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Report on the PhD manuscript written by Stancho Georgiev Stanchev under the supervision of N.V. Vitanov at Sofia University (Bulgaria).

The thesis manuscript, written by S.G. Stanchev, is about high fidelity methods for Quantum Process Tomography techniques to precisely and accurately extract various types of errors characterizing quantum gates and more generally quantum circuits. Three scientific papers are associated to the present work and have been published in international physics reviews:

1- Stanchev S.G., Vitanov N.V., "Coherent interaction of multistate quantum systems possessing the Wigner–Majorana and Morris–Shore dynamic symmetries with pulse trains." ***J. Phys. B: At. Mol. Opt. Phys.*** **56 014001 (2023).**
2- Stanchev S.G., Vitanov N.V., "Characterization of high-fidelity Raman qubit gates." ***Phys Rev A*** **109, 012605 (2024).**
3- Stanchev S.G., Vitanov N.V., "Multipass quantum process tomography." ***Sci Rep*** **14, 18185 (2024).**

In quantum information (QIP), it is essential to completely know the quantum state of the object (photon, electronic or nuclear spin) which carries the information. This is possible through a procedure called quantum tomography, which consists of measuring the quantum system by successive operation and determining defects and errors generated during the manipulation of these quantum bits. Among various technical methods, Quantum State Tomography aims to characterize an unknown quantum state from experimental data leading to an estimation of process fidelity (or infidelity) and deviation of the measured process from the true one.

The work realized by S.G. Stanchev is part of an international effort in quantum technologies on improving the computational performances of quantum circuits by developing reliable and efficient error estimation codes during information processing by quantum gates. The work presented in this manuscript makes an important contribution to the precise and accurate evaluation of quantum computation errors by a method based on multiple repetitions of the operation of a single quantum gate called Multipass Quantum Process Tomography (MQPT). This method is demonstrated to be superior to other standard approaches such as Randomized Benchmarking or Gate Set Tomography in delivering precise and accurate information not only about infidelity but also about the quantum matrix process itself. The MQPT protocol has also proved to be more precise and accurate than the standard QPT in the determination of process infidelity by employing gate repetition.

The manuscript in its form is well written. The first two chapters are devoted to generalities on quantum information processing, and high-fidelity quantum tomography at the interface between theoretical and computational aspects. **Chapter 2** recalls the basics of quantum information processing theory, measurement processes based on the density matrix formalism adapted to closed quantum systems and a modified von-Neumann equation for open quantum systems including decoherence. **Chapter 3** presents the techniques for characterizing errors generated by the application of quantum logic circuits consisting of a succession of quantum gates and measurement of the final result. The notion of preparation and reading error of the quantum state, precision and accuracy of the measurement are presented. Finally, **chapters 4, 5 and 6** constitute the original contributions of S.G. Stanchev's thesis work.

Chapter 4 presents a method to enhance the precision and accuracy of Quantum Process Tomography by mitigating errors caused by state preparation and measurement performing a Multipass Quantum Process Tomography (MQPT) protocol. The main idea is to amplify or accumulate errors (from state initialization, non perfect quantum state manipulation and measurement) during information processing by using repetitions of the same quantum gate. Errors are finally evaluated through algorithmic based inversion methods (post-processing iteration or linear solve of a set of Silvester equations). The author proposes the so-called distance metrics as the “diamond norm”, error process estimation between the target and the actual process and process infidelity parameters to evaluate and characterize various error sources. Simulations of a noisy single qubit $\sqrt{X}$ gate and a CNOT gate including known errors are performed to demonstrate the superior efficiency of the MQPT protocol in precisely extracting and improving accurate evaluation of error matrix components and process infidelity (based on the open source IBM QISKIT process Tomography module).

Chapter 5 presents exact analytic formulae to describe dynamics of multistate quantum systems (or qudits) exhibiting the so-called SU(2) Wigner-Majorana and Morris-Shore symmetries while interacting with a train of electromagnetic pulses. The goal of this work is to elaborate propagators for complex quantum systems ultimately based on a simple but fundamental two-level description of Bloch vector dynamics through a Cayley-Klein parametrization. These analytical formulae might also be used to explore the efficiency of various dynamical decoupling methods to protect qubit and qudit against noise. Indeed, such a theoretical description is limited by the fact that each pulse (or a set of pulses) is assumed to have identical variation of the pulse area as well as the fact that multiple states are supposed to be separated by the same energy amount (ignoring for example the second order Zeeman effect in a non degenerate multistate architecture breaking the SU(2) rotational symmetry or by including additional terms breaking the rotating wave approximation).

Finally, chapter 6 presents the application of the MQPT method for the characterization of high-fidelity Raman qubit gates under a Morris-Shore transformation. The new protocol is applied to amplify gate errors through constructive interferences repeating the quantum gate process several times. Thus amplified gate errors are easily extracted to correct a single-pass quantum gate processing with precision and accuracy.

In conclusion, a new simple and reliable Multipass Quantum Process Tomography (MQPT) protocol is presented to precisely and accurately estimate processing errors related to the manipulation of quantum information by a repetitive application of a single quantum gate. Compared to other quantum tomography methods such as Randomized Benchmarking (RB), it delivers not only process infidelity but also complete information on error matrices with precision while increasing accuracy through the number of gate repetitions. SU(2) analytic formulae are derived for qudit gates (multiple quantum state equally spaced in energy and interacting with identical electromagnetic fields under particular assumption) that can be reduced to the dynamics of a two-level quantum system by symmetry considerations. These explicit formulae also offer the possibility to explore new quantum control methods for qutrits and might be of a strong interest for quantum sensing applications based on Ramsey interferometry with qudits.

The theoretical material and results presented in this PhD manuscript are nicely supported by quantum simulations demonstrating the superior efficiency of the iterative and linear MQPT protocol in evaluating the quantum error process matrix for a $\sqrt{X}$ and a CNOT gate. The algorithms based on the iteration or the repetition of processes which are presented in this manuscript are crucial for precision tomography related to accurate quantum gate characterization. The motivations of the PhD project are well explained in the introduction and supported by appropriate references within each thesis chapter. S.G. Stanchev has finally participated in various international conferences (ICAP, CAMEL, ECAMP). Three scientific publications in high quality international physics reviews have been published between 2023 and 2024. I therefore fully agree to a PhD defense by S.G. Stanchev before the end of the year 2024.

Dr. Thomas Zanon-Willette @ SU (30/08/2024)