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.
Augmented Reality Interfaces for Additive Manufacturing

This paper explores potential use cases for using augmented reality (AR) as a tool to operate industrial machines. As a baseline we use an additive manufacturing system, more commonly known as a 3D printer. We implement novel augmented interfaces and controls using readily available open source frameworks and low cost hardware. Our results show that the technology enables richer and more intuitive printer control and performance monitoring than currently available on the market. Therefore, there is a great deal of potential for these types of technologies in future digital factories.

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Authors: Eiríksson, E. R. (Intern), Pedersen, D. B. (Intern), Frisvad, J. R. (Intern), Skovmand, L. (Ekstern), Heun, V. (Ekstern), Maes, P. (Ekstern), Aanæs, H. (Intern)
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Computer Vision for Additive Manufacturing.
Ever since the commercialization of additive manufacturing in the late 80’s, it has been clear what enormous potential the technology could have, potentially disrupting several industries. However, we have yet to see the technology fully adopted by the manufacturing industry. One of the issues that has prevented widespread adoption of 3D printing for use within manufacturing is the apparent lack of quality control during and after the printing process. This thesis demonstrates how computer vision may be applied in beneficial ways within additive manufacturing. The main contributions aim at solving part of the challenges required for the technology to reach its full envisioned potential, and to reach widespread industry adoption as a de-facto manufacturing modality. Quality control has been a major milestone to overcome in this regard. As a result, a core part of the contributions revolves around this central topic. The work is separated into three main categories: The first two concerning process and quality control of appearance and geometry. The third category concerns machine interaction paradigms within additive manufacturing. Here, challenges are addressed within the 3D ecosystem, aiming towards facilitating a fluid integration of additive manufacturing within the factory of tomorrow.

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Organisations: Department of Applied Mathematics and Computer Science, Image Analysis & Computer Graphics, Department of Mechanical Engineering, Manufacturing Engineering
Authors: Eiríksson, E. R. (Intern), Aanæs, H. (Intern), Pedersen, D. B. (Intern)
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Computer Vision for Additive Manufacturing.
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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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Failure detection, Computer vision, Fused deposition modeling (FDM)
Source: PublicationPreSubmission
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Publication: Research › peer-review › Article in proceedings – Annual report year: 2017

**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 this knowledge can be used to update the machine code of the printer such that printing of the object can be resumed in the new location. This opens possibilities for embedding and assembling foreign parts into the additive manufacturing pipeline, adding another layer of flexibility to the process. However, due to various errors, sources in estimating the orientation of the object, more work is needed before this update can be applied.

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Repositioning, Photogrammetry, Computer vision, Additive manufacturing
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**PicPrint: Embedding pictures in additive manufacturing**
Here we present PicPrint, a method and tool for producing an additively manufactured lithophane, enabling transferring and embedding 2D information into additively manufactured 3D objects. The method takes an input image and converts it to a corresponding height-map, indicating the material density required to achieve a brightness specified at any given location. Non-linear scattering properties are compensated for using predefined falloff profiles. Using the produced height-map, a watertight mesh is distorted to match the specified material densities, after which the mesh is ready for either direct print.
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.
A self-calibrating robot based upon a virtual machine model of parallel kinematics

A delta-type parallel kinematics system for Additive Manufacturing has been created, which through a probing system can recognise its geometrical deviations from nominal and compensate for these in the driving inverse kinematic model of the machine. Novelty is that this model is derived from a virtual machine of the kinematics system, built on principles from geometrical metrology. Relevant mathematically non-trivial deviations to the ideal machine are identified and decomposed into elemental deviations. From these deviations, a routine is added to a physical machine tool, which allows it to recognise its own geometry by probing the vertical offset from tool point to the machine table, at positions in the horizontal plane. After automatic calibration the positioning error of the machine tool was reduced from an initial error after its assembly of ±170 μm to a calibrated error of ±3 μm. Excelling by speed, the calibration was executed in less than 3 min.
Designing for Color in Additive Manufacturing

In this paper we present a color design pipeline for 3D printed or additively manufactured parts. We demonstrate how to characterize and calibrate a commercial printer and how to obtain its forward and backward color transformation models. We present results from our assistive color design tool, allowing for colorimetric accurate prints and visualization of the printed outcome, prior to print. Lastly, we demonstrate our pipeline by accurately reproducing a real physical object.

GyroVR: Simulating Inertia in Virtual Reality using Head Worn Flywheels

We present GyroVR, head worn flywheels designed to render inertia in Virtual Reality (VR). Motions such as flying, diving or floating in outer space generate kinesthetic forces onto our body which impede movement and are currently not represented in VR. We simulate those kinesthetic forces by attaching flywheels to the users head, leveraging the gyroscopic effect of resistance when changing the spinning axis of rotation. GyroVR is an ungrounded, wireless and self
contained device allowing the user to freely move inside the virtual environment. The generic shape allows to attach it to different positions on the users body. We evaluated the impact of GyroVR onto different mounting positions on the head (back and front) in terms of immersion, enjoyment and simulator sickness. Our results show, that attaching GyroVR onto the users head (front of the Head Mounted Display (HMD)) resulted in the highest level of immersion and enjoyment and therefore can be built into future VR HMDs, enabling kinesthetic forces in VR.

**General information**

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Organisations: Department of Applied Mathematics and Computer Science, Image Analysis & Computer Graphics, University of Ulm, MIT Media Lab
Authors: Gugenheimer, J. (Ekstern), Wolf, D. (Ekstern), Eiríksson, E. R. (Intern), Maes, P. (Ekstern), Rukzio, E. (Ekstern)
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**In-Situ Monitoring in Additive Manufacturing Using Contact Image Sensors**

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Publication: Research - peer-review › Article in proceedings – Annual report year: 2016

**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.

**General information**

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Organisations: Department of Applied Mathematics and Computer Science, Image Analysis & Computer Graphics, Department of Mechanical Engineering, Manufacturing Engineering
Predicting Color Output of Additive Manufactured Parts

In this paper we address the colorimetric performance of a multicolor additive manufacturing process. A method on how to measure and characterize color performance of said process is presented. Furthermore, a method on predicting the color output is demonstrated, allowing for previsualization of parts prior to print. Results show that color prediction can be achieved with an average color difference error of $\Delta E^*_{00} = 1.5$ and std.dev $\sigma = 0.75$, with similar order of magnitude as the literature defined threshold for ‘Just Noticeable Difference’ (JND).

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.

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 game.

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**Projects:**

**Computer Vision based geometrical and textural control for 3D print and injection moulding processes**

Department of Applied Mathematics and Computer Science
Period: 01/12/2013 → 29/09/2017
Number of participants: 6
Phd Student: Eiriksson, Eyþór Rúnar (Intern)
Supervisor: Pedersen, David Bue (Intern)
Main Supervisor: Aanæs, Henrik (Intern)
Examiner: Carstensen, Jens Michael (Intern)
Krüger, Norbert (Ekstern)
Taylor, John (Ekstern)
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