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Multidimensional color image storage, retrieval, and compression based on quantum amplitudes and phases

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ABSTRACT

In this study, we propose a new representation method for multidimensional color images, called an n-qubit normal arbitrary superposition state (NASS), where n qubits represent the colors and coordinates of 2^n pixels (e.g., a three-dimensional color image of $1024 \times 1024 \times 1024$ using only 30 qubits). Based on NASS, we present an $(n+1)$-qubit normal arbitrary superposition state with relative phases (NASSRP) and an $(n+2)$-qubit normal arbitrary superposition state with three components (NASSTC) for lossless and lossy quantum compression, respectively. We also design three general quantum circuits to generate NASS, NASSRP, and NASSTC states, where we retrieve an image from a quantum system using different projection measurement operators. Finally, we define the quantum compression ratio and analyze lossless and lossy quantum compression algorithms of multidimensional quantum images. For the first time, we implemented the compression of multidimensional color images on a quantum computer. Thus, we address the theoretical and practical aspects of image processing on a quantum computer.

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1. Introduction

Quantum computing [7] exploits the unique computing performance of quantum coherence, entanglement, superposition of quantum states and other inherent characteristics, and it has become an international research focus. Indeed, by utilizing these unique properties, Shor's discrete logarithms and integer factoring algorithms in polynomial time [18], Deutsh's parallel computing algorithm with quantum parallelism and coherence [4], and Grover's quadratic speedup for unordered database search algorithms [9] deliver better performance than any known classical algorithms. Quantum algorithms such as the quantum search algorithm [17,19], quantum watermarking [11], quantum encryption and decryption [22,26], quantum-behaved particle swarm optimization [20,21], quantum Fourier transform (QFT) [15,18], and quantum wavelet transform (QWT) [8] are also more efficient than their classical counterparts.

In a quantum system, the frequency of the physical nature of color could represent a color instead of the RGB model or the HSI model, thus a color may be represented by only a 1-qubit quantum state and an image can be stored in a quantum array [23,24]. A flexible representation of a quantum image can store the colors and coordinates of a two-dimensional grayscale image of 2^n pixels using $n+1$ qubits [12]. A set of quantum states for M colors and a set of quantum states for N coordinates

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were proposed to represent M the colors and coordinates of N pixels in an image, respectively [13]. A previous study [13] also discussed the retrieval of images stored in a quantum system. Phase-space distribution functions (Wigner and Husimi functions) have been used to store an image in a quantum system [16]. Information storage and retrieval were achieved based on the quantum amplitude in previous studies, as well as the quantum phase [1,25].

Quantum computing can be implemented using quantum gate operations. A finite set of basic gate operations can be used to construct any quantum gate operation [5]. Universal quantum gates are expressed as combinations of one-bit and two-bit gates [2,6,15]. An efficient scheme has been proposed for initializing a quantum register with an arbitrary superposed state and the application of this scheme to three specific cases was discussed [14].

In this study, we propose an n-qubit normal arbitrary superposition state (NASS) that represents a multidimensional color image with 2^n pixels. Supposing that 1 qubit is equivalent to 1 bit, the classic compression ratio (i.e., memory) of NASS is $2^n \times 24/n$ (the classic compression ratio of a 1024×1024 RGB color image is 1258291.2). Based on NASS, we present an $(n+1)$-qubit normal arbitrary superposition state with relative phases (NASSRP) to represent a multidimensional color image with 2^n pixels and some additional information. Thus, an $(n+1)$-qubit NASSRP can represent 2^n colors, 2^n coordinates, and 2^{n+1} integers. In order to reduce computational resources required by a quantum computer, we employ NASSRP and an algorithm (Algorithm 2) to implement lossless quantum compression. The simulation results showed that NASSRP facilitates the lossless quantum compression of binary images. We also apply QFT and QWT based on NASS to enable the lossy quantum compression of grayscale images. Our simulation results showed that NASS facilitates the lossy quantum compression of grayscale images. We also use an $(n+2)$-qubit normal arbitrary superposition state with three components (NASSTC) for the lossy quantum compression of color images. Our simulation results demonstrated that NASSTC allowed the lossy quantum compression of color images.

The paper is organized as follows: some basic quantum gate operations and representations of multidimensional color images are described in Section 2. Multidimensional color image storage is explained in Section 3 and multidimensional color image retrieval is discussed in Section 4. Multidimensional image compression is presented in Section 5. Our conclusions are provided in Section 6.

2. Basic quantum gates and representations of multidimensional color images

2.1. Basic quantum gates

A state of a quantum system is described as a vector in a Hilbert space, which is called a ket by Dirac. $|\cdot\rangle$ and $\langle\cdot|$ are the symbols used to represent the right ket and left ket, respectively. $|v\rangle$ and $\langle v|$ are a pair of Hermite conjugate states in a quantum system, which are defined as

$$|v\rangle = \begin{bmatrix} v_0 \\ v_1 \\ \vdots \\ v_{n-1} \end{bmatrix}$$

and

$$\langle v| = |v\rangle^+ = \begin{bmatrix} v_0^+ & v_1^+ & \cdots & v_{n-1}^+ \end{bmatrix}$$

where v_i $(i = 0, 1, \ldots, n-1)$ is a complex number.

The symbol $\otimes$ represents the tensor product of matrix, which is defined as

$$|u\rangle \otimes |v\rangle = \begin{bmatrix} u_0|v\rangle \\ \vdots \\ u_{n-1}|v\rangle \end{bmatrix} = \begin{bmatrix} u_0 v_0 \\ \vdots \\ u_0 v_{n-1} \\ \vdots \\ u_{n-1} v_0 \\ \vdots \\ u_{n-1} v_{n-1} \end{bmatrix}$$

where $|\mathrm{u}\rangle = [\, u_0 \quad u_1 \quad \cdots \quad u_{n-1} \,]^T$ and u_i $(i = 0, 1, \ldots, n-1)$ is a complex number. $|u\rangle \otimes |v\rangle$ can also be represented as $|u\rangle|v\rangle$ or $|uv\rangle$.

The notations of some basic quantum gates and their corresponding matrices are shown in Fig. 1. The identity (I), Hadamard (H) and Pauli-X (X) gates were defined in Ref. [15]. Let U, 1-Controlled U (1CU), 0-Controlled U (0CU), and n qubit Controlled U (nCU) be the fourth, fifth, sixth, and seventh gates in Fig. 1, where the explanations of these gates are as follows.

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