Quantum Image Processing

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1 Introduction

In the first half of the 20th century, the field of quantum mechanics was born. The first to create this concept was the physicist Marx Planck, who through the observation of the phenomena produced by the radiation of a black body. Over time several physicists contributed more concepts to this field, such as Albert Einstein and his explanation of the photoelectric effect, or Erwin Schrödinger's wave equation.

It wasn't until the 1980s when the first theories emerged aimed at applying these formulas to the world of computing, with the aim of improving the performance of certain highly complex calculations. The progenitors of this new movement were Paul Benioff and Richard Feynmann.

Currently, quantum computing is an important research topic around the world, and companies with a great impact on the IT sector, such as IBM or Google, are working on the development of quantum computers.

2 Objectives

My focus in this project is to deepen my knowledge into the quantum machine learning and quantum image encoding field, with the purpose of implementing and enhancing quantum neural network models for image classification or image enhancing algorithms.

2.1 First objectives

- Perform an image classification using quantum neural networks models like Quantum CNN [1].

2.2 Final objectives

- Enhance the used model via optimal ways of quantum encoding and denoising [2].
- Using a Quantum-based or Quantum-classical approach NN to perform image super-resolution.[3]

3 Material

To be able to carry out this project, there are some required software tools:

3.1 Qiskit

Qiskit[4] is an open-source quantum computing software development framework developed by IBM, and will be the most important tool during the project. It provides a comprehensive set of tools and libraries for programming quantum computers, simulating quantum circuits, and conducting quantum research. Its documentation facilitate the first steps into the quantum computing field and recently it has been updated to release version.

3.2 Pennylane

PennyLane[5] is an open-source software library developed by Xanadu Quantum Technologies. It is designed to facilitate the integration of quantum computing and machine learning by providing a platform for hybrid quantum-classical computations. Unlike Qiskit, which is developed by IBM, PennyLane is hardware-agnostic and can be used with a variety of quantum computing backends.

3.3 PyTorch

Framework oriented to classical machine and deep learning. It is going to be helpful for interpreting and treating the data at the end of the image processing.

4 Firsts implementations

In this section, I will explain some research and tutorial material I have been working on during these starting part of the project.

4.1 Quantum Neural Networks

The motivation behind quantum machine learning is to integrate notions form quantum computing and classical machine learning to create new and improved learning schemes. This principle is applied by combining classical neural networks and parameterized quantum circuits. During this tutorial presented by the Qiskit ML documentation I have learned about how to declare quantum circuits and its components, how a QNN is initialized, and basic concepts about forward and backward passes. The focus point in this example are two basic neural network class, provided by the qiskit-machine-learning library, named EstimatorQNN, which is based on the evaluation of quantum observables, and SampleQNN, which is based on the samples resulting from measuring a quantum circuit.

4.2 Quantum Convolution Neural Network

This type of neural networks behave in a similar manner to classical CNNs. First, the data is encoded into a quantum circuit using a feature map. After encoding, convolutional and pooling layers are applied with the objective of reducing the dimensionality of the circuit until it is only of one qubit. Finally, the data is classified by measuring the output of this single qubit. During this tutorial presented by the Qiskit ML documentation I have learned about the differences between classical and quantum CNN, the different components of the model, and its processes of training and testing.

4.3 Image representations and encoding

In quantum computing, we usually represent the image data in the same way as classical machines: using pixel coordinates and pixel intensities to describe it; but the difference is found in how we codify this data [6]. In the quantum approach, the use of quantum properties such as entanglement and superposition offer a different representation of image data. The physical values of pixel properties are represented by the different possible states of a qubit and its amplitude. We can classify this quantum representation in three types of algorithms:

4.3.1 Continuous representation

This representation allows to use a single qubit for pixel intensity and coordinate encoding, with the drawback of requiring multiple measurements to estimate high precision values.

OQIM The OQIM model[7] is an example that follows the continous representation method. It uses the different basis states of the qubits to perform an intensity sorting, ordering the values according to the gray value of the pixel. Then, a single qubit to store the intensity and the coordinate value of the pixel, and an additional qubit to control the mode of representation(coordinate or intensity). Number of required qubits for this method are:

$$2n + 2$$

For a $2^n * 2^n$ image.

4.3.2 Discrete representation

In this representation, each qubit state corresponds to a separate intensity or coordinate value.

NEQR The NEQR model[8] follows the discrete representation method. Its purpose is to improve the FRQI model, which I will explain later in this article. NEQR uses two entangled qubit sequences to store the intensity values and the coordinate values of all the pixels. The number of required qubits for this method are:

$$q + 2n$$

For a $2^n * 2^n$ image with 2^q gray value range.

4.3.3 Mixed representation

This representation either uses discrete and continuous methods, where the first one is used for pixel coordinates, and the second one for intensity values.

FRQI The FRQI model follows the mixed representation method. It stores in a single qubit the coordinate information for each pixel and uses its amplitude for the grayscale values storage. The difference between this model and NEQR lies in the complexity, the second stores the information in a more efficient way, so information like the intensity can be distinguished better. The number of required qubits for this method are:

$$2n + 1$$

For a $2^n * 2^n$ image.

5 Planification

The complete roadmap of the project is represented in a Gantt chart [Figure 1], a bar chart that illustrates the project schedule, specifing the timelines of every task and subtask, to make the process more visual and comprehensible. Each activity has been placed accordingly to its difficulty and development requirements. The whole project timeline extends since 8 February 2024 till 20 July 2024.

6 Code examples

The implementations and tutorials done until now are posted in a public repository: `https://github.com/kaitouser/QML_TFG`

References

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[2] Denny Mattern and Darya Martyniuk and Henri Willems and Fabian Bergmann and Adrian Paschke. Variational Quanvolutional Neural Networks with enhanced image encoding. (2021). `https://arxiv.org/abs/2106.07327`

[3] Kudyshev, Z.A., Sychev, D., Martin, Z. et al. Machine learning assisted quantum super-resolution microscopy. Nat Commun 14, 4828 (2023). `https://doi.org/10.1038/s41467-023-40506-4`

[4] Qiskit contributors. Qiskit: An Open-source Framework for Quantum Computing. (2023). `https://docs.quantum.ibm.com/`

[5] Ville Bergholm et al. PennyLane: Automatic differentiation of hybrid quantum-classical computations. 2018. `arXiv:1811.04968`

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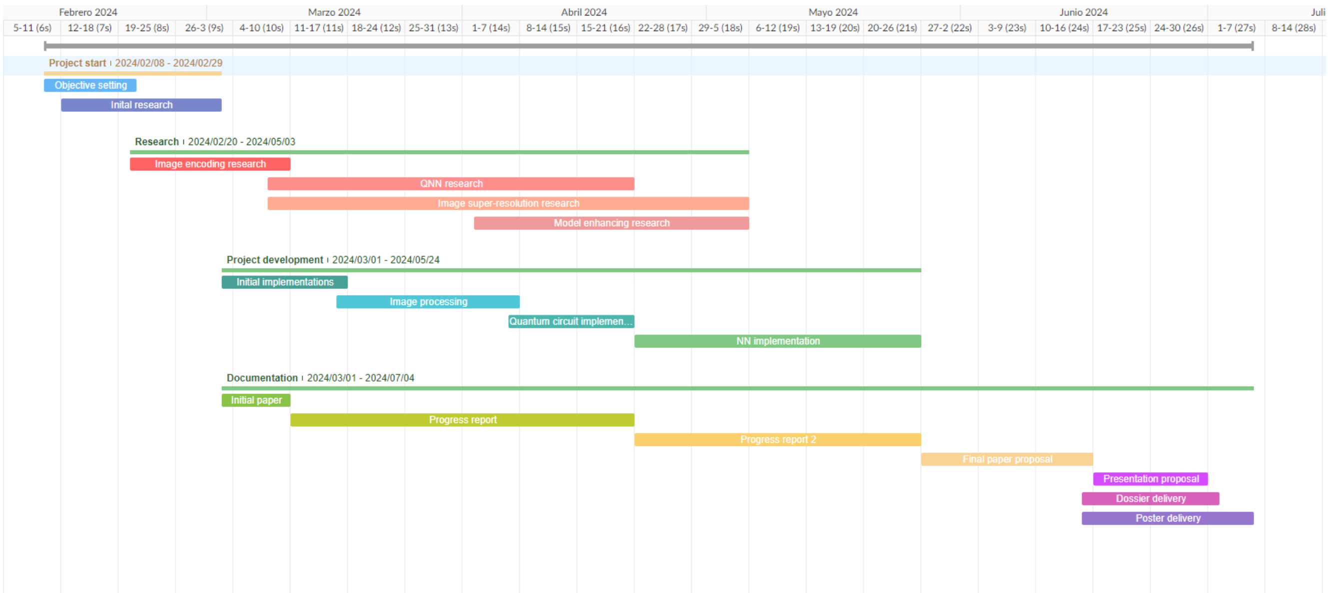

Fig. 1: Timeline of the project displayed as a Gantt diagram

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[8] EZhang, Y., Lu, K., Gao, Y. et al. NEQR: a novel enhanced quantum representation of digital images. Quantum Inf Process 12, 2833–2860 (2013). https://doi.org/10.1007/s11128-013-0567-z