Skoltech
Skolkovo Institute of Science and Technology

Thesis Changes Log

Name of Candidate: Dmitry Popov

PhD Program: Engineering Systems

Title of Thesis: Topology and parameter optimization for additive manufacturing based on function representation

Supervisor: Prof. Iskander Akhatov

The thesis document includes the following changes in answer to the external review process.
I sincerely appreciate constructive feedback, comments, and recommendations for my PhD Thesis provided by Reviewers. Thank you very much for your time and efforts. Provided feedback helped me to improve many aspects of my work including delivery, reasoning, and readability. Moreover, it showed great possibilities for further research investigation and analysis. Although I tried to address each point at my best, some of the comments might take a deeper perception and might be considered as the prospects of my research.
Professor Clement Fortin (Skoltech, chair)
Comment 1: *The chapter on the Introduction needs to be revised and improved. It contains mainly anecdotal information and very few solid scientific references, unlike the other chapters of the thesis. The author also uses the term CAM for Computer Aided Manufacturing for the programming of both CNC machine- tools and additive manufacturing. However, CNC machine-tools are using mainly exact geometry for their programming, and it is inexact to state that they use the STL format for their programming. I therefore suggest using the term CAM for AM or a similar term to avoid confusion. The quality of the English language also needs to be improved significantly in this chapter* **Response:** Thank you for highlighting the lack of scientific references and informal text style in the Introduction chapter as well as ambiguity in sentences about CNC. **Changes:** 1) The Introduction chapter was revised. 16 additional references were added to support the statements of this chapter. The language was double-checked and additionally revised with a typing assistant. 2) CNC programs considered in the chapter were explicitly specified as CNC programs used for AM.

Comment 2: *I have included comments and corrections in the submitted document to help for this revision. These changes must be included before the defense.*

Response: Thank you for your careful reading and suggestions for the update. Your comments were used for the revision of the Introduction chapter.

Changes: The Introduction chapter was updated with references and more accurate statements in the part of the historical review. Table 1.1 was revised.

Assistant Professor Dmitry Kolomenskiy (Skoltech)

Comment 1: *Page 54: "We can see that the modified algorithm is approximately twice as fast as the original one." Is it twice as fast for the same accuracy or for the same computational cost? Don't multiquadric splines present an approximation of a higher order than the bilinear spines? In any case, the accuracy and computational complexity should be discussed in the thesis.*

Response: Thank you for the comment. A more detailed discussion on the algorithm efficiency was provided.

Changes: Two paragraphs were updated (updated highlighted with yellow):

Page 54: Results of the computational test are shown in Table 5.1. The modified algorithm is approximately twice as fast as the original one for the same accuracy concerning the computational grid resolution. It can be easily explained using different spline basis functions. When the bilinear spine is used instead of the multiquadric-spline, the time-consuming operation of matrix inversion is not required. Thus, the modified algorithm works faster for the same number of knot points in the basis function. The reason is that it has linear complexity competing with the quadratic complexity of the original algorithm. Two obtained optimized bodies are shown in Figure 5-3(a).

Page 56: At the same time, both algorithms produce similar values of the objective function, differing in the third significant digit, depending on the optimization case. It does not sound obvious recalling different basis functions used in algorithms. Multiquadric splines can propose better quality of boundary approximation than bilinear splines. However, analysis from [Bendsoe and Sigmund, 2003] shows that better solutions to the considering optimization problem are connected with the complexity of topology rather than with shape accuracy. Therefore, since both basis functions are radial basis functions, topology depends on the number of knot points. Thus, the number of knot points affects the objective function more than the local quality of the shape.

Comment 2: *Page 56: "At the same time, both algorithms produce similar values of the objective function, differing in the third significant digit, depending on the optimization case." It seems to me that the two optimization algorithms use, respectively, two different approximate expressions for the objective function: one is based on bilinear splines, the other is based on multiquadratic splines. Am I right? If so, the author should discuss possible consequences, such as sensitivity to the grid resolution.*

Response: Thank you for the comment. You are right about different spline functions used in compared algorithms. The proposed discussion was addressed in changes made to the previous comment on Page 56.

Comment 3: *Page 54: "see details in Appendix A of [Popov et al., 2021a]"; page 56: "These modifications are listed in Appendix B of [Popov et al., 2021a]"; page 83: "A more detailed description can be found in Appendix A of [Popov et al., 2020b]"; page 88: "can be found in Appendix B of [Popov et al., 2020b]." The author should include these appendixes in the thesis to make the document self-contained.*

Response: Thank you for the comment. Appendixes were added.

Changes: Appendixes mentioned on Page 83 and Page 88 were added to the thesis. Appendices from Pages 54 and 56 were arranged as GitHub repositories. Corresponding references were added to the text.

Comment 4: *Page 93: "Thus, the efficiency of adaptive criteria such as IA and AA increases with increasing precision of the calculated curve in one layer." The efficiency should be formally defined and quantified before making this claim. Figures 6-10 and 6-11 only show that the time increases with the increasing resolution. The time of computation using a regular grid with the finest resolution can be taken as the baseline, for instance.*

Response: Thank you for the comment. The mentioned statement was rewritten more accurately.

Changes: The mentioned paragraph was updated (updates highlighted with yellow):
Thus, the difference in execution time between algorithms based on adaptive criteria, such as IA and AA, and the exhaustive enumeration algorithm increases with increasing precision of the calculated curve in one layer. Additionally, we can say that IA and AA work better with algebraic surfaces, especially with quadratic ones. However, the error of overestimation increases when we use transcendental functions or loops for describing complex models. The time efficiency of adaptive contouring techniques is more notable for computations with high XY resolution.

Comment 5: *Page 93: "This means that with increasing model complexity, the use of adaptive methods become reasonable only with finer accuracy." Does this relate with the fractal dimension of the object?*

Response: Thank you for the comment. The claim about model complexity was explained in more detail.

Changes: The mentioned paragraph was updated (updates highlighted with yellow):

That means that with increasing model complexity, the use of adaptive methods becomes reasonable only with better accuracy. It relates to the number of operations used in the model definition and their computational complexity. The computation of adaptive criteria for these models takes more time than the time benefit from empty regions passing. Moreover, increasing the number of non-affine computational operations leads to interval overestimations (see [Fryazinov et al., 2010]). A finer computational grid provides a larger number of empty regions. The adaptive subdivision with revised AA is preferred concerning the choice between adaption criteria.

Assistant Professor Ivan Sergeichev (Skoltech)

The review of Professor Ivan Sergeichev has no comments on suggested updates.

Response: Thank you for your feedback.

Associate Professor Igor Shishkovsky (Skoltech)

Comment 1: *My major comment connect with Conclusion section. The author lists what he did. However, the narration does not contain the main conclusions of the dissertation, the provisions of which the author issues to defense and guarantees their novelty and/or exclusivity.* **Response:** Thank you for your comment. The Conclusion chapter was updated for highlighting novelty and/or exclusivity. **Changes:** The following paragraph was added to the Conclusion chapter on Page 114: Therefore, this dissertation describes the novel modeling system for advanced 3D printing. It is the first proposed CAD/CAM system with a unique geometry representation containing modeling, optimization, and CNC code generation for AM components. The system resolves several challenges of excising commercial CAD/CAM software. It excludes errors of model geometry that come from transformations between optimization and modeling modules. Moreover, it avoids the smoothing of optimized parts because the proposed level-set-based optimization algorithms control the smoothness of the resulting geometry by appropriate choice of basis functions and knot point. These algorithms can be used with shape constraints and parameter optimization for more precise control of critical regions of a solid. Finally, the web-based architecture of the software allows arranging user collaboration for modeling tasks. The system uses proposed algorithms with improved time efficiency.
Comment 2: *'CSG Constructie Solid Geometry ' instead of 'CSG Constructive Solid Geometry'* **Response:** Thank you for the comment. The typo was corrected.
Comment 3: *'the pseudo-time variable' . - What is means?* **Response:** Thank you for your comment. The meaning of the mentioned term was explained. **Changes:** Two following sentences were added to the end of the quoted paragraph: This variable introduces continuous changes in the defining function during the optimization process. Optimization algorithms use discrete values of increasing pseudo-time iteratively.
Comment 4: *'For example, we use the exact value of the material Young's modulus for elements 1, 2, 3, 4, 5 and 6 in Figure 2-1(b), but it is reduced proportionally to the volume occupied by the solid body Ω for elements 7 and 8.' - Where did the authors get the exact values of the Young's modulus ?* **Response:** Thank you for your comment. Sources for used values of Young's modulus were added. **Changes:** Two following sentences were added to the end of the quoted paragraph: The Young's modulus of stainless steel used for experimental validation is assumed to be 205 GPa, and the Poisson's ratio, ν, is supposed to be 0.27 (see Section 5.2). The properties of the material from our laboratory were studied in [Kuzminova et al., 2019].
Distinguished Professor Jeng Ywan Jeng (NTUST)

Comment 1: *In scientific thesis, it had better to be written in 3rd passive point of view, like the wording of "we" (active point of view--emotion) had better to be changed into it. For example, there are several wordings of "we" has been written in abstract. This problem is not happened just in abstract, but also in most of the sections.*

Response: Thank you for your comment. The point of view was changed in the manuscript.

Changes: Sentences with "we" proposition were rewritten in Abstract, chapters "Background", "Thesis Objectives And Novelty", "FRep-based modeling system", 'Optimization of FRep objects", "Conclusion", and Appendix A.

Comment 2: *In abstract, too few scientific information is expressed, like only "fast algorithms" is used. There is no more information about this scientific information and how good to be compared with others. And, what is problem of the existed algorithm is not described. Also, the achievement is not mentioned, so it is difficult to attract reader to continue for other sections. "function representation & FREP" seem important keyword and contribution in this research, it should be mentioned and briefly explained in abstract to make the abstract more comprehensive.*

If the abstract will be too long, the first section can be shortened about the general common sense.

Response: Thank you for your comment. The Abstract was updated.

Changes: Updates of the Abstract are highlighted with yellow:

Additive manufacturing opened a new vision of design. This manufacturing technology provides extra freedom in possible shapes and structures. However, new opportunities arose new challenges for design tools. Problems with precision, correctness, interoperability, and standards became highly sensitive. Moreover, this freedom forces people to choose from more design options. It leads to a new need that is addressed in modeling systems. Users want a software to help them with their choice.

The core of this work consists of a computer-aided design and manufacturing system development suitable for the needs of additive manufacturing. It analyses existing solutions and problems and proposes an architecture of the system and its prototype. The thesis describes the modeling and manufacturing framework for 3D printing technology. Its routines exploit a unique representation of the geometry, function representation. It allows avoiding problems with converting models in different formats. Therefore, all modeling, optimization, and control program generation for 3D printing works with one geometry representation.

The modeling component of the system is implemented as a web-based service. It provides users opportunities for collaborative work. The geometric core based on function representation allows storing models in a compact symbolic form. The thesis proposes rendering algorithms for these models, which rely on parallel computation with a graphics processing unit performed in a browser.

The optimization component of the framework uses an updated topology optimization algorithm based on the level-set method. Its modifications allow performing an optimization

faster. Moreover, the thesis discusses aspects of including shape constraints in the optimization process, parameter optimization of a model, and their combination in one optimization process. The manufacturing component of the proposed system exploits time-efficient algorithms based on exhaustive enumeration, interval arithmetic, and affine arithmetic to prepare parts for 3D printing. They are flexible for different scales and structural complexity of the models. The described component allows users to generate control programs for 3D printing equipment with open protocols. The developed system was applied for the design and manufacturing of several example parts. Mechanical tests of these parts were performed to validate the developed system.
Comment 3: *P.14 BRep is the oldest approach for describing solid bodies used in CAD systems.— This statement is not absolutely correct in scientific thesis, in particular for this thesis is to focus on the topology of AM modeling.* **Response:** Thank you for your comment. A similar comment was already processed in response to Comment 2 of Professor Clement Fortin. Updates to the Introduction chapter were made.
Comment 4: *In this section in P.14 about the relationship or logic from CSG and BRep to Function Representation is not clear. Even, this terminology of FRep will be explained in later section, which is not logically reasonable. https://en.wikipedia.org/wiki/Function_representation* **Response:** Thank you for your comment. The Introduction chapter was revised and updated.
Comment 5: *The purpose of Table 1.1: Geometry representations in CAD systems is to show the BRep is used in most of CAD systems. This logic seems not absolutely reasonable. Please re-think about the problem 4.* **Response:** Thank you for your comment. The mentioned table was revised.
Comment 6: *P.31 The second important algorithm we need to consider is slicing. It is a procedure of CNC program generation. This statement is also scientifically questionable.* **Response:** Thank you for your comment. The mentioned statement was rewritten. **Changes:** The mentioned paragraph was updated (updates highlighted with yellow): The second important algorithm is slicing. Within this thesis, the term slicing denotes a procedure of CNC program generation for AM. However, FRep is not the only representation where slicing can be challenging. It implies the conversion of 3D models to so-called 2.5D geometry representation, which is challenging except you use 2.5D models, e.g., layered depth-normal images [Chen and Wang, 2011], as a geometric kernel. Nonetheless, the thesis needs to propose an efficient and competitive slicing algorithm.

Comment 7: *P.35 The class Structure stores more complex objects made of several primitives in a JSON format. What is this JSON format? It seems not defined before and not so popular in AM society.*

Response: Thank you for your comment. More details on the JSON format were provided.

Changes: The link to the format description and more information about it were added (updates are highlighted with yellow):

The CAD component was implemented with JavaScript, PHP, and GLSL languages. JavaScript code supports the main functionality of the system and user interactions with its interface. You can see its class diagram in Figures 4-2. The Element class and its children's classes Primitive and Structure provide fields and methods for working with solid objects. Their FRep defining functions are arranged as codes in JavaScript saved in the jscode field. The class Structure stores more complex objects made of several primitives in a JSON format ECMA [2022]. JSON (JavaScript Object Notation) is a lightweight data-interchange format. It is easy for machines to parse and generate. Our system uses this format for storing symbolic descriptions of primitives, a composition of primitives in structures, and attributes of models. Methods "loadFromCloud", saveToFromCloud, and removeFromCloud realize interactions with MySQL database exploiting Lumen Taylor Otwell [2022] PHP framework. Visualization routines exploit WebGL The Khronos Group Inc [2022] Application Programming Interface (API) running shaders written in GLSL (see Section 4.3)

Comment 8: *The rendering of the proposed model is illustrated and explained in section 4.3 P.42., but it started from 3D instead of N-space with other functional representation. Is it possible to design a FRep with variable functional lattice/cellular structure or even with variable material properties, like composite material with forming material filled in a close cell? Reference-- Mayur Jiyalal Prajapati, AjeetKumar, Shang-ChihLin, and Jeng-YwanJeng, "Multi-material additive manufacturing with lightweight closed-cell foam-filled lattice structures for enhanced mechanical and functional properties", Additive Manufacturing Volume 54, June 2022, 102766.*

Response: Thank you for your comment. More details on rendering options.

Changes: The following paragraph was added to the "FRep-based modeling system" chapter on Page 44:

The proposed rendering algorithm can be adopted for the models rendering with variable material properties, like composite material [Prajapati et al., 2022]. The FRep concept assumes that an object description can have additional real-valued functions. These functions define object properties, such as material, textures, and opacity. The rendering algorithm can be updated for using these functions in objects' color calculations.

Comment 9: *P. 44 This tool assumes that the drawn objects consist of textured portions of surfaces, e.g. triangles, as in classical BRep. If this BRep can be replaced by STL, it seems more reasonable and strongly related to AM application, because triangle seems not the most popular in BRep.*

Response: Thank you for the comment. The sentence was rewritten.

Changes: The sentence was updated as (updates are highlighted with yellow):

This tool assumes that the drawn objects consist of textured portions of surfaces, e.g. triangles, as in the ".STL" file format.

Comment 10: *The optimization of cantilever beam is shown in Fig. 5.2 Section 5.2, and then analyzed in next several sections. How to model the beam is defined using other complicated lattice structure or cellular structures, like reference Aamer Nazir, Ahmed Gohar, Shang-Chih Lin, Jeng-Ywan Jeng, "Flexural properties of periodic lattice structured lightweight cantilever beams fabricated using additive manufacturing: experimental and finite element methods", 3D Printing and Additive Manufacturing, 29 Jul 2022.*

Response: Thank you for your comment and the proposed reference.

Changes: The link to the mentioned paper with complicated models was added on Page 54 (updates are highlighted with yellow):

Four more optimization cases shown in Figure 5-2 were considered to check the observed tendency. More interesting models with complicated lattice structures or cellular structures can be found in [Nazir et al., 2022]. Figure 5-3 shows the results of optimization algorithms testing. The efficiency of the algorithms for these cases is compared in Table 5.2. The results show that the modified algorithm is faster.

Comment 11: *Hip implant was employed as an example to evaluate the case application of the proposed FRep model. How to model and optimization of the lattice structure of hip implant as shown in the paper, Ref: Kalayu Mekonen Abat, Aamer Nazir, and Jeng-Ywan Jeng, "Design, Optimization and Selective Laser Melting of Vin Tiles Cellular Structure-Based Hip implant", The International Journal of Advanced Manufacturing Technology (2021) 112:2037–2050.*

Response: Thank you for the helpful reference.

Changes: The mentioned paper is cited on Page 65.

Full Professor Pierpaolo Carlone (UNISA)

Comment 1: *Due to the aforementioned considerations, the overall evaluation is strongly positive. No significant revisions are needed (just a double check of the texts for typos here and there).*

Response: Thank you for your comment and advice.

Changes: The text was double-checked for typos and additionally revised with a typing assistant.