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Quantum Techniques for Image Processing

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Abstract*—Quantum computing is revolutionizing every field of knowledge. With advent of affordable quantum computing almost possible the importance and relevance of quantum computing for all the recent research trends cannot be overemphasized. We have already witnessed quantum analogues of most celebrated classical algorithms starting from Shor's algorithm for integer factorization, Grover's search algorithms for unstructured database. Quantum Image Processing is an emerging field borne by applying quantum computing techniques to the Image Processing problems. This paper attempts to summarize and review the state of development in the field of Quantum Image Processing. All major quantum computing platforms have been presented, At the end a discussion on the current trends and future possibilities is presented.

Keywords*— Quantum computing, Image Processing, qubit, bra and ket, quantum optimization.

I. INTRODUCTION

Quantum computing traces its roots in the strange behaviour of fundamental particles, the building blocks of nature. Principles of superposition of quantum states and wavefunction collapse are the physical phenomenon behind the extraordinary promise of quantum computing as compared to classical computing. Though theoretically all computing problems which can be solved on a classical computer can also be solved on a quantum computer and any problem which can also be solved on a quantum computer can be solved on a classical computer however may be in exponentially larger timeframe.

In this paper we are not focussing the physics which makes implementation of the quantum computing algorithms possible. We assume that the implementation of these algorithms is available through a cloud on any other similar mechanism.

Quantum algorithms work on quantum units of information called quantum bits or qubits in most of the quantum computing models [1]. Though alternate models of quantum computing such as Hamiltonian Oracle model are also available [2]. In the spirit of quantum bit model of quantum computation several algorithms which promise surprisingly fast performances over the classically available algorithms have been invented. Algorithms such as the Shor's factorization algorithm, Grover's algorithm for search in a unstructured database, Quantum sorting to optimization algorithms and Quantum linear equation solver etc motivated similar research and application of quantum computing techniques in the field of image processing.

Quantum Image Processing offers not only unparalleled speed up over the classical image processing but also fool-proof security and reduced storage.

II. BACKGROUND

A research paper titled Quantum Computations and Image Recognition published in 1996-97 by Alexander Yu. Vlasov, St Petersburg Russia is regarded as the seminal paper in the field of Quantum Image Processing (QIP). This paper focussed on the recognition of orthogonal images utilising quantum computing. Since then the research had through a period of hiatus until late 2000s when it attracted the attention of the researchers once again. In this period image representation in the quantum realm were deliberated upon.

All these efforts have been categorized into three broad classifications by Yan, F.Iliyasu, A. M., & Le, P. Q. (2017). Quantum image processing: A review of advances in its security technologies. International Journal of Quantum Information.

A. *Quantum-assisted* digital image processing (QADIP): In this category are the advances which exploit a few bizarre quantum computing phenomena to improve the known digital or classical image processing techniques.

B. *Optics-based quantum imaging (OQI):* The research in this category focusses on development of techniques for optical imaging and parallel information processing using the quantum nature of light and its inherent parallelism.

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C. *Classically inspired QIP:* Research in this category aimed at extending the classical image processing techniques into realm of quantum computing framework.

For this paper we are concerned with category C only.

III. IMAGE REPRESENTATION

The next breakthrough in QIP was use of quantum algorithms to find the specific image patterns in binary images. Later several more image representation approaches were discovered, these are listed as following:

A. Qubit Lattice: One of the disruptive gains in this field of QIP was Qubit Lattic representation of the quantum images by Venegas-Andraca and Bose [3]. This method exploits the superposition of quantum states of qubit to store image information. To store an image of size i*j, a two-dimensional lattice of qubits is needed. Each qubit has k-1 qubit, in an identical state as the first qubit, behind it forming a lattice structure. This redundancy is used to retrieve the image [4].

B. RealKet: Another parallel approach to image representation in the quantum world was Real Ket notation proposed by Lattorre. In this representation the aim was to achieve effective compression of quantum images. To achieve the representation of image in Real Ket, the image pixels are split into 4 quadrants; each quadrant represented by a number 1,2,3,4 in clockwise direction. Each quadrant is again divided in 4 quadrants with numbering 1,2,3,4 in clockwise direction. This division process is continued till we reach individual pixels of the image. Real Ket represents these regions in a sequence of r- qudits (a quantum state with 4 basis states). In this representation the values of pixels are represented in coefficients of r-qudits which turn out to be far lesser than the no. of qubits as in the Quantum Lattice representation [6].

C.Flexible Representation for Quantum Images (FRQI):In this method the colors and corresponding pixel positions of the image are captured in a normalized quantum state. The normalized state is then incorporated into the quantum state by applying tensor product [7]. The polynomial preparation theorem (PPT), one of the important result in QIP tells that an efficient FRQI implementation exists which requires a computational complexity of 2^4n for n*n image.

D.Multi-Channel representation of Quantum Images (MCQI): This is an extension of the FRQI representation. In this representation each color is encoded by one qubit of quantum image representation [8]. This Quantum Image representation had set the stage for high level image processing tasks to be performed on the quantum images.

*E.Novel Enhanced Quantum image Representation (NEQR):*This new representation of Quantum Images stores the grey scale pixels of the image and its position in two entangled qubit sequences. In this representation q+2n qubits are required to store a 2^n*2^n sized image with depth of 2^q.

TABLE I. COMPUTATIONAL COMPLEXITIES

Method	**Computational Complexity**
FRQI	$O(2^{4n})$
NEQR	$O(2^{n})$
Classical Techniques	O(n)

Source: A Review on Quantum Image Processing [16]

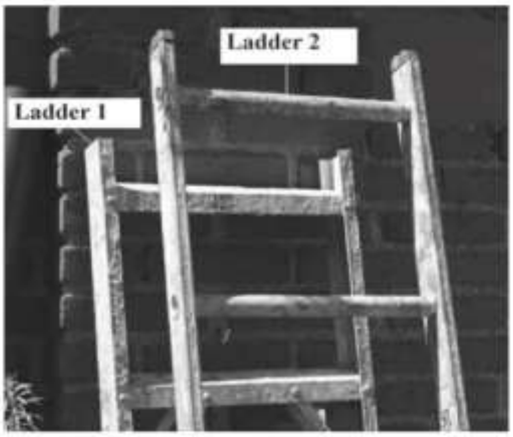
III. APPLICATIONS

A. Edge Detection:

One of the very first application of Quantum Image Processing had been Edge Detection [9]. To obtain edge detection in quantum image processing the quantum versions of basic classical image transforms such as the Fourier transform, Hadamard and Haar wavelet transforms are utilized. These transforms take a polynomial complexity (O(n)) in quantum realms while their classical versions are of O(n*2^n) complexity.

B. Image Segmentation

Image segmentation has been one of the most challenging tasks of the classical image processing. It is partly it is due to context dependence of the objective in this task. This challenge is still visible in the quantum realm. E. Venegas-Andraca, J. L. Ball have proposed a quantum routine for segmentation of images using maximally entangled quantum systems. They have detected corners in the image which are utilized to construct shapes corresponding to the shapes of the objects being considered. An example is cited from the original paper below:



Source:[17]

C. Quantum Machine Learning:

It is an emerging branch of quantum computing which employs concepts of machine learning on the quantum computer to achieve a specific objective. This provides Machine Learning based traditional Image processing tasks a huge benefit. The algorithms in this sub-field of quantum computing can be classified as following:

a) Classical Data with classical machine learning (CC): This is the usual model of machine learning.

b) Hybrid Quantum Classical model: Classical Data with Quantum algorithms (CQ) and Quantum Data with classical machine learning: This is the hybrid aspect of Quantum Machine learning.

c) Quantum Data with Quantum machine learning (QQ): This is another aspect of Quantum Machine Learning.

We are concerned with (b) & (c) for the scope of this paper. Quantum Machine Learning exploits exponential speed ups of linear algebra, routines implemented on quantum computer. Since most of Machine Learning is dependent on process of optimization, Quantum Optimization Algorithms are at the heart of Quantum Machine Learning. In this area the following Quantum Optimization Algorithm have been proposed.

1) Quantum Least Square Fitting
2) Quantum Semidefinite Programming
3) Quantum Combinatorial Optimization
4) Quantum Annealing
5) Quantum Neural Network
6) Hidden Quantum Markov Model

IV. QUANTUM COMPUTING PLATFORMS

In recent years, several quantum computing platforms have come up which provides cloud-based access to their quantum computing machines on free/ trial/ payment basis. A few such Quantum Computing Platforms are summarized below.

TABLE II. QUANTUM COMPUTING PLATFORMS

Sl. No.	Platform	Specifications of the Quantum Computer	Availability Criteria	Remarks
1.	IBM Q Experience	5 and 16 qubit Quantum Processor is publicly available. A 32-qubit cloud-based simulator software is also available.	Based on Qiskit an IBM quantum computing platform. A drag and drop programming interface available. Free, online.	https://quantum-computing.ibm.com/
2.	Azure Quantum by Microsoft	It is a simulation developed by Microsoft Research creating an ecosystem for developers' researchers and consumers.	Based on Q# Quantum Computing Language and Quantum Development Kit (QDK) developed by Microsoft. Free trial available with Microsoft account.	http://azure.microsoft.com/en-us/

3.	Quantum Computing Playground	It is a simulation which provides up to 22 qubit which can run Grover's and Shor's Algorithm	It is available free of cost through a browser-based IDE.	http://www.quantumplayground.net/#/home
4.	Quantum in Cloud by University of Bristol	Simulator as well as 4 qubit real quantum processor	Both the simulator and the Quantum Computer are free available. Registration is required.	http://cnotmz.appspot.com/
5.	Quantum Inspire by Qutech	2, 5 qubit quantum processor fully programmable with online access. QX a quantum emulator up to 26 qubits available.	Free access available after account is created	https://www.quantum-inspire.com/
6.	FOREST by Riggeti Computing	31 qubits deployed on May 20th, 2020. A programming language has been implemented developed by Riggeti Computing.	Register with the website to request access, also available through AWS	https://rigetti.com/
7.	FORGE by QC ware	Binary Optimization, Machine Learning, Quantum Annealing available. One of the first quantum computer companies D-Wave is behind this platform.	30 days free trial available. cross linking is available with other platforms.	https://forge.qcware.com/

V. DISCUSSION AND CONCLUSION

As we see in the TABLE II above up to 32 -bit qubit quantum processor is available through cloud-based access. Moreover, the leading companies are determined to provide quantum-like experience and training to the researchers through their simulation platforms till the real scalable and commercially quantum computing platforms are developed and integrated with the existing cloud based eco -systems. In the context of Quantum Computing an important concept is of Quantum Supremacy-which means that capability of achieving a task on quantum computer has been demonstrated which was not possible to accomplish on classical computer. On 23rd October 2019 Google has claimed that they have achieved quantum supremacy on 54 qubit quantum computers. However, their claims have been questioned by IBM.

Irrespective of goggle's claim of 2019, quantum supremacy does not seem to be far away. Very soon cloud based quantum computing powered by scalable quantum processors will be a reality.

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