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Skolkovo Institute of Science and Technology

Jury Member Report – Doctor of Philosophy thesis.

Name of Candidate: Ilias Giannakopoulos

PhD Program: Computational and Data Science and Engineering

Title of Thesis: Memory compression of the Galerkin Volume Integral Equations and coil modeling for the electrical property mapping of biological tissue

Supervisor: Prof. Maxim Fedorov

Date of Thesis Defense: 12 May 2020

Name of the Reviewer: Nikolay Koshev

I confirm the absence of any conflict of interest (Alternatively, Reviewer can formulate a possible conflict)	**Signature:** **Date: 18 April 2020**

The purpose of this report is to obtain an independent review from the members of PhD defense Jury before the thesis defense. The members of PhD defense Jury are asked to submit signed copy of the report at least 30 days prior the thesis defense. The Reviewers are asked to bring a copy of the completed report to the thesis defense and to discuss the contents of each report with each other before the thesis defense.

If the reviewers have any queries about the thesis which they wish to raise in advance, please contact the Chair of the Jury.

Reviewer's Report

Thesis background

Magnetic Resonance Imaging (MRI) is a powerful and very elegant technique of tomography applied to organic matter (human body tissues). The MRI technique use the fact that organic tissues are transparent with respect to magnetic field, which allows usage of rather strong magnetic fields (1-7 Tesla) in order to obtain a good resolution of tomography. The medical research needs, however, better resolution, which can be reached by application of the greater magnetic fields. Application of the field with the magnitude greater than 7 Tesla, however, has some issues both in terms of safety and computational needs. First of all, the greater field needs application of high frequency RF fields, which can lead to damage of the tissues. The design of the coils demands new techniques for precise mathematical modelling (simulation) of EM fields. Secondly, the greater resolution needs too much memory for processing the data,

needs application of high frequency RF fields, which can lead to damage of the tissues. The design of the coils demands new techniques for precise mathematical modelling (simulation) of EM fields. Secondly, the greater resolution needs too much memory for processing the data, which makes it hardly usable with GPUs. Thus, greater resolution demands also new techniques of compression and fast and economic computational algorithms.

The thesis is devoted to two main problems, arising in high-resolution MRI:

- development of a new memory-efficient algorithms for the execution of the electromagnetic simulations via FFT-based volume integral equations method;
- Investigation of the problem- and person-dedicated RF coil design for efficient Global Maxwell Tomography (GMT).

Both problems are undoubtedly actual and highly needed by both medical and scientific societies.

Structure of the thesis

In terms of the structure, the thesis is divided into six chapters including the conclusion.

The first chapter is an introductory chapter and contains a very global description of the problems being under consideration in the thesis, the review of the literature and state-of-the-art of the area being under consideration. The review of the literature and state of the art are given in a very sophisticated and clear manner. The text is a good causal structure and given in a form which is very easy and interesting to read.

The second chapter gives a structured consideration of the electromagnetism theory related to the research of the thesis. It starts with the Maxwell system, its forms and some fundamental theorems of electromagnetism. After that, the wave equations and the surface and volume equivalence principles are being under consideration. The chapter finishing with a brief review of some computational methods and techniques taking part in the EM simulations. In my opinion, the chapter is very good although it does not contain the application of the considered theoretical base to the MRI in order to show reader the physics of MRI in a sophisticated way. Despite that fact, the chapter is very accurate, mathematically strict and gives information in a clear and understandable way.

The third chapter is devoted to full review of the Integral Equations method, its specificity and particularity in application of it to EM simulations. The chapter starts with Surface Integral Equations (SIE) and continues with Volume Integral Equations (VIE) and Volume-Surface Integral Equations. The descriptions of SIE and VIE methods take the main part of the current chapter and are considered in a very detailed way. Some examples of VIE simulations and its analysis finish the chapter. The chapter is made with high accuracy and is easy-understandable.

The fourth chapter is devoted to the review of methods for the memory footprint reduction of the tensors appearing in FFT-VIE methods, and to the presentation of a set of novel matrix-vector product implementations. All implementations are given in form of algorithms, which is

useful and helps to understand the methods better. The chapter finishes with a set of numerical experiments demonstrating pros and cons of proposed methods.

The Fifth Chapter is dedicated to the investigation of GMT's performance with realistic RF coils, in simulation, for the EP reconstruction of tissue-mimicking phantoms and more complex structures such as highly inhomogeneous human head models. The chapter starts with consideration of GMT and continues with the statement of the optimization problem for design of RF coils. The chapter also shows a big number of numerical experiments and their results showing applicability and usefulness of the proposed methods.

The last chapter gives the conclusion, some discussion and claim of the future research. The conclusion is clear and relevant to the research and results of the thesis.

Specific comments

The objective of this section is to provide several specific comments and recommendations on how to improve the quality of the presentation. The provided comments are not critical and mostly related to some inaccuracies in the thesis appearance.

1. The formula (4.3): orthogonality commonly means equality of the inner product to zero.
2. Some inaccuracy in Figures presentation: 4.5 – the time should be given in seconds, as caption says; 4.10 – description states comparison with traditional approach (FFT-JVIE) while the labels on Figure are "Tucker" and "HOSVD"; 4.12 is hardly understandable because of absence of the labels near each picture; also, 4.12 presented before fig. 4.11; it's also hard to find any difference on the figure 4.11. Obviously, it should be like that but it might be better to present, for example, logarithm of difference in modelling with different algorithms.
3. At the start of the section 5.1 author says that since GMT is noised inverse problem and thus, the regularization should be applied. It is not true: a lot of inverse problems with noisy input can be solved without regularization. For example, the inverse Radon transform does not need any regularization. In order to claim the need for regularization, the ill-posedness should be proven or cited.
4. The formula (5.5) is, first of all, not the equation, and, secondly, should be clarified. Does it use the finite-difference Laplacian (Δ_q)?

Summary and conclusion

In my opinion, the thesis is a very sophisticated work which shows high level of the researcher due to the following statements:

- The topic of the thesis is relevant to its actual content.
- The thesis contains a big and accurate research on the state of the art methods and algorithms, which guaranties that all methods used in the thesis are fresh and relevant to the problems.
- The results of the thesis are actual and undoubtedly scientifically significant and relevant to international level and current state of the art.

- The research is devoted to the applied problems and considered in realistic way with realistic parameters, which automatically makes the results applicable and highly demanded by scientific and medical societies.
- During the research, author of the thesis published several high-quality publications in known and highly regarded journals.

The thesis seems to present a novel work, which value for scientific and industrial modelling is doubtless high. The research presented in the thesis is definitely actual and refers to contemporary results in the area. Despite some insignificant inaccuracies in the thesis appearance, the research is interesting. Author of the thesis definitely proved his ability to perform a research and to achieve high-rated scientific results. I am glad to recommend the thesis to the defense.

Provisional Recommendation

☒ *I recommend that the candidate should defend the thesis by means of a formal thesis defense*

☐ *I recommend that the candidate should defend the thesis by means of a formal thesis defense only after appropriate changes would be introduced in candidate's thesis according to the recommendations of the present report*

☐ *The thesis is not acceptable and I recommend that the candidate be exempt from the formal thesis defense*