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Skolkovo Institute of Science and Technology

Jury Member Report – Doctor of Philosophy thesis.

Name of Candidate: Ioannis Georgakis

PhD Program: Computational and Data Science and Engineering

Title of Thesis: Fast integral equation methods and performance bounds of modern magnetic resonance coils

Supervisor: Prof. Maxim Fedorov

Co-advisor: Prof. Athanasios Polimeridis

Chair of PhD defense Jury: Prof. Ivan Oseledets **Email:** *I.Oseledets@skoltech.ru*

Date of Thesis Defense: 28 November 2019

Name of the Reviewer:

I confirm the absence of any conflict of interest (Alternatively, Reviewer can formulate a possible conflict)	**Signature:** **Nikolay Koshev** **Date: 28 October 2019**

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
Reviewers report should contain the following items: • Brief evaluation of the thesis quality and overall structure of the dissertation. • The relevance of the topic of dissertation work to its actual content • The relevance of the methods used in the dissertation • The scientific significance of the results obtained and their compliance with the international level and current state of the art • The relevance of the obtained results to applications (if applicable) • The quality of publications The summary of issues to be addressed before/during the thesis defense

1 Thesis background

Magnetic Resonance Imaging (MRI) is a powerful tomography technique being applied to organic tissues (human body). One of the most important advantages of MRI is that the body tissues are transparent with respect to magnetic field, which, with proper organization of the coils, makes this kind of tomography very safe unlike, for example, the X-ray tomography. The higher resolution, however, demands usage of extremely strong magnetic fields. Increase of the field leads to a number of effects, which can make the technique unsafe or inaccurate due to non-homogeneity of the magnetic fields over the computational domain (body or its part). The MRI tomography based on usage of three sets of magnetic fields. The first one is static, oriented along one of axes (Z-axis) of the system under research, and responsible for alignment of the magnetic moments of the atoms along Z-axis. The second one is a radiofrequency (RF) field directed perpendicularly to the first one and responsible for the precession of the magnetic moment around the direction of Z-axis. The third set of fields are gradient fields responsible for the image formation. The resolution of the method depends on the strength of the first and second fields. The increase of the fields demands, however, very sophisticated tuning of all three fields in order, firstly, to decrease the affection of the RF field on the tissues and, secondly, to increase signal-to-noise rate. The proper balance of the fields may be provided using the simulation since the experiment might be very expensive and even dangerous.

2 General comments

The thesis is devoted to the development of simulation (mathematical modelling) techniques for MRI fields in order to obtain a good balance and uniformity of the magnetic fields applied to the system under investigation. The challenges are related to the facts that increase of the primary field (Ultra-High-Field, UHF) leads to increased absorbed power (safety), comparability of the effective wavelength with human body size (non-uniformity of the RF field), to local peaks of power absorbed with the tissues (hot-spots, might be dangerous). The fields and its interaction with the coils and tissues is being described with the Maxwell equations. Two main techniques for numerical solution of Maxwell equations are Differential Equation (DE) method and Integral Equation method (IE). Chapter 1 and chapter 2 of the thesis contain introduction and theoretical base of MRI measurements. The presented introduction and theoretical explanations are very clear and accurate, including a big number of sources and references to contemporary research on the area. In Chapter 3, Author is introducing the novel performance metric called Ultimate Intrinsic Transmit Efficiency, or UITXE, presented with the maximum possible transmission efficiency for the specific object of interest and parameters of the experiment such as strength of the primary field. The metric can be used for RF shimming, allowing to calculate the optimal coils configuration. Author provided series of numerical experiments with simple spherical models in order to investigate the behavior of the UITXE metric in dependence on the primary field strength, on the area of interest size etc. The Chapter 4 is devoted to the integral equations (VIE) methods for EM fields computations in MRI. Author derives the fast high-order VIE solver based on the equivalent polarization currents with discontinuous piecewise-linear basis functions. Author provides a series of numerical experiments showing accurate and stable convergence within the computation of EM scattering from highly inhomogeneous and high contrast objects (human head). In order to increase the performance, Author uses discretization with uniform meshes, which allows to apply Fast Fourier Transform. The developed solver can be applied not only for

MRI purposes and will be a part of the MARIE 2.0 suite. Chapter 5 stressed on the description of detailed algorithm for generation numerical EM fields basis. Author studies impacts of separating electrical distance (the distance between the coils and the object of research) on the basis generation, showing the larger electrical distance leads to better convergence in UISNR and UITXE computations. The chapter also demonstrates how the vectors of total EM fields basis can be applied in optimization procedures and used to calculate performance bounds such as UITXE. The numerical results of the chapter are accurate and provided with usage of inhomogeneous head models. The results on UITXE behavior compared with the same within a uniform sphere, 2 considered in the previous chapter; Author showed the behaviors are similar when the dimensions of models are comparable. The latter gives the strategy on coils construction (number, field) allowing to have the best possible result of research inhomogeneous objects such as human head or body. At the conclusion author gives a brief discussion on the future work.

3 Summary and Conclusion

I find the thesis to be a very sophisticated and accurate work, provided by the Author. As for appearance, the thesis is written very good. The background is shown in a very clear and detailed way. The new proposed methods, metrics and approximations are accurately justified and completely researched both theoretically and numerically. The VIE method proposed by Author is analyzed and compared with the existing methods. The conclusion is given in a very clear way. The research topic is doubtlessly actual, the algorithms are novel and might contribute to the field of MR imaging. The only comment I can give to Author is that the thesis contains some misprints, which, of course, should be accurately fixed before the presentation. Author shows a great ability to provide a big and complicated research in a very accurate and sophisticated way. He is definitely able to achieve a very good results during the future research independently on the area. I am therefore glad to recommend the thesis to the defense in order to receive the Ph.D. degree.

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*