

Representational Biases in Quantum Image Encodings: A Functional and Spectral Perspective

Sergio Hernández^{1,2}, Pedro Brandimarte², Iker Pastor²

¹University of Deusto, Universities Avenue, 24, Bilbao 48007, Spain

²Vicomtech, Mikeletegi Promenade, 57, Donostia San Sebastian, 20009, Spain

sergio.h@deusto.es

Abstract.

Data encoding plays a central role in Quantum Machine Learning, determining the class of functions that a quantum model can represent. While Fourier-based analyses have provided valuable insights into angle-encoded models [1], the representational biases induced by commonly used quantum image encodings remain poorly understood.

In this work, we investigate the functional structure induced by common embeddings used in Quantum Computer Vision through the lens of spectral and functional analysis. Building on recent advances in the characterization of parameterized quantum models [2], we develop a framework that enables the systematic study of image-oriented encoding strategies, including regular qubit-efficient and image-specific approaches. This perspective allows us to analyze the structural constraints, inductive biases, and representational capabilities imposed by different embeddings independently of downstream optimization procedures.

Using a combination of analytical and empirical techniques, we compare several representative quantum image encodings, including established approaches such as FRQI and Hamiltonian image encoding, together with qubit-efficient embedding strategies. To characterize their induced function spaces, we introduce quantitative descriptors that capture aspects such as the effective dimensionality, controllability, and geometric structure of the accessible representations.

Our analysis reveals substantial differences in the accessibility and organization of these function spaces. In particular, we observe that qubit-efficient embeddings often exhibit a surprisingly limited degree of control over the induced Fourier expansions, even when the corresponding Fourier spaces are of low degree and contain relatively few coefficients. Conversely, image-specific encodings frequently fail to generate complete Fourier expansions, exhibiting missing terms and, in some cases, entire inaccessible frequency sectors. These limitations manifest through strong geometric constraints, controllability hierarchies, and expressive bottlenecks that are not captured by conventional measures of representational capacity.

Our results suggest that the practical expressivity of quantum image representations is determined not only by the size of their Fourier support or the variability of its coefficients, but also by the controllability of the accessible coefficient space. In particular, the observed controllability and expressive bottlenecks are consistent with recent studies reporting the progressive suppression of higher-order Fourier components in quantum models [3]. At the same time, the fact that several models have demonstrated promising empirical performance despite these representational restrictions suggests considerable room for improvement through the design of embeddings with richer and more controllable functional structures or access to larger quantum system. More broadly, this work provides new insight into the foundations of Quantum Computer Vision and establishes functional analysis as a practical framework for understanding, comparing, and designing quantum learning architectures for high-dimensional visual data.

References

- [1] M. Schuld, R. Sweke, and J. J. Meyer, “Effect of data encoding on the expressive power of variational quantum machine-learning models,” *Phys. Rev. A* 103, 032430 (2021).
- [2] N. A. Nemkov, E. O. Kiktenko, and A. K. Fedorov, “Fourier expansion in variational quantum algorithms,” *Phys. Rev. A* 108, 032406 (2023).
- [3] H. Mhiri et al., “Constrained and Vanishing Expressivity of Quantum Fourier Models,” *Quantum* 9, 1847 (2025).