

Quantum Image Representation: A Systematic Literature Review of Evolutions, Paradigms, and Methodologies

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Abstract

As quantum computing transitions from theoretical physics to practical computation, the mapping of classical visual data into quantum states, known as Quantum Image Representation (QIR), has emerged as a vital research area. This paper presents a systematic review that categorizes the evolution of QIR from basic qubit mapping to advanced discrete and higher-dimensional systems. We analyze the mathematical trade-offs between qubit count and circuit depth while outlining a step-by-step methodology for researchers to synthesize quantum-specific literature in the NISQ era.

1 Introduction

Quantum systems utilize mechanical properties—superposition, entanglement, and interference—to process visual information. In a classical computer, an image is a collection of bits; in a quantum system, it is a complex superposition of qubits. A systematic literature review in this field addresses the need to critique historical models while conceptualizing emerging trends like hybrid quantum-classical compression and qutrit-based state spaces.

The primary goal of this review is to bridge the gap between theoretical proposals and practical implementation, identifying the "loading problem" that currently bottlenecks the field.

2 Methodology of the Systematic Review

A systematic review in the quantum domain must move beyond an annotated bibliography to provide a critical evaluation of research.

2.1 Categorization and Selection Criteria

To assess the reliability of QIR literature, the reviewer must categorize studies based on encoding mechanics:

- **Primary Sources:** Original proposals of encoding circuits (e.g., FRQI, NEQR).
- **Theoretical Bounds:** Papers discussing the mathematical limits of qubit storage.
- **Methodological Frameworks:** Studies addressing non-square images or multi-wavelength data.

3 Synthesis of Quantum Image Representations (QIR)

Quantum Image Representation (QIR) defines how classical pixel values (color and position) are mapped into quantum states.

3.1 Foundational and Mixed Representation Models

The inception of QIR began with the **Qubit Lattice** and **QPR** models, which directly mapped pixel colors to the probability amplitudes of qubits. While simple, these models were limited as they did not support multidimensional images.

The **Flexible Representation of Quantum Images (FRQI)** addressed this by utilizing normalized states to store position and color information, requiring only $2n + 1$ qubits. However, despite its space efficiency, FRQI is evaluated as probabilistic; retrieving the exact pixel intensity requires high measurement counts, leading to computational overhead during the state-readout phase.

3.2 Discrete and High-Fidelity Representation Techniques

To overcome the measurement limitations of continuous models, the **Novel Enhanced Quantum Representation (NEQR)** uses basis states of quantum sequences to store color information. This deterministic approach allows for accurate pixel measurement and is highly suitable for complex image transformations.

Further refinements include:

- **GQIR (Generalized Quantum Image Representation):** Extends NEQR to support non-square ($M \times N$) images.
- **INEQR (Improved NEQR):** Designed to handle image scaling without being restricted to $2^n \times 2^n$ dimensions.

3.3 Multi-Channel and Specialized Spectral Encoding

Advancements in color imaging led to the **Multi-Channel Quantum Image (MCQI)**, which stores RGB information simultaneously using $2n + 3$ qubits. For specialized data, the **Quantum Representation of Multi-Wavelength Images (QRMW)** encodes spectral bands for satellite or medical imagery. Niche models such as **QUALPI** (log-polar images) and **SQR** (infrared radiant energy) further demonstrate the versatility of quantum state mapping.

3.4 Higher-Dimensional and Optimized State Spaces

Recent research has moved toward higher-dimensional states like **qutrits** (3-level systems) to reduce circuit complexity. Models like **FQR3I** utilize expanded state-spaces for ternary images. Furthermore, **Hybrid Models** incorporating compression-aware techniques have demonstrated significant reductions in gate overhead—up to 75%—making them more scalable for contemporary quantum simulators.

4 Comparative Analysis and Evaluation Metrics

Evaluation of these models focuses on three critical metrics: qubit requirements, circuit depth, and reconstruction fidelity.

Table 1: QIR Synthesis and Performance Matrix

Model	Qubits	Retrieval	Complexity	Application
FRQI	$2n + 1$	Probabilistic	$O(2^{2n})$	Geometric Transforms
NEQR	$2n + q$	Deterministic	$O(qn2^{2n})$	Image Filtering
MCQI	$2n + 3$	Probabilistic	$O(2^{2n})$	RGB Color Processing
GQIR	$2n + q$	Deterministic	$O(qnMN)$	Non-square Images

Recent hardware tests on IBM platforms have quantified reconstruction accuracy through fidelity (reported as high as 0.99) and Mean Square Error (MSE). Research indicates that while FRQI remains the most qubit-efficient, discrete methods like NEQR provide superior results for denoising and precision-based tasks.

5 Discussion and Future Directions

The “loading problem” remains the primary gap in research. While quantum algorithms offer speedup, the initialization of classical data into a quantum state remains computationally expensive. Future research must focus on:

1. **Hardware-Aware Design:** Circuits optimized for the limited coherence times of NISQ devices.
2. **Advanced Scrambling:** Integration of Hilbert quantum image scrambling for secure representation.
3. **Higher-Dimensional Gates:** Further exploration of qutrit and qudit systems to minimize qubit counts.

6 Conclusion

This review has presented a systematic evolution of Quantum Image Representation. By navigating the complexities of probabilistic vs. deterministic models, researchers can select the most appropriate framework for their visual data applications. As hardware matures, the shift toward hybrid and higher-dimensional representations will be essential in overcoming the constraints of current quantum technologies.

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