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Review

of doctoral dissertation

A COMPUTATIONAL INTELLIGENCE FRAMEWORK FOR PDE-CONSTRAINED TOPOLOGY OPTIMIZATION

written by NIKHIL TATKE, M.Sc., Eng.

1. Legal basis of the review

The present review has been prepared on the basis of the letter No. RDIMc.512.1.2026 issued by the Chair of the Scientific Discipline Council for Mechanical Engineering at the Silesian University of Technology, **PhD, DSc, Eng. ALICJĘ PIASECKĄ-BELKHAYAT, prof. SUT**, together with the attached doctoral dissertation entitled "*A Computational Intelligence Framework for PDE-Constrained Topology Optimization*" authored by **M.Sc. Eng. NIKHIL TATKE**. The dissertation supervisor is **PhD, DSc, Eng. JAROSŁAW KACZMARCZYK, Prof. SUT.**

2. General overview of the thesis and the candidate

The reviewed dissertation was presented in English language on 139 A4-size typed pages. The dissertation consists of: Abstract in English and Polish, List of Figures, List of Tables, List of Abbreviations, List of Notations, and 6 main chapters. At the end of the dissertation, the Author included four Appendices (A through D), along with a Bibliography consisting of 134 literature items. The dissertation contains the following main chapters:

(1) *Introduction*

(2) *Literature Review*

(3) *Methodology*

(4) *Numerical Experiments*

(5) *Results and Discussion*

(6) *Conclusion and Future Work*

Chapter (1) introduces the research background, motivation, objectives, and scientific context of the dissertation. The Author discusses the computational challenges associated with PDE-constrained topology optimization, particularly in the case of high fidelity and three dimensional finite element models. The chapter clearly formulates the research problem, defines the research objectives and questions, and outlines the principal scientific contributions of the dissertation. Furthermore, the scope and limitations of the study are explicitly stated, providing a transparent framework for the subsequent methodological developments.

Chapter (2) presents a review of the literature related to topology optimization, multifidelity computational strategies, and machine-learning-assisted optimization methods. The Author discusses also the historical development of topology optimization methods, including density-based, level-set, phase-field, and evolutionary approaches, with particular emphasis on the SIMP methodology adopted in the dissertation. The literature review concludes with the identification of existing research gaps and the positioning of the proposed framework within the current state of the art.

Chapter (3) constitutes the main methodological part of the dissertation. The Author presents the mathematical formulation of the minimum-compliance topology optimization problem under a global volume constraint, together with the finite element discretization and SIMP interpolation scheme. Attention is devoted to the proposed Multifidelity Acceptance Safeguard (MFAS), which introduces runtime verification into the multifidelity optimization loop. The chapter additionally describes the integration of a U-Net-based neural architecture as a warm-start mechanism within the optimization framework.

Chapter (4) is devoted to nnumerical analyses and the adopted computational methodology. The Author describes the benchmark problems considered in both two-dimensional and three-dimensional settings, together with the corresponding discretization strategies and numerical parameters. The chapter further discusses dataset generation procedures, experimental design, ablation studies, and the evaluation metrics together with the statistical reporting procedures implemented in the experiments.

Chapter (5) presents and discusses the results obtained from the numerical experiments. The Author analyzes the convergence behavior, compliance values, design quality, runtime performance, and acceleration effects achieved by the investigated method variants. Separate analyses are provided for two-dimensional and three-dimensional benchmark cases, including extensive ablation studies examining the influence of verification frequency and acceptance tolerances on the performance of the MFAS framework.

Chapter (6) contains the final conclusions and summarizes the scientific contributions of the dissertation. The Author provides answers to the formulated research questions and evaluates the extent to which the stated research objectives have been achieved. The limitations of the proposed approach are discussed in a critical manner, and several directions for future research are identified, including algorithmic extensions, scaling strategies, and broader applications of machine-learning-assisted topology optimization.

The Author has taken up a very challenging problem of developing a runtime-verified multifidelity framework for minimum-compliance topology optimization under a global volume constraint in linear elasticity. The Author has successfully implemented analytical formulations, computational experiments, and machine learning architectures to achieve the goals and objectives of the thesis, considering three main tasks: **(1)** *Achieving a verified computational acceleration relative to a fine-mesh SIMP baseline*; **(2)** *Preventing silent solution degradation and ensuring reliability through an acceptance/rejection mechanism* and **(3)** *Quantify the incremental benefit of integrating ML-based initialization into the verified multifidelity framework*.

The detailed subtasks consisted of the following items:

- Analysis of topology optimization fundamentals, multifidelity methods, and machine learning integration, explicitly highlighting research gaps such as lack of systematic acceptance safeguards or limited cross-dimensional validation.
- Formulation of the fine and coarse discretization alongside the strict 2 x refinement mapping operators (Restriction and Prolongation).
- Development of the MFAS logic utilizing a trust-ratio in 2D and a relative acceptance tolerance in 3D, embedding PDE residual-based verification directly into the optimization loop.
- Training and injection of the U-Net architecture to predict initial density fields based on boundary conditions and loads, while subjecting its output to the identical physical acceptance criteria as coarse-only proposals.
- Execution of numerical experiments including comprehensive ablation studies to evaluate verification frequency and acceptance thresholds.
- Detailed statistical reporting of runtime speedups, compliance retention, and gray fraction reduction using paired-seed evaluations and Wilcoxon signed-rank tests.

Mr. NIKHIL TATKE, M.Sc. Eng., is a co-author of 2 journal publications indexed in SCOPUS database and 2 book chapters, which together deserves a special emphasis and distinction. Furthermore, the Author has presented his research results in 3 international conferences. This achievement demonstrates the high scientific value of the developed methodology and significantly fulfills the requirements for the submission of a doctoral dissertation.

3. Detailed overview of the thesis

3.1 Structure and organization

The Dissertation is organized in a logical and generally transparent manner. Its structure follows the standard framework of an engineering-oriented doctoral dissertation, including theoretical background, methodological development, numerical investigations, and final conclusions. In the opinion of the Reviewer, the organization of the dissertation adequately reflects the adopted research procedure and allows the reader to follow the successive stages of the conducted investigations. The individual chapters are arranged in a sequence corresponding to the progression from theoretical background through methodological development to experimental verification and analysis of result.

3.2 Literature review

The literature review has been prepared very reliably and covers the major topics related to topology optimization, multifidelity methods, and machine-learning-assisted computational design. The Author demonstrates a good understanding of the theoretical foundations of the field and appropriately identifies the limitations of existing approaches, particularly regarding the trade-off between computational efficiency and reliability.

A valuable aspect of the review is its critical character, as the Author does not merely summarize previous work but also identifies a clear research gap motivating the proposed methodology.

3.3 Objective and its implementation

The main objective of the dissertation has been formulated clearly and consistently implemented throughout the work. The Author aims to develop a computational framework for accelerating PDE-constrained topology optimization while preserving solution reliability. The individual research tasks are logically connected with the principal objective and are adequately addressed in the subsequent chapters.

In the Reviewer's opinion, the stated objective has been achieved within the assumed scope of the dissertation. The proposed framework has been properly validated using representative benchmark problems and the achieved outcomes have been thoroughly discussed. The Reviewer did not observe major shortcomings or methodological errors in this scope.

3.4 Research methods

The Author employed an appropriate and well-selected set of research methods, including finite element analysis, multifidelity optimization strategies, and machine-learning-assisted initialization techniques. The major strength of the dissertation is **the development of an original verification-driven optimization methodology integrating runtime acceptance safeguards with multifidelity topology optimization procedures**. The proposed framework demonstrates a high level of methodological maturity and reflects a strong understanding of both computational mechanics and modern optimization strategies. The numerical experiments are extensive and include both two-dimensional and three-dimensional benchmark cases, ablation studies, and comparative analyses between different optimization variants.

The adopted research methods correspond well to contemporary scientific and engineering standards in computational structural optimization. The Author also demonstrates good competence in the implementation and evaluation of advanced computational procedures, including the integration of warm-start mechanisms based on neural networks within the optimization loop.

3.5 Results and their interpretation

The results are presented in a generally clear and systematic manner using numerical comparisons, figures, and benchmark analyses. The Author demonstrates the ability to interpret the obtained findings correctly and discusses both the advantages and limitations of the proposed methodology.

The analyses confirm the effectiveness of the proposed multifidelity framework in reducing computational cost while maintaining acceptable solution quality. Particularly valuable are the ablation studies examining the influence of verification parameters. On the other hand, some figures and plots included in the dissertation have worse quality and style than others, i.e. Figure 4.2 has very large fonts while characteristics shown in Figures 5.5 and 5.6 are not sufficiently consistent with the style of other figures/plots within the thesis.

3.6 Practical significance of the work

The dissertation has clear practical relevance and addresses an important problem in computational structural optimization. The proposed framework demonstrates significant implementation potential, particularly in applications requiring efficient large-scale topology optimization with controlled reliability.

An important advantage of the work is the integration of acceleration techniques with runtime verification mechanisms, which increases the practical credibility of the proposed methodology. The practical discussion could nevertheless be extended by providing more detailed information concerning implementation limitations and possible industrial deployment scenarios.

4. Strong points of the dissertation

The Reviewer would like to emphasize the strong points of the dissertation, which demonstrates a very high scientific quality of the studies conducted:

1. A detailed literature discussion on topology optimization, multifidelity strategies, and state-of-the-art machine learning implementations. This introduction demonstrates that the Author has extensive knowledge of the present topic and properly identifies the crucial gap within the investigated research area.
2. The dissertation is well written, and its structure creates a cause-and-effect sequence characterizing the successive stages of the proposed MFAS framework. The high quality

of the graphical presentation and style, combined with clear and concise language, makes the work highly readable. The logical structure and professional layout significantly facilitate following the methodology and interpreting the results.

3. A clear and precise description of the objectives and research questions in Chapter 1. The Author explicitly highlights the necessity of achieving accelerated computation without sacrificing the reliability of the high-fidelity PDE solutions.
4. Implementation of a highly rigorous evaluation protocol spanning both 2D (MBB beam, tip cantilever, mid cantilever) and 3D (cantilever, L-bracket) benchmarks.
5. The explicit decision to treat the U-Net machine learning model purely as an initialization (warm-start) tool rather than a replacement for physics-based optimization. This preserves the structural integrity of the final topologies and eliminates the risk of silent solution degradation.
6. Comprehensive ablation studies testing the boundaries of the framework, particularly regarding the verification frequency parameter and acceptance thresholds, which provides strong practical guidance for future implementation.

5. Main questions, points for discussion and comments

After reviewing the content of the entire dissertation, the reviewer would like to point out the following comments and remarks:

- Throughout the thesis, the Author utilizes a strict 2 x spatial refinement rule, corresponding to a 4:1 element count reduction in 2D and an 8:1 reduction in 3D. The question is: how sensitive is the developed MFAS to larger scale disparities (e.g., a 3x or 4x spatial refinement ratio), and would such adaptive refinement ratios require fundamental changes to the adopted multifidelity framework?
- The Author chose a simpler MSE loss function for the 3D model to save computational power, rather than the SSIM used in 2D. However, since MSE looks only at individual pixels/voxels, could this cause the 3D shapes to lose their continuity or structural integrity compared to the 2D results? This is particularly evident in Figure 5.8 for the M1 method, where visible discontinuities occur. Does the proposed framework require a post-processing cleanup step to restore physical integrity, or is the subsequent PDE-constrained optimization expected to resolve these topological gaps?
- The 3D L-bracket benchmark showed that Method M3 was slower than the baseline M1 at the default verification frequency setting due to the stress concentrations around the re-entrant corner. While it is suggested that reducing the verification frequency could recover speedup for M3, is there a way to make the algorithm smart enough to change this setting by itself during the test?
- The observation that Method M3 underperforms the baseline M1 due to stress concentrations at the re-entrant corner highlights a limitation in the fixed verification

frequency strategy. Since the local convergence behavior in topology optimization is strongly dependent on the gradient landscape, has the Author considered implementing a "smarter" algorithm, which automatically adjusts how often it checks for accuracy based on the current complexity of the problem?

- The efficiency of multifidelity frameworks depends on the trade-off between the coarse-mesh speedup and the cost of high-fidelity verification. How does the current acceptance logic ($\epsilon_{rel} = 0.01$) perform under the mesh densities typical for industrial FEA? Is there a risk that the rejection rate increases significantly with mesh scale, effectively negating the computational savings achieved by the MFAS framework?

6. Minor questions, points for discussion and comments

Additional remarks are presented below. The reviewer outlines some elements of the work that could be improved, but have a minor impact on the scientific quality of the thesis:

- The dataset generated for the 3D U-Net training is relatively small, comprising 360 cantilever and 160 L-bracket effective samples after augmentation. A brief discussion on the risk of overfitting during the extended 150 training epochs would strengthen the methodology section.
- In the 2D results discussion, the Author states compliance values are deterministic across all seeds and standard deviations are exactly zero due to the hash-based load perturbation and direct solver. While factually true for this specific setup, testing with genuinely randomized initial noise might have provided a better picture of algorithmic robustness. Assessing the sensitivity of the converged topology to stochastic perturbations would be particularly valuable, as such robustness is a prerequisite for reliable deployment in industrial-scale FEA problems.
- In Figures 5.4, 5.5, and 5.6, the plotted curves for relative compliance and relative gray fraction utilize different colors in a legend compared to the curves included in the chart.

7. Editorial, grammar and stylistic errors

The Reviewer found only a few errors, which, however, do not influence a very high scientific and application level of the dissertation submitted for evaluation. Some selected remarks are as follows:

- The Polish summary (Streszczenie) contains several stylistic imperfections, which result from a direct English-to-Polish translation; as a consequence, some sentences sound unnatural.
- In general, the doctoral thesis is written in high-quality academic English, and only a few minor typos or grammatically awkward sentences were identified.

8. Final conclusion

The dissertation provides an original solution to a scientific problem and demonstrates both a high level of theoretical knowledge and the ability to conduct sophisticated optimization analyses. The dissertation meets the requirements for doctoral theses specified in the relevant Act (*Prawo o szkolnictwie wyższym i nauce* z dnia 20.07.2018 r.), and falls within the scientific discipline of Mechanical Engineering

Therefore, **the Reviewer asks for admission to the final defense.**

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