupted data of a real-time structured light system, and it is shown that it improves the quality of surface reconstructions visually and quantitively.

Quality Assurance Based on Descriptive and Parsimonious Appearance Models

In this positional paper, we discuss the potential benefits of using appearance models in additive manufacturing, metal casting, wind turbine blade production, and 3D content acquisition. Current state of the art in acquisition and rendering of appearance cannot easily be used for quality assurance in these areas. The common denominator is the need for descriptive and parsimonious appearance models. By ‘parsimonious’ we mean with few parameters so that a model is useful both for fast acquisition, robust fitting, and fast rendering of appearance. The word ‘descriptive’ refers to the fact...
that a model should represent the main features of the acquired appearance data. The solution we propose is to reduce the degrees of freedom by greater use of multivariate statistics.

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Structured Light Scanning of Skin, Muscle and Fat
We investigate the quality of structured light 3D scanning on pig skin, muscle and fat. These particular materials are interesting in a number of industrial and medical use-cases, and somewhat challenging because they exhibit subsurface light scattering. Our goal therefor is to quantify the amount of error that various encoding strategies show, and propose an error correcting model, which can bring down the measurement bias considerably. Samples of raw and unprocessed pig tissue were used with the number of sampled surface points Nmeat = 1.2 * 10^6, Nskin = 4.0 * 10^6 and Nfat = 2.1 * 10^6 from 8 different pieces of tissue. With the standard N-step phase shifting method, the bias and RMS errors were found to be 0.45 ± 0.22mm (muscle), 0.51 ± 0.19mm (skin) and 0.14 ± 0.16mm (fat). After applying a linear correction model containing view, light angles and point distances, the bias was almost completely removed on test data, and standard deviations slightly reduced. To our knowledge this is the first quantitative study of the measurement error of structured light with biological tissue.

VirtualTable: a projection augmented reality game
VirtualTable is a projection augmented reality installation where users are engaged in an interactive tower defense game. The installation runs continuously and is designed to attract people to a table, which the game is projected onto. Any number of players can join the game for an optional period of time. The goal is to prevent the virtual stylized soot balls, spawning on one side of the table, from reaching the cheese. To stop them, the players can place any kind of object on the table, that then will become part of the game. Depending on the object, it will become either a wall, an obstacle for the soot balls, or a tower, that eliminates them within a physical range. The number of enemies is dependent on the number of objects in the field, forcing the players to use strategy and collaboration and not the sheer number of objects to win the
Accurate and Simple Calibration of DLP Projector Systems

Much work has been devoted to the calibration of optical cameras, and accurate and simple methods are now available which require only a small number of calibration targets. The problem of obtaining these parameters for light projectors has not been studied as extensively and most current methods require a camera and involve feature extraction from a known projected pattern. In this work we present a novel calibration technique for DLP Projector systems based on phase shifting profilometry projection onto a printed calibration target. In contrast to most current methods, the one presented here does not rely on an initial camera calibration, and so does not carry over the error into projector calibration. A radial interpolation scheme is used to convert features coordinates into projector space, thereby allowing for a very accurate procedure. This allows for highly accurate determination of parameters including lens distortion. Our implementation acquires printed planar calibration scenes in less than 1s. This makes our method both fast and convenient. We evaluate our method in terms of reprojection errors and structured light image reconstruction quality.

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This paper presents an approach to 3-D diffusion tensor image (DTI) reconstruction from multi-slice diffusion weighted (DW) magnetic resonance imaging acquisitions of the moving fetal brain. Motion scatters the slice measurements in the spatial and spherical diffusion domain with respect to the underlying anatomy. Previous image registration techniques have been described to estimate the between slice fetal head motion, allowing the reconstruction of 3D a diffusion estimate on a regular grid using interpolation. We propose Approach to Unified Diffusion Sensitive Slice Alignment and Reconstruction (AUDiSSAR) that explicitly formulates a process for diffusion direction sensitive DW-slice-to-DTI-volume alignment. This also incorporates image resolution modeling to iteratively deconvolve the effects of the imaging point spread function using the multiple views provided by thick slices acquired in different anatomical planes. The algorithm is implemented using a multi-resolution iterative scheme and multiple real and synthetic data are used to evaluate the performance of the technique. An accuracy experiment using synthetically created motion data of an adult head and an experiment using synthetic motion added to sedated fetal monkey dataset show a significant improvement in motion-trajectory estimation compared to current state-of-the-art approaches. The performance of the method is then evaluated on challenging but clinically typical in utero fetal scans of four different human cases, showing improved rendition of cortical anatomy and extraction of white matter tracts. While the experimental work focuses on DTI reconstruction (second-order tensor model), the proposed reconstruction framework can employ any 5-D diffusion volume model that can be represented by the spatial parameterizations of an orientation distribution function.
In this paper we present a novel sensing system, robust Near-infrared Structured Light Scanning (NIRSL) for three-dimensional human model scanning application. Human model scanning due to its nature of various hair and dress appearance and body motion has long been a challenging task. Previous structured light scanning methods typically emitted visible coded light patterns onto static and opaque objects to establish correspondence between a projector and a camera for triangulation. In the success of these methods rely on scanning objects with proper reflective surface for visible light, such as plaster, light colored cloth. Whereas for human model scanning application, conventional methods suffer from low signal to noise ratio caused by low contrast of visible light over the human body. The proposed robust NIRSL, as implemented with the near infrared light, is capable of recovering those dark surfaces, such as hair, dark jeans and black shoes under visible illumination. Moreover, successful structured light scan relies on the assumption that the subject is static during scanning. Due to the nature of body motion, it is very time sensitive to keep this assumption in the case of human model scan. The proposed sensing system, by utilizing the new near-infrared capable high speed LightCrafter DLP projector, is robust to motion, provides accurate and high resolution three-dimensional point cloud, making our system more efficient and robust for human model reconstruction. Experimental results demonstrate that our system is effective and efficient to scan real human models with various dark hair, jeans and shoes, robust to human body motion and produces accurate and high resolution 3D point cloud.
SLStudio: Open-source framework for real-time structured light
An open-source framework for real-time structured light is presented. It is called “SLStudio”, and enables real-time capture of metric depth images. The framework is modular, and extensible to support new algorithms for scene encoding/decoding, triangulation, and aquisition hardware. It is the aim that this software makes real-time 3D scene capture more widely accessible and serves as a foundation for new structured light scanners operating in real-time, e.g. 20 depth images per second and more. The use cases for such scanners are plentyfull, however due to the computational constraints, all public implementations so far are limited to offline processing. With “SLStudio”, we are making a platform available which enables researchers from many different fields to build application specific real time 3D scanners. The software is hosted at http://compute.dtu.dk/~jakw/slstudio.
Adapting Parcellation Schemes to Study Fetal Brain Connectivity in Serial Imaging Studies

A crucial step in studying brain connectivity is the definition of the Regions Of Interest (ROI's) which are considered as nodes of a network graph. These ROI's identified in structural imaging reflect consistent functional regions in the anatomies being compared. However in serial studies of the developing fetal brain such functional and associated structural markers are not consistently present over time. In this study we adapt two non-atlas based parcellation schemes to study the development of connectivity networks of a fetal monkey brain using Diffusion Weighted Imaging techniques. Results demonstrate that the fetal brain network exhibits small-world characteristics and a pattern of increased cluster coefficients and decreased global efficiency. These findings may provide a route to creating a new biomarker for healthy fetal brain development.

Fast and Practical Head Tracking in Brain Imaging with Time-of-Flight Camera

This paper investigates the potential use of Time-of-Flight cameras (TOF) for motion correction in medical brain scans. TOF cameras have previously been used for tracking purposes, but recent progress in TOF technology has made it relevant for high speed optical tracking in high resolution medical scanners. Particularly in MRI and PET, the newest generation of TOF cameras could become a method of tracking small and large scale patient movement in a fast and user-friendly way required in clinical environments. We present a novel methodology for fast tracking from TOF point clouds without the need of expensive triangulation and surface reconstruction. Tracking experiments with a motion controlled head phantom were performed with a translational tracking error below 2mm and a rotational tracking error below 0.5°.
Real Time Surface Registration for PET Motion Tracking

Head movement during high resolution Positron Emission Tomography brain studies causes blur and artifacts in the images. Therefore, attempts are being made to continuously monitor the pose of the head and correct for this movement. Specifically, our method uses a structured light scanner system to create point clouds representing parts of the patient's face. The movement is estimated by a rigid registration of the point clouds. The registration should be done using a robust algorithm that can handle partial overlap and ideally operate in real time. We present an optimized Iterative Closest Point algorithm that operates at 10 frames per second on partial human face surfaces. © 2011 Springer-Verlag.
Computer Vision Assisted Motion Correction in Medical Imaging

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