

Quantum Computing and Computed Tomography: A Roadmap towards QuantumCT

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Abstract:

Quantum computing (QC) is seen as an emerging leader in computing technology, offering tremendous potential for innovative solutions to complicated computational problems beyond the capabilities of contemporary supercomputers. Nonetheless, the direct use in quotidian contexts is deficient in both large-scale quantum computers and quantum algorithms, namely software. We are initiating the first project on a pathway to quality control-enabled Computed Tomography (CT). In this article, we discuss this initiative after its first year of a five-year span and outline the preliminary measures taken with the community. It is important to note that the hardware for quantum computing is still under development, indicating that most of the software research is in the process of preparing for industrial use cases.

Introduction:

As quantum computers become more accessible, several organizations are initiating their initial forays into the realm of quantum computing to acclimate themselves with the technology and explore its integration with their respective domains of expertise. The first inquiries are to the use of quantum computers in addressing or enhancing industrial challenges using quantum algorithms. The difficulty is in identifying an appropriate problem and developing the solution, since quantum computing necessitates a distinct methodology compared to conventional programming. In contrast to a classical computer that operates using bits representing the values 0 and 1, a quantum

computer utilizes a quantum bit (qubit) capable of existing in arbitrary superpositions of these binary

states. This superposition allows the quantum computer to concurrently execute a single calculation over a broad spectrum of values, representing one of the benefits offered by quantum computing. The superposition of quantum states facilitates the entanglement of numerous qubits, which is the most

defining characteristic of quantum computing and is essential to its core conceptual benefits. Nonetheless, the challenges arise in the concluding phase when one seeks to get the outcome of that calculation. Upon individual qubit measurements, the qubits will collapse into one of their two base states. The former are then assigned classical values of 0 and 1. The value measured is contingent upon the quantum state of the system, which is often a superposition of the basic states. Repeated measurements will conform to the corresponding probability distribution. The result is that a singular quantum computation often fails to provide the intended value immediately. The computation must be performed several times, referred to as shots, contingent upon the number of qubits, to provide a statistical distribution that facilitates the identification of the required result. The timeframe required for repeated quantum measurements may surpass the benefits a quantum computer offers relative to the computation time of a conventional computer. To get a performance advantage, a quantum algorithm is necessary that minimizes the required number of shots by leveraging constructive and destructive interference in the computation, as shown in the renowned Deutsch-Jozsa and Grover algorithms. We initiated a five-year research within the

publicly financed BayQS collaboration aimed at exploring the possibilities of quantum computing in computed tomography.

Roadmap towards Quantum Computed Tomography (QCT):

In 2021, the Fraunhofer-Gesellschaft obtained exclusive access to the IBM Q System One, the European IBM quantum computer located in Ehningen (near Stuttgart), to conduct research and create innovative technical solutions in quantum computing. This advanced quantum computer employs 27 qubits and offers the German business and innovation sector several application-specific research and development prospects. It provides scientists the opportunity to evaluate their algorithms on the IBM quantum computer in accordance with European data protection and intellectual property legislation [4]. We want the community to collaborate in analyzing which of our technological challenges may be effectively addressed using a quantum computer. Consequently, the project detailed herein aspires to serve as both a groundbreaking scientific endeavor in a relevant application domain and a catalyst for innovative concepts within the community.

<https://doi.org/10.58286/26565> The development or feasibility assessment of QCT is more intricate than just substituting conventional computers with quantum computers. A set of computational tasks for CT with potential complexity is necessary. Unlike medical applications, industrial CT is used to examine a diverse array of components. To get high-quality photos, several acquisition factors must be identified and tuned prior to each acquisition.

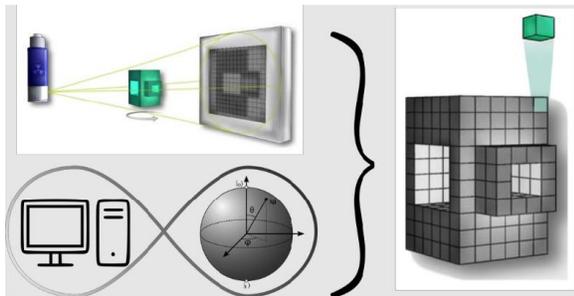


Figure 1 Idea of a QC enabled computed tomography.

In the BayQS project, one objective is to explore the feasibility of using QC to autonomously ascertain the

optimal configuration of a CT system. One method involves synthetically generating potential locations on a route (e.g., by simulation) and selecting the optimal ones based on specified boundary conditions. Planning approaches for intricate sensor systems may be used in the context of the Travelling Salesman Problem under certain circumstances. This issue is previously shown to be solvable more rapidly using quantum annealing techniques (see e.g. [5]). Another objective of BayQS is to investigate the use of QC in CT image reconstruction. One method is to formulate the reconstruction issue as a mathematical optimization problem and resolve it using established quantum computing methods (e.g., quantum annealing, quantum approximation optimization algorithm (QAOA)). This may be the first step towards Quantum Computing Technology. We will present first findings on addressing optimization difficulties associated with CT reconstruction and acquisition planning.

Technical Framework:

A program is executed on a quantum computer by composing a classical software script on a classical machine. Within this script, the "quantum program" is compiled and sent to the quantum computer. The quantum computer performs the program. The script should ultimately provide the duration of the quantum computing, the number of executions of the quantum program (referred to as shots), and the resultant distribution of measurement outcomes. An interface is required for communication between a quantum computer and a classical computer. This interface relies on the quantum computing system, namely the IBM Q System One in our instance. This quantum computer is available globally via the Python module Qiskit, which offers the necessary software abstraction. Qiskit is an open-source software development kit designed for interfacing with quantum computers at the levels of pulses, circuits, and application modules. Qiskit facilitates seamless connectivity to quantum computers for the transmission of quantum programming. These programs are automatically queued, and the quantum computer conducts each task sequentially. The quantum program is also developed using Qiskit. Developing a quantum program resembles the construction of a circuit. It specifies the quantity of

qubits and bits to be used, their starting states, and the operations to be performed. Every operation on each qubit must be explicitly specified and documented. These processes are referred to as gates, analogous to classical computers where gates function on bits. These quantum gates may, for instance, invert qubits or entangle them. To get a result from the qubit system, the qubit states must be measured at the conclusion of the program. Upon measurement, a qubit collapses to one of its base states, either 0 or 1. The measurement of a qubit may provide varying outcomes owing to its quantum mechanical wave characteristics. Consequently, a quantum program often requires several executions to get the result distribution. The quantum computer running the quantum program must meet the specifications of the quantum program. Consequently, the quantity of qubits, the number of gates, and the method of qubit entanglement inside the circuit must be Contemplated. Quantum computer hardware architecture sometimes precludes the entanglement of every feasible combination of two arbitrary qubits. In some quantum computers, only designated qubits may be entangled via certain gates with other qubits, significantly influencing the architecture of a quantum circuit. Moreover, the quantum states of the qubits lack prolonged stability. Consequently, it is essential to ensure that the constructed quantum circuit is minimized in length and completed prior to the decay of the specified states. Otherwise, erroneous findings of unstable qubit states are obtained. For the evaluation of quantum programs using a limited number of qubits, one may execute the quantum program on a simulator operating inside a classical system. One can ascertain the wave function of each qubit at any moment, since the complete system is computed by linear algebra. This aids in comprehending and verifying the effects of gate operations on qubits.

Image processing on a QC: a challenge by itself:

Image processing, with the measuring gear, is one of the most formidable aspects of computed tomography. Typically, we discuss thousands of photos, each comprising between 10^6 and 10^7 pixels (ranging in dimensions from 1024×1024 to 4096×4096), which need loading, post-correction, filtering, and processing using a reconstruction technique. Data is often stored

as 16-bit to 32-bit grayscale values in a linear sequence inside the volatile or non-volatile memory of specialist computers using advanced graphics processing units for highly parallel data processing. In traditional computers, the location of each pixel in a picture is determined by its memory address, and retrieving the gray values entails measuring the possible state of the physically available memory [9]. Consequently, regarding the storage of these pictures, the pixels may be considered independently due to the absence of interaction among them. For a standard 16-bit picture including 1024×1024 pixels, this necessitates $1024 * 1024 * 16 = 16,777,216$ classical bits for its storage. The use of a quantum computer for image processing presents entirely new potential and problems. The qubits of a quantum system may exist in a quantum mechanical superposition state, allowing for the encoding of a picture with a minimal number of qubits. The encoding of quantum pictures, referring to the actual representation of data on a quantum device, is a significant challenge and may be accomplished via numerous methods. The predominant methods for storing grayscale pictures are termed flexible representation for quantum images (FRQI) [10] and new enhanced quantum representation (NEQR) [11]. Both methods use the same concept that the gray value and the pixel's location are encoded in distinct groups of qubits. In contrast to a conventional computer, which requires distinct bits for each pixel's gray value, these systems use the same qubits to encode the information of all pixels by using the superposition principle of quantum states. In the FRQI scenario, a single qubit suffices to encode the grayscale value, but in the NEQR situation, the quantity required is contingent upon the image's bit-depth. The quantity of qubits required to encode the location of each pixel in a picture is contingent upon the image's size. For instance, an image measuring 1024×1024 pixels, which equals 2^{20} or 1,048,576 distinct positions, necessitates 20 qubits for encoding. This illustration of picture storage exemplifies a significant advantage of quantum computers: parallelism via the quantum mechanical concept of superposition. Rather of allocating distinct bits for the information of each pixel, quantum computers use the same qubits for all pixels. This significantly lowered the necessary number of qubits. For the storage of a 16-bit picture of 1024×1024 pixels

on a quantum computer, just 21 qubits (FRQI) or 24 qubits (NEQR) are required [12]. However, this decrease in the quantity of qubits incurs a cost. The transmission of an image to a quantum computer is complex and requires a significant number of quantum gates, considering a picture of dimensions $2n \times 2n$ pixels with a grayscale range of $[1, \dots, 2^q - 1]$. NEQR necessitates $O(qn2^{2n})$ and is hence less computationally intensive than FRQI, which needs $O(2^{4n})$ [12]. Secondly, owing to the characteristics of quantum physics, retrieving the picture from a quantum computer requires numerous measurements of the same state that represents the image. The NEQR method needs a certain number of repetitions to reconstruct the picture, but the FRQI system can only provide an estimate of the actual image with several repeated measurements. This indicates that the quantum picture, along with all subsequent image operations, must be created and measured several times before entire information can be extracted. Numerous quantum image processing operations have already been established. These include translation [13], rotation [14], scaling [15], compression [16] [17], interpolation [18] [19], median filtering [20], quantum image comparison [21], and searching [22]. Furthermore, initiatives have been undertaken to integrate quantum machine learning with quantum image processing, such as image classification [23] and picture recognition [24]. Despite significant advancements in quantum image processing in recent years, the discipline remains nascent, primarily concentrating on the adaptation of classical methods to their quantum equivalents [25]. It remains not It remains uncertain if these novel quantum variants provide a performance enhancement, given there is no comprehensive research that meticulously analyzes the computational complexity of contemporary conventional and quantum image processing methods [25]. In the future, innovative quantum algorithms must be devised to harness the principles of quantum physics, a challenging endeavor. In summary, several problems must be resolved before X-ray projections or CT volumes may be processed on a quantum computer. Diverse methodologies exist for encoding and storing picture data in qubits, despite the existing quantum computers' limited computational capacity (number of qubits and permissible sequential gates) hindering practical implementation. The information

inside the pictures is less readily accessible than on a traditional computer, hence the calculation of standard CT applications such as filtering and projection/summation will continue to be a subject of study in the next years. Furthermore, extracting visual information from a quantum computer is a time-intensive procedure.

Summary and Upcoming work:

Quantum computing signifies a prospective technological advancement that may transform the approach to difficult computer operations. Quantum computing may facilitate novel innovations and progress in computer science and its applications across several industrial sectors. This is particularly applicable to the domain of industrial computed tomography, where Quantum CT might facilitate more effective CT measurement planning or expedite picture reconstruction methods. Or even more intricate picture assessment jobs on the sophisticated datasets derived from CT scans. As the spatial resolution of CT scans increases, the amount of data expands, resulting in prolonged calculation times. Quantum computing enables the development of novel methods for image processing, therefore decreasing evaluation times and facilitating high-resolution scans of larger objects. Moreover, intricate measurement trajectories may be enhanced by quantum algorithms, resulting in superior picture quality with reduced acquisition time. Despite the technology emerging from the laboratory into practical applications, it is swiftly advancing and developing; for instance, IBM intends to augment the qubit count of their quantum computers by over 15 times over the next two to three years [27]. Consequently, it is essential to interact with this emerging technology promptly to use its benefits for practical applications, such as our initiative with QuantumCT. During the inaugural year of this project, which marked our introduction to the novel technology, we primarily engaged in groundbreaking efforts to comprehend quantum physics, accumulate experience in quantum algorithm design and simulation, and formulate initial concepts for adapting existing quantum computing algorithms to computational tasks related to computed tomography. From an abstract perspective, tomographic reconstruction and associated processing challenges may be distilled into optimization tasks and Fourier

processing, both of which are fundamental and vigorously investigated components of quantum computing. A primary subsequent step in our project is to tackle the challenge of efficiently storing CT data (i.e., voxel data). In this context, efficient storage refers to a method of representing voxel data with minimal qubit expenditure while still aligning with the requirements of quantum computing data processing algorithms. Regarding the CT measurement planning issue, our subsequent step will include the reformulation of carefully selected planning challenges in the style of traveling salesman problems, aiming to tackle them using established solutions from the literature. Additional community-related inquiries that we want to address throughout the project's progression include: Is QCT practical, and what conditions are necessary? Will quantum computing technology (QCT) demonstrate advantage over traditional computing methods, and under what circumstances? When will QCT become operational?

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