Skoltech
Skolkovo Institute of Science and Technology

Thesis Changes Log

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

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

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The thesis document includes the following changes in response to the external review process.

The responses below are presented according to the chronological order with which the external reviews were received. Similarly, the corresponding changes have been integrated into the thesis with the same order.

Response to the review of Prof. Nikolay Koshev

Thank you for your encouraging and thoughtful comments. The thesis has been proofread again and all found misprints and typos have been corrected.

Response to the review of Prof. Francesca Vipiana

Thank you for your encouraging and thoughtful comments. The following minor issues have been addressed:

1. *In the abstract define "TXE".*
The abbreviation has been defined.

2. *Check the titles of the cited papers: acronyms have to be capitalized (e.g. "Stable fft-jvie solvers for fast analysis of highly inhomogeneous dielectric objects," should be "Stable FFT-JVIE solvers for fast analysis of highly inhomogeneous dielectric objects,")*
The acronyms at the titles of the cited articles in the bibliography have been capitalized.

Response to the review of Prof. Dmitry Dylov

Thank you for your encouraging and thoughtful comments, as well as your suggestions and questions that are of value for future research work and could facilitate the translation of the theoretical and numerical results of this thesis to practical MRI applications. The following comments have been addressed:

1. *The subject of optimization seems not to be sufficiently robust in terms of mathematical formulation presented in (5.50)-(5.55). Perhaps, a more robust approach to the computational derivation of an optimal*

shape of the excitation pattern would be beneficial to completing the story. The numerical part, however, is sufficiently robust and sound.
The mathematical formulation of the optimization problems for SNR and TXE and the corresponding computational derivations of the optimal excitation patterns are the subject of detailed studies in the literature. For SNR, they can be found at Appendix A of [12] and for TXE, at [186,171]. That being said, a clearer link to these studies and a direct description of the subject of optimization have also been added.

2. *The rationale behind choosing a new performance metric, UITXE, which is claimed to provide the largest theoretical response for a given coil design is not covered sufficiently well in the introduction part to the section 3. The claim itself could be elaborated to clarify the cases when the theoretical considerations fail to depict experimental observations. How well does this relate to the real magnets today?*
UITXE provides the largest theoretical response independent of any particular coil design since it is computed by a complete basis of EM fields where more and more basis fields are added and every EM basis field can be associated with a hypothetical coil which guarantees that UITXE is an upper-bound of transmit performance. Additionally, UITXE considers only sample losses, while in an experimental setup there are power losses due to radiation, losses in dielectric materials other than the sample, losses in lumped elements, and losses due to reflected power [171] which all make the TXE of an array in an experiment smaller than that in a simulation setup and further guarantee that the measured TXE will be smaller than the UITXE. With regard to real magnets, there is an experimental research study that evaluates the performance of a 32-element receive array with respect to UISNR [25] and a similar study for transmit arrays performance evaluation could be the subject of future work. To address this comment, the above clarifying statements have been integrated into the introduction of Chapter 3.

3. *Even after reading the thesis, this jury member was left dubious with regard to the most important question: should we continue increasing RF magnitude in hopes to see greater detail in the images? There is room for improving the relevant description.*
This is an interesting question for which we believe the answer is subjective and depends on how the MR scanner is operated and how the image is acquired, both in terms of hardware and software. In our opinion, increasing the field strength above 7T can result in considerable B_1^+ inhomogeneities, particularly if the MR scanner is not operated properly, and one can end up having worse imaging results than from a 3T or lower field strength scanner that yields smoother B_1^+ fields and deposits less power to the human body. Additionally, a UHF MR scanner may be operated sub-optimally with the fear of excessive heat deposition to the patient. However, given a substantial body of research, both theoretical and experimental, which demonstrates that pushing the limits to UHF strengths can indeed make the difference (a representative example is this: https://med.umn.edu/news-events/medical-bulletin/still-pushing-limits), we believe that it is indeed worth pursuing UHF MRI, which effort should be accompanied by substantial research and development that takes into account the challenges described in this thesis and should aim to develop novel, task-optimal RF arrays that respect the underlying EM fields considerations in MRI. To address this comment, an additional paragraph discussing the above has been added at the end of Section 6.1.

4. *Pages 166-168 contain post-editing gibberish and should be removed.*
These pages contained the movies with the evolution in time of ICP which, however, in many computers appear not to be working properly or even crash the PDF file, therefore, for compatibility reasons they have been removed.

5. *How about tackling the SNR "hot spots", caused by the absorbance difference (SAR), with simple digital artefact removal pipelines? Perhaps, the future plans section could be written in such a way that the theoretical sections preceding the conclusion should naturally lead towards the future of MR imaging.*
Thank you for this suggestion. Indeed, SNR bright areas or constructive interferences, as referred in the literature, could possibly be tackled with digital artefact removal pipelines. However, at UHF strengths due to dielectric phenomena and due to the comparable to the human body dimension effective wavelengths, there also arise dark areas (destructive interferences) where the receive B_1^- field signal intensity is close to zero (see [106] as well as Figures 4.12, 4.14, 4.16, and 4.17). Therefore, the proposed digital artefact removal pipelines could only tackle part of the problem, which, however could be worth looking into with more attention. Another technique that is used in practice is dielectric shimming where high-permittivity pads are attached externally to the region of the body that is to be imaged and result in the B_1 illumination of

previously dark areas. Regarding the future plans section, an additional paragraph has been added focusing on the future of MR imaging at Section 6.2.

6. *What are the outcomes expected from an imaging system capable of generating MR echo and the complex excitation sequences in time? Will detectors keep up with the excitations sequences? Can the ultra-strong component of the magnetic field introduce strong nonlinear response with the second order relaxation effects in the biological tissues?*
This is a really interesting question that could in fact lead to a future study where the RF excitations could be the SNR-optimizing ICP in a combined Bloch/Maxwell simulator, in a similar manner with previous studies where Bloch simulation suites have been introduced [165,166]. As a first step, such simulations can provide useful insight into the SNR-related improvement level of the MR images with respect to images acquired with traditional RF excitations. A second step could be an experimental study focusing on the MR image acquisition from RF arrays that approach the shape of the ICP, thus the UISNR, and that are driven with the optimal RF shimming weights. Such experimental study could give an answer to the question of how the RF detectors would behave given a complex excitation sequence and how the resulting MR image compares to images acquired with traditional birdcage coils. For completeness, these considerations have been added to the future plans section discussing the future of MR imaging. Regarding the relaxation time dependence on the B_0 field strength, there is a rich investigative activity, where an interested reader can refer to [a-g]. In brief, T_1 increases and T_2 practically remains unchanged. No matter how interesting such study may be, we believe that it refers to a research direction that is not an integral part of this thesis and it requires a different theoretical background. However, it is indeed worth investigating it as a future direction, especially in an experimental setup and with respect to the existence of second-order relaxation effects in biological tissues.

7. *The prospect of improved signal to noise ratio (SNR), higher spatial/spectral resolution and shorter imaging time are well described to provide motivation for the reader. Although patient safety is mentioned, the literature search with regard to the highly oscillatory and compensatory component of the RF magnetic field is not presented.*
Patient safety due to RF power and heat deposition to the tissue is presented in a detailed way mentioning local and global SAR aspects, how SAR changes with respect to the operating frequency, and the effects that local transmit coils might have at superficial tissues. In addition, SAR mainly depends on the electric field while the RF magnetic field does not have in practice adverse effects, except of inducing the corresponding electric field and electric currents on conductive tissues. The adverse effects of the magnetic fields are primarily associated with the static and the gradient magnetic fields which take values of *T* and *mT*, respectively, while RF fields take values of μT. The spatial gradient of the static field can exert a translational force on an object and the fast on and off switching of the gradient coils can induce electric fields that might cause peripheral nerve stimulation. However, there is indeed room to mention that the peak magnitude of the RF electric field depends on the peak magnitude of RF magnetic field and the operating frequency and that electric currents are generated due to magnetic induction due to which the problem of heating can be acute when metallic implants are present. Furthermore, an interesting study explores the role of EM fields polarization as a significant factor that increases biological activity [130] with its associated risks and it is worth to be mentioned. To address this comment these remarks have been added at the end of Section 2.2.

8. *As a suggestion to re-unite the reader with the Data Science, it is recommended to add a short speculation on the subject of modern Image-to-Image translation approaches that attempt to generate ultra-high field MR imagery from the low-detail images. See, for example, this work and explain how your approach relates to this work: https://link.springer.com/chapter/10.1007%2F978-3-319-46976-8_5*
Thank you for this suggestion. Such image-to-image translation approaches can indeed be of great practical value for generating higher-resolution 7T images at the cost of a 3T MR scanner. However, there is not such a direct connection of this study to the work presented in thesis as much as to another relevant study that aims at the electrical properties reconstruction from MR measurements with Global Maxwell Tomography [95]. To address this comment a connection to data science approaches has been added at the paragraph discussing the future of MR imaging at Section 6.2.

9. *With regard to strict derivation of the integral equation, phrases like "surprisingly stable convergence" should be avoided or, alternatively, a justification of why the expectations had been below the obtained ones should be provided.*
We have used these strong expressions regarding the convergence of the iterative solver with the proposed current-based formulation because it indeed has a really stable convergence both for the case of *h*- and *p*-refinement. Such behaviour is not so common for IEs for which the iteration count typically diverges with *h*-refinement (see for example the iteration count of the flux-based solver at Figure 4.9). Additionally, the iteration count for the same current-based solver with PWL basis functions remains the same as the grid is refined, while for the lower-order PWC scheme it slightly increases which leads to the conclusion that *p*-refinement stabilizes the iteration count and that the spectral properties of the operators are preserved. That being said, additional justifications have been added at Section 4.3.

Response to the review of Prof. Vladimir Okhmatovski

Thank you for your encouraging and thoughtful comments. The thesis has been proofread again and all found misprints and typos have been corrected.

Response to the review of Prof. Ivan Oseledets

Thank you for your encouraging and thoughtful comments. The following comments have been addressed:

1. *The claim in the conclusion that solver is well-conditioned is not correct: the solver cannot be well-conditioned, only the matrix of the linear system can be well-conditioned.*
Thank you for this comment. We have corrected the statement in the conclusion.

2. *The claim that VIE can be solved by FFT for the uniform grid is known from the literature. (Section 6.1) and in the prior work. I do not understand what comes under the statement «We show that» in the contribution sections.*
Thank you for this comment. Indeed, FFT-based VIE solvers exist in the literature and in prior work. We have modified our statement to be clearer that this is not a contribution of the thesis rather an existing method that has been used for the acceleration of the matrix-vector product.

3. *Personal contributions should be clearly stated and usage of «we» avoided. For example, section 5.2.2. describes the derivation of the generalized eigenvalue problem for computing the extremal case, but is it the contribution of the thesis?*
Extremizing the ratio of quadratic forms for TXE can be viewed as a generalized eigenvalue problem and indeed such approach is known from the literature and not part of the contribution of this thesis. We have modified our statements to more explicitly explain this.

4. *The numerical experiment on a sphere shows O(h) convergence, not O(h^2). It seems like a drawback of the method. This should be commented.*
Indeed, despite the use of PWL basis and testing functions, the convergence rate is $O(h)$ instead of $O(h^2)$. This can probably be explained by numerical inaccuracies originating from the staircase approximation of a sphere, when discretized with voxels. This explanation is commented at subsection 4.3.3 and it has also been added at the conclusion for completeness.

5. *What happens if the contrast in the media is large (with the solver?).*
In problems with high contrast, as demonstrated at subsection 4.3.3 at the numerical experiment with the high-dielectric ($\epsilon_r = 300$) pad attached to the head model, the solver with PWL basis functions provides reliable results comparable to those of a commercial FDTD package. However, the iteration count significantly increases and around 700 iterations are required (Figure 4.15) whereas 160 suffice when the high dielectric pad is not attached (Figure 4.9) to achieve a solution with the same GMRES tolerance. Therefore, it is expected that the higher the contrast the more iterations are required for convergence in an iterative solver similarly to the case of high-frequency problems. Such remarks have been added to subsection 4.3.4 for completeness.

Bibliography

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