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Novel quantum gray-scale image matching

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ABSTRACT

Image matching, also known as correspondence problem, can be defined as the establishment of the correspondence between two or more digital images depicting at least partly the same scene. In this paper, we propose a method for matching gray-scale images consisting of quantum information. Quantum template image is directly mapped with quantum reference image, i.e., the quantum register representing each corresponding pixel of the quantum template image is subtracted from that of the quantum reference image by running a quantum subtracter. According to the quantum measurement results, we can save the gray-scale difference and sum all the differences. Then we compare the sum with Tolerance value. If the sum is smaller than Tolerance value, then quantum image matching succeeds. Experimental simulations show that the proposed approach can distinguish any two quantum gray-scale images successfully. Compared to the schemes based on flexible representation of quantum images (FRQI), our approach based on novel enhanced quantum representation of digital images (NEQR) has the advantages of retrieving the original classical image accurately from the quantum image so that it can be generalized to the case where the dimension of quantum template image is smaller than that of quantum reference image.

1. Introduction

Processing images on classical computers have been studied extensively. With the development of quantum computation, classical image processing is naturally extended to the quantum scenario. Research on quantum image processing started with proposals on quantum image representations [1–6]. On the other hand, quantum transformations have been implemented and shown more efficient than their classical counterparts [7–13]. Accordingly, quantum algorithms have been developed to speed up classical image processing problems because of their proven efficiency over the classical versions [14–19]. However, there are some special classical image processing operations that cannot be applied on quantum images, for example convolution and correlation [20], because all operations in quantum computation must be invertible.

Image matching, known as the correspondence problem, automatically establishes the correspondence between primitives extracted from two or more digital images depicting at least partly the same scene. Currently, image matching is widespreadly used in medicine, biology, information processing and other areas. Image matching can be divided by two categories: gray-based image matching and feature-based one. Classical image matching is naturally extended to quantum scenario. Ref. [21] proposed a method to analyze the similarity between two quantum images of the same size based on the flexible representation of quantum images (FRQI). The similarity value is estimated according to the probability distribution of the results from quantum measurements. However, to read the similarity between two quantum images, many copies of the quantum states have to be prepared, and measured to summarize some sort of histogram.

In this paper, we propose a method for matching gray-scale images consisting of quantum information. Using the novel enhanced quantum representation of digital images (NEQR) [5] and a quantum subtracter [22], the quantum template image is directly mapped with the quantum reference image, i.e., the quantum register representing each corresponding pixel of the quantum template image is subtracted from that of the quantum reference image. Through quantum measurements, the classical information can be retrieved accurately from the quantum state, not probabilistically. This implies that many copies of the quantum states

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are not necessary. Experimental simulations show that the proposed approach can distinguish two quantum gray-scale images successfully.

2. Novel enhanced quantum representation of digital images (NEQR)

Suppose the gray range of image is 2^q, the binary sequence $C_{YX}^0 C_{YX}^1 \cdots C_{YX}^{q-2} C_{YX}^{q-1}$ encodes the gray-scale value $f(Y, X)$ of the corresponding pixel (Y,X) as in Eq. (1):

$$f(Y,X) = C_{YX}^0 C_{YX}^1 \cdots C_{YX}^{q-2} C_{YX}^{q-1},\ C_{YX}^k \in [0,1],\ f(Y,X) \in [0, 2^q - 1]. \quad (1)$$

The representative expression of a quantum image for a $2^n \times 2^n$ image can be written as in Eq. (2):

$$|I\rangle = \frac{1}{2^n} \sum_{Y=0}^{2^n-1} \sum_{X=0}^{2^n-1} |f(Y,X)\rangle |YX\rangle = \frac{1}{2^n} \sum_{Y=0}^{2^n-1} \sum_{X=0}^{2^n-1} \bigotimes_{i=0}^{q-1} |C_{YX}^i\rangle |YX\rangle. \quad (2)$$

3. Quantum plain adder and subtracter

An explicit construction of quantum plain adder was introduced in ref. [22]. A quantum plain adder consists of quantum logic gates whose computational steps are synchronized in time. The outputs of some gates are connected by wires to the inputs of others. Binary inputs are encoded in the computational basis of selected qubits often called a quantum register. The addition of two registers $|a\rangle$ and $|b\rangle$ can be written as $|a, b\rangle \rightarrow |a, a+b\rangle$. To prevent overflows, the second register should be sufficiently large, i.e., if both ***a*** and ***b*** are encoded on n qubits, the second register should be of size $n+1$. In addition, the quantum plain adder also requires a temporary register of size $n-1$, initially in state $|0\rangle$, to which the carries of the addition are provisionally written. The operation of the quantum plain adder is illustrated in Fig. 1. Fig. 2(a) and (b) illustrates the sum and carry modules, respectively.

If we reverse the quantum plain adder from right to left in time, the quantum subtracter is realized. If we run the quantum subtracter with the input (***a***,***b***), the output will produce (***a***,***a***–***b***) when $a \geq b$. When $a < b$, the output is $(a, 2^{n+1} - (b-a))$, where $n+1$ is the size of the second register. In this case the most significant qubit of the second register will always contain 1. By checking this "overflow bit" it is therefore possible to compare the two numbers ***a*** and ***b***.

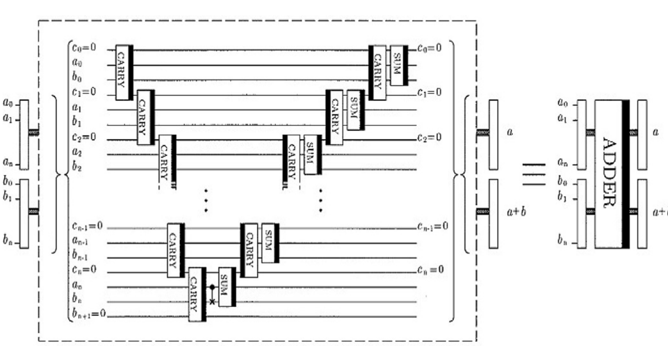

Fig. 1. Quantum plain adder circuit. Note the position of a thick black bar on the right or left hand side of basic carry and sum circuits. A circuit with a bar on the left side represents the reversed sequence of elementary gates embedded in the same circuit with the bar on the right side.

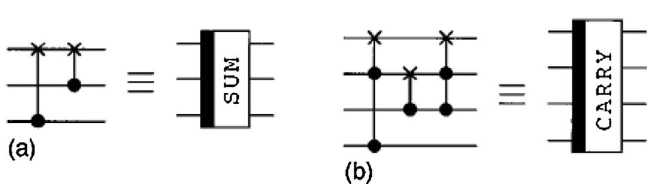

Fig. 2. Basic sum and carry operations for plain addition network.

4. Quantum image matching algorithm for quantum gray-scale images

For simplicity and without loss of generality, we assume two quantum images, i.e., quantum template image and quantum reference image have the same size. As we know, an image consists of many pixels and the intensity value of a gray-scale image varies from 0 (pure black) to 255 (pure white), allowing us to have 256 different shades of gray values. The gray-scale information of each pixel is encoded in the computational basis of a quantum register. For a pixel with 256 gray scales, its gray-scale information should be encoded in a quantum register with 8 qubits.

In the proposed algorithm, we will adopt gray-based image matching strategy. Since we just take the color information of the quantum image into consideration, the quantum template image and the quantum reference image are written as $|T\rangle = \otimes_{i=0}^{N^2-1} |t_i\rangle = \otimes_{i=0}^{N^2-1} |t_{i1} t_{i2} \cdots t_{i8}\rangle$ and $|R\rangle = \otimes_{i=0}^{N^2-1} |r_i\rangle = \otimes_{i=0}^{N^2-1} |r_{i1} r_{i2} \cdots r_{i8}\rangle$, respectively. Here, i represents the pixel number in the image. t_i and r_i denote the gray-scale information of each pixel of the template image and the reference image, respectively. $t_{i1} t_{i2} \cdots t_{i8}$ and $r_{i1} r_{i2} \cdots r_{i8}$ are binary representation of t_i and r_i, respectively. $|t_{ij}\rangle$ and $|r_{ij}\rangle$ are in the von-Neumann basis $\{|0\rangle, |1\rangle\}$, $j = 1, 2, \ldots, 8$.

Steps of the quantum image matching algorithm are described as follows.

a. Prepare quantum registers corresponding to the template image and the reference image, respectively, i.e., each quantum register encodes the gray-scale information of a pixel.
b. Template image is directly mapped with reference image, i.e., each corresponding pixel $|t_i\rangle$ is subtracted from the reference image $|r_i\rangle$ by operating the quantum subtracter circuit with the input $(|r_i\rangle, |t_i\rangle)$. Then we can get the output $(|r_i\rangle, |r_i - t_i\rangle)$ if $r_i \geq t_i$, else get $(|r_i\rangle, |256 - (t_i - r_i)\rangle)$.
c. Make quantum measurements on the quantum register encoding $|r_i - t_i\rangle$ or $|256 - (t_i - r_i)\rangle$ and save it as difference.
d. Then we add up all the differences and compare the sum with the Tolerance value. If the sum is smaller than the Tolerance value, then the image matching succeeds. Otherwise, it fails. Note that an appropriate tolerance value is taken according to the fault-tolerance requirements of the quantum image matching algorithm.

5. Numerical simulation and analysis

The simulations are based on linear algebraic constructions. To simulate the quantum states, the complex vectors are used, and the quantum subtracter circuit can be simulated by the unitary matrices. The final step in these simulations is the measurement, which converts the quantum information into the classical information. Using the NEQR representation model [5], the original classical image can be retrieved accurately from the quantum image, not probabilistically.

MATLAB is a mathematics software. It facilitates the representation and manipulation of large arrays of vectors and matrices which makes it a good tool for simulating quantum states (such as our quantum image states) and their transformations. In particular, by treating the quantum images as large matrices, it is possible for the simulation of the transformation by using linear algebraic