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Quantum Engineering of Qudits with Interpretable Machine Learning

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Higher-dimensional quantum systems (qudits) offer advantages in information encoding, error resilience, and compact gate implementations, and naturally arise in platforms such as superconducting and solid-state systems. However, realistic conditions such as non-Markovian noise, non-ideal pulses, and beyond rotating wave approximation (RWA) dynamics pose significant challenges for controlling and characterising qudits. In this work, we present a machine-learning-based graybox framework for the control and noise characterisation of qudits with arbitrary dimension, extending recent methods developed for single-qubit systems. Additionally, we introduce a local analytic expansion that enables interpretable modelling of the noise dynamics, providing a structured and efficient way to simulate system behaviour and compare different noise models. This interpretability feature allows us to understand the mechanisms underlying successful control strategies; and opens the way for developing methods for distinguishing noise sources with similar effects. We demonstrate high-fidelity implementations of both global unitary operations as well as two-level subspace gates. Our work establishes a foundation for scalable and interpretable quantum control techniques applicable to both NISQ devices and finite-dimensional quantum systems, enhancing the performance of next-generation quantum technologies.

Authors: MAYEVSKY-MATTIACCIO, Yule (RMIT University); YOUSSEY, Akram (RMIT University)

Co-authors: Mr SAREEN, Ritik (RMIT University); Dr PAZ-SILVA, Gerardo A. (Griffith University); PERUZZO, Alberto (Quantum Photonics Laboratory and Centre for Quantum Computation and Communication Technology, RMIT University, Melbourne, VIC 3000, Australia)

Presenters: MAYEVSKY-MATTIACCIO, Yule (RMIT University); YOUSSEY, Akram (RMIT University); Mr SAREEN, Ritik (RMIT University)

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