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Strategy for quantum image stabilization

Fei YAN[1]*, Abdullah M. ILIYASU[2], Huamin YANG[1] & Kaoru HIROTA[3]

[1]*School of Computer Science and Technology, Changchun University of Science and Technology, Changchun* 130022*, China;*
[2]*College of Engineering, Prince Sattam Bin Abdulaziz University, Al-Kharj* 11942*, KSA;*
[3]*Department of Computational Intelligence and Systems Science, Tokyo Institute of Technology, Yokohama* 2268502*, Japan*

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Abstract Image stabilization is a process to smooth the unstable motion vector of video sequences to achieve its stabilization. Even though the classical image stabilization techniques seem already very mature so far, similar advances have not been extended to the quantum computing domain. In this study, we explore a novel quantum video framework and make a modest attempt to perform the image stabilization based on it by utilizing the quantum comparator and quantum image translation operations. The proposed method is capable of estimating the camera motion during exposure and compensating for the video jitter caused by the motion. In addition, the quantum properties, i.e., entanglement and parallelism, ensure that the quantum image stabilization is feasible and effective. Finally, a simple experiment to stabilize a four-frame jittered quantum video is implemented using Matlab based on linear algebra with complex vectors as quantum states and unitary matrices as unitary transforms to show the feasibility and merits of this proposal.

Keywords quantum computation, image stabilization, quantum video, image translation, quantum measurement

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1 Introduction

Image stabilization is a process to smooth the unstable motion vector of video sequences to achieve its stabilization [1]. It is widely used in both the military and civilian areas such as aerial reconnaissance, fire control system, and video surveillance because unstable image frames bring viewers' fatigue and it is also harmful to the progress of judgment [2]. In earlier implementations of image stabilization, mechanical image stabilization and optical image stabilization used to play important roles, however, electronic image stabilization (EIS) has become more popular because it is more accurate, it has lower cost, and it is easier to realize small stabilization devices [2, 3].

EIS is actually a technique to realize the image stabilization by using the digital image processing methods [4]. Firstly, a motion estimation module retrieves a motion vector between consecutive frames. Then, a motion filter module separates intentional motion from jitter. Finally, a motion compensation

* Corresponding author (email: yanfei@cust.edu.cn)

module modifies error [4]. A number of related methods have been proposed recently, such as image block-based approaches [5, 6], phase correlation-based approaches [7, 8], and image fusion-based approaches [9, 10].

Even though the classical EIS technologies seem already very mature so far, similar advances have not been extended to the quantum computing domain. By utilizing the quantum properties, i.e., entanglement and parallelism, we assume the quantum image stabilization (QIS) will be more effective. In recent years, quantum computation and quantum information processing have gained widespread acceptance in applications related to information security, cryptography, error correction, etc. [11, 12]. Although the research in quantum image processing has already made a lot of progress [13, 14] with the theoretical discussion concerning the representation and storage [15, 16], also the applications in the image watermarking [17], edge extraction [18], and image database searching [19, 20], quantum video does not appear to have advanced like other areas. Perhaps this is because of the large size (in terms of number of frames) and the huge workload required to process the video content. In addition, quantum video needs to be processed in real time, which is time-consuming to realize. The need to process vast amounts of data in very short time intervals imposes a great burden on video codec, storage space requirements, and network communications [21].

In 2011, Iliyasu et al. [22] proposed a framework for representation and producing movies on quantum computers. It extends the classical movie applications and terminologies toward a new framework to facilitate movie representation and production on quantum computers. Building on this, later on, motivated by the extension from flexible representation of quantum image (FRQI) [23] to multi-channel quantum images (MCQI) [24], a notion of a multi-channel quantum video was broached in [25] and its application on moving target detection was proposed in [26].

In this paper, we explore an NEQR-based quantum video (a quantum video based on a novel enhanced quantum representation of digital images in [27]), and make a modest attempt to achieve the image stabilization based on it. The quantum comparator is used for the motion estimation and the quantum image translation is utilized for the motion compensation. This combined approach facilitates the QIS in quantum computing domain for the first time, in addition, it serves as a fast estimation and a parallel compensation method.

The representation for NEQR-based quantum video is presented in Section 2. The strategy to execute the QIS operation on quantum video is proposed in Section 3. In Section 4, an experiment to show the feasibility and effectivity of our proposal is implemented. Section 5 concludes the paper.

2 Representation for NEQR-based quantum video

2.1 NEQR quantum representation

NEQR is a novel enhanced quantum representation for digital images that uses the basis state of a qubit sequence to store the grayscale value of every pixel [27]. Two entangled qubit sequences are used to store the whole image, which represent the grayscale and positional information of all the pixels.

The representative expression for a $2^n \times 2^n$ NEQR image can be written as

$$|F(n)\rangle = \frac{1}{2^n}\sum_{y=0}^{2^n-1}\sum_{x=0}^{2^n-1}|f(y,x)\rangle|yx\rangle = \frac{1}{2^n}\sum_{y=0}^{2^n-1}\sum_{x=0}^{2^n-1}\bigotimes_{i=0}^{q-1}|C_{yx}^{i}\rangle|yx\rangle, \tag{1}$$

where

$$|f(y,x)\rangle = |C_{yx}^{q-1}C_{yx}^{q-2}\cdots C_{yx}^{0}\rangle, C_{yx}^{k}\in\{0,1\}, f(y,x)\in[1,2^q-1], \tag{2}$$

encodes the grayscale value of the image and its range is 2^q, and

$$|yx\rangle = |y_{n-1}y_{n-2}\cdots y_0\rangle|x_{n-1}x_{n-2}\cdots x_0\rangle, y_j, x_j\in\{0,1\}, \tag{3}$$

represents corresponding positions of the image.

Figure 1 Schematic of QIS strategy.

2.2 Quantum video representation based on NEQR

Credit for conceiving the sub-field of quantum movies goes to the work in [22], wherein a framework to represent and produce movies on quantum computers (quantum movie) was proposed. In this approach, however, the frames that make up the content of the movie were single channel FRQI quantum image states [23]. To convey the notion of color video, therefore, representation was extended to encode content of the frames based on the MCQI representation [24].

In this study, we investigate an NEQR-based quantum video and realize the QIS of it by conducting the procedure of motion estimation and motion compensation operations.

The NEQR representation is sufficient to encode a single frame as required for our application because it possesses two important features:

- It is flexible enough to constrain a smaller region of interest (ROI) within a frame to facilitate smaller operations as dictated by the video script.
- It captures the color information of every point by using a binary sequence to facilitate the quantum operations such as comparator and image translation.

In order to formalize our description of a quantum video in latter sections, we adopt the basic quantum movie groundwork established in [22], particularly, the definition for a video frame. NEQR quantum images are encoded into a collection of 2^m-ending frames as required to capture the information necessary to represent the shots and scenes of a video. This representation referred to here as the video strip or simply a strip is presented in Definition 1.

Definition 1. An NEQR video strip, $|S(m,n)\rangle$, is an array comprising 2^m NEQR quantum images, which is defined by

$$|S(m,n)\rangle = \frac{1}{2^{m/2}} \sum_{s=0}^{2^{2m}-1} |F_s(n)\rangle \otimes |s\rangle, \tag{4}$$

where $|F_s(n)\rangle$ is an NEQR quantum image as defined in Eq. (1) at position $|s\rangle$ $(s = 1, 2, \ldots, 2^m - 1)$, m is the number of qubits required to encode the images in the video.

It is noteworthy that similar to the definitions in [22], in NEQR quantum video, key frame is utilized for summarizing the content of a video for content browsing and retrieval. Nonetheless, viewing frame and makeup frame are adopted to generate the in-between content in order to adequately convey a scene as dictated by the video script. Several conceptual devices that were proposed in quantum movie [22], i.e., quantum CD, quantum player, and movie reader, are used to achieve the preparation, manipulation, and measurement of our proposed NEQR quantum video. Quantum CD is referred as a device to prepare, initialize, and store 2^m multiple frames, while the quantum player is utilized to manipulate the content of these frames to convey a scene from the video. In addition, the movie reader measures the contents of the sequence of frames in order to retrieve and recover the contents of the video.

3 Quantum video stabilization

The purpose of the QIS operation is to remove or minimize undesired jitter by motion estimation and motion compensation. The QIS framework, which is basically similar to EIS in classical image processing, generally comprises of three modules (as shown in Figure 1): motion estimation, motion filter, and motion compensation. Motion estimation aims to extract the global motion vectors of image sequences (they are the parameters of translation, rotation, and zoom between the current frame and reference frame); quantum filter is to filter the global motion vectors and divide the smooth movement components and the jitter movement components; motion compensation is then employed to counteract the perceived motion

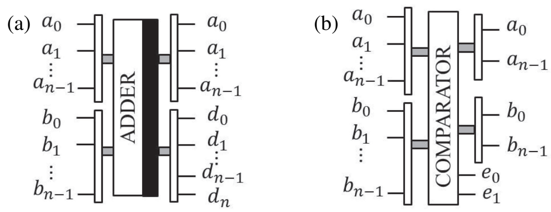

Figure 2 (a) Quantum adder; (b) quantum comparator.

offset and conduct the geometric transformation of image to eliminate the jitter in order to obtain stable image sequences [2].

The global motion is divided into intentional motion that happens when the camera scans the scene and unintentional motion which is caused by the carrier shaking. The jitter caused by camera translation (movement along horizontal and/or vertical direction) is a common/basic case in the video sequence, especially in the video surveillance, so in this study, we focus on this situation to provide the quantum circuits for the motion estimation and motion compensation in order to realize a stable quantum video output.

3.1 Motion estimation module in QIS

As a premise, we introduce two popular quantum operations, i.e., the quantum adder and quantum comparator for the motion estimation module and the following motion compensation module in QIS. Assume that $|a\rangle = |a_{n-1}a_{n-2}\cdots a_0\rangle$ and $|b\rangle = |b_{n-1}b_{n-2}\cdots b_0\rangle$ are two n-qubit binary numbers, $a_i, b_i \in \{0,1\}$, $i = n-1, n-2, \ldots, 0$. Reference [28] gives the quantum network ADDER that can add $|a\rangle$ and $|b\rangle$, which is shown below:

$$|d\rangle = |a\rangle + |b\rangle, \tag{5}$$

where the output $|d\rangle = |d_n d_{n-1} d_{n-2}\cdots d_0\rangle$ is an $(n+1)$-qubit number and d_n is the carry. If $a+b < 2^n$, $d_n = 0$; otherwise, $d_n = 1$. The circuit of quantum adder is shown in Figure 2(a).

On the other hand, [29] provides a quantum comparator circuit as shown in Figure 2(b) which is used to compare $|a\rangle$ and $|b\rangle$. Its useful outputs are two qubits $|e_0\rangle$ and $|e_1\rangle$. After the measurement, if the result of e_0e_1 is 10, then $a > b$; if the result of e_0e_1 is 01, then $a < b$; if the result of e_0e_1 is 00, then $a = b$.

Now, we introduce how to use the quantum comparator to realize the motion estimation. Assume $F(x, y)$ is the original image, where (x, y) is the pixel coordinates, $x, y = 0, 1, \ldots, 2^n - 1$. The image translation is defined as follows:

$$x_t = x \pm t_x, y_t = y \pm t_y, \tag{6}$$

where (x_t, y_t) is the pixel coordinates in the translated image, (t_x, t_y) is the translation parameter which specifies the desired horizontal and vertical pixel displacements, $0 \leqslant t_x, t_y \leqslant 2^n - 1$. If $+$ is used, the image is translated right and/or down; if $-$ is used, the image is translated left and/or up.

We know that blocks matching is a common method to conduct the motion estimation in classical EIS operation [30]. It selects a block with fixed size in the reference image as a template, then according to a certain algorithm, searches for a sub-image corresponding to the template in a specified searching area of the current frame as the matching result. Inspired by this, we will select a block (b_0) in the reference frame of a quantum video. Then in an assigned searching area of the current frame, we intend to find a block (b_k) that matches b_0. As discussed in the last section, $|C_{yx}^{q-1}C_{yx}^{q-2}\cdots C_{yx}^{0}\rangle$ is used to represent the color of a pixel. We prepare q ancilla qubits $|0\rangle$ to compose a binary string for storing the color information of the reference image. We aim to swap the color information on $|C_{yx}^{q-1}C_{yx}^{q-2}\cdots C_{yx}^{0}\rangle$ with $|00\cdots0\rangle$ (The swap operators can be built using three CNOT gates as shown in Figure 3(a)). Then, another q ancilla qubits $|0\rangle'$ are prepared for storing the color information of the current frame. By utilizing the control conditions on the s axis and y/x axis, we can confine a desired block (sub-image) in a specified frame. We use a comparator operation to compare the block (b_k) in the current frame with the block (b_0) in the reference image. 'COMPARATOR k' in Figure 4 is a quantum comparator for comparing two blocks. It

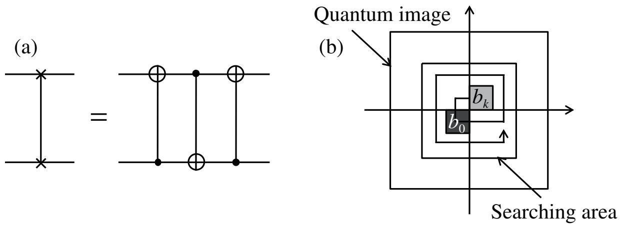

Figure 3 (a) Swapping operation and (b) schematic diagram of quantum blocks matching.

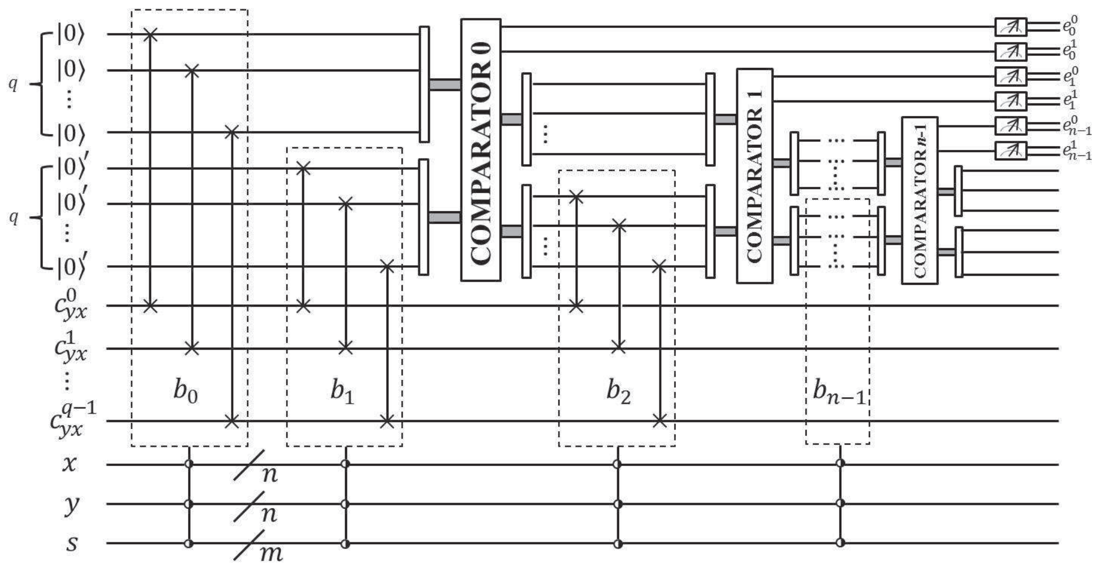

Figure 4 Motion estimation operation in QIS.

could be fulfilled by controlling the position information in the block. The output from the comparator after the measurement is $e_k^0 e_k^1$. We keep going to the comparison (the block, b_k, translates anticlockwise centered by the origin in the assigned searching area as presented in Figure 3(b)) until the outputs $e_k^0 e_k^1$ from 'COMPARATOR k' are 00, hence, we say block b_k ($k \neq 0$) matches b_0 in the reference image. Meanwhile, we say the two blocks are matched with each other in k steps. So by analyzing the motion trail, we could obtain the motion vector of the current frame compared with reference image.

3.2 Motion compensation module in QIS

Motion compensation is achieved by global translation (GT), which is an operation to translate the whole image horizontally and/or vertically, then fill the vacated position with black and abandon the pixels over the image boundary [31]. We provide a motion compensation module (as presented in Figure 5) to realize the QIS by using the motion vector obtained in the motion estimation operation.

As stated in [31], the image translation processing can be decomposed into two separable steps: X-direction translation and Y-direction translation. In this study, we use X-direction in our discussion on the motion estimation and motion compensation for the QIS in quantum video.

The half moon symbol [13] on the S-axis indicates either 0 or 1 control condition to decide which frame we are focusing on. Then the GT operation is responsible for the motion compensation module. As mentioned earlier, the compensation on the X-direction and Y-direction could be separately treated. So we only discuss the X-direction compensation and ditto to the Y-direction.

(1) When the frame is needed to translate right ($x_t = x + t_x$), the GT operation can be described as follows:

$$c_{x_t y} = \begin{cases} 0, & 0 \leqslant x_t \leqslant t_x - 1, \\ c_{xy}, & t_x \leqslant x_t \leqslant 2^n - 1. \end{cases} \tag{7}$$

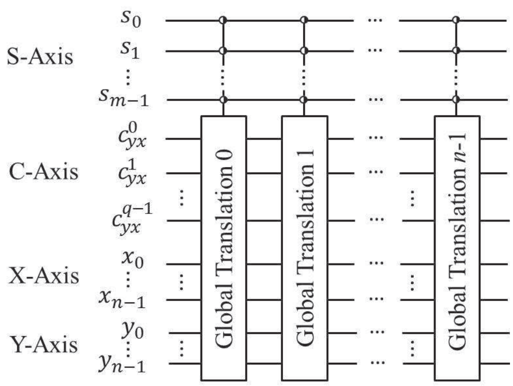

Figure 5 Motion compensation operation in QIS.

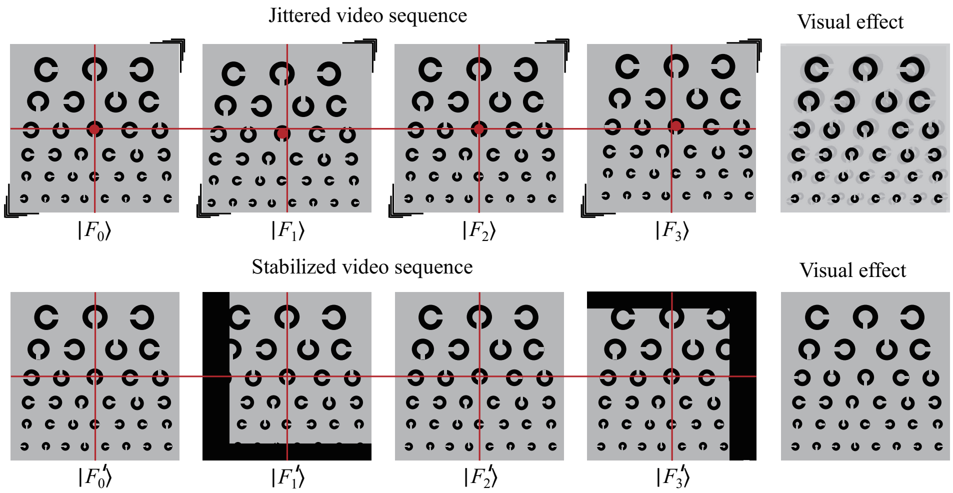

Figure 6 (Color online) Experiment of QIS strategy on visual chart.

The quantum adder is used firstly to obtain x_t. Then, the carry qubit x_{tn} can be utilized as the control qubit: if $x_{tn} = 0$, set $c_{x_t y_t} = c_{xy}$; otherwise, set $c_{x_t y_t} = 0$. The quantum circuit for GT to right could be found in Figure 6(a) in [31], which indicates the network complexity is $40n - 12$.

(2) When the frame is required to translate left ($x_t = x - t_x$), the GT operation can be described as below:

$$c_{x_t y} = \begin{cases} 0, & 2^n - t_x \leqslant x_t \leqslant 2^n - 1, \\ c_{xy}, & 0 \leqslant x_t \leqslant 2^n - 1 - t_x. \end{cases} \tag{8}$$

The quantum comparator is used firstly to compare x with t_x. Then, the reversed ADDER is used to calculate $x - t_x$. Finally, the output qubit e_0 of the comparator is employed as the control qubit: if $e_0 = 0$ ($x \geqslant x_t$), set $c_{x_t y_t} = c_{xy}$; otherwise, set $c_{x_t y_t} = 0$. The quantum circuit for GT to left could be found in Figure 6(b) in [31], which shows the network complexity is $24n^2 + 46n - 12$.

According to the motion vector that we obtained from the motion estimation module, we assign them as the compensation parameters to perform the translation to achieve the stabilization. After the appropriate translations to the specified frames, the quantum video is stabilized as output. As the measurement to quantum video, some available literatures have fully studied it [22, 26]. We recommend interested readers to find more information there.

4 Experiment of QIS

For the experiment, we expediently adopt a simulation of a 4-frame (each is a 128×128 NEQR grayscale

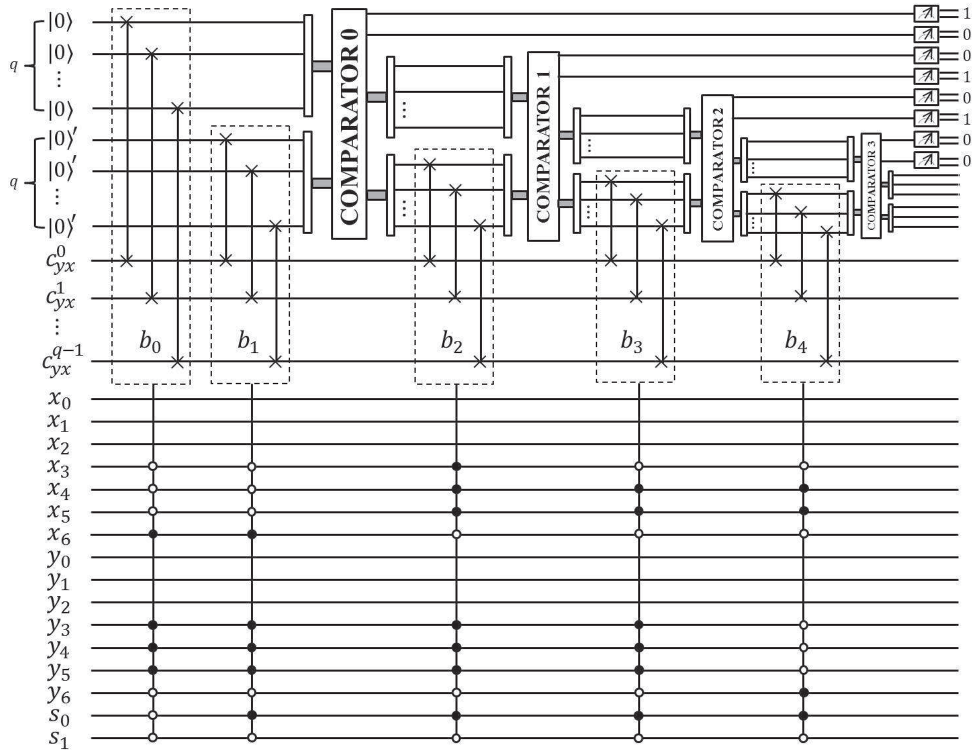

Figure 7 Motion estimation of $|F_1\rangle$ in the video sequence in Figure 6.

image) quantum video in order to elaborate on the cogency of our proposed QIS strategy. A C-shape visual chart is taken as the scene in order to clearly see the jitter and motion blur caused by the camera. $|F_0\rangle$ is the reference image (frame) and the jitter of the other frames are corrected by using the position of $|F_0\rangle$ as reference. We draw two red cross lines to discern the position of the target and the origin is treated as the center of the image. In addition, the red dot indicates the center of the reference frame. Obviously, $|F_1\rangle$ shows that the camera vibrating to the up-right direction, $|F_2\rangle$ presents the camera moving back to the original position, and $|F_3\rangle$ indicates the camera vibrating to the left-down direction. It is obvious from the combined image that due to the motion of the camera, the video sequence becomes blurry. It likes a myope to see the visual chart and it is very difficult to tell the direction of the C-shape in the visual chart. So we can see that the jittered video will affect the judgement of people and it is also a fatigue to human eyes if we stare at that long.

As proposed above, we utilize the motion estimation and motion compensation operations to stabilize the video sequence to obtain a stable video output.

Specifically, we conduct the motion estimation operation firstly on the video sequence in Figure 6. We select a 8×8 block in the frame to make the matching and a selected 32×32 sub-area is regarded as its active range. According to the discussion in Section 3.1 and the illustration in Figure 3(b), the 8×8 block originates from the (0, 0) position and moves to the left then down in 8 pixels. As presented in Figure 7, after 4 matchings, the output from the comparators is 10010100, which means the matching is successful in 4 steps. Now, we find that the block at $(-16, -8)$ in $|F_1\rangle$ matches the block we selected in the reference image. So we can estimate the motion vector of $|F_1\rangle$ is $MV^1_{x^+} = 16$, $MV^1_{y^+} = 8$ (x/y with $+/-$ indicates the translation to the positive or negative direction along the x/y axis). In the same manner, the motion vectors of $|F_2\rangle$ and $|F_3\rangle$ are $MV^2_{x^+} = 0$, $MV^2_{y^+} = 0$ and $MV^3_{x^-} = 16$, $MV^3_{y^-} = 8$, respectively.

Subsequently, we conduct the motion compensation operation by using the motion vectors obtained earlier. For the compensation, we could divide them to two operations along the X-direction and Y-direction. We use the control condition on the S-axis to focus the transformation on specified frames. In the first part (surrounded by dashed line) in Figure 8, it reflects the compensation (translation) operations

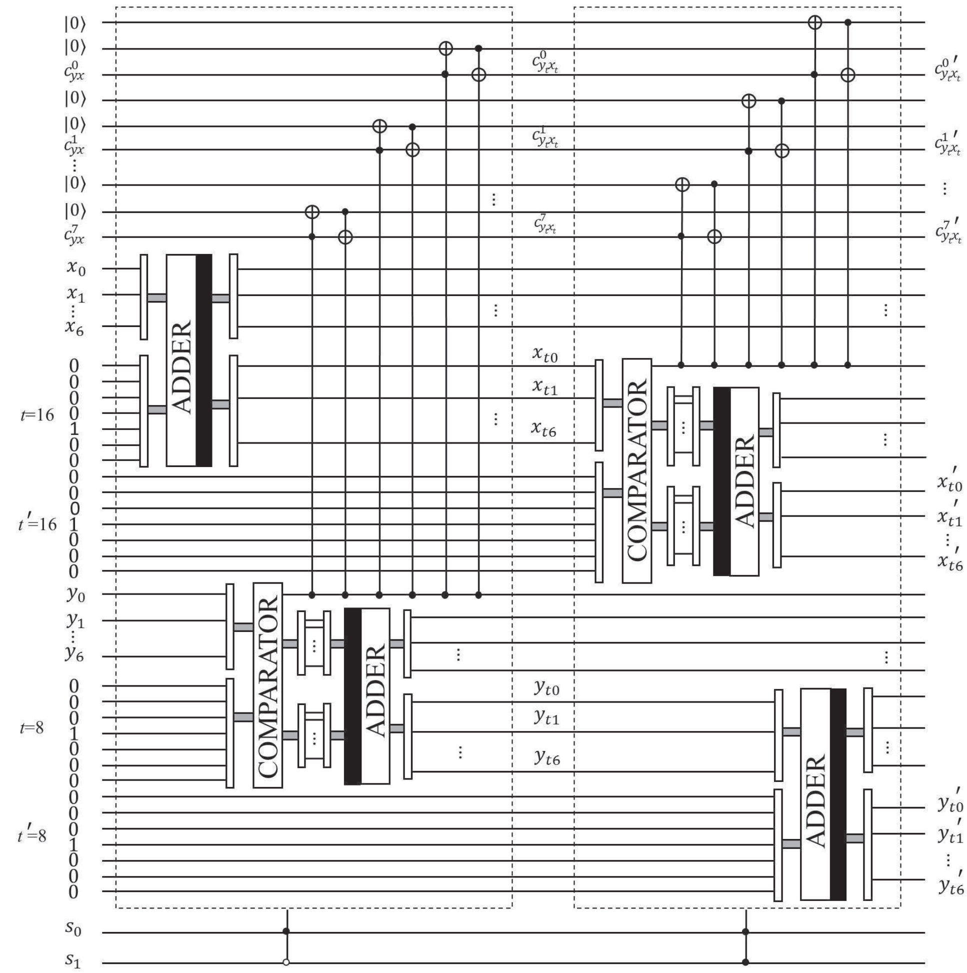

Figure 8 Quantum circuit of the motion compensation in the experiment.

on $|F_1\rangle$. The translation to x positive direction for 16 pixels and then y positive direction for 8 pixels will correct this frame. In the same manner, the second part in Figure 8 is used to correct the jitter in $|F_3\rangle$ (the translation is moving towards x negative direction for 16 pixels and then y negative direction for 8 pixels), and apparently, no operations are needed on $|F_2\rangle$. After the motion compensation, we can see the visual effect of the combined video sequence is very clear without blur and unwanted jitter.

In the experiment, we show the feasibility of the QIS in quantum video. We need to notice that it is the first time to extend this image stabilization technique to quantum computing domain, and the associated advantages of this attempt are (1) when we perform the motion estimation, it is possible to compare two desired blocks in any two specified frames. And by the outputs from the comparators, we could estimate the motion vectors of the global motion; (2) when we conduct the motion compensation, if the camera jitters in a regular way (always in the same amplitude), we can correct them concurrently due to the parallel property of quantum computing. However, in classical EIS, we need to perform it each by each.

5 Conclusion

This study proposed a strategy of QIS in quantum video. It is the first time to focus on this study in quantum computing domain. Due to the parallel property of quantum computing, the motion estimation and motion compensation operations are implemented very effectively. An experiment was implemented where the circuits and discussions verified the feasibility and advantage of this proposal.

For the future work, we will focus on the following aspects. First, the motion estimation is the most important and time-consuming process. In our proposed strategy, it is usually difficult to decide the size of the block for matching. If it is too small, it probably cannot find/match the correct block and also it will take longer time. But if it is too big, it will be very difficult to traverse every pixel in the searching area. Second, in this study, we only investigated the basic common case when the jitter in the video sequence is caused by the translation. In the future, we will consider more complicated transformations, e.g., rotation and zoom. Probably some strategies such as the registration method in [32] and interpolation method in [33] could be used there.

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Conflict of interest The authors declare that they have no conflict of interest.

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