QuIT: Quantum Imaging for Tomography

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ABSTRACT
We detail how the transformations that are used for quantum state reconstruction (quantum tomography) can also be used for medical tomography, with radiation reduction as a goal. We implemented a full software package that recovers the raw data from Siemens tomography machines and provides medical-quality reconstructions. We compared our method with the traditionally used ones, such as Filtered Back Projection (FBP) and the Simultaneous Iterations Reconstruction Technique (SIRT). We performed quantitative analyses, using customary benchmarks (signal-to-noise ratio, contrast-to-noise ratio, etc.). Moreover, a qualified qualitative comparison will be performed by professional medical staff in the last months of the project.

Keywords: Medical Imaging, Healthcare, Tomography, Prevention.

1. INTRODUCTION

• Computerized Tomography (CT) is extremely useful from a diagnostic point of view, but is used only in serious cases because the patient receives a high dose of radiation from a typical CT scan. A method that could produce high-quality images with less irradiation would open the possibility to employ CT scans in areas where it currently cannot be used, such as pediatrics or preventative medicine. Our project analyzes how one can achieve this goal through quantum state reconstruction (QST).
• QST is a procedure that is used to recover the quantum state of a system from repeated measurements. Our project's breakthrough was to realize that the same mathematical transformations at the basis of QST can be also applied to medical tomography. The fact that QST is a procedure honed for quantum mechanical systems suggests that it is extremely efficient in recovering the required information.
• In addition to successfully demonstrating this potentiality with data from commercial tomographic machines (we used a Siemens Somaton Definition Edge) with promising results, we have also developed a full software suite appropriate to the aims of the project. It can produce medical-quality images from raw data. It has the main capabilities of commercial-quality software (fan beam elaboration, windowing, contrast adjustments, resolution optimization, etc.). It can produce reconstructions using also the customary algorithms, such as Filtered Back Projection (FBP) and the Simultaneous Iterations Reconstruction Technique (SIRT), so that these conventional procedures can be effectively compared to ours. It can produce a quantitative analysis of these reconstructions, by calculating a host of metrics, detailed below. It can simulate the input data for situations (such as extremely-low-radiation doses) where real-world data is inaccessible. The code has additional useful features, such as docker deployment, code coverage, unit testing, continuous integration and deployment, possible delegation of computation-intensive tasks to remote servers, web-based visualization and control. In addition to the software package, we will also obtain the professional evaluation of our reconstructions from dedicated medical staff. The Covid19 has delayed this part of the project, since the medical staff in our Vicenza node was largely unavailable during the emergency.

2. STATE OF THE ART

Tomography is based on illuminating the target with an X-ray source from different angles, and then using the resulting 1D intensity profiles at the detectors to reconstruct a 2D image. Many such images can then be stacked for a 3D reconstruction. The intensity at each point x for each angle φ is proportional to the probability that each photon goes through the sample, which in turn is proportional to the exponential of the integrated transmissivity of the sample at that position in that direction (because the joint probability of a photon going through the infinitesimal sample slices is the product of the probability of going through each slice):

$$I(x,\varphi) = I_0 \exp[-\int_{\mathbb{R}} ds\ \mu(x\cos\varphi - s\sin\varphi, x\sin\varphi + s\cos\varphi)], \quad (1)$$

where I is the intensity, I_0 is the intensity in the absence of the sample, $\mu(w, z)$ is the sample transmissivity at position w, z in a 2D plane orthogonal to the rotation axis at the position of the detector strip. The aim of tomography is to recover μ from the measurement of I. Conventional methods, such as Filtered Back Projection (FBP), invert Eq. (1) using a mathematical transformation called inverse Radon transform. This inversion is mathematically ill defined (it involves the principal part of a divergent integral). Moreover, the binning inherent in the recovery of the intensity profile from single-photon data introduces a bias: the bin width is arbitrary. Higher quality images with lower radiation dosage would be possible if these problems are overcome.

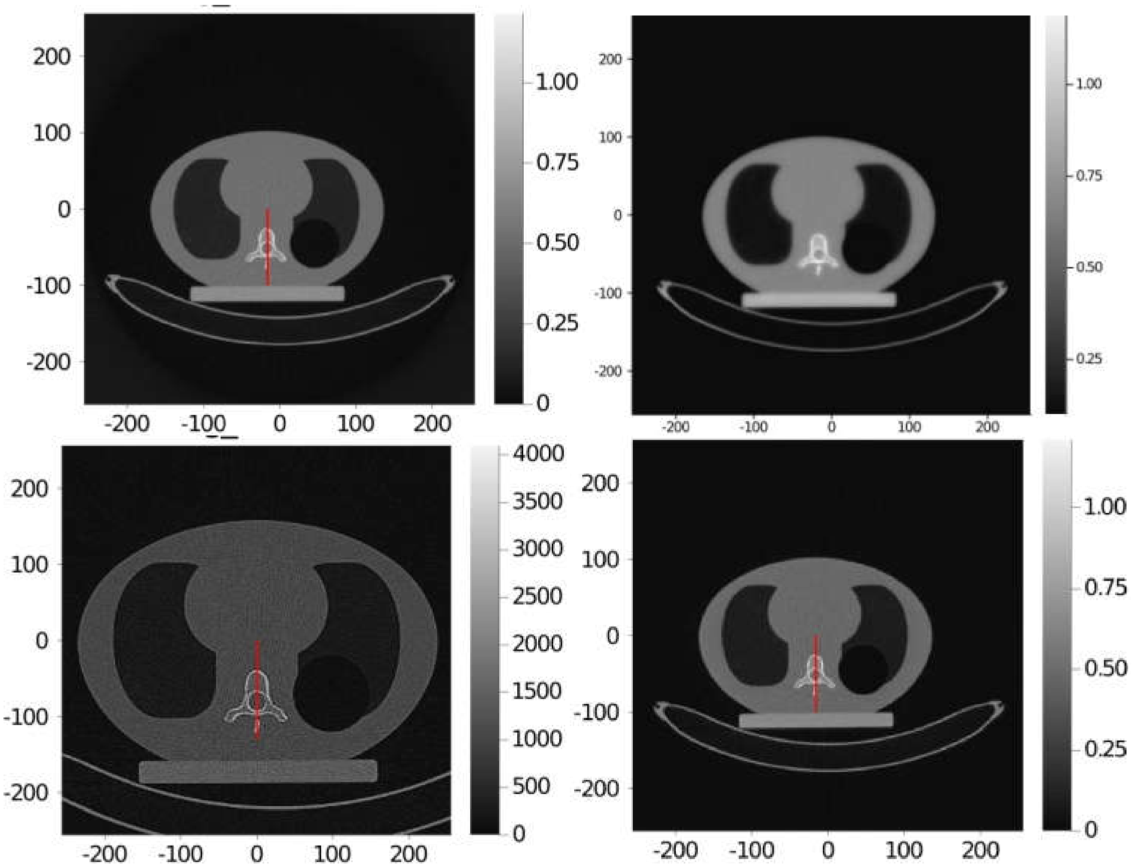


Fig. 1. Comparison between different reconstruction techniques. These images were reconstructed from the same raw data from a Siemens Somaton Definition Edge CT scanner and depict a calibration phantom. From left to right, top to bottom: FBP, SIRT, the CT scanner's own reconstruction and the one from our method. The images refer to a low-dose irradiation (3kV, 10mAs).

3. BREAKTHROUGH CHARACTER OF THE PROJECT

Quantum State Reconstruction (QSR) is a procedure that reconstructs the quantum state of a system by repeated measurements on many copies of the system. Historically, the first QSR methods employed the same transformation (inverse Radon transform) of medical tomography, hence the alternative name for QSR, "quantum tomography". However, soon new mathematical transformations, based on "pattern functions" were discovered. These removed the inherent bias (bin width) in the inverse Radon transform and also removed all divergencies, for specific representations (bases) for the state in the Hilbert space. The space restrictions of this report do not allow us to provide a full account and the mathematical description of the method, which can be found in [1].

The breakthrough character of our project is to apply these mathematical transformations developed for QSR back to medical tomography. Very preliminary results, reported in [1], showed that the idea worked, and very preliminary estimates of the reduction of radiation dose were truly promising. The primary goal of this project is to investigate whether those preliminary results were solid and to bring that very rough idea all the way to a TRL of 4 or 5.

While the Covid19 emergency has delayed the final part of the project, in which professional radiographers will evaluate the quality of the images, the results obtained so far, and detailed in the next section, are promising.

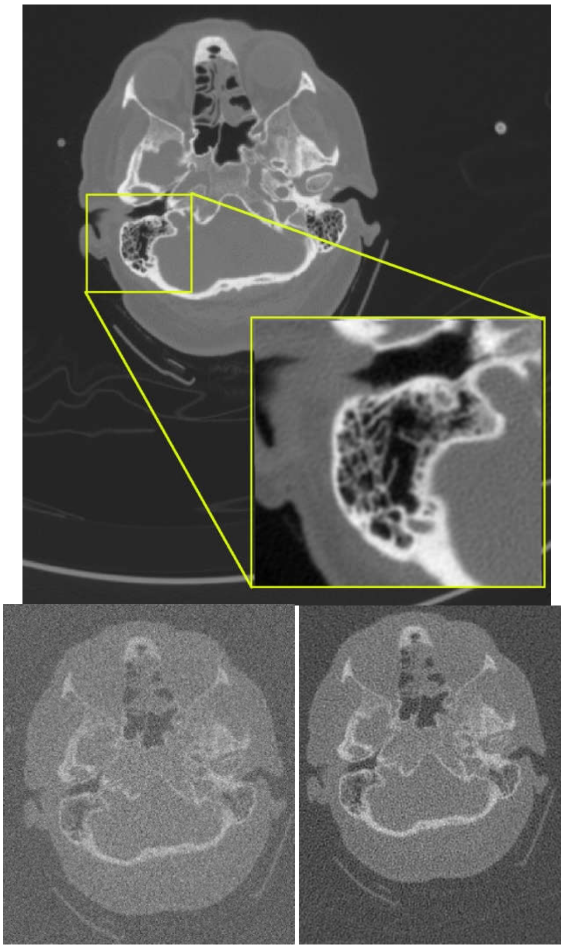


Fig. 2. Top: example of medical-quality reconstruction from our method from true data. The insert shows the magnification potential. Bottom: reconstruction of the same image from simulated data for extremely low radiation (only 1 million X-ray photons per phase). Left: FBP, right ours.

4. PROJECT RESULTS

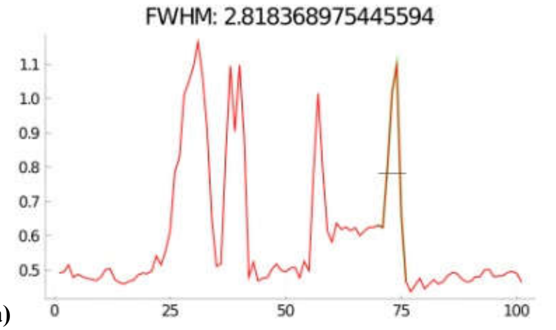
(1) we built from scratch a full software suite that implements all the mathematical transformations involved in the tomographic reconstruction both of our method and of conventional methods for comparison purposes. The software also implements a full series of tests on those images. (2) we obtained and read the raw data from actual CT-machines located in the Vicenza project node. (3) we reconstructed test images from this data and from simulated data and ran a series of quantitative tests on them. (4) in the last two months of the project we will obtain expert qualitative evaluation of our images from professional radiographers and technicians.

The software suite was fully developed by Nicola Mosco, the PostDoc that was funded by the project. It implements the following: (a) it reads the CT machines raw data (we have used a “Siemens, Somaton Definition Edge” machine). Alternatively, it simulates the data with Monte Carlo techniques. We used simulated data to validate the method prior to accessing true data, and to perform tests in regimes where the true data is unavailable, such parallel beam geometries or extremely-low radiation. (b) it elaborates the raw data so that it can be used as input to our algorithm. In particular, the typical geometry of CT machines is “fan beam”, originating from a point X-ray source, and this must be converted to “parallel X-ray beam”. (c) it implements the reconstruction using our method and, for comparison purposes, using the conventional methods such as FBP and SIRT. A typical comparison is shown in Fig. 1 where the same raw data is elaborated with different methods. (d) export the reconstructed image into a calibrated DICOM format so that they can be evaluated by the expert medical staff in a familiar setting. (e) run an extensive series of tests (lifted from the literature) on the reconstructed images to obtain quantitative comparisons between our method and the customary ones. In particular, we implemented the following tests: (1) the intensity profile of the image along some segment (e.g. Fig. 3a), which allows to visually gauge the noise and the sharpness; (2) Signal-to-Noise ratio: the ratio between the image intensity and its fluctuations in a uniform region of the image (e.g. Fig. 3b); (3) Contrast-to-Noise ratio: the ratio between the contrast (image minus background intensity) and its fluctuations; (4) the quantitative measurement of the width of localized features (edges) of the image: a smaller width is equivalent to a sharper image. (5) the linearity of the densitometry: we simulated data for a target with a linear increase in the absorption and verified that the reconstructed image had linear intensity. (6) geometric distortion: we tested our method on calibrated images to test for geometric distortions.

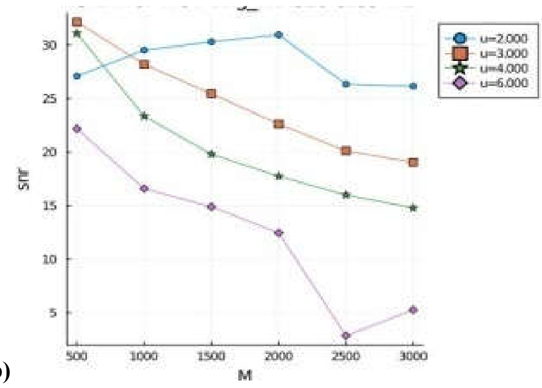
The results of these tests were positive: our method often scored better. However, we have realized that these tests are typically not indicative of the quality of the images. For example, SIRT can easily score much better on the Signal-to-Noise ratio test, because it can produce images that are so out of focus that their noise fluctuations are completely evened out. Even if we had good results from these quantitative tests, we believe that the true imprimatur can come only from the quality assessment of the professional radiographers.

The software was developed in a variety of programming languages and metalanguages (C++, Julia, Python, Matlab, etc.). Its development made use of techniques such as code coverage, unit testing and continuous integration and deployment. To ensure portability, after various tests, we settled on a docker implementation that can run on Mac and Pc hardware. It can push computationally intensive tasks to remote servers through the internet: we used a powerful computer of our quantum information theory group. Finally, it allows the visualization of the results and a very fine remote control of the software using web browsers, through the use of Jupyter and Pluto.jl notebooks, a useful feature during the Covid19 isolation.

The main challenges we had to overcome were: (1) obtaining the true raw data from the machine. Siemens provided a software tool under a nondisclosure agreement. (2) implementing the fan beam geometry transformations. (3) calibrating the image for DICOM export.



(a)



(b)

Fig. 3. (a): intensity profile of our reconstruction along the red vertical segment in Fig.1 and calculation of the Full-Width-Half-Maximum of the last feature. (b): example of SNR plots as a function of different parameter values of our reconstructions.

5. FUTURE PROJECT VISION

5.1. Technology Scaling

As clear from the “Results” section above, our project is currently at TRL 4-5: we have adapted the mathematical transformations of quantum state reconstruction to medical tomography [1] (TRL1-2), we validated the idea on simulated data (TRL3), we created from scratch a full software suite real-world data capable (TRL4). And, finally, before the end of the project our tomographic reconstructions will be validated by professional healthcare experts (TRL5). To reach the TRL5-7, we will need to embed our algorithm inside the tomographic machines. To achieve this goal, we need an industrial partner, Siemens Healthineers, arguably the main builder of CT machines. We held multiple discussion with their R&D team (specifically, Thomas Flohr and Sebastian Faby). They had expressed strong interest in our method but concluded we had not yet fully proven its potential. The phase 1 achieved this goal, so we believe they will eagerly participate to phase 2. We also contacted the Siemens Heidelberg group that are developing single-photon capable machines. To achieve TRL6 we will merge (or rewrite) our software for current or future generation machines. Possibly, new hardware will also have to be developed. Finally, TRL7 will be achieved when the prototypes produce reconstructions of the phantoms used for calibration, and TRL8 once we attain reconstructions from actual patients.

5.2. Project Synergies and Outreach

We will need to see the details of the phase-2 project call before we can provide a list of conclusive future partners. Certainly the current team (Pavia University and Vicenza ULSS 8 Berica) will be completed by an industrial partner. Siemens Healthineers has participated to the phase 1 as an external partner, and they have provided us with crucial tools for our project and useful feedback. Siemens Healthineers is interested and will be involved. Other partners (e.g. Napoli University) will be probed.

Regarding dissemination. We will publish our results (an extended version of this report) in a scientific journal. We will participate to imaging and healthcare conferences to present it, both to technical experts and, in more accessible presentations, to the end users of our technology (doctors, healthcare technicians). Moreover, our industrial partner will follow the usual routes of advertising a new breakthrough technology (based on quantum mechanics!) for their products.

5.3. Technology application and demonstration cases

Our phase 2 will address the healthcare societal challenge. Having a lower-dose CT scan will allow tomography to be more widely used as a diagnostic tool. If it is possible to lower the dose to achieve its use in preventative medicine, it would constitute a revolution in healthcare, since its diagnostic capabilities are far superior than other alternative tools.

One of the partners is an educational institution (Pavia University), so clearly the project will also be beneficial to the education sector, since students (at undergraduate, PhD and Post-Doc level) will be involved in the research and benefit from it. Indeed, the phase 1 has benefited our Post-Doc student Nicola Mosco whose salary was funded by Attract and who has very fruitfully used this to achieve mastery in many advanced software techniques that he needed to entirely write the software suite that is one of the main results of the current project. He has also enjoyed the opportunities offered by academia, such as the participation to conferences, the involvement in other research lines, and the participation to the enterpreneurship school organized by Attract.

Another benefit will be the financing of a major industrial player in Europe, namely Siemens Healthineers. It is obvious that, to remain competitive, industries have to invest in R&D, but the internal budget is often insufficient. A public financing that aids in this respect is crucial and will be put to good use for retaining market share by Siemens.

5.4. Technology commercialization

As discussed above, we have received strong statements of interest in our method from Siemens Healthineers. They will provide the commercialization of our results, by embedding our method in their products. Siemens Healthineers has a well-established product line in CT machines. Commercialization will not be a problem at all, once our method is embedded in their machines.

5.5. Envisioned risks

The main risk we envision is that our method may be judged unsatisfactory, if the reduction of the radiation dose that it allows is not sufficiently large to justify its implementation. This is a marginal risk to phase 2, because such evaluation will have to be done during the preparation of the phase 2 project proposal, before its beginning.

Another risk is that our method may prove to be computationally too demanding for current hardware. The mitigation strategy would be to use dedicated off-the-shelf hardware for computationally demanding tasks, such as GPU computation or cloud computation. Our algorithm is well suited to both these techniques, since it is easily parallelizable.

5.6. Liaison with Student Teams and Socio-Economic Study

Our project, being at the juncture of very diverse fields (healthcare and quantum mechanics) is very suited to reach students from very different fields and backgrounds. Pavia University has a strong tradition of medical physics at the Master level (having unique facilities such as a research nuclear reactor for tissue irradiation and one of the handful particle accelerators devoted to cancer treatment in the world), and is thus exceptionally placed for this: we have exceptional educators in both fields that have strong experience in engaging students that will be directly involved in this aspect of the project, as well as the department of medicine. Additionally, we will work with our industrial partner to produce accurate and accessible informative material regarding our technology that will be suited to the end users of their machines, which certainly lack any knowledge of quantum mechanics.

In contrast to most physics projects, we do expect that the outcomes of the project will bring actual socioeconomic impact to the population at large, if our technology allows a larger deployment of CT.

6. ACKNOWLEDGEMENT

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7. REFERENCES

[1] G. M. D’Ariano, L. Maccone, “Quantum Tomography for Imaging”, Electronic Notes in Discrete Mathematics, 20, 133 (2005), Proceedings of the Workshop on Discrete Tomography and its Applications 13-15 June 2005 Ed. G. T. Herman; A. Kuba.