INSTITUTE OF MACHINE
AND INDUSTRIAL DESIGN

FME

Faculty of Mechanical Engineering
Brno University of Technology

Review of Doctoral Thesis

1. PhD candidate
Ing. Martin Krčma / Martin.Krcma1@vut.cz
2. Name of PhD programme
Design and Process Engineering (Mechanical Engineering Design)
3. Title of PhD thesis
Large scale robotic 3D printing of polymercomposites

4. Principal supervisor
doc. Ing. David Paloušek, Ph.D. / david.palousek@one3d.cz
5. Co-supervisor
Ing. David Škaroupka, Ph.D./ David.Skaroupka@vut.cz

6. Reviewer
Dr. Ena Lloret-Fritschi / ena.lloret.fritschi@usi.ch
Università della Svizzera italiana

7. Overview of the scope of PhD thesis[1]
Good

8. Significance of the topic and clarity of problem statement
Very good
The research topic of gaining a thorough understanding of fusion deposition/3D printing for large-scale printing is vital today is a crucial topic. Because it promises to transform industries, reduce environmental impact, advance several industries, and drive innovation. It is a technology that is reshaping how we manufacture, design, and create, making it essential for research and industries to stay informed and adapt to its rapid developments.

9. Knowledge of existing literature
Good

[1] Overview of the scope of PhD thesis is a short description of objectives of PhD thesis's research and summary of main findings and scientific achievements.

There is a comprehensive understanding of existing literature and research within the field. However, a few references date back to 2011, and reviewing and updating them with more recent studies would be advisable. Additionally, it would be beneficial to incorporate references to the work of PhD Joris Burger, who has published numerous examples of large-scale 3D printing, as well as the research conducted by Daniel Swendemann from OST on recycling of polymers, CH and the research of Jelle Feringa. Ferringa and Burger have printed large scale elements and should therefore also be mentioned in the SoA.

10. Choice of methods and technical soundness

Good

The methods and results are somewhat challenging to evaluate due to occasional omissions of references and cross-references. Addressing this issue would likely enhance the comprehensibility of the manuscript. Moreover, enriching the method descriptions to match the depth found in the attached papers would undoubtedly contribute to the overall quality of the thesis. It's worth noting that the experimental methods' technical soundness is well-established and sound. While these methods are thoroughly described in the attached papers, they are somewhat less detailed in the main body of the thesis.

11. Quality, originality and significance of the results

Very good

The core of this thesis comprises three journal articles, which unfortunately are only included as supplementary material. The primary objective of the central thesis is to offer an overview of the methods employed, the achieved results, and insights into unpublished work. However, the thesis's structure poses a challenge for readers since it frequently references a series of articles that readers still need to have the opportunity to review. Typically, readers follow a linear reading approach, starting from the beginning and progressing to the end. This structure presents an issue in the thesis layout. Therefore, there are two possible solutions: either rigorous cross-referencing, adhering to conventional citation practices, should be included in the thesis, or the thesis should undergo restructuring, with the articles integrated as individual chapters. It is worth noting that the attached papers are of high quality, and considering them, the thesis's work is commendable. The first article, published in the Rapid Prototyping Journal, focuses on polymer concrete processing for 3D printing. Its objective is to validate Hypothesis 1, which initially anticipated that 3D printing would result in weaker mechanical properties for polymer concrete than traditional casting due to thermal degradation and porosity. However, this hypothesis was disproven, as careful control of porosity and anisotropy enabled 3D-printed parts to attain mechanical performance similar to cast parts, demonstrating promising outcomes regarding strength and ductility. The second article, published in The International Journal of Advanced Manufacturing Technology, addresses the requirements for implementing and testing various multiaxis 3D printing methods. This paper aims to address Hypothesis 2, which suggests that oriented 3D printing would significantly enhance buildability and surface quality compared to 3-axis printing, benefiting both large-scale and desktop-scale 3D printing. However, it was revealed that oriented 3D printing alone did not significantly impact buildability, underscoring the significance of employing toolpaths with adequate surface coverage. This discovery ultimately led to the development of the Intralayer height variation method.The third article, published in the journal 3D Printing and Additive Manufacturing, introduces a novel method for multiaxis 3D printing involving variable intralayer height. It provides practical examples and verification of the method's effectiveness. The paper explores Hypothesis 3, which posited that planar slicing, coupled with adjustments for actual layer height, could yield improvements in buildability similar to those achieved with nonplanar slicing. This hypothesis was validated, with the Intralayer height variation method proving highly effective for large-scale composite printing. It enabled the creation of overhangs exceeding 80° while maintaining strong layer adhesion, all without the complexities associated with nonplanar slicing.

12. Quality of attached papers

Very good

The peer-reviewed papers provide me with confidence that the research is sound and well-executed. However, this level of conciseness and rigor is lacking in the main body of the thesis.

13. Overall assessment, strengths and weaknesses (based upon the above evaluation categories 8–12)

Good

The thesis aims to develop a large-scale 3D printing process using recycled polymer composites to create complex functional objects. A comprehensive study is presented. However, the depth and conciseness of the work is only clearly revealed through the attached papers. A series of general comments are given to each section, following Introduction: The introductory section starts by stating the topic and sets out a clear target, however, in the section 1.2. Moreover, 1.3 appears repetitive (to 4.), and it would be helpful to clarify the primary focus of the thesis and merge with section 4. State of the Art: The state-of-the-art section lacks depth and precise citations, and it would benefit from references to supporting materials, such as images, to aid understanding. Analysis of Literature: This section might be better placed as a conclusion to the state-of-the-art section, eliminating the need for a separate chapter. Aim of the Thesis: The content in this section can be merged with the introductory section (1.3) for conciseness. Materials and Methods: This section could benefit from more clarity and structure and should provide more detailed descriptions of individual methods used in the thesis. Results and Discussion: The reader faces challenges when referencing papers that still need to be read. Improved referencing and clarity regarding cross-referenced papers are needed. Conclusion: The conclusion refers to studies described in the papers, making it unclear what should be evaluated. List of Publications: This section reveals the vital work performed in the thesis. Generally, the structure of the thesis presents challenges when it comes to referencing articles that the reader still needs to review. One potential method of restructuring could involve incorporating the papers as individual chapters. Alternatively, suppose the thesis is to remain a classic monograph as currently intended. In that case, an apparent reorganization and cross-referencing system for the papers should be implemented, in addition to the comments mentioned above. Furthermore, it is crucial to adhere to the convention of placing figures after the relevant text to assist readers in comprehending the content and easily referring to the figures as necessary. A thorough grammar check would also be advisable.

14. Questions and comments

As numerous references and cross-references are missing along with clarity in the general structure, I would like to know if the thesis has the chance to be resubmitted with adjustments.

15. Conclusion

PhD thesis is an independent scientific work that presents a novel solution to a significant problem in the research area and demonstrates the candidate's ability to conduct independent research.

yes, based on the attached papers, but there is room for discussion regarding whether a thesis restructuring and a review for clarity should be contemplated.

16. Date and signature

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Brno University of Technology

10/10/2023	Ena Lloret-Fritschi	

Please note

A. *Evaluate categories 7 to 13 using the following scale: unacceptable, acceptable, satisfactory, good, very good, excellent. The qualification of 'excellent' should only be given for a PhD Thesis in the top 3% of the research in your field of expertise.*
B. *E-mail the completed form to: Klara.Javorcekova@vut.cz*

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FME

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Review of Doctoral Thesis

1. PhD candidate
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5. Co-supervisor
Ing. David Škaroupka, Ph.D./ David.Skaroupka@vut.cz

6. Reviewer
Roberto Naboni/ ron@iti.sdu.dk
SDU CREATE - University of Southern Denmark

7. Overview of the scope of PhD thesis[1]
Very good
The reviewed PhD thesis explores the potential use of a novel composite material, composed of recycled polypropylene waste and sand filler, for large scale application, such as the construction industry. This material, predominantly filler-based, exhibits promise due to its mechanical and cost-effective properties. The primary research objective is to assess its compatibility with 3D printing, specifically focusing on its suitability for large-scale single-walled objects printed with closed loops. The study employs four distinct 3D printing strategies, employing an industrial robotic arm and a pellet-fed screw extruder. To achieve this, custom scripts for nonplanar slicing and tilt control during multi-axis printing were developed. The results, evaluated through 3D scanning and mechanical testing, highlight two key findings: (1) the exclusive use of 5-axis motion does not significantly enhance printing outcomes.(2) Nonplanar printing has the potential to improve surface quality, although its effectiveness depends on the geometry of the printed object.This research offers valuable insights into material and technique optimization for 3D printing large-scale single-walled objects in the construction industry.

8. Significance of the topic and clarity of problem statement
Good

[1] Overview of the scope of PhD thesis is a short description of objectives of PhD thesis's research and summary of main findings and scientific achievements.

This thesis delves into the realm of large-scale 3D printing, specifically targeting the application of polymer concrete. Its pivotal contribution lies in the introduction of a novel multiaxis 3D printing technique tailored to the demands of large-scale polymer composite printing. The outcomes of this research hold substantial relevance for the fields of construction, architecture, and large-scale tooling. The study meticulously addresses the intricate interplay of material composition, process parameters, and toolpath planning. The initial segment of the thesis is dedicated to an in-depth exploration of the material itself, laying afoundation for the subsequent investigation. The latter part of the thesis pivots toward the critical aspect of software processing and toolpath planning. This shift in focus underscores the profound impact that the optimization of toolpaths can have on the overall quality and efficacy of 3D printing processes.

9. Knowledge of existing literature

Good

The thesis incorporates a literature review encompassing key topics such as the printing of recycled plastic composites and their mechanical performance, conformal 3D printing methods and applications, and the optimization of printing trajectories to enhance print quality. While the review provides sufficient understanding of the subjects, it seems somewhat limited in depth and breadth in the dissertation, particularly in comparison to the information available in the attached papers. Additionally, there appears to be a slight disconnect between the discussion of the composite material and the exploration of geometric considerations within the literature review. Further integration and synthesis of these elements could have strengthened the coherence and depth of the literature review section within the thesis.

10. Choice of methods and technical soundness

Very good

The methods used in the thesis are appropriate and well documented. The thesis thoroughly outlined the experimental setup, material compositions, mechanical performance testing, and surface quality assessment procedures. It also provided a clear explanation of the software techniques used for robotic 3D printing and introduced innovative processes like tilt control, which enhanced the comprehensiveness of the research. Furthermore, the thesis demonstrated a notable development of various methods relevant to multiaxis 3D printing, including toolhead reorientation with limited tilt, motion interpolation, and a nonplanar slicing algorithm. These methods were effectively isolated and compared, with results succinctly presented in the journal articles. This level of detail and the comprehensive approach to methods underscored the technical soundness of the thesis, adding to its overall quality and value.

11. Quality, originality and significance of the results

Very good

The methods devised in this thesis significantly expand the buildability of the 3D printing process, as demonstrated through verification prints. Innovative process parameters enable the fabrication of functional objects, such as planters, stools, and vases, while material properties are characterized and compared to their as-cast state. Though not explored in-depth, the successful modification of the print path to reduce deformation by an order of magnitude is a noteworthy achievement. The thesis's originality lies in its approach to improving 3D printing processes and its potential significance in making 3D printing more reliable and versatile for various practical applications.

12. Quality of attached papers

Very good
The dissertation has three attached papers of good quality. They are clearly written and present significant results.

13. Overall assessment, strengths and weaknesses (based upon the above evaluation categories 8–12)
Very good
The dissertation covers a topic of interest, the one of large-scale 3D printing, covring material and geometrical criticalities that arise at a large scale. Through the various experiments, the candidate developes, test and document various methods that are relevant for the upscaling of the technology, and to the scientific communities of additive manufacturing, construction 3D printing, advanced manufacturing. As a piece of writing, the thesis body is less efficiently communicating the results compared to the attached papers. The writing was in some parts very essential and did not provide a strong link between the various parts of the work.

14. Questions and comments

15. Conclusion
PhD thesis is an independent scientific work that presents a novel solution to a significant problem in the research area and demonstrates the candidate's ability to conduct independent research.
YES

16. Date and signature
15/10/2023

Please note

A. *Evaluate categories 7 to 13 using the following scale: unacceptable, acceptable, satisfactory, good, very good, excellent. The qualification of 'excellent' should only be given for a PhD Thesis in the top 3% of the research in your field of expertise.*
B. *E-mail the completed form to:* Klara.Javorcekova@vut.cz

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Brno University of Technology

Principal supervisor's final report on the PhD study

1. PhD candidate
Martin Krčma / **martin.krcma1@vut.cz**
2. Name of PhD programme
Machines and Equipment
3. Title of PhD thesis
Large-Scale Robotic 3D Printing of Polymer Composites

4. Principal supervisor
doc. Ing. David Paloušek, Ph.D. / **david.palousek@vutbr.cz**
5. Co-supervisor
Ing. David Škaroupka, Ph.D. / **skaroupka@fme.vutbr.cz**

6. Stays at other institutions (min. 7 days)
Creative Robotics Laboratory, UfG Linz, 3 months, 2021

7. Teaching activities
Course name **Klikněte nebo klepněte sem a zadejte text.**
Engineering Drawing Fundamentals (1K) Engineering Drawing (2K) CAD (3CD) Design and CAD (4KC) Team Project (ZKP) CAD Modelling (ZM1) Rapid prototyping and 3D digitalization (YRP) Plastic prototypes (ZPP)

8. List of main publications
Krčma, M., Škaroupka, D., Vosynek, P., Zikmund, T., Kaiser, J. and Palousek, D. (2021), "Use of polymer concrete for large-scale 3D printing", Rapid Prototyping Journal, Vol. 27 No. 3, pp. 465-474. https://doi.org/10.1108/RPJ-12-2019-0316
Krčma, M., Paloušek, D. Comparison of the effects of multiaxis printing strategies on large-scale 3D printed surface quality, accuracy, and strength. Int J Adv Manuf Technol 119, 7109–7120 (2022). https://doi.org/10.1007/s00170-022-08685-4

Martin Krčma, David Paloušek, David Škaroupka, Johannes Braumann, and Daniel Koutný. Method of Multiaxis Three-Dimensional Printing with Intralayer Height Variation for Stairstep Effect Compensation.3D Printing and Additive Manufacturing. ahead of print http://doi.org/10.1089/3dp.2022.0097

Conference proceedings:
Martin Krčma, doc. David Paloušek, PhD, Structural Members Manufactured By Freeform Deposition Of Polymer Concrete, BE.AM 2020, ISBN 9798561621192, Darmstadt, pp. 126-127 2020

Martin Krčma, David Škaroupka, PhD, Polybet, BE.AM 2020, ISBN 9798561621192, pp. 120-121 Darmstadt, 2020

9. Assessment of the supervision process

Very good

Justification for evaluation: The main communication with the student regarding the topic of his thesis was carried out in the form of regular or requested meetings. The student handled all research activities independently. He contributed his own ideas to the solution of the work's objectives, which he subsequently published. Overall, the student's supervision was without problems, as he was well organized. During the COVID-19 crisis, work was limited, and the completion of the entire dissertation was extended.

10. Assessment of the candidate's ability to work independently

Very good

Justification for evaluation: The student demonstrated the ability to work independently, ability to plan his research, formulate hypotheses, and test them with experiments he designed. Based on the experiments, he formulated conclusions with suggestions for possible explanations. He has also been involved in several research projects and contracts with industrial partners since the beginning of his studies. Martin was also involved in developing the hardware he needed for his experiments. He designed and created software algorithms that were used for hypothesis testing. As part of his studies, he organised a study visit abroad and gained new experience for his work.

11. Assessment of the contribution that the research makes to knowledge in the field

Good

Justification for evaluation: The work focused on research and development in the area of large scale robotic 3D printing. The work is designed as a commentary on the author's main articles and contains scientific questions and hypotheses. Although Martin's work is a scientific in nature, part of it is devoted to hardware and software development that was necessary to achieve the goals. Martin has succeeded experimentally verifying the technological influences on the 3D printing process. This area has not been well described before. Martin's work provided a comprehensive view of the topic of robotic 3D printing. In doing so, he has uncovered several technological approaches and principles that include material characterisation of the printed composite, measuring of the effects of different 3D printing methods, and developing of a new 3D printing method for large-scale robotic printing systems. The knowledge and methods developed in the part of the work dealing with printing paths lead to realistic applicability to the growing field of large-scale 3D printing. The main outcomes of the study are three meaningful, peer-reviewed articles that fulfil the core of the work rationale.

12. Other comments
I would also like to mention student's participation on the following national grant projects: • TJ04000408, Development of robotic additive fabrication technology strategies for large scale lattice structures • FW01010513, Development of production system of large format additive production of highly filled waste thermoplastics • TJ01000354, Development of process parameters of additive manufacturing of highly filled waste thermoplastics And internal specific projects: • FSI-S-17-4144, Development of processing parameters for manufacturing of unique metal parts using selective laser melting • FSI-S-20-6296, Research on the mechanical and physical properties of structured material manufactured using additive technologies • FV 19 – 03 Innovation of the Rapid prototyping course by introducing generative design tools

13. Conclusion
The presented PhD thesis is an independent scientific work that presents a novel solution to a significant problem in the research area and demonstrates the candidate's ability to conduct independent research.
YES

14. Date and signature	
02/01/2023	

Please note

A. *Evaluate categories 9 to 11 using the following scale: unacceptable, acceptable, satisfactory, good, very good, excellent.*
B. *In each category 9 to 11 explain reasons for evaluation using between 100–200 words.*
C. *E-mail the completed form to: Klara.Javorcekova@vut.cz*