Laser-based Additive Manufacturing
Department of Mechanical Engineering
Technical University of Munich

Investigation of multispectral imaging algorithm for temperature determination on a numerical experiment platform in Laser-based Powder Bed fusion of Metals

Untersuchung des multispektralen Bildgebungsverfahrens zur Temperaturbestimmung auf einer numerischen Experimentierplattform beim Laser-basierten Pulverbett-Schmelzverfahren von Metallen.

Semester Thesis

at the Department of Mechanical Engineering of the Technical University of Munich

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Laser-based Additive Manufacturing

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Scope of Work

Title of the Semester Thesis:

Investigation of multispectral imaging algorithm for temperature determination on a numerical experiment platform in Laser-based Powder Bed fusion of Metals

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Setting:

Laser-based Powder Bed Fusion of Metals (PBF-LB/M) is an additive manufacturing process which produces components with a laser by successively melting metal powders applied in layers. This additive manufacturing process offers the advantage of a complex lightweight design. However, complicated thermal histories during laser-metal interaction can lead to process defects such as keyholing. Since the process is thermally driven, acquiring the absolute temperature distribution in the laser-material interaction zone is vital to gain a deeper understanding of the process. However, no measurement system in PBF-LB/M is currently available to determine the absolute temperature due to unknown emissivity. Multispectral Imaging (MSI) has the potential to determine the absolute temperature and emissivity simultaneously by capturing multiple wavelengths of radiance from the melt pool.

Objective:

This work aims to optimize the MSI algorithm to determine the absolute temperature accurately. Since the mapping between the digital value and radiance still needs to be investigated, direct optimization of the MSI algorithm based on the experimental data is challenging. Therefore, the first step is to develop a virtual experiment to obtain "ideal" radiance determined by the given temperature distribution and emissivity. This way, the MSI algorithm can be optimized based on the input and calculated temperature and emissivity. The virtual experiment platform will also allow for the investigation of various temperature distributions and emissivity models in a time- and cost-efficient manner.

Methodology:

The content of the present thesis can be subdivided into the following tasks

- Literature review regarding MSI, material emissivity model and curve fitting algorithms
- Development of a virtual experiment platform
- Generate virtual experiments with various emissivity models and temperature fields
- Optimization of the MSI algorithm based on virtual experiments
- Scientific documentation of the results

Declaration

I hereby confirm that this semester thesis was written independently by myself without the use of any sources beyond those cited, and all passages and ideas taken from other sources are cited accordingly.

....
Location, Date Signature

With the supervision of Mr. Zhaoyong Wang by Mr. Ruihang Dai intellectual property of the Professorship Laser-based Additive Manufacturing (LBAM) flows into this work. A publication of the work or a passing on to third parties requires the permission of the head of the professorship. I agree to the archiving of the printed thesis in the LBAM library (which is only accessible to LBAM staff) and in LBAM's digital thesis database as a PDF document.

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Abstract

temperature is one of the most important parameters in PBF-LB/M. so, monitoring the temperature at melt pool necessary. in oder to archieve this, a numerical experiment platform is formed. then parameter is calculated

Zusammenfassung

Hier könnte Ihre Kurzzusammenfassung stehen.

Contents

1 LaTeX-Tutorial

Dieses Tutorial liefert eine Kurzeinführung in die Verwendung von Latex.

1.1 Titelseite

Die Titelseite wird in ./main.tex definiert. Der Studienarbeitstyp wird durch Ein- und Auskommentieren der Befehle

- `\IWBstudentthesisTitlePageCustomMastersThesis`,
- `\IWBstudentthesisTitlePageCustomBachelorsThesis` und
- `\IWBstudentthesisTitlePageCustomSemesterThesis`

ausgewählt und die Seite entsprechend der Argumente gesetzt. Die Professoren und Lehrstuhle können mittels der Makros

- `\IWBnamesProfReinhart \newline \IWBlangChairMWIWBLBM` oder
- `\IWBnamesProfZaeh \newline \IWBlangChairMWIWBLWF`

ausgewählt werden.

1.2 Zitation

Zum Zitieren stehen die Standartbefehle `\textcite` und `\parencite` zur Verfügung. Soll der Autorename im Satz verwendet werden, eignet sich ersteres, z.B. **Bayerlein2018** bezieht sich auf **Bayerlein2016469**. Soll das Zitat in Klammern nach die Aussage gestellt werden empfiehlt sich zweiteres [**Zaeh2018385**]. Sammelzitationen am Satzende schreiben sich wie folgt [**Kleinwort2018658**, **Kleinwort20189**, **Kleinwort2018631**]. Die Zitation von Online-Quellen kann schwierig sein, da nicht immer der Autor und das Erscheinungsjahr verfügbar sind. Vergleicht man **Heuss2018** und **iwb-Startseite**, stellt man fest, dass bei zweiteren der Seitentitel statt des bekannten Schemas eingesetzt wird.

Normen werden als dargestellt. Im Bibtex-Export des verwendeten Literaturverwaltungsprogramm sind bestimmte Einstellungen vorzunehmen. Dokumententyp ist “@book” mit folgenden Einträgen:

- Normtyp und Nummer als “title”
- Langtitel als “subtitle”
- Verlag als “publisher”
- Jahr als “date”
- “author” darf nicht belegt werden!

1.3 Abkürzungen

In ./source/abbreviations.tex können Abkürzungen definiert werden. Es gibt Besonderheiten zu Ausdrücken, deren Pluralendung nicht auf s endet. Hier müssen ggf. Kurz- und Langformen des Ausdrucks auch für den Plural definiert werden.

- `\gls{ros}`: schreibt beim ersten Auftreten im Dokument ausführlich Robot Operating System (ROS), ab dem zweiten Auftreten wird abgekürzt ROS
- `\glspl{ap}` verwendet den Plural in Langform Arbeitspakete (APs) und danach in Kurzform APs

1.4 Glossar

In ./source/glossary.tex können Begriffe erklärt, abgegrenzt oder definiert werden. Begriffe erhalten einen Namen und eine Beschreibung als Glossareintrag sowie ein Lable zum Referenzieren im Text. Ein Glossar ist Optional.

- `\gls{latex}`: Schreibt den Namen aus dem Glossarverzeichnis mit Verweis auf den Glossareintrag Latex

1.5 Abbildungen

Graphiken und Bilder können in beliebigen Dateiformaten eingebunden werden, vergleiche fig. 1. Vektorgraphiken sind im Allgemeinen Pixelgraphiken in Schärfe und Speicherbedarf überlegen.

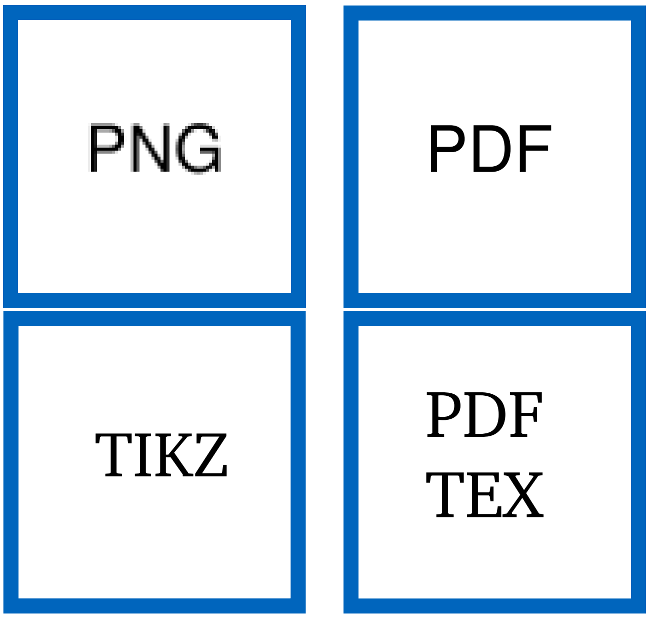

Figure 1: Beschreibung des Bilds. Außerdem machen wir nun die Bildunterschrift unnötig lang um die Formatierung zu testen.

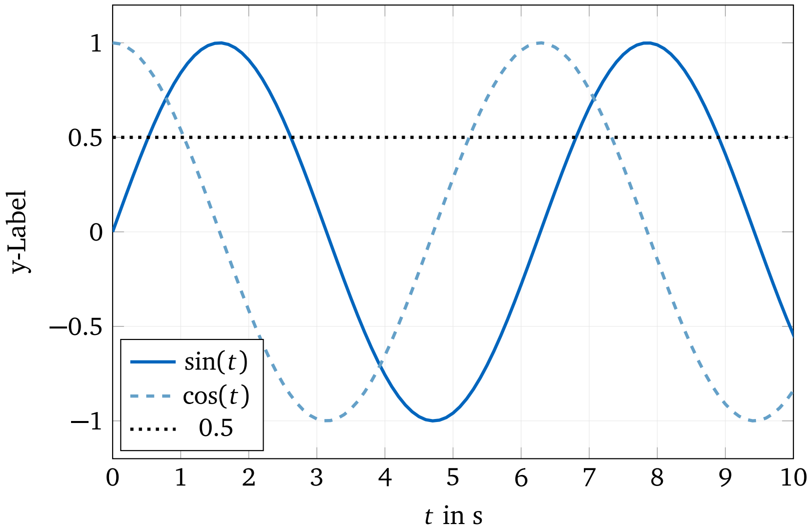

Figure 2: Beschreibung des Plots. Außerdem machen wir nun die Bildunterschrift unnötig lang um die Formatierung zu testen.

Für Nutzer mit perfektionistischen Anspruch empfiehlt sich die Nutzung von Ti*k*Z. Vorteil ist, dass die Erzeugung von Daten und die Darstellung komplett getrennt werden. Die Darstellung erfolgt einheitlich gemäß eines generischen Mark-Ups, vergleiche figs. 2 and 3.

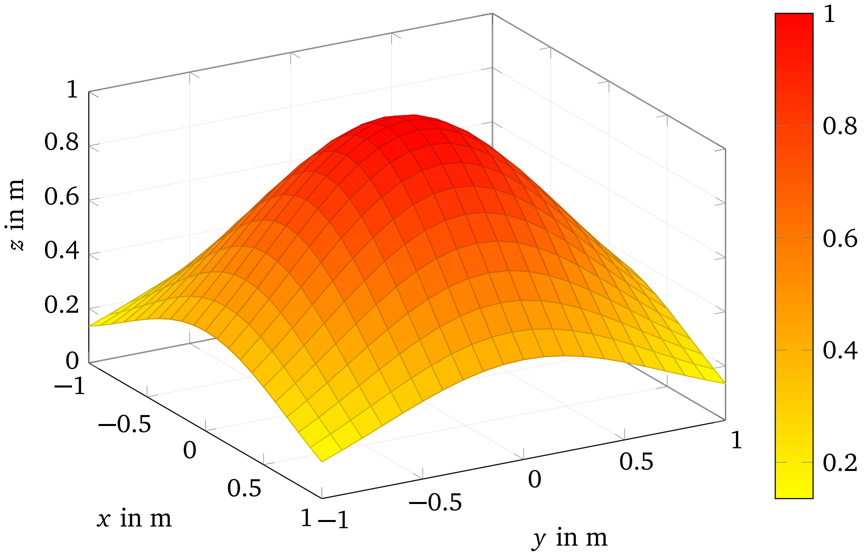

Figure 3: Beschreibung des Plots. Außerdem machen wir nun die Bildunterschrift unnötig lang um die Formatierung zu testen.

2 Introduction

Additive Manufacturing (AM) is a different type of processing technology to conventional manufacturing methods. Instead of removing material from the raw part, additive manufactoring is usually described as "a process of joining materials to make objects layer by layer or element by element"[1]. It is a useful method for reducing the the duration from product design to product manufacturing and imporving the material utilization[2].

There are several AM technologies that can be sorted into different categories. Laser-based Powder Bed Fusion of Metals (PBF-LB/M), which also called Selective Laser Sintering (SLS), is one of the powder based AM processes[3]. In this process, a laser beam with high energy density is focused onto the surface of a metal powder bed, which was heated up to a temperature near the melt temperature. Then, the metal powder is melted and form the upper surface of the object. Last, the building platform will go downwards to build next layer. This process will be repeated until the desired object is built[4].

Since the process is based on the phase change of materials, processing parameters such as laser power, layer thickness, hatch distance and scanning strategies are critical for producing dense materials, minimize defects, improve surface quality and build rate[5]. The common denominator between them is that the parameters of the process are varied by controlling the temperature profile of the metal powder[2]. Thus, the importance of obtaining the temperature information on the surface layer is high.

The solidification front of metal powders moves with a high velocity (generally $0.01 \sim 10\,\mathrm{m/s}$)[6], the cooling rate of material is normally at range of $10^5 \sim 10^6\,\mathrm{K/m}$[5]. Thus, a contactless temperature measurement is required to obtain the temperature of the surface area.

Two different methods is used for monitoring the surface temperature in recent studies, namely conventional infrared irradiation temperature measurement methods and multi-wavelength techniques[7]. Infrared irradiation technique is cost-effective, but it requires information about the emissivity of the material[8]. On the contrary, a multi-color pyrometer with a specific wavelength range could be used in the case of changing emissivity[9]. In this thesis, a virtual experiment platform using a multispectral imaging algorithm is developed to simulate the output behavior of a spectral pyrometer.

After obtaining the radiation image, a curve fit algorithm is applied to estimate the temperature field of the image and emissivity field simultaneously. This semester thesis aims to develope a stable temperature estimation program based on curve-fit algorithm. With the results obtained from the virtual experiment platform, the performance of the temperature estimation algorithm is verified.

3 State of the art

haha[10]

3.1 Process monitoring

3.2 Multispectral imaging

3.3 Emissivity model

3.4 Temperature field in Laser-based Powder Bed Fusion

3.5 Motivation of this thesis

4 Theory and methodology

As mentioned in previous sections, forming a virtual experiment platform is necessary for investigating the temperature estimation algorithm. So, a virtual experiment platform is developed based on Planks'law, then, a virtual multi-spectral pyrometer is applied to obtain the digital value (also called image).

4.1 Physical value of radiation

Radiation is emitted from any object with a temperature above 0K. In equation 4.1 can be found, that the radiation depends on the black body radiation $B(\lambda, T)$ and emissivity $\varepsilon(\lambda, T)$. Both value are temperature T and wavelength λ dependent.

$$L(\lambda, T) = B(\lambda, T) \cdot \varepsilon(\lambda, T) \tag{4.1}$$

$$B(\lambda, T) = \frac{2hc^2}{\lambda^5} \cdot \left[\exp\left(\frac{hc}{\lambda k_B T}\right) - 1\right]^{-1} \tag{4.2}$$

4.2 Integration method

why we use integration model, we also used linear model for validation

4.3 Digital value of radiation

4.4 Temperature estimation algorithm

4.5 Used model in validation

5 Validation

name should be changed, what we actually done to validate the platform or just virtual platform in order to validate and improve the performance of temperature estimation algorithm, several models is imported.

here we talk about what model is used to generate raw data for validation

5.1 Temperature field

5.2 Emissivity model

5.3 Integration method

5.4 Emissivity model

5.5 Curve fit algorithm

5.6 Parameters in calculation

quantum efficiency, lens factor

6 Calcualtion results and analysis

6.1 Calculation results

6.1.1 Temperature field

6.1.2 Emissivity field

6.2 Data analysis

6.2.1 Sensitivity analysis of emissivity models

6.2.2 Performance between different materials

A Appendices

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

This is the second paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

And after the second paragraph follows the third paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

After this fourth paragraph, we start a new paragraph sequence. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

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Glossary

Latex	Generische Mark-up-Sprache zum Erstellen wissenschaftlicher Texte. Sie ist in jeder Hinsicht Word überlegen, welches einem visuellen Mark-Up entspricht. Das X von LaTeX wird als ç (Stimmloser palataler Frikativ) ausgesprochen, vergleiche deutsche Aussprache von *ch*.
Ti*k*Z	Frontend-Paket, das auf PGF-Plot aufbaut und zum Erstellen von Graphiken dient.
Tutorial	Kurze Gebrauchsanleitung welche ein Thema, einen gewissen Vorgang oder eine Funktion erklärt. Hat nicht den Anspruch auf Vollständigkeit.

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List of Abbreviations

AM	Additive Manufacturing
AP	Arbeitspaket
LBAM	Professorship Laser-based Additive Manufacturing
MSI	Multispectral Imaging
PBF-LB/M	Laser-based Powder Bed Fusion of Metals
ROS	Robot Operating System
SLS	Selective Laser Sintering

Disclaimer

I hereby declare that this thesis is entirely the result of my own work except where otherwise indicated. I have only used the resources given in the list of references.

Garching, July 31, 2023

(Signature)